Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-1679

Influence of Atmospheric Conditions on the Structural Evolution and Mechanical Behaviour of Mine Tailings

João P. Oliveira*
University of Coimbra, Coimbra, Portugal, joaopsvo@uc.pt

Luis Araújo Santos
Polytechnic University of Coimbra, SUScita, Coimbra, Portugal

Joana Ribeiro
University of Coimbra, Institute Dom Luiz, Coimbra, Portugal

António M. G. Pedro
University of Coimbra, ARISE, ISISE, Coimbra, Portugal

David M. G. Taborda
Imperial College London, London, UK

Paulo Coelho
University of Coimbra, CITTA, Coimbra, Portugal

ABSTRACT: The global increase in mineral and metal consumption, driven by the energy transition and the demand for green technologies, has led to intensified mining activity and a corresponding rise in the generation of tailings. These materials must be managed safely to mitigate social and environmental risks, while simultaneously pursuing sustainable reuse strategies aligned with circular economy principles. When tailings are exposed to atmospheric conditions, physicochemical transformations progressively alter their properties. This time-dependent process, known as ageing, can significantly influence the mechanical behaviour of tailings, with direct implications for the long-term stability of storage facilities and for the feasibility of alternative applications. This study examines the effects of ageing on the structure and mechanical behaviour of tailings from a Portuguese tungsten mine. Samples representing different ageing stages were tested, including freshly reconstituted material, recently collected undisturbed samples, and intermediate-aged specimens that had been exposed to atmospheric conditions for several months. Triaxial and oedometer tests were performed to assess stress-strain-strength response and structural evolution. In addition, electron microscope images were taken to observe changes in microstructure resulting from prolonged exposure. The results show that ageing promotes microstructural rearrangement and increased interparticle bonding, leading to measurable changes in compressibility and stiffness. The photomicrographic evidence supports these findings, revealing signs of cementation and particle aggregation in older samples. These results underline the importance of accounting for the effects of ageing when assessing the mechanical performance of tailings, whether for storage stability or for reuse in geotechnical applications.

KEYWORDS: mine tailings, ageing effects, oedometer tests, triaxial tests, microscopic analysis.

1 INTRODUCTION

The deposition of mine tailings constitutes one of the main challenges in geotechnical engineering, both due to the volume generated and the need to ensure long-term stability. In the case of strategic minerals such as tungsten, the growing interest in their extraction has resulted in a significant production of fine tailings, whose mechanical behaviour is strongly influenced by physicochemical processes after deposition. At the Panasqueira mine, located in the Central region of Portugal, the tailings resulting from mineral processing are primarily composed of quartz, wolframite, pyrite, arsenopyrite, and other sulphides, which, when in contact with oxygen and water, give rise to mineral alteration and natural cementation phenomena.

Several studies, such as Oliveira et al. (2024a), have shown that ageing induces significant changes in the internal structure of these materials, affecting compressibility and shear strength. These aspects become particularly relevant within a circular economy context, where the valorisation of tailings for sustainable geotechnical uses is an increasingly explored strategy (Rico et al., 2008). However, the literature specifically addressing tungsten tailings remains limited, and there is a need to deepen understanding of how factors such as storage time, deposition history, and artificial reconstitution influence the overall mechanical behaviour.

The main objective of the present work is to compare the performance of undisturbed samples aged in the laboratory for twenty months (U20) with laboratory-reconstituted samples (RA), systematically analysing the effect of ageing, particularly on compressibility and shear strength.

2 MATERIALS AND METHODS

2.1 *Material under study*

The Panasqueira mine in Portugal, active for over a century, represents a significant source of tailings with specific geotechnical characteristics. The studied materials were collected from a deposition slope with an average inclination of twenty degrees, subject to controlled surface drainage. Grain size analysis indicated that the tailings predominantly consist of a sand fraction (70%), with the remaining 30% mainly composed of silt, as shown in Figure 1. The Atterberg limits registered average values of 23.2% for the liquid limit and 14.1% for the plastic limit, corresponding to a plasticity index of 9.1%, characteristic of low-plasticity materials. The average specific gravity obtained was 3.15, consistent with the presence of heavy minerals such as wolframite (Oliveira et al., 2024a).

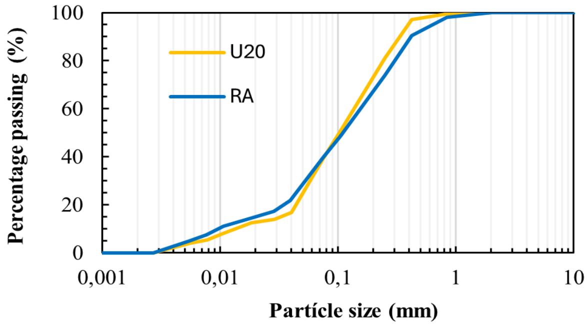

Figure 1. Particle size distribution curves of the undisturbed and reconstituted samples (adapted of Oliveira et al., 2024a).

2.2 *Sample types and preparation methods*

Three types of samples were considered: undisturbed (U20), freshly reconstituted (RA0), and aged reconstituted (RA3). The U20 samples were extracted directly from the surface slope, wrapped in plastic film, and stored in a chamber with controlled relative humidity (98%) and constant temperature (25ºC) for approximately twenty months, minimising significant changes in water content. The RA0 samples were prepared from dry material collected from the same area, mixed with water to reach a water content of 27%, using a paddle mixer for fifteen minutes to ensure homogeneity (Oliveira et al., 2024b). Deposition was carried out by gravity, maintaining the natural density without artificial compaction. To evaluate structural recovery, part of the reconstituted samples was left to rest for three months, covered with plastic film to prevent moisture loss, resulting in the RA3 samples.

2.3 *Experimental plan*

The experimental programme included oedometer (one-dimensional compression) tests and undrained triaxial compression tests. The oedometer tests were performed on samples with a diameter of 70 mm, subjected to load increments ranging from 15 to 7200 kPa, with each step maintained until deformation stabilised (Oliveira et al., 2024a). The main objective was to evaluate the compressibility of the different structural states of the samples, particularly the evolution of the structure under vertical loading.

In the triaxial tests, samples measuring 38 mm in diameter and 76 mm in height were saturated until B > 0.98, isotropically consolidated to effective stresses (p'_0) of 200 and 800 kPa, followed by the shear phase at a strain rate of 1.6% per hour. These tests allowed the evaluation of shear strength and behaviour under undrained loading, a condition particularly representative of rapid loading events, such as seismic events or sudden failures. The overall experimental programme is summarised in Table 1

Table 1. Experimental programme.

Sample	Sample Type	Time After Collection (Month)	Time After Recon. (Month)	p'_0[1] (kPa)
RA0-200	*Reconstitued*	-	*0*	*200*
RA0-800	*Reconstitued*	-	*0*	*800*
RA3-200	*Reconstitued*	-	*3*	*200*
RA3-800	*Reconstitued*	-	*3*	*800*
U20-200	*Undisturbed*	*20*	-	*200*
U20-800	*Undisturbed*	*20*	-	*800*

[1]p'_0 refers to the initial effective mean stress in triaxial tests and is not applicable to oedometer tests.

Additionally, microstructural analysis was carried out on samples in two distinct states: loose material, corresponding to reconstituted tailings used in laboratory tests, and undisturbed U20 samples, collected directly from the deposit and preserved in their original structure. Observations were made using a LEICA DM750P microscope, equipped with LEICA Application Suite X software, under reflected white light and with 5× and 10× magnification objectives. The images obtained allowed the identification of significant differences in particle arrangement and the degree of interparticle cementation, complementing the interpretation of the mechanical results.

3 RESULTS AND DISCUSSION

3.1 *Behaviour in one-dimensional compression*

The oedometer tests (Figure 2) allow the evaluation of the one-dimensional compression behaviour of intact samples (U20) and freshly reconstituted samples (RA0), representing, respectively, material with a natural structure developed through prolonged ageing and structureless material. The results showed significant differences between the two sample types, particularly in terms of initial stiffness and deformation under vertical loading.

The e - log σ'_v curves of the U20 samples revealed a stiffer response, with lower vertical deformations for the same increments of effective stress, highlighting the role of natural structure in limiting compressibility. This behaviour is associated with the presence of interparticle bonds and the microstructural evolution of the tailings over time, under conditions of high humidity and without mechanical disturbance, as observed by Oliveira et al. (2024a).

In contrast, the RA0 samples exhibit significantly higher deformability, with greater compression at similar stress levels. The absence of structure makes the material more susceptible to the rearrangement of fine particles, resulting in a behaviour typical of reconstituted soils. The difference between the compression coefficients (*Cc*) obtained for the two conditions is notable, with RA0 values approximately twice as large as those of the U20 samples.

For effective vertical stresses above approximately 3000 kPa, a convergence of the curves is observed, indicating the progressive destruction of the structure in the U20 samples. This loss of influence of structure with increasing stress is consistent with the principles of progressive destructuration of naturally cemented soils, as described by Burland (1990).

These results demonstrate that the natural structure of the Panasqueira tailings plays a decisive role in the compressibility of the material, with important implications for the prediction of settlements and the performance of engineering works on these deposits. Ageing under stable conditions imparts the material with stiffness that cannot be replicated by simple laboratory deposition or reconsolidation.

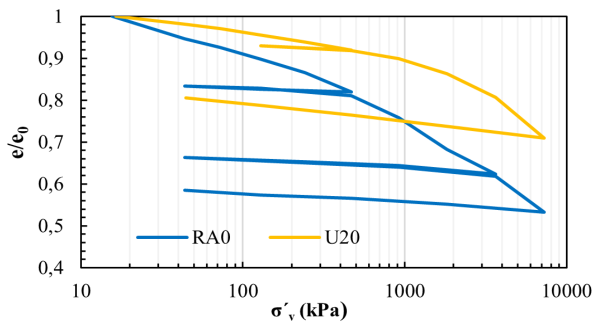

Figure 2. Behaviour of undisturbed and unaged reconstituted samples in one-dimensional compression.

3.2 *Shear strength in triaxial tests*

The analysis of the results obtained from the undrained triaxial compression tests, as illustrated in Figure 3, allows for the evaluation of the impact of the natural structure on the shear strength of the Panasqueira tailings.

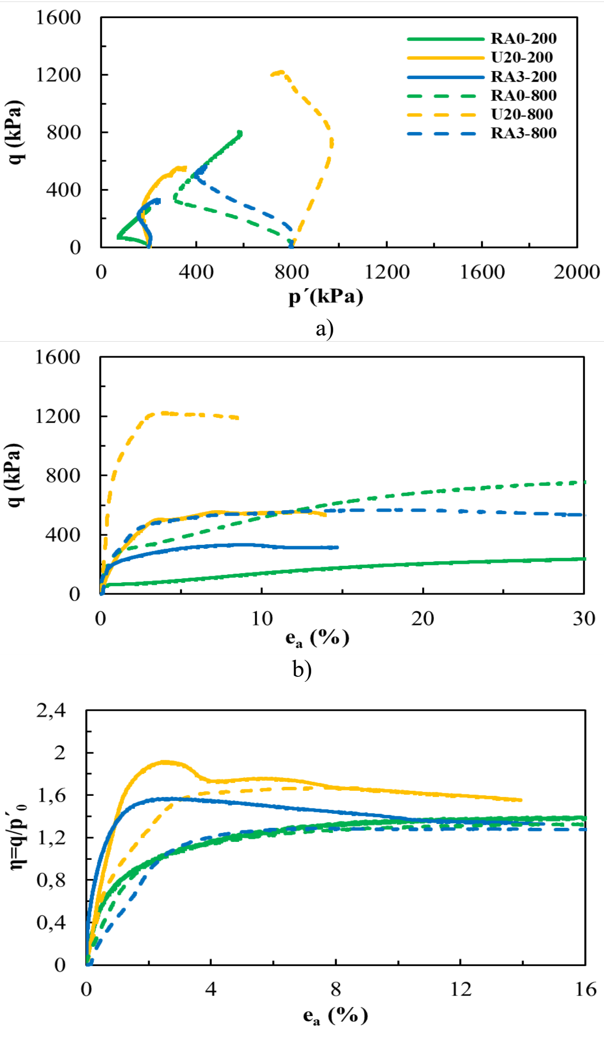

Figure 3. Influence of the ageing process in the stress-strain behaviour: (a) p´-q stress path; (b) stress-strain curves; (c) normalized stress-strain curves.

The comparative analysis between undisturbed samples aged for approximately 20 months (U20) and reconstituted samples (RA0) reveals significant differences in the mechanical behaviour of the tailings.

Figure 3a shows that the U20 samples follow almost vertical paths, resulting in moderate generation of pore pressures, whereas the RA0 samples exhibit paths markedly inclined to the left, associated with greater increments in pore pressure and loss of effective strength. Figure 3b confirms this behaviour, with the U20 samples displaying a stiffer and stronger response than that of the RA0 samples.

The reconstituted samples aged for three months (RA3) exhibit intermediate behaviour. This is particularly evident in Figure 3c, where the normalised stress-strain curves of the RA3 samples lie between those of the RA0 and U20 samples. In the case of the RA3-200 sample, the response approaches that of the U20-200, indicating some structural recovery and strength improvement. However, under higher consolidation stresses (RA3-800), the behaviour remains similar to that of the freshly reconstituted sample, suggesting that the bonds formed during initial ageing are still fragile and degrade easily under higher stresses.

3.3 *Microscopic observations*

Microscopic observation of the samples (Figure 4), obtained using a Leica microscope at 5× magnification, allows a direct correlation to be made between the microstructural state of the tailings and their mechanical performance observed in laboratory tests. The analysed images correspond to two distinct states: in the first (Figure 4a), an isolated particle from disaggregated tailings, used for the preparation of reconstituted samples (RA), is visible. This particle has a relatively clean surface with a loosely bonded structure, showing only localised areas with greyish cementing particles, indicating the initial formation of interparticle bonds. The overall structure remains essentially loose, with limited interconnection between particles, which is consistent with the softer and more deformable behaviour recorded in the triaxial and oedometer tests of these samples. The absence of a continuous system of cementing bridges limits the capacity to transmit stresses, resulting in lower stiffness and undrained strength.

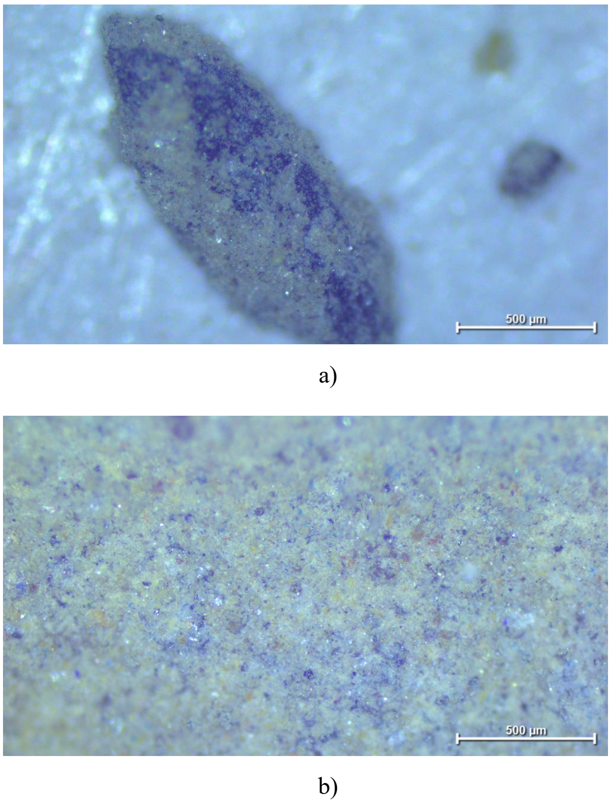

Figure 4. Photomicrographs of tailings: (a) reconstituted material (RA) with initial cementation; (b) undisturbed sample (U20) showing extensive interparticle bonding.

In contrast, the second image (Figure 4b) shows the surface of an intact sample (U20), collected directly from the deposit and preserved in its natural state. A densely compact granular matrix is observed, where multiple cemented contact points are clearly distinguishable and broadly distributed. These bonds, developed over time through geochemical processes and mineral oxidation under atmospheric exposure, form a solid and continuous network that binds the particles, imparting greater cohesion to the material (Zhau et al., 2021; Antunes et al., 2022). The more homogeneous tone and absence of clean exposed surfaces suggest a widespread presence of more advanced cementing material, which enhances shear strength and reduces compressibility. This microstructural state explains the higher initial stiffness and peak strength values recorded in the U20 samples, as well as the lower deformations observed under loading, when compared to the RA samples.

The direct comparison of these two photomicrographs unequivocally highlights the central role of ageing in the structural evolution of the tailings. The transition from a loose particulate state, with predominantly frictional contacts, to a granular network interconnected by cementing bridges results in a significant increase in mechanical strength and a reduction in deformability. This evolution confirms that microstructure decisively influences mechanical behaviour and must be considered in the long-term stability assessment of tailings deposits and in the analysis of their feasibility for reuse in geotechnical applications.

4 CONCLUSIONS

The results obtained in this study clearly demonstrate that the ageing process exerts a decisive influence on the structural evolution and mechanical behaviour of the Panasqueira mine tailings. From the overall interpretation of the laboratory tests and microscopic observations, the following conclusions can be drawn:

- Intact and long-term aged samples exhibited a noticeably higher initial stiffness when compared with freshly reconstituted samples. This behaviour confirms the fundamental role played by interparticle bonds that progressively develop over extended periods of exposure under stable moisture and temperature conditions, leading to a more resistant structure.
- When subjected to higher vertical stresses, the mechanical response of structured and unstructured samples became progressively more similar. This convergence reflects the gradual destructuration of the cemented fabric and the corresponding loss of the beneficial effects of natural cementation as the applied loads increase, eventually reaching a point where the original structure is no longer dominant.
- Ageing was shown to be effective in both reducing the generation of excess pore water pressures and in increasing undrained shear strength in triaxial tests. These beneficial effects were more pronounced in the samples subjected to prolonged ageing, thereby highlighting their contribution to improved overall stability and resistance to rapid loading events.
- Reconstituted samples that were allowed to age for three months displayed an intermediate mechanical behaviour between the freshly reconstituted and the long-term aged specimens. This finding suggests the potential for partial structural recovery to occur within relatively short time frames; however, the cementation bonds formed at this early stage still revealed fragility and degraded more easily when subjected to higher consolidation stresses.
- Microscopic analysis provided clear visual evidence of the transition from a loose granular arrangement, characterised by predominantly frictional particle contacts, to a densely interconnected network containing multiple cementation bridges. This microstructural transformation is directly responsible for the observed increase in stiffness, the reduction in compressibility, and the overall improvement in shear strength parameters.
- Taken together, these findings reinforce the importance of explicitly considering the “ageing time” factor when assessing the long-term stability of tailings storage facilities. They also underline its relevance in the formulation of strategies for the sustainable reuse of these geomaterials in geotechnical applications, thereby contributing to enhanced safety, durability, and performance over the operational lifespan of engineering works.

5 ACKNOWLEDGEMENTS

The authors acknowledge the financial support of the Foundation for Science and Technology to GeoSusTailings Project through the Research Grant PTDC/ECI-EGC/4147/2021 and the support of the company Beralt Tin and Wolfram Portugal, S.A., which operates the Panasqueira mine concession in Portugal and collaborates with the research project by supplying the tungsten tailings for testing.

6 REFERENCES

Antunes, I.M.H.R., Neiva, A.M.R., Silva, M.M.V.G., and Farinha, J.V.M. 2022. Geochemical and mineralogical changes in mining tailings during weathering: implications for stability and reuse. *Applied Geochemistry* 137, 105–226.

Burland, J.B. 1990. On the compressibility and shear strength of natural clays. *Géotechnique* 40(3), 329–378.

Oliveira, J. P., Araújo Santos, L., Ribeiro, J., Coelho, P., and Pedro, A. M. G. 2024a. Influence of Environmental Conditions on the Behaviour of Tailings from Tungsten Mining for Sustainable Geotechnical Applications and Storage. *Sustainability* 16(24), 10987.

Oliveira, J.P.; Coelho, P.; and Araújo Santos, L. 2024b. Application of the Slurry Deposition Method to the Reconstitution of Samples of Wolframite Ore Tailings. In *Proceedings of the XVIII ECSMGE*, Lisbon, Portugal.

Rico, M., Benito, G., Salgueiro, A. R., Díez-Herrero, A., and Pereira, H. G. 2008. Reported tailings dam failures – a review of the European incidents in the worldwide context. *Journal of Hazardous Materials* 152(2), 846–852.

Zhao, X., Wang, L., Zhang, J., Chen, Y., and Liu, S. 2021. Microstructural evolution and its effect on the mechanical behaviour of tailings during ageing. *Engineering Geology* 291, 106–223.