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Comparison of reconstitution methods for mine tailings materials

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Article

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Compaction curves
Specimen uniformity
Shear strength
Fabric

Abstract

The paper studies the effect of sample reconstitution for three commonly employed procedures, namely static compaction and standard and modified moist tamping methods, in the context of laboratory testing of mine tailing materials. The effect of initial water content and compaction energy on the resulting densities and uniformity of the samples are examined. Equivalencies between different reconstitution methods were established to attain a given target density. Then, the effect of the resulting fabric was investigated by means of isotopically consolidated undrained triaxial tests, on samples prepared with similar densities and water contents but with different reconstitution techniques. The results showed that all reconstitution techniques studied produced samples with acceptable uniformity and good repeatability. Although similar results were obtained across the different methods, the modified moist tamping technique yielded slightly higher undrained peak strengths and exhibited a more pronounced hardening behavior upon reaching the critical state line compared to the static compaction method. In contrast, the moist tamping and static compaction methods produced comparable responses in loose specimens. These results suggest that dynamic and static reconstitution methods may create subtle differences in the fabric of the samples, influencing their behavior under shearing.

1. Introduction

Reconstitution techniques to obtain good-quality specimens for triaxial testing can be challenging depending on the type of material. They are necessary to evaluate the behavior of soils where good quality undisturbed samples are difficult to obtain or the techniques necessary to obtain them are prohibitively expensive; this problem is common in sands, gravels, and some mine tailings. Therefore, many researchers rely on preparing reconstituted samples, with similar properties to the in-situ material, that can be used to obtain engineering parameters. In practice, the most used reconstitution methods (RM) are moist tamping (Castro, 1969; Ladd, 1978), static compaction (Serratrice, 2022; Venkatarama & Jagadish, 1993, Alkiki et al., 2021), air and water pluviation (Miura & Toki, 1982), and slurry deposition (Carraro & Prezzi, 2008). However, although reconstituted specimens can reproduce in situ volumetric conditions (dry or wet density and void ratio), it is much harder to reproduce the structure of the material (mainly fabric in the case of uncemented soils) (Corrêa & Oliveira, 2019) where water content and the compaction method and energy play an important role (Lambe & Withman, 1969; Sloane & Kell, 1966). Significant effects due to soil's structure have been reported in static or cyclic triaxial tests (Yang et al., 2008; Vaid & Sivathayalan, 2000; Miura & Toki, 1982; Carraro & Prezzi, 2008), although critical state conditions appear to be independent of the initial state, fabric, and testing conditions (Fonseca et al., 2022; Verdugo & Ishihara, 1996; Fourie & Tshabalala, 2005).

It has been identified that the moist tamping method generates a greater contractive response in loose soils with fines compared to other reconstitution methods (Vaid et al., 1999; Thevanayagam et al., 2002; Corrêa & Oliveira, 2019). Some authors also suggest that subaqueous deposition techniques, such as slurry deposition and water pluviation, can better reproduce the in situ soil's structure and the stress-strain response of liquefiable sand deposits, with or without fines, such as alluvial deposits, hydraulics fills, and mining waste deposits (Carraro & Prezzi, 2008), while static compaction and moist tamping can reproduce structures similar to rolled materials (Kuerbis & Vaid, 1988).

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One major issue of reconstituted specimens is the possible lack of uniformity, where the lower portion tends to become denser due to the compaction of each successive layer. Consequently, several techniques for evaluating the uniformity of specimens have been reported in the literature, such as digital image analysis (Al-Shibli et al., 1996), X-ray computed tomography (Lee, 1994; Mooney, 2002; Thomson & Wong, 2008), interlayer dyeing (Flores, 2008) and specimen solidification with gelatine (Emery et al., 1972), where variations in the void ratio within the specimen have been identified, that depend on the reconstitution method (Mulilis et al., 1977; Vaid & Negussey, 1988; Vaid & Sivathayalan, 2000; Frost & Park, 2003).

This study aims to compare three commonly employed reconstitution methods in the context of laboratory testing of mine tailing materials. Particularly, the static compaction and the standard and modified moist tamping methods were addressed in this research. Results on specimen uniformities, compaction curves, and isotropic consolidated undrained (CIU) triaxial tests are presented, for different initial void ratios and water contents. They provide relevant insights into the performance of the adopted reconstitution techniques, particularly on the resulting undrained behavior of the samples under shearing, as well as identified limitations and shortcomings.

It is important to note, however, that this study does not address the representativeness of samples prepared using the methods studied here in relation to field conditions. This remains an open problem in geotechnical engineering, which has gained renewed attention following recent large-scale tailing dam failures (Morgenstern et al., 2016; Robertson et al., 2019; Arroyo & Gens, 2021). For hydraulically deposited tailings, water pluviation may appear to be a suitable method for approximating field conditions. However, it is virtually impossible to consistently obtain contractive specimens that exhibit undrained softening (i.e. flow liquefaction) using pluviation techniques (Fourie & Tshabalala, 2005), contradicting the accepted explanations for observed large-scale failures. Furthermore, even when "undisturbed" sampling is feasible, brittleness tends to be underestimated due to the small deformations required to mobilize peak undrained strengths (Reid et al., 2024), which can be attained during sampling. Therefore, at least for now, the preferred reconstitution method is one that offers the greatest control over the initial void ratio, rather than one that best replicates the in-situ depositional environment (Fourie et al., 2022). On the other hand, for artificially compacted tailings, as in the case of dry stacking (Cacciuttolo Vargas & Pérez Campomanes, 2022), a stronger case can be made for the representativeness of a given reconstitution technique in approximating the compaction method used in the field. In any case, the authors believe that further research on this topic is certainly required.

2. Materials

Two mine tailings materials were considered for this study. The first one (M1) comes from a mine located in the State of Chihuahua, Mexico, while the second one (M4) was obtained from a tailing storage facility (TSF) located in Minatitlan, State of Colima, Mexico. These materials are the byproduct of crushing and processing to obtain silver, gold, and iron. Some physical properties are summarized in Table 1. They exhibit high fine contents, 82 and 44% for M1 and M4, respectively, with basically null plasticity and, therefore, they were classified as ML and SM according to the Unified Soil Classification System (USCS). Figure 1 shows the particle-size distribution of their coarse fraction.

For material M1, specimens were reconstituted using static compaction and modified moist tamping methods. The resulting specimens were assessed through visual inspection, uniformity evaluation, and compaction curves.

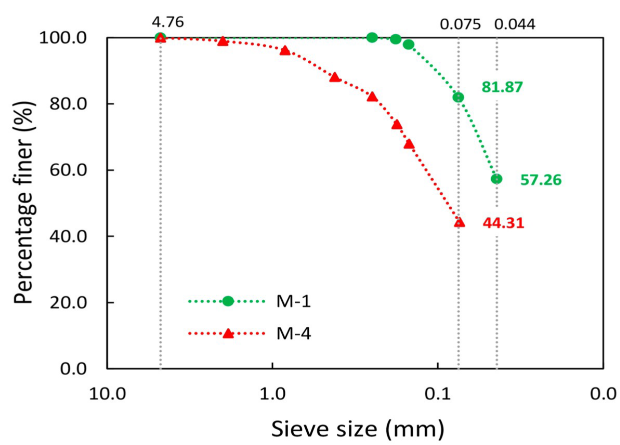


Figure 1. Particle-size distribution for mine tailing M1 and M4.

Table 1. Properties of the mine tailings used in this study.

Sample	Specific gravity, G_s	Liquid limit, LL	Plastic limit, PL	< 0.074 mm	< 0.044 mm	Max. void ratio, e_{max}[a]	Min. void ratio, e_{min}[a]
-	-	%	%	%	%	-	-
M1	2.67	26.90	-	81.87	57.26	1.57	0.94
M4	3.19	24.87	-	44.31	-	1.89	0.72

[a]Using the methodology proposed by Lade & Yamamuro (1997).

Their behavior under shearing was examined using CIU triaxial compression tests at different initial densities. Similarly, for material M4, specimens were reconstituted with static compaction and moist tamping methods. These specimens also underwent visual inspection and compaction curve analysis, and their shear behavior was assessed through CIU tests under loose conditions.

3. Specimen reconstitution methods

3.1 Static compaction (SC)

The equipment consists of a split mold, usually with an internal diameter of 3.6 cm and height of 8.6 cm, and a tamper, 3.4 cm in diameter, with adjustable mass ranging from 0.2 kg to a maximum of 24 kg (Figure 2). Specimens are compacted in 5 to 10 layers, by placing the tamper on each layer for 10 seconds and repeating the process for subsequent layers. The amount of total dry material ranges between 0.08 and 0.2 kg, and the amount of material for each layer depends on the adopted mass of the tamper and water content. To ensure uniform densities, an undercompaction approach can be adopted (Ladd, 1978) using smaller amounts of soil or changing the mass of the piston for each layer from bottom to top. Generally, using different amounts of soil for each layer is preferred, since it allows for a rapid sample preparation without the need for adjustments in the tamper mass.

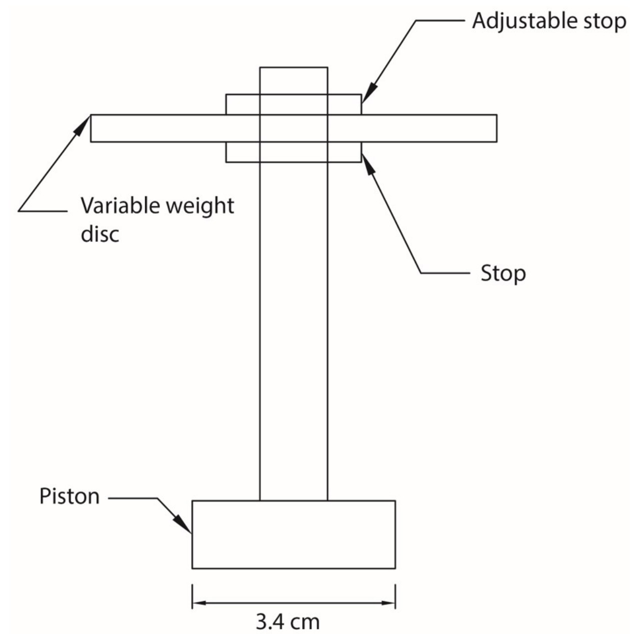


Figure 2. Tamper used in the static compaction method.

3.2 Moist tamping (MT)

The moist tamping method is similar to SC, where a split mold, in this case 3.6 cm in diameter and 8.6 cm in height, is used to compact the soil in layers (from 5 to 10) by means of a tamper of adjustable mass. However, the tamper has a reduced diameter, in this case of 1.5 cm. Therefore, each layer is tamped several times, according to the sequence shown in Figure 3.

The dimensions of the mold and the tamper used here are based on those reported by Ladd (1978). As in the SC method, the amount of dry material for each layer depends on the adopted mass of the tamper and the water content.

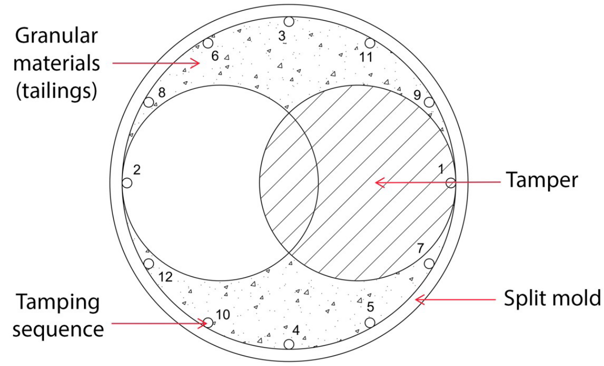


Figure 3. Tamping sequence in the moist tamping method.

3.3 Modified moist tamping (MMT)

Characteristics of the modified moist tamping method are also comparable to the SC method, where similar dimensions of the split mold and the tamper are adopted (Figure 4). However, in this case, compaction energy is provided by dropping a hammer onto the tamper from a specific height. The tamper is generally made of acrylic, which is attached to a steel rod that guides the fall of the hammer (see Figure 4). The rod has an adjustable stop to control the drop height. The drop height, the mass of the hammer, and the number of blows can be adjusted to control the compaction energy. The sample is usually compacted in five layers. As in the previous methods, an undercompaction approach can be adopted to improve uniformity, for instance adjusting the drop height (Bradshaw & Baxter, 2007).

3.4 Recommendations for reconstitution

From the application of the aforementioned reconstitution methods, some general recommendations can be drawn regarding its application for mine tailing materials:

- For loose specimens, it is crucial to maintain water content below 15% to prevent the formation of porous and non-uniform structures. As identified by the authors, the maximum water content should be approximately 4 to 5% less than the liquid limit to avoid water leakage from the mold's bottom during the compaction process;

- Layer thickness larger than 25 mm should be avoided for molds with diameters less than 10 cm (Ladd, 1978);
- Compaction curves should be obtained before selecting a water content for reconstitution, especially if in situ parameters like void ratio or unit weight are not known;
- Density variations of each layer must be identified if an undercompaction strategy is required;
- A visual inspection of the different specimens must be performed;

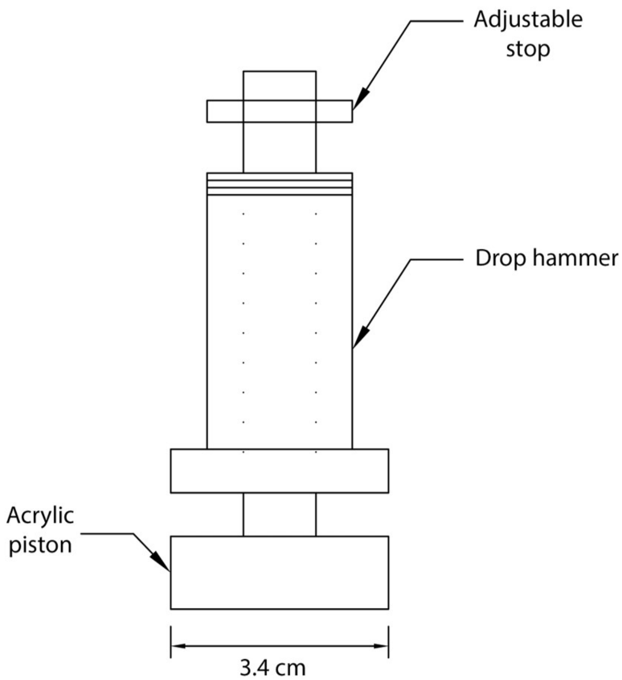


Figure 4. Tamper used in the modified moist tamping method.

- Water contents for reconstitution are generally around 5% for sands and are usually higher for silty and clayey soils. This is due to different water retention capacities, permeabilities, and particle sizes;
- For low water contents, drop heights higher than 3 cm cause material lifting in the MMT method;
- Acetate sheets should be used to prevent the material from adhering to the mold; this problem becomes more significant as the water content is increased;
- Scarification of the top of each layer is required before placing the next to improve friction between the layers;
- Use of a small spirit level during compaction to avoid non-uniform placement, which can generate uneven compaction;
- When very dense specimens are needed, MMT can be more effective using larger hammer masses and drop heights. In the SC method, tamper masses larger than 12 kg make the procedure impractical.

It is also important to mention that the adopted methods did not produce considerable particle crushing during compaction, at least for the masses and drop heights adopted. This was verified by determining the particle-size distribution before and after reconstitution in the most critical cases considered, i.e. a piston mass of 3 kg for the SC method and a hammer mass of 0.127 kg and a drop height of 4 cm for the MMT method. The obtained differences between the two particle-size distributions were only about 1%.

4. Densities achieved

4.1 Static compaction (SC)

Compaction curves from the SC method, for different water contents (w) and tamper masses (TM) are shown in Figure 5a and Figure 5b for materials M1 and M4, respectively.

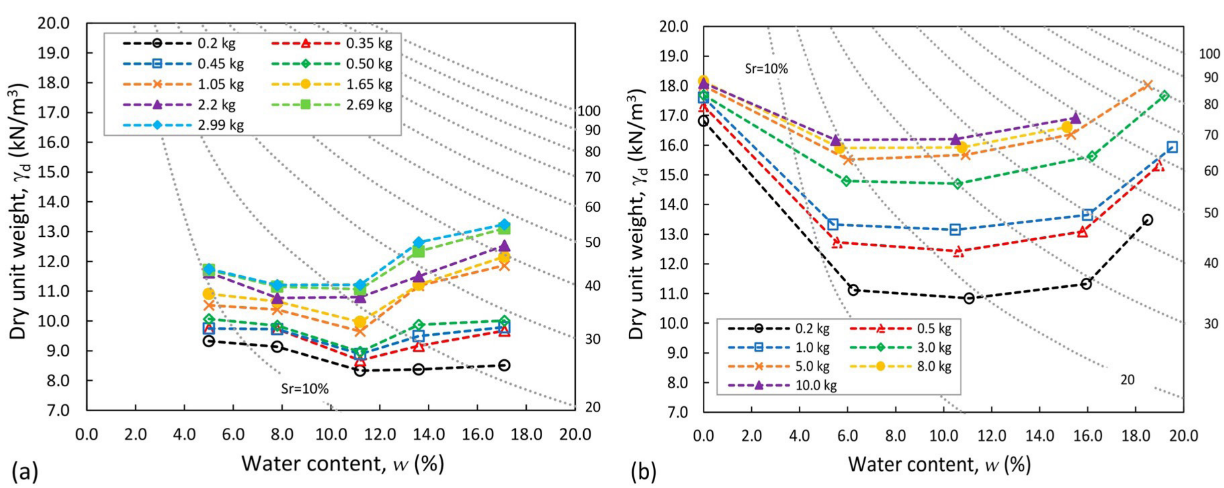


Figure 5. Compaction curves with the SC method for different tamper masses for materials (a) M1 and (b) M4.

The curves have a non-typical shape, where a clear peak value is not obtained within the range of water contents considered; this behavior is common for static methods, and similar findings have been reported by Honda et al. (2003). The initial decrease in the dry unit weight γ_d, observed for both materials, can be attributed to the formation of water menisci between soil grains (thus the development of matric suction) that hinders the rearrangement of particles and favor agglomerations (Mitchell & Soga, 2005).

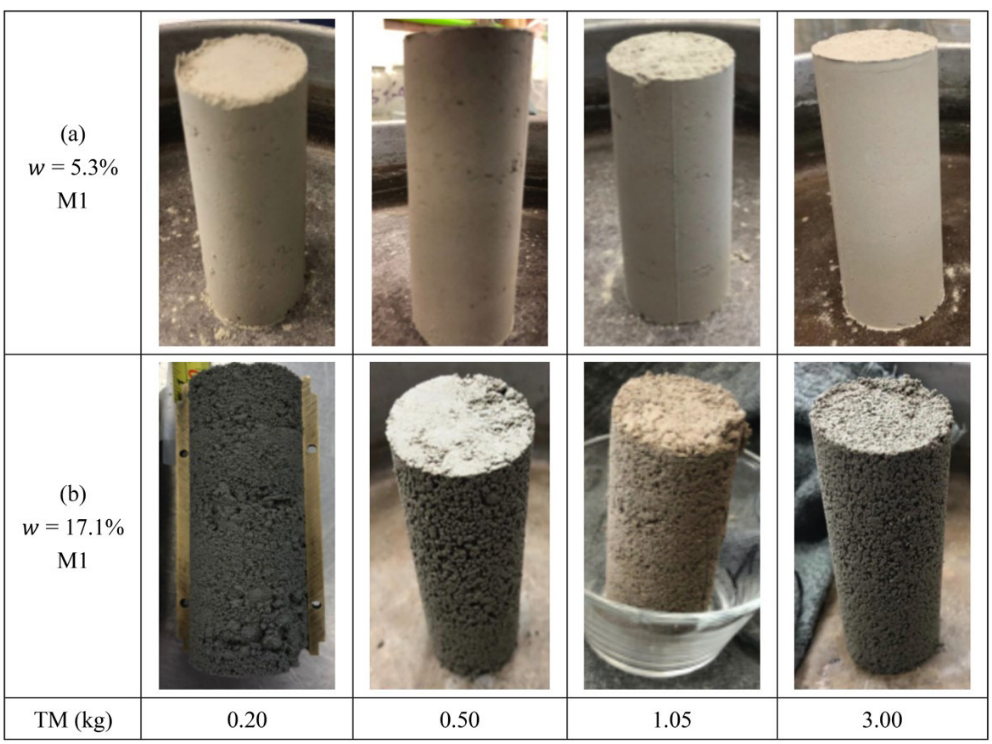
Water contents selected for specimen fabrication affect the appearance of the specimens (see Figures 6 and 7). High water contents result in non-uniform and porous specimens, regardless of the tamper mass used (Figures 6b and 7b). Conversely, lower water contents, around 5% in this case, produce much more uniform samples (Figures 6a and 7a). Therefore, it is important to consider this factor when selecting a water content for specimen reconstitution for triaxial testing to ensure more uniform specimens.

4.2 Modified moist tamping (MMT)

In this case, only material M1 was considered. A constant mass of the hammer was adopted and variations in the drop height and the number of blows were explored. Specimens were compacted in 5 layers. Table 2 summarizes the considered variables and their corresponding compaction energies. Similar compaction energies were obtained by varying the number of blows and the drop height to investigate whether there is any influence in the way energy is delivered with respect to the achieved dry unit weight γ_d. Water contents between 5 and 12% were considered, based on the results obtained from the SC method.

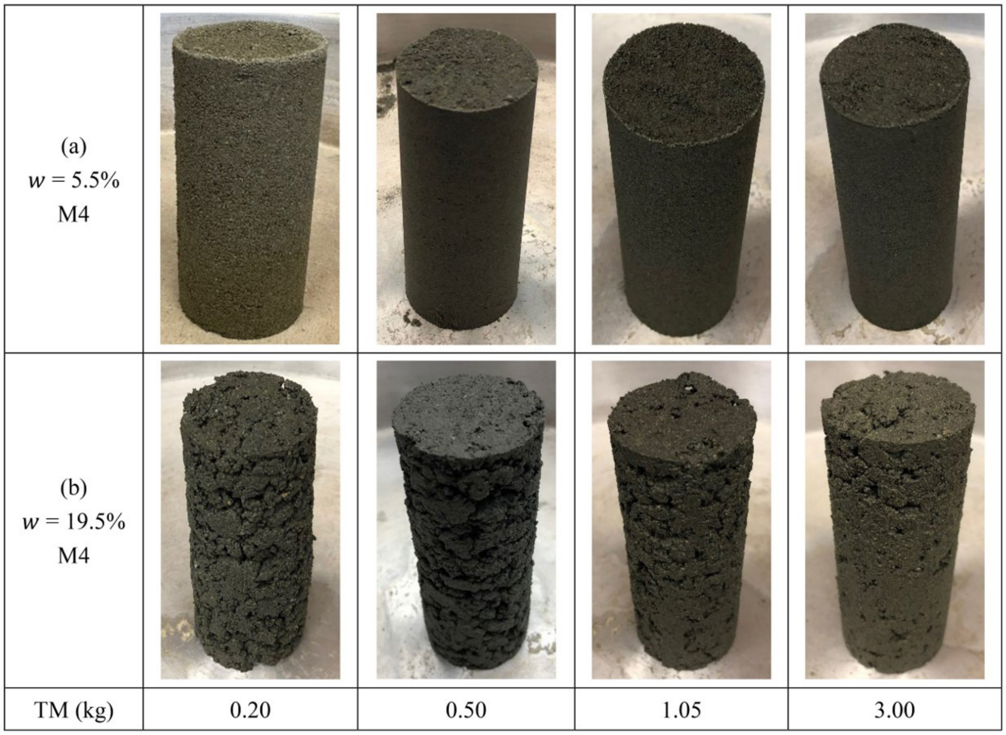
Figure 8a shows the influence of the number of blows N and drop height h on the achieved dry unit weight for w = 5.3%. It can be identified that, for a given drop height, there is a certain number of blows where the effect on γ_d starts to decrease. Similarly, the effect of increasing the drop distance seems to decrease significantly for values larger than 3 cm in this case, at least for a number of blows of 10 or below. However, as shown in Figure 8b, the achieved dry unit weight seems to be approximately independent of the specific combination of N and h, and it is solely a function of the compaction energy E_c.

As shown in Figure 9, this latter conclusion seems to hold for different water contents, where a unique relation between compaction energy and dry unit weight can be identified for each of the water contents considered. Obtained results are presented in Figure 10 in terms of compaction curves for different compaction energies, the latter obtained with different combinations of N and h. As expected, the curves move upward as the compaction energy is increased. They show the typical shape resulting from dynamic compaction, where the dry unit weight first increases with the water content, up to a maximum value, and then decreases.



w: water content; TM: tamper mass.

Figure 6. Specimens with different water contents reconstituted with the SC method for material M1.



w: water content; TM: tamper mass.

Figure 7. Specimens with different water contents reconstituted with the SC method for material M4.

Table 2. Adopted variables and compaction energies used in the MMT method.

Number of blows, N	Drop height, h	Tamper mass, *TM*	Compaction energy, E_c
-	cm	kg	(kJ/m^3)
5	1		3.42
10	1		6.84
25	1		17.10
5	2		6.84
10	2		13.68
25	2	0.128	34.20
5	3		10.26
10	3		20.52
25	3		51.30
5	4		13.68
10	4		27.36
25	4		68.4

4.3 Equivalence between SC and MMT

To achieve specimens with the same void ratio (e) using both the SC and MMT methods, an equivalence can be established. Figure 11a shows a dual y-axis graph to obtain a certain void ratio as a function of the tamper mass (3.4 cm tamper diameter) for SC (black y-axis) and compaction energy for MMT (red y-axis). From this figure, it can be determined what tamper mass for SC results in a specimen with an equal void ratio corresponding to a certain compaction energy from the MMT method.

To obtain equal void ratios in the SC and MMT methods, the tamper mass and the compaction energy show the relation depicted in Figure 11b, which can be approximated with the polynomial function shown. These results were obtained for M1 with void ratios between 1.2 and 1.8 and for w = 5.3%.

4.4 Equivalence between SC and MT

Before performing the triaxial tests, it was necessary to establish an equivalence between the MT and SC methods to achieve the target density. Trials indicated that a tamper

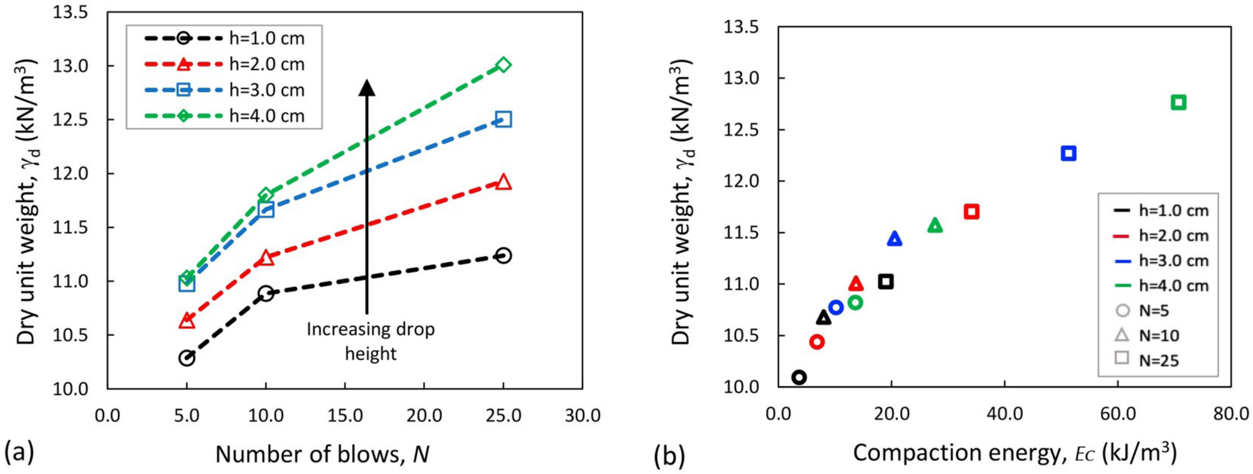


Figure 8. Effect of the (a) drop height h and number of blows N and (b) of the compaction energy on the achieved dry unit weight for w = 5.3% with the MMT method.

mass of 0.5 kg for the MT method was equivalent to 2.0 kg for the SC method. The compaction curves for reconstituted samples of material M4, shown in Figure 12 are similar and follow the same trend observed with the SC method.

4.5 Interlayer density variations

Simple and inexpensive procedures can be used to verify the uniformity of the reconstitution procedure. Because the most important variations generally occur in the lowest portion of the specimen, a measure of uniformity can be obtained by comparing the density (or void ratio) of the first layer with respect to the average density of the sample. This is achieved by placing a spacer to separate the first layer, allowing for accurate measurement of both the weight and dimensions of the two portions (Figure 13b), thereby enabling independent density determination for each of them. This procedure was applied in selected samples of the material M1, where differences of about 2.5% and 3% with respect to the average density were identified for both the SC and the MMT methods, respectively, on specimens with a void ratio of around 1.38

Another approach consists of dyeing the soil of alternate layers and reconstituting the sample within a translucent mold, so that the thickness of each layer, and therefore its density, can be estimated (Figure 13a) (Flores, 2008). The layer thickness is generally measured at three orientations (0°, 120°, and 240°) so that an average value can be determined and used to estimate the density of each layer. Figure 14 illustrates the variation of void ratio for loose and dense specimens of material M1, prepared using both the SC and MMT methods. The values presented represent the average of two specimens, both showing the same trend. Generally, the lowest two layers tend to be denser. However, for the loose sample prepared using the MMT method and the dense sample using the SC

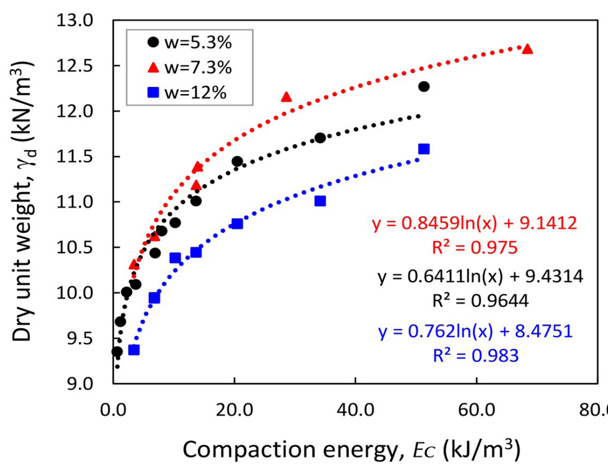


Figure 9. Effect of compaction energy and water content on the achieved dry unit weight with the MMT method.

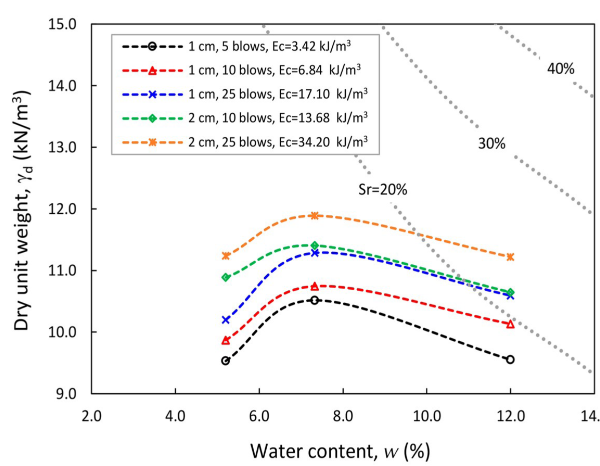


Figure 10. Compaction curves obtained with the MMT method.

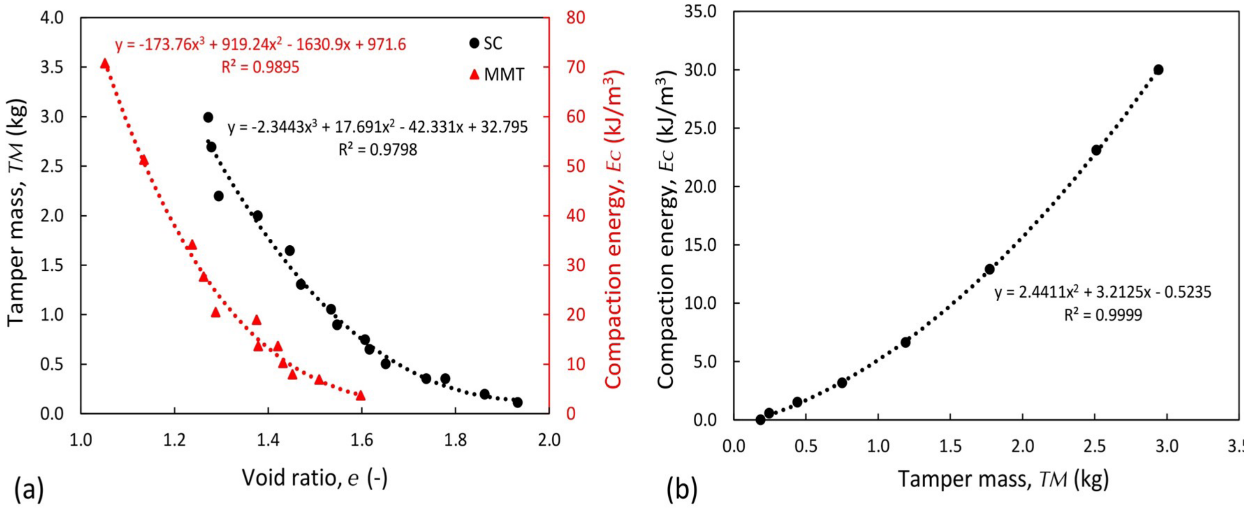


Figure 11. Equivalence between SC and MMT methods. (a) Effect of tamper mass or compaction energy on void ratio, and (b) equivalence between reconstitution methods.

method, the highest density (indicating the lowest void ratio) occurred in the second layer from the bottom. For the MMT method, this could be attributed to wave reflections at the rigid base during the compaction of the first layer, which may hinder efficiency. However, this explanation does not apply to the SC method, leaving a satisfactory explanation still pending. These results contrast somewhat with those reported by Frost & Park (2003), who observed the lowest density in the second layer when using the standard moist tamping method.

Only one specimen exhibited a local deviation in relative density of 10.6% (corresponding to a 7.6% deviation in void ratio) from the average. This occurred in one of the dense MMT samples, where the first layer reached a higher density. Such deviations are common when compacting granular materials in layers, as each successive layer can further densify the layer beneath (Ladd, 1978). Overall, however, deviations from the average remained typically under 7.9% (5% in terms of void ratio), which is usually deemed acceptable (Reid et al., 2024). However, when compared to water pluviation, where relative density variations are reported in the order of 2 to 3% (Vaid & Negussey, 1988), it is evident that the SC and MMT methods yield less uniform specimens.

5. Triaxial testing

5.1 Test procedure

A series of consolidated isotropic undrained (CIU) triaxial tests were conducted on specimens reconstituted with different methods, for different initial void ratios e and consolidation stress σ'_3, according to the guidelines from ASTM D4767-11 (ASTM, 2020). As described in Section 3, specimens were reconstituted in a split mold of 3.6 cm in diameter and 8.6 cm in height, and compacted in 5 layers for MMT and SC, and in 10 layers for MT, using the appropriate tamper for each reconstitution technique.

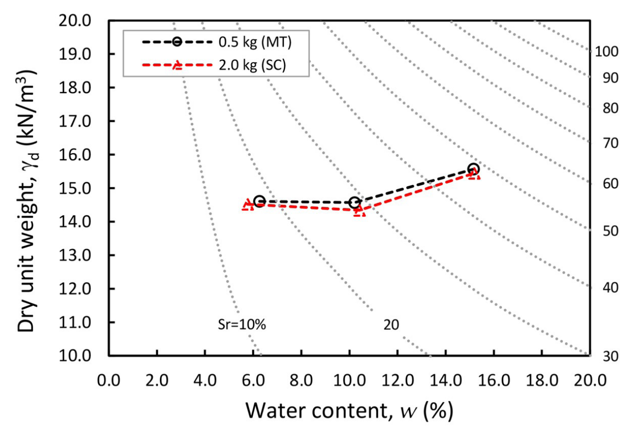
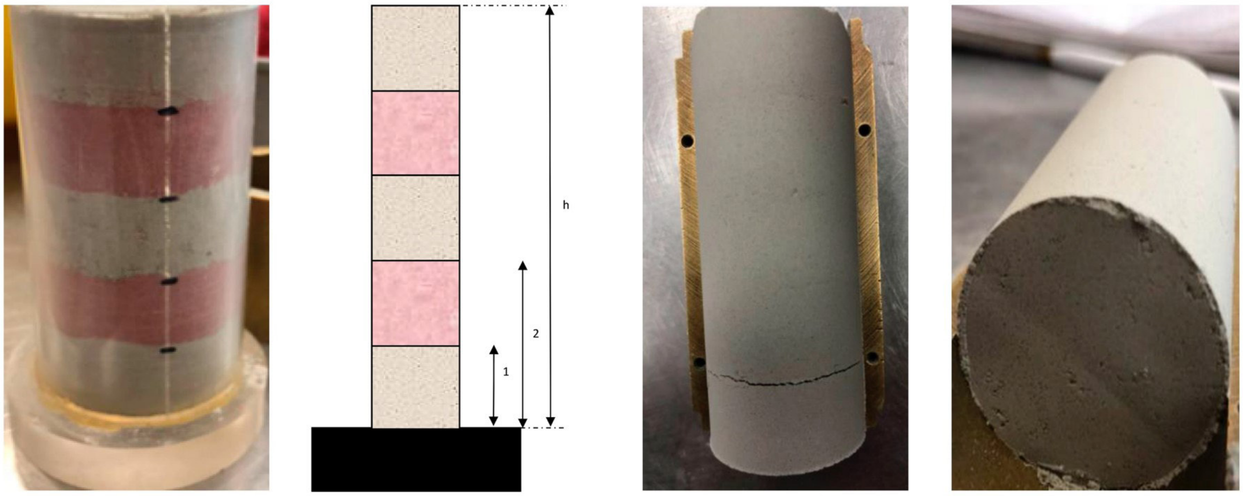


Figure 12. Compaction curves for MT and SC methods, sample M4.

Specimens were reconstituted with initial water contents ranging from 5% to 10%, as this range yielded the most uniform specimens (see Section 4). Different initial void ratios were considered to assess the effects of density variations among the reconstitution techniques studied. Tests were conducted at effective confining pressures of approximately 100 and 150 kPa for materials M4 and M1, respectively. This level of confinement is readily attained in any tailing storage facilities (TSF), yet it excludes the possibility of particle breakage (Wagner et al., 2024), which was not part of the scope of the present work.

Membrane correction and the use of thin membranes are crucial for very loose specimens, as thicker membranes



(a) (b)

Figure 13. Evaluation of uniformity. (a) Interlayer dyeing method and (b) Last layer spacer method.

can adhere tightly to the specimen, potentially leading to unintended densification. According to ASTM D4767-11, the membrane thickness must not exceed 1% of the specimen's diameter (ASTM, 2020).

For saturation, carbon dioxide (CO_2) was first circulated through the specimen at a low pressure (~3 to 10 kPa) for 45 minutes. Since CO_2 is more soluble in water than air, this aids in the saturation process and prevents the use of high backpressures. Then, distilled and de-aired water was circulated at a pressure of 10 kPa (Fonseca et al., 2021). For material M4, a total volume of 170 ml was circulated through the sample, while for M1 the volume was approximately 100 ml. The latter lower value is because of the lower permeability exhibited by material M1, making this process more time-consuming. Finally, specimens were saturated using backpressure until achieving values of Skempton's (1954) B parameter of at least 0.95. Backpressure increments were applied maintaining a constant effective mean stress of about 10 kPa. Samples were sheared by applying a constant axial strain rate of 0.065%/min, which guaranteed pore-pressure equilibration under undrained conditions (ASTM, 2020).

5.2 Comparison between modified moist tamping (MMT) and static compaction (SC)

CIU tests were performed on specimens of material M1, prepared with the MMT and SC methods. Table 3 summarizes some characteristics of the tests performed. All specimens were prepared with an initial water content of 5.3% and for three different target densities (note that test numbers refer to the different density levels). In the case of the MMT method, different final void ratios were obtained using a constant mass of the hammer and varying the drop height and the number of blows, while for the SC method, different tamper

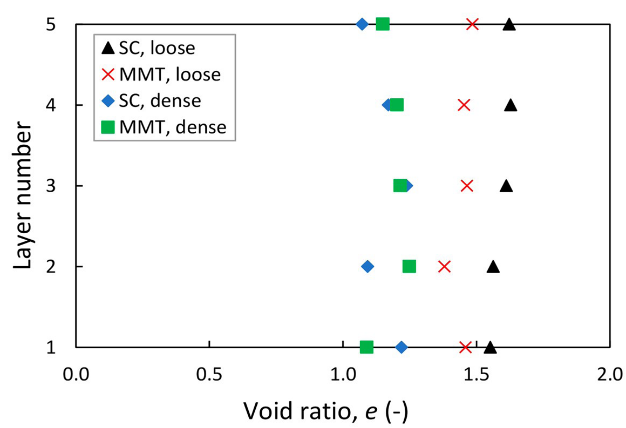


Figure 14. Variations of void ratio per layer with the SC and MMT methods.

masses were adopted. Similar void ratios were obtained with both methods for each density level, which allows for an objective comparison.

For the lowest density, both reconstitution procedures initially achieved void ratios higher than those typically found in situ for mine tailings and sands (> 1.4; see e.g. Oliveira et al., 2023). However, these specimens exhibited a significant densification during mounting and saturation. This densification of very loose specimens during the setup has been previously reported in the literature for these RMs (Sladen et al., 1985; Paz, 2015). Membrane effects are also quite significant for these very loose samples and, therefore, membrane correction (Kuerbis & Vaid, 1990) is of paramount importance. They also tend to form a noticeable uneven diameter along their height, with the smallest diameter in the center of the specimen.

Table 3. Properties of samples for testing reconstituted with the MMT and SC methods.

Reconstitution method and test number	Tamper mass, TM	Drop height,	Number of blows, N	Compaction energy, E_c	Layers	Water content, w	Consolidation stress, σ'_3	Initial void ratio, e_i	Final void ratio, e_f
-	kg	m	-	kJ/m³	-	%	kPa	-	-
MMT-1	0.127	0.01	2	1.37	5	5.3	143.0	1.66	1.11
MMT-2	0.127	0.01	5	3.42			144.2	1.44	1.04
MMT-3	0.127	0.02	10	13.68			143.7	1.10	0.97
SC-1	0.350	-	-	-			140	1.69	1.13
SC-2	0.650	-	-	-			143.1	1.47	1.06
SC-3	2.90	-	-	-			144.1	1.08	0.95

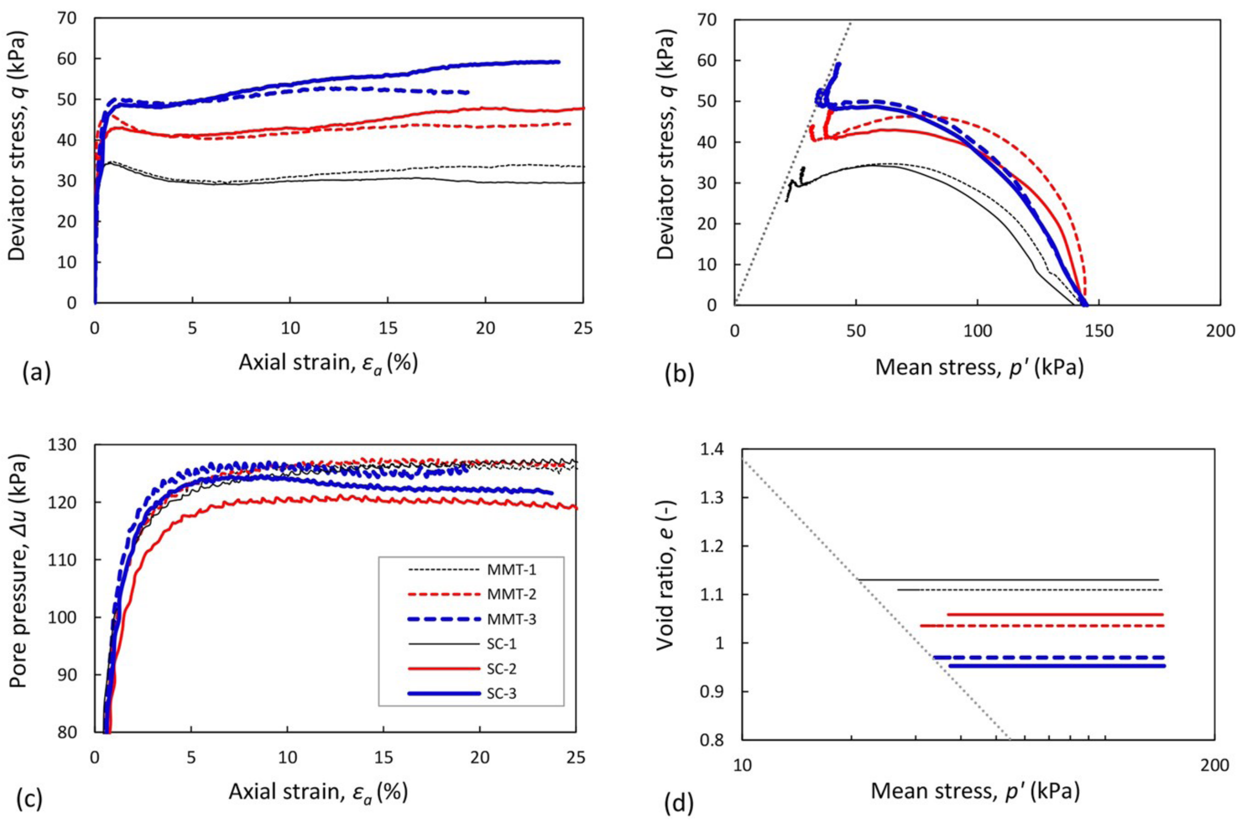


Figure 15. Results from undrained triaxial tests on samples reconstituted with the MMT and SC methods. (a) Stress-strain curves, (b) stress paths and, (c) pore-water pressure evolution, and (d) compression plane.

Figure 15 shows the results of the CIU tests in terms of (a) stress-strain curves, (b) effective stress paths, (c) pore-water pressure evolution, and (d) the compression plane. As expected, regardless of the RM or initial density, all samples reached, approximately, the critical state line (CSL) in the p-q (Figure 15b) and compression (Figure 15d) planes.

As previously mentioned, the CSL is known to be independent of the initial state of the sample and the reconstitution procedure (Fonseca et al., 2022). Therefore, under a similar effective confining pressure, there is a significant influence of the initial density, increasing the undrained strength as the void ratio is decreased. All samples showed an initial contractive behavior, with the accumulation of excess pore-water pressure and, for the lowest and intermediate density levels, a limited softening response. However, on approaching the CSL, all samples showed a slightly dilatant behavior with hardening and, in some cases, with a subtle reduction of water pressures, except for the loosest test with the static compaction method SC-1, which showed a somewhat inconsistent behavior towards the end of the tests. All samples generated similar pore-water pressures, around 120 and 125 kPa, regardless of the initial density or RM. In general, samples from both methods showed similar behavior. However, for the two highest densities, the undrained peak strength before reaching the CSL is somewhat higher with the MMT method, while the subsequent hardening response is significantly more noticeable in the case of the SC method. Since no particle crushing was identified in either RM, results suggest that, for similar densities and confinement pressures, the SC and MMT methods result in slightly different fabrics.

The loosest samples showed quite similar behavior between both RM methods, with virtually the same peak undrained strength. This might be due to the very small drop height and small number of blows (see Table 3), which makes the two procedures tend to be analogous.

5.3 Comparison between moist tamping (MT) and Static compaction (SC)

Two additional CIU triaxial tests were performed on specimens of the material M4 to assess differences between the MT and SC methods. Both specimens were prepared with an initial water content of 10% and tested under an effective confining pressure of 100 kPa. The same saturation procedure, described in Section 5.1, was also adopted here. Table 4 summarizes some characteristics of the tests performed. It can be identified that quite similar void ratios were achieved for both reconstitution procedures, allowing for an objective comparison.

Figure 16 shows the obtained results in terms of (a) stress-strain curves, (b) effective stress paths, and (c) pore-water pressure evolution. Unlike the behavior of the tests in Figure 15, both samples exhibit flow liquefaction, with a distinct undrained peak strength and a subsequent abrupt softening response until reaching a total liquefied condition, i.e. a null effective mean stress. Furthermore, both tests showed quite similar behavior in all plots, only with a slightly smaller undrained peak strength in the case of the SC method. In general, it can be stated that, for similar densities and confinement pressures, both the SC and MT methods result in analogous samples. These results suggest that, for these tamper-based RMs, differences in fabric occur between static and dynamic compaction procedures and not between variants of the static methods.

It is important to note that the strain-stress curves (Figure 16a) and stress paths (Figure 16b) exhibit small

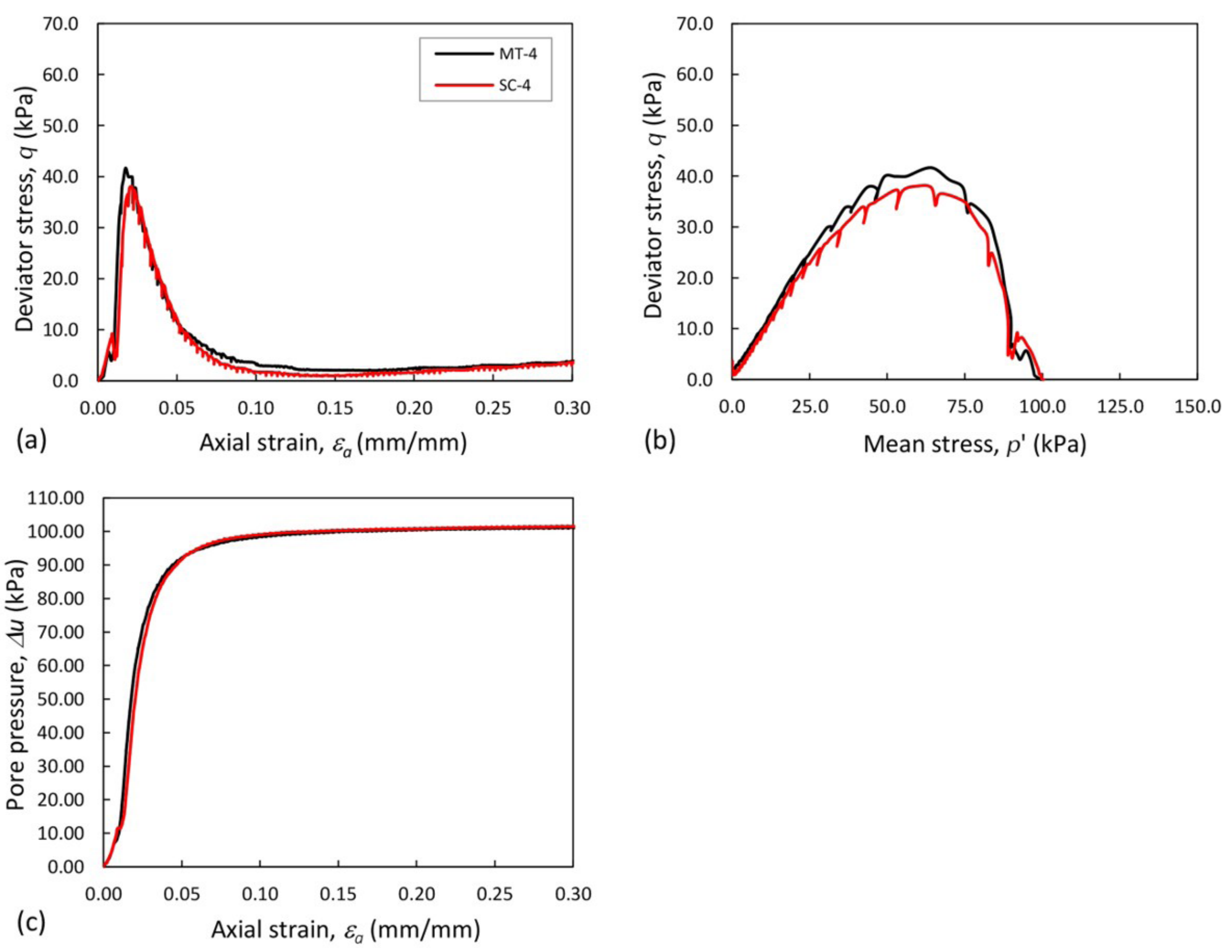


Figure 16. Results from undrained triaxial tests on samples reconstituted with the MT and SC methods. (a) Stress-strain curves, (b) stress paths and, (c) pore-water pressure evolution.

Table 4. Properties of samples for testing reconstituted with the MT and SC methods.

Reconstitution method and test number	Tamper mass, TM	Layers	Water content, w	Consolidation stress, σ_3'	Initial void ratio, e_i	Final void ratio, e_f
-	kg	-	%	kPa	-	-
MT-4	0.5	10	10.0	99.58	1.073	0.890
SC-4	2.0	10	10.0	100.33	1.105	0.899

oscillations. This behavior can be attributed to the use of a servo-controlled equipment, which enables highly precise data acquisition, with a load cell precision of around 2 kPa. The high resolution of the system highlights minor fluctuations, resulting in the observed oscillations.

6. Conclusions

This paper presented the results of an experimental program aimed to assess three commonly employed reconstitution procedures, namely the static compaction and the standard and modified moist tamping methods, in the context of testing mine tailing materials. The following conclusions can be drawn from this study:

- In general, the methodologies assessed are readily applied and do not generate particle crushing, at least for the conditions studied. Very loose to medium dense specimens can be formed, and under compaction strategies can be applied to reduce non-uniformities;
- The modified moist tamping method resulted in specimens that tend to have somewhat higher undrained peak strengths compared to the static compaction method, while the latter showed a more noticeable strain hardening response on reaching the CSL. These results suggest that somewhat different fabrics are attained between static and dynamic compaction procedures. However, these differences become less important for looser specimens, where the dynamic methods require very small drop heights and a low number of blows, which tend to make them analogous to a static compaction;
- In the case of the modified moist tamping method, the way compaction energy is delivered does not seem to have a significant effect on the resulting density;
- Due to its simplicity and ease of use, the static compaction method provides an appealing alternative for the reconstitution of loose to medium dense tailing samples, showing analogous behavior to the moist tamping method;
- However, the initial water content represents a major factor in the resulting fabric of the reconstituted specimens. Higher water content facilitates the formation of lumps, resulting in porous and non-homogenous specimens. Maximum water contents of around 4 to 5% less than the liquid limit of the fine fraction resulted in adequate compaction and reasonable uniform specimens.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Mauricio Bernal López: conceptualization, data curation, investigation, visualization, writing – original draft, methodology. Luis Gerardo Cruz Flores: conceptualization, data curation, investigation, methodology, visualization, validation, writing – original draft, methodology. Eduardo Botero Jaramillo: supervision, funding acquisition, writing – review & editing, project administration, resources. Miguel Ángel Mánica Malcom: supervision, funding acquisition, writing – review & editing, project administration, resources. Osvaldo Flores Castrellón: supervision, funding acquisition, project administration, resources.

Data availability

All data produced or examined in the course of the current study are included in this article.

Declaration of use of generative artificial intelligence

This work was prepared with the assistance of generative artificial intelligence (GenAI) [ChatGPT] for the purpose of identifying grammatical errors and improving the clarity of wording in certain parts of the text. The entire process of using this tool was supervised, reviewed, and edited by the authors as necessary. The authors take full responsibility for the content of the publication, including any sections where GenAI tools were utilized.

List of symbols and abbreviations

e	Void ratio
e_f	Void ratio prior to shearing
e_{max}	Maximum void ratio
e_{min}	Minimum void ratio
h	Drop height
p'	Mean effective stress
q	Deviator stress
w	Water content
ASTM	American Society for Testing and Materials
B	Skempton's pore pressure coefficient
CIU	Isotropic consolidated undrained tests
CO_2	Carbon Dioxide
CSL	Critical state line
E_c	Compaction energy
G_s	Specific gravity
LL	Limit liquid
M1	Mine tailings from Chihuahua.
M4	Mine tailings from Colima
ML	Low plasticity silt
MMT	Modified moist tamping
MT	Moist tamping
N	Number of blows
PL	Plastic limit
RM	Reconstitution method
SC	Static compaction
S_r	Degree of saturation
SM	Silty sand
TM	Tamper mass
TSF	Tailing storage facilities
USCS	Unified Soil Classification System
γ_d:	Dry unit weight
ε_a:	Axial strain
σ'_3:	Consolidation effective stress
Δu:	Excess pore water pressure

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