

Impact of lime stabilization on strength, permeability, and critical state characteristics of mine tailings

Luis Cruz, Eduardo Botero, Miguel Mánica

Institute of Engineering, National Autonomous University of Mexico, Mexico City, Mexico, LCruzF@ingen.unam.mx

Marcos Arroyo

Department of Civil and Environmental Engineering, Universitat Politècnica de Catalunya, Barcelona, Spain.

ABSTRACT: This study investigates the mechanical properties of lime-stabilized mine tailings, focusing on the effects of compaction and curing time. A series of tests were conducted on reconstituted specimens, both untreated and stabilized, including consolidated drained and undrained triaxial tests, unconfined compression tests, constant-head permeability tests, and multi-stage oedometer tests. Additionally, scanning electron microscopy (SEM) and energy-dispersive spectroscopy (EDS) were used to examine changes in particle morphology and chemical composition. In general, the observed changes in mechanical behavior can be attributed to two mechanisms: (1) flocculation and agglomerations, which alter particle size and morphology, and (2) pozzolanic reactions, which form a gel that acts as a cementing agent and alters the materials chemical composition. The first mechanism occurs shortly after lime addition and is responsible for increases in compressibility, permeability, and the slopes of the critical state line (CSL) in both the compression and p' - q planes. The second mechanism progresses over time and is responsible for an increase in yield stress, unconfined compressive strength, and the upward shift of the CSL in the compression plane. It also provides some cohesion to the material, although it tended to degrade during consolidation in the triaxial tests. Regarding the effect of compaction, higher energies enhance lime stabilization and lead to a more sustained gain in strength. However, if compaction is not performed promptly after lime addition, it increases the resistance to densification, leading to lower densities and, therefore, reducing the efficiency of the treatment. These findings provide valuable insights into the effects of lime stabilization on enhancing the mechanical characteristics of mine tailing materials.

KEYWORDS: Critical state, mine tailings, soil stabilization, curing period, permeability.

1 INTRODUCTION

Mine tailings are a by-product of ore processing, consisting predominantly of fine-grained, low-plasticity materials, with mean particle sizes (D_{50}) typically ranging from 10 μm to 1 mm (Torres-Cruz and Santamarina, 2020). Global production is estimated at 5 to 7 billion tons per year (Edraki et al., 2014) and the most common disposal method involves the impoundment of slurried tailings behind dams. Given the vast quantities generated, there is growing interest in the reuse of mine tailings as part of sustainable mining waste management strategies (Edraki et al., 2014; Araujo et al., 2022). For instance, tailings have been explored as a substitute for sand in mortar production (Andrews et al., 2022) and are frequently used to construct raised embankments in tailings dams, particularly using the upstream daywall paddock method. However, these dams have demonstrated potential susceptibility to flow liquefaction (Fourie, Blight and Papageorgiou, 2001; Mánica et al., 2022)

The stabilization of mine tailings has attracted growing interest, since stabilization can potentially enhance the mechanical behavior of materials for a wide range of applications (Firoozi et al., 2017). One standard method is lime stabilization, which involves the incorporation of lime to improve strength, durability, and workability, as well as to facilitate heavy metal immobilization and overall performance. The effectiveness of this technique depends on several factors, including lime content, moisture conditions, mellowing period, compaction efficiency, curing time and environment, lime type, and the chemical composition of the soil (Consoli, da Silva Lopes and Heineck, 2009; Amadi and Okeiyi, 2017; Baldovino et al., 2019; Zhang et al., 2020).

When using quicklime (CaO), the first reaction is lime hydration, an exothermic process that requires at least 0.33 grams of water per gram of lime. This is followed by several reactions such as: (i) flocculation and agglomeration, promoted by the increase in pH (above 10), which enhances electrostatic attraction between fine particles; (ii) carbonation, wherein lime reacts with carbon dioxide (CO_2) to form calcium carbonate

(CaCO_3); and (iii) pozzolanic reactions, involving the reaction of hydrated lime with silica and alumina minerals in the soil to form cementitious gels that bind particles together (Joel and Edeh, 2013; Baldovino et al., 2019).

Within this context, the study aims to provide information on the effect of lime stabilization for mine tailings, emphasizing the role of compaction and curing time on the critical state parameters of the mixtures. To this end, several consolidated drained and undrained triaxial tests were conducted on reconstituted specimens, with varying compaction degrees and 6% lime content, under confining pressures ranging from 46 to 200 kPa. The critical state lines (CSLs) in the p' - q and compression planes were determined for different curing periods. Scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) were employed to analyze changes in particle morphology, as well as elemental and chemical composition. Constant head permeability tests were also performed to assess changes in permeability due to lime addition and the effect of curing time at various void ratios. The evolution of soil structure over time was also examined employing conventional multi-stage oedometer and unconfined compression tests. Results provide valuable insights into the effects of lime stabilization for improving the mechanical characteristics of mine tailings for various applications.

2 MATERIALS AND METHODS

The mine tailings used in this study are the by-product of a polymetallic mining operation in Chihuahua, Mexico, primarily focused on the extraction of gold and silver. They consist mainly of non-plastic fines, with a fines content of 82 %, and are classified as ML according to the Unified Soil Classification System. Some physical and index properties are presented in Table 1.

Table 1. Physical and index properties of the mine tailings used in this study.

Property	Value	Unit
Specific gravity, G_s	2.67	-
Liquid limit, LL	26.9	%
Plastic index, PI	-	%
< 0.074 mm	81.87	%
pH	8.53	-

Calcium oxide, hereafter referred to as lime, was employed as the stabilizing agent. Specimens were prepared using a lime content of 6 % by dry weight. The material was prepared by initially mixing dry tailings with lime, followed by the addition of distilled water; all components were mixed for 6 minutes. After mixing, the material was allowed to mellow for 20 minutes (except for compaction tests conducted after varying mellowing periods).

For triaxial and unconfined compression tests, specimens were compacted in five layers within a split mould, 3.6 cm in diameter and 8.6 cm in height, using variable-mass tampers. For oedometer tests, compaction was performed in two layers within a rigid steel ring, 7.99 cm in diameter and 2.02 cm in height. Further details on the reconstitution procedures can be found in Bernal López et al. (2025). The compacted specimens were stored in a humidity-controlled room for curing periods ranging from 0 to 270 days.

The experimental program conducted in this study included several tests aimed at evaluating the effects of lime stabilization on the mechanical properties of compacted mine tailings. These tests included compaction, permeability, unconfined compression, oedometric, and consolidated drained and undrained triaxial tests. Additionally, SEM and EDS were employed to analyze changes in particle morphology and identify the formation of cementitious compounds. A brief description of the tests performed, as well as the testing procedures adopted, is provided below.

Compaction curves were determined according to the standard Proctor energy. However, due to the considerable amount of material required in the standard procedure, equivalent compaction curves were determined using the modified moist tamping (MMT) method (Bernal López et al., 2025). Samples were compacted in three layers using a hammer weighing 0.93 kg, with a drop height of 10.5 cm and 28 blows per layer. Compaction curves were determined for various mellowing times to assess the effect of delayed compaction.

Conventional multi-stage oedometer tests were conducted on compacted specimens of untreated and stabilized tailings, under ASTM D2435 procedures, employing a load increment ratio of two every 24 hours. The objective was to assess the evolution of the yield stress σ'_y , and compressibility parameters (compression C_c and recompression C_r indices) resulting from the incorporation of lime as a function of curing time. Curing periods ranged from zero to 270 days.

Isotropically consolidated undrained (CIU) and drained (CID) triaxial compression tests were conducted under ASTM D4767 and ASTM D7181, respectively. Specimens were reconstituted using a tamper mass of 3.0 kg to achieve a loose state, both for untreated and lime-stabilized (6 % lime content) conditions. Additionally, specimens compacted with varying tamper masses were prepared to evaluate the influence of initial compaction. Distilled and de-aired water was circulated from bottom to top through the specimens at a pressure of 10 kPa (da Fonseca et al., 2021) until approximately 100 ml of water was collected from the top drainage line. Subsequently, specimens were saturated using backpressure, ensuring that the Skempton

B-coefficient (Skempton, 1954) reached values of at least 0.95, while maintaining a constant effective mean stress p' of approximately 10 kPa. Curing periods of 0, 7, 28, and 90 days, as well as confining pressures ranging from 46 to 200 kPa, were considered.

Constant head permeability tests were conducted to assess the effect of lime addition and curing time on soil permeability. Permeability values at different void ratios were estimated from three tests performed under hydraulic heads ranging between 1 and 5 m. Specimens were saturated following the same procedure described for the triaxial tests.

Unconfined compression tests (UCT) were also performed to assess the time-dependent evolution of strength. UCTs were conducted in partially saturated conditions. Extreme care was also needed during demolding to avoid damaging the specimens and inducing a failure plane before shearing. Specimens were sheared by applying a constant axial strain rate of 1.162% per minute.

Finally, SEM was employed to directly observe changes in particle size and morphology resulting from the addition of lime. Images were obtained using a JEOL JSM-7600F scanning electron microscope, offering magnifications up to 1,000,000x. Alongside SEM imaging, EDS was used to identify the elemental composition of features observed by SEM and to generate elemental mappings. Together, SEM and EDS provided valuable insights to help understand and explain observed changes in the mechanical behavior due to lime stabilization.

3 RESULTS AND DISCUSSION

3.1 Compaction curves

To assess the influence of lime on the compaction behavior of the mine tailings studied, compaction tests were conducted on both the untreated material and the material with 6 % lime content, considering different mellowing periods for the latter. Understanding the impact of delayed compaction is particularly important, as time gaps between lime addition and compaction are common on construction sites. Figure 1 shows the resulting compaction curves.

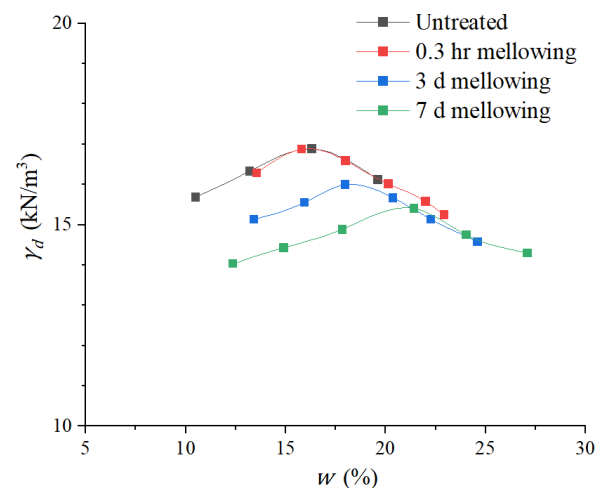


Figure 1. Influence of lime and mellowing time on compaction curves.

Overall, delayed compaction tends to reduce the dry unit weight γ_d and increase the optimum water content w_{opt} , resulting in compaction curves that shift downward and to the right. This effect is primarily due to the advancement of pozzolanic reactions, which progressively stiffen the cementitious gel formed by the interaction between lime and soil minerals. As the gel hardens, the material becomes less compressible during

compaction and retains more water, leading to a higher w_{opt} (Olaniyi, 2017). Conversely, when the material is compacted immediately after lime is added, the compaction curve remains nearly unchanged compared to that of the untreated tailings, since the pozzolanic reactions have not yet significantly progressed.

Because compaction delays tend to diminish its effectiveness, it is advised to compact the material soon after lime addition and mixing to attain maximum densification and, therefore, enhanced strength. This aligns with observations reported in several previous studies (Osinubi and Nwaiwu, 2006; Raja and Thyagaraj, 2020).

3.2 SEM and EDS analysis

Figure 2 shows a SEM image (1000x magnification) of the untreated tailing material. The angular shape of the particles, resulting from the crushing and grinding processes, is readily apparent. EDS analyses performed in some areas revealed that the main elements present in the analyzed tailing particles are oxygen, silicon, aluminum, magnesium, and iron.

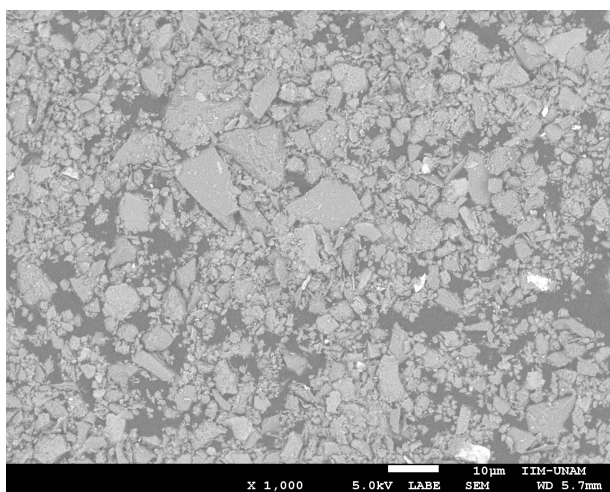


Figure 2. SEM image (1000x magnification) of untreated tailings.

Figure 3 shows a SEM micrograph of the tailings treated with 6 % lime, taken after 7 days of curing. The image reveals evident flocculation and agglomeration, resulting from the elevated pH conditions ($pH > 10$), which promote electrostatic attraction between fine-grained particles (Ross, 1988). These agglomerated structures are subsequently covered by a cementitious gel, formed through pozzolanic reactions between lime and the reactive components of the tailings. Most of the morphological changes associated with agglomeration and gel formation occur within the first seven days, with only minor alterations observed thereafter.

An EDS analysis was also performed on the particle agglomerations, revealing calcium as one of the main elements present. Overall, the results indicate that lime stabilization alters the particle size distribution through flocculation and agglomeration, changes the elemental composition of the material, and modifies particle morphology, with some of these changes being time-dependent.

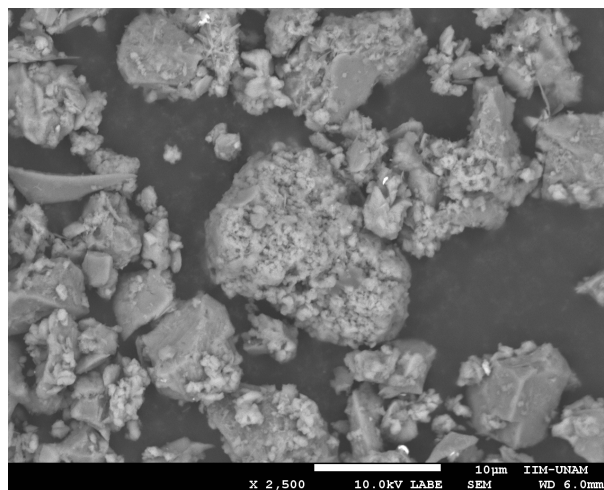


Figure 3. SEM image (2500x magnification) of treated tailings.

3.3 Unconfined compression test

Figure 4 illustrates the evolution of unconfined compressive strength q_u for specimens cured for different periods. These tests were conducted under partially saturated conditions and, therefore, the results are not directly comparable to those of the triaxial tests discussed later. However, the strength evolution over time follows a similar trend to that observed in the oedometer and undrained triaxial tests.

Despite their limitations, these unconfined compression tests demonstrate the progressive strength gain induced by lime stabilization. As expected, strength increases with curing time due to the advancement of pozzolanic reactions, which lead to the formation of cementitious bonds within the tailings' matrix (Mitchell and Soga, 2005). The rate of strength gain decreases with time, with approximately 86 % of the maximum strength (measured at 60 days) being achieved within the first 28 days. Nevertheless, continued strength development is still evident beyond 60 days. In contrast, specimens tested shortly after lime addition and mixing exhibited strength values nearly identical to those of the untreated material, indicating that insufficient time had elapsed for significant pozzolanic activity to occur.

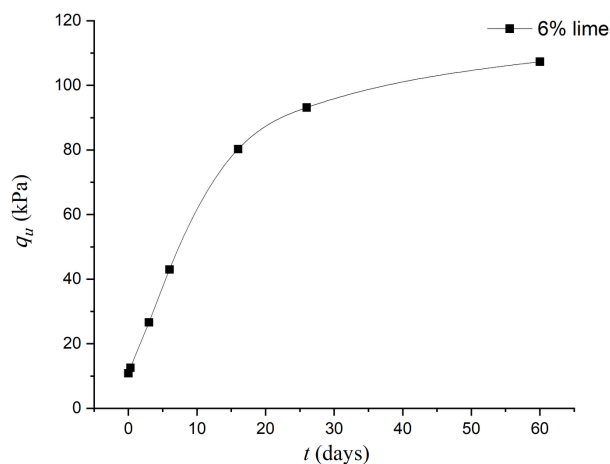


Figure 4. Influence of lime and curing time on unconfined compression strength.

3.4 Oedometric tests

Conventional multi-stage oedometric tests were performed on specimens of the untreated tailing material and the material with a 6% lime content and different curing periods. Specifically,

curing times of 0, 3, 7, 28, 90, and 270 days were considered. The resulting compressibility curves are shown in Figure 5.

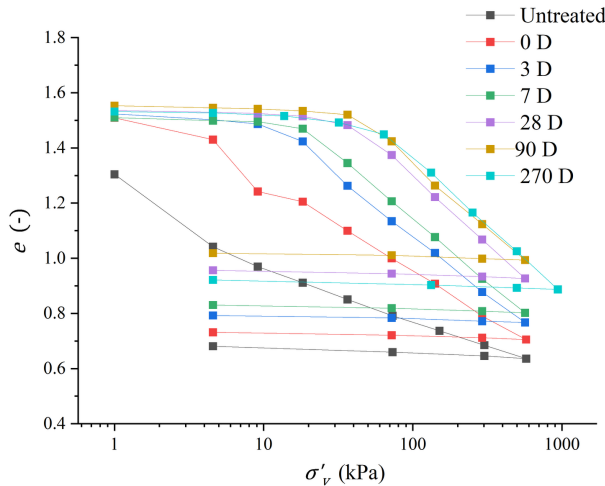


Figure 5. Influence of lime and curing time on compressibility curves.

It can be identified that lime stabilization increases σ'_y and C_c , while slightly reducing C_r (see Table 2). However, it is interesting to notice that while the yield stress increased monotonically over time, at least up to curing times of 90 days, changes in the compressibility parameters occurred only in the first seven days. Afterwards, no meaningful changes were identified in C_c and C_r and, therefore, the compressibility curves are parallel to each other. This suggests that changes in compressibility are related to flocculation and agglomeration, while the increase in the yield stress is driven by the evolution of pozzolanic reactions, i.e., with the formation of cementation.

Table 2. Compressibility parameters and yield stress as a function of time.

Curing period (days)	C_c	C_r	σ'_y
Untreated	0.172	0.020	0
0	0.345	0.012	5
3	0.323	0.012	13
7	0.465	0.014	18
28	0.500	0.014	35
90	0.481	0.012	42
270	0.499	0.015	51

The test performed shortly after lime addition and mixing (zero days) showed an increased stiffness after yielding had been achieved by the third load increment. This is because, at this stage, the strength evolves rapidly (see Figure 4) and, therefore, the constant load increment duration of 24 hours resulted in re-cementation. Consequently, the subsequent load increment resulted in a partial elastic response before resuming normal compression.

All curves lie to the right of the normal compression line (NCL) of the untreated material. The curves corresponding to the cemented material are nearly parallel to each other—parallel compression curves with spacing related to the degree of cementation have been previously reported (Rios et al., 2012). The structure conferred by cementation enables the tailings to sustain higher stress levels at a given void ratio (Burland, 1990; Leroueil and Vaughan, 1990). However, although the curves tend to approach the NCL, they do not converge within the applied pressure range, suggesting that full destructuration was not yet achieved.

3.5 Constant-head permeability tests

Figure 6 illustrates how lime addition and curing time influence the permeability of the material. The incorporation of lime led to an increase in permeability of approximately one order of magnitude compared to the untreated tailings; however, no significant changes were observed with increasing curing time. This behavior is associated with the formation of calcium silicate hydrates (CSH) and calcium aluminate hydrates (CAH), which bind the agglomerated particles and promote the rapid development of a more structured pore network. These changes increase the size of soil particles and enhance pore connectivity, thereby facilitating water flow through the material. These findings are consistent with those reported by Elkady et al. (2016), who observed only minor variations in permeability after seven days of curing, attributing this to the early-stage completion of fabric rearrangement and changes in pore size distribution in lime-treated soils.

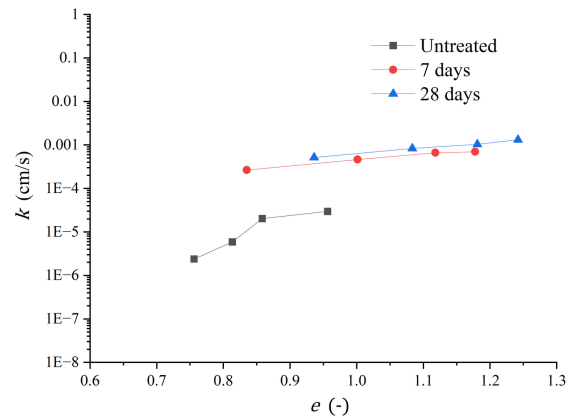


Figure 6. Influence of lime and curing time on permeability.

3.6 Triaxial CIU and CID tests

Triaxial test results performed on loose specimens under drained and undrained conditions, under confining pressures ranging from 46 kPa to 200 kPa, were employed to estimate CSLs in the p' - q and compression planes. A summary of the CSLs for each case can be seen in Figure 7, and the respective critical state parameters are reported in Table 3.

In the compression plane (Figure 7b), the slope (λ) and the vertical intercept (Γ) of the critical state lines increased with curing time. This trend aligns with findings from previous studies on lime-stabilized clays (Kasama et al., 2006) and silty sands (Cruz and Rodrigues, 2011). Since the observed changes persist beyond seven days, they cannot be attributed solely to variations in particle morphology or size distribution caused by agglomeration; instead, the continued development of pozzolanic reactions likely plays a role. Notably, while the vertical position of the CSLs (represented by Γ) shows significant evolution over time, the slope λ appears to stabilize at early curing stages, a behavior similar to that observed for the oedometer tests.

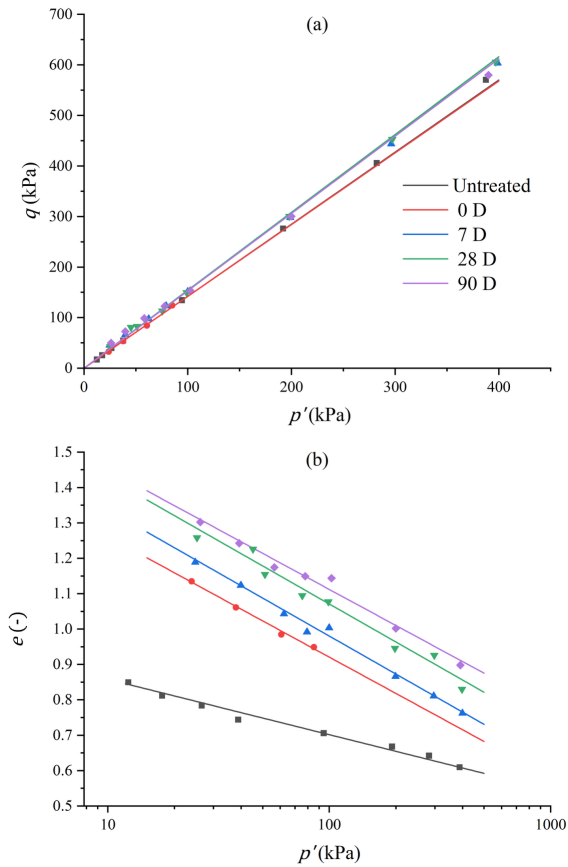


Figure 7. Influence of lime and curing time on the critical state lines in the (a) p' - q and (b) compression planes.

Table 3. Evolution of critical state parameters with curing time.

Curing period (days)	M	Γ	λ
Untreated	1.43	2.01	0.068
0	1.42	2.60	0.149
7	1.54	2.69	0.155
28	1.54	2.78	0.154
90	1.53	2.78	0.147

In the p' - q plane, a slight increase in the M value is observed between 0 and 7 days of curing, after which the critical state line remains essentially constant over time. This is likely because M is strongly influenced by particle shape (Cho et al., 2006; Sadrekarimi and Olson, 2011), and the morphological changes caused by particle agglomeration mainly take place during the early stages of curing.

Figure 8 shows the evolution of the stress ratio η with axial strain for lime-stabilized tailings cured for different periods, tested under different confinement pressures and under drained conditions. The slight increase due to lime addition is evident; however, the stabilized specimens converged toward a unique η value of about 1.53, which corresponds to M , i.e. the stress ratio at critical state. Since the drained tests condition involves much longer stress paths and greater accumulation of plastic deformations during shearing, all cementation is degraded before reaching the CSL. However, at lower confining pressures, some cementation remains after the consolidation stage, resulting in steeper stress paths as the curing period increases. As the confining pressure increases, the effect of cementation is mostly lost during consolidation, causing the curves to converge asymptotically toward the CSL.

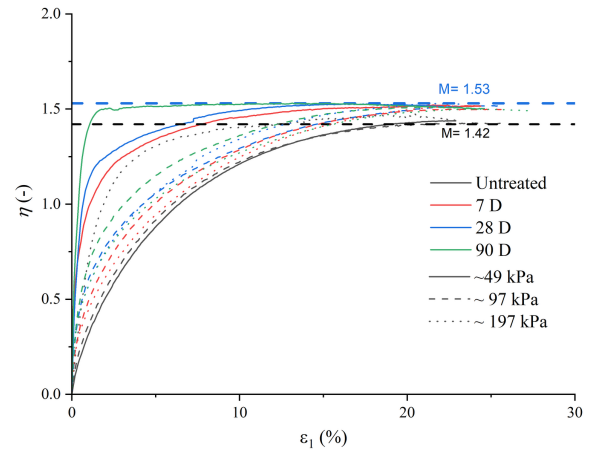


Figure 8. Stress ratio versus axial strain from triaxial tests on loose, lime-stabilized tailings under drained conditions.

The effect of initial compaction on the behavior of lime-stabilized tailings was also analyzed, particularly regarding the critical state line (CSL) in the p' - q plane under undrained conditions (see Figure 9). Only some specimens reconstituted with 3 kg and 12 kg tampers were able to sustain a peak deviatoric stress above the CSL, which gradually decreased towards it. In the remaining tests, yielding and degradation of most of the cementation-induced cohesion occurred during the consolidation stage.

Additionally, the specimens show an increase in M with compaction energy, which is consistent with findings from other studies (Haeri et al., 2005). This behavior may be attributed to denser particle packing during agglomeration, potentially leading to differences in clump shapes, or to strain localization, where the test becomes a complex boundary value problem.

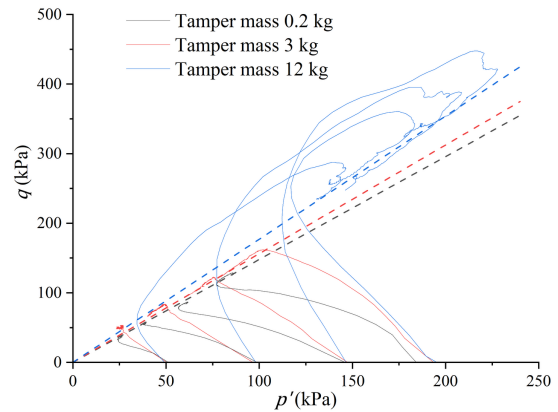


Figure 9. Influence of initial compaction on M .

4 CONCLUSIONS

This study evaluates the effects of lime stabilization on mine tailings, focusing on how initial compaction and curing time influence mechanical behavior. Laboratory testing included triaxial (drained and undrained), unconfined compression, oedometer, and permeability tests, along with SEM and EDS analyses to better understand physical and chemical changes in the material.

Lime treatment generally improved stiffness, yield stress, peak strength, and brittleness of the tailings, especially as curing time increased. These improvements are mainly due to two mechanisms:

- Flocculation and agglomeration, which occur soon after lime is added, causing changes in particle size and

structure. This mechanism mainly affects compressibility, permeability, and the slope of the CSLs—particularly λ in the compression plane, and slightly M in the p' - q plane.

- Pozzolanic reactions, which develop over time, generate cementation by forming a binding gel, increasing yield stress, and shifting the CSL vertically. Although this cohesion improves strength, it can be lost during the consolidation stage especially for loose specimens or with short curing periods. Nevertheless, these cases still exhibit higher strengths than the untreated tailings.

Delaying compaction after lime addition reduces the achievable density, as the cementing gel progressively hardens and resists further densification. This underscores the importance of compacting promptly after lime incorporation, since higher densities contribute to greater strength.

Treated tailings can be a feasible option for dry stacking, particularly where high moisture contents after filter/pressing are common. In such cases, adding lime reduces moisture, potentially reducing or eliminating the need for solar drying. Furthermore, the resulting gains in mechanical properties could enable greater stack heights and/or steeper slopes, and the treated material could also be used for the construction of berms/buttresses to enhance stability conditions.

5 ACKNOWLEDGEMENTS

The first author has been supported by a scholarship from the National Council for the Humanities, Science, and Technology (CONAHCYT). The authors would also like to thank Ing. Juan José Torres and MEng. Carlos Omar Vargas, who provided the tailings material for this research. Additionally, the authors express their gratitude to Dr. Omar Novelo Peralta for his support with the SEM-EDS tests.

6 REFERENCES

- Amadi, A.A. and Okeiyi, A., 2017. Use of quick and hydrated lime in stabilization of lateritic soil: comparative analysis of laboratory data. *International Journal of Geo-Engineering*, 8(1). <https://doi.org/10.1186/s40703-017-0041-3>.
- Andrews, A., Nyarko, E.F., Adjaottor, A.A., Nsiah-Baafi, E. and Adom-Asamoah, M., 2022. Reuse and stabilization of sulphide mine tailings as fine aggregate for construction mortar. *Journal of Cleaner Production*, 357. <https://doi.org/10.1016/j.jclepro.2022.131971>.
- Araujo, F.S.M., Taborda-Llano, I., Nunes, E.B. and Santos, R.M., 2022. *Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications*. *Geosciences (Switzerland)*, <https://doi.org/10.3390/geosciences12090319>.
- Baldovino, J. de J.A., Izzo, R.L. dos S., Moreira, E.B. and Rose, J.L., 2019. Optimizing the evolution of strength for lime-stabilized rammed soil. *Journal of Rock Mechanics and Geotechnical Engineering*, 11(4). <https://doi.org/10.1016/j.jrmge.2018.10.008>.
- Bernal López, M., Cruz-Flores, L.G., Botero-Jaramillo, E., Manica-Malcom, M.Á., and Flores-Castrellón, O., 2025. Comparison of reconstitution methods for mine tailings materials. *Soils and Rocks*, 48(2). <https://doi.org/10.28927/SR.2025.002624>.
- Burland, J.B., 1990. On the compressibility and shear strength of natural clays. *Geotechnique*, 40(3). <https://doi.org/10.1680/geot.1990.40.3.329>.
- Cho, G.-C., Dodds, J. and Santamarina, J.C., 2006. Particle Shape Effects on Packing Density, Stiffness, and Strength: Natural and Crushed Sands. *Journal of Geotechnical and Geoenvironmental Engineering*, 132(5). [https://doi.org/10.1061/\(asce\)1090-0241\(2006\)132:5\(591\)](https://doi.org/10.1061/(asce)1090-0241(2006)132:5(591)).
- Consoli, N.C., da Silva Lopes, L. and Heineck, K.S., 2009. Key Parameters for the Strength Control of Lime Stabilized Soils. *Journal of Materials in Civil Engineering*, 21(5). [https://doi.org/10.1061/\(asce\)0899-1561\(2009\)21:5\(210\)](https://doi.org/10.1061/(asce)0899-1561(2009)21:5(210)).
- Cruz, N. and Rodrigues, C., 2011. *The influence of cementation in the critical state behaviour of artificial bonded soils*. [online] Available at: <https://www.researchgate.net/publication/277364311>.
- Edraki, M., Baumgartl, T., Manlapig, E., Bradshaw, D., Franks, D.M. and Moran, C.J., 2014. Designing mine tailings for better environmental, social and economic outcomes: A review of alternative approaches. *Journal of Cleaner Production*, 84(1). <https://doi.org/10.1016/j.jclepro.2014.04.079>.
- Elkady, T.Y., Shaker, A. and Al-Shamrani, M., 2016. Hydraulic Conductivity of Compacted Lime-Treated Expansive Soils. <https://doi.org/10.1061/9780784480014.007>.
- Firoozi, A.A., Guney Olgun, C., Firoozi, A.A. and Baghini, M.S., 2017. Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, 8(1). <https://doi.org/10.1186/s40703-017-0064-9>.
- da Fonseca, A.V., Cordeiro, D. and Molina-Gómez, F., 2021. Recommended Procedures to Assess Critical State Locus from Triaxial Tests in Cohesionless Remoulded Samples. *Geotechnics*, 1(1). <https://doi.org/10.3390/geotechnics1010006>.
- Fourie, A.B., Blight, G.E. and Papageorgiou, G., 2001. Static liquefaction as a possible explanation for the Merriespruit tailings dam failure. *Canadian Geotechnical Journal*, 38(4). <https://doi.org/10.1139/cgj-38-4-707>.
- Haeri, S.M., Hosseini, S.M., Toll, D.G. and Yasrebi, S.S., 2005. The behaviour of an artificially cemented sandy gravel. *Geotechnical and Geological Engineering*, 23(5). <https://doi.org/10.1007/s10706-004-5110-7>.
- Joel, M. and Edeh, J.E., 2013. Soil modification and stabilization potential of calcium carbide Waste. In: *Advanced Materials Research*. <https://doi.org/10.4028/www.scientific.net/AMR.824.29>.
- Kasama, K., Zen, K. and Iwataki, K., 2006. Undrained shear strength of cement-treated soils. *Soils and Foundations*, 46(2). <https://doi.org/10.3208/sandf.46.221>.
- Leroueil, S. and Vaughan, P.R., 1990. The general and congruent effects of structure in natural soils and weak rocks. *Geotechnique*, 40(3). <https://doi.org/10.1680/geot.1990.40.3.467>.
- Mánica, M.A., Arroyo, M., Gens, A. and Monforte, L., 2022. Application of a critical state model to the Merriespruit tailings dam failure. *Proceedings of the Institution of Civil Engineers: Geotechnical Engineering*, 175(2). <https://doi.org/10.1680/jgeen.21.00001>.
- Mitchell, J.K. and Soga, K., 2005. *Fundamentals of Soil Behavior*. 3rd Edition. *Angewandte Chemie International Edition*, 6(11), 951–952.
- Olaniyi, D.A., 2017. Evaluation of the Effect of Lime and Cement on the Engineering Properties of Selected Soil in a University in Southwestern Nigeria. *Journal of Advancement in Engineering and Technology*, 5(4).
- Osinubi, K.J. and Nwaiwu, C.M., 2006. Compaction Delay Effects on Properties of Lime-Treated Soil. *Journal of Materials in Civil Engineering*, 18(2). [https://doi.org/10.1061/\(asce\)0899-1561\(2006\)18:2\(250\)](https://doi.org/10.1061/(asce)0899-1561(2006)18:2(250)).
- Raja, P.S.K. and Thyagaraj, T., 2020. Effect of compaction time delay on compaction and strength behavior of lime-treated expansive soil contacted with sulfate. *Innovative Infrastructure Solutions*, 5(1). <https://doi.org/10.1007/s41062-020-0268-2>.
- Rios, S., Viana da Fonseca, A. and Baudet, B.A., 2012. Effect of the Porosity/Cement Ratio on the Compression of Cemented Soil. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(11). [https://doi.org/10.1061/\(asce\)gt.1943-5606.0000698](https://doi.org/10.1061/(asce)gt.1943-5606.0000698).
- Sadrekarimi, A. and Olson, S.M., 2011. Critical state friction angle of sands. *Geotechnique*, 61(9). <https://doi.org/10.1680/geot.9.P.090>.
- Skempton, A.W., 1954. The pore-pressure coefficients a and b . *Geotechnique*, 4(4). <https://doi.org/10.1680/geot.1954.4.4.143>.
- Torres-Cruz, L.A. and Santamarina, J.C., 2020. The critical state line of nonplastic tailings. *Canadian Geotechnical Journal*, 57(10). <https://doi.org/10.1139/cgj-2019-0019>.
- Zhang, Y., Daniels, J.L., Cetin, B. and Baucom, I.K., 2020. Effect of Temperature on pH, Conductivity, and Strength of Lime-Stabilized Soil. *Journal of Materials in Civil Engineering*, 32(3). [https://doi.org/10.1061/\(asce\)mt.1943-5533.0003062](https://doi.org/10.1061/(asce)mt.1943-5533.0003062).