

## Article

# Influence of Environmental Conditions on the Behaviour of Tailings from Tungsten Mining for Sustainable Geotechnical Applications and Storage

João Pedro Oliveira <sup>1</sup>, Luís Araújo Santos <sup>2</sup> , Joana Ribeiro <sup>3</sup> , Paulo Coelho <sup>4</sup>  and António M. G. Pedro <sup>5,\*</sup> 

- <sup>1</sup> Department of Civil Engineering, University of Coimbra, 3030-788 Coimbra, Portugal; joaopsvo@uc.pt  
<sup>2</sup> Cities and Urban Intelligence (SUScita), Research Group on Sustainability, Polytechnic University of Coimbra, 3045-093 Coimbra, Portugal; lmsantos@isec.pt  
<sup>3</sup> Department of Earth Sciences, Institute Dom Luiz, University of Coimbra, 3030-790 Coimbra, Portugal; joana.ribeiro@uc.pt  
<sup>4</sup> Department of Civil Engineering, Transports and Environment (CITTA), Research Centre for Territory, University of Coimbra, 3030-788 Coimbra, Portugal; pac@dec.uc.pt  
<sup>5</sup> Department of Civil Engineering, Advanced Production and Intelligent Systems (ARISE), Institute for Sustainability and Innovation in Structural Engineering (ISISE), University of Coimbra, 3030-788 Coimbra, Portugal  
\* Correspondence: amgpedro@dec.uc.pt; Tel.: +351-239797224

**Abstract:** Modern societies require increasingly large amounts of minerals and metals for their development. Therefore, huge amounts of waste must be stored in safe and cost-effective massive tailing storage facilities that would benefit from using tailings in sustainable geotechnical applications within the context of the circular economy. However, to consider tailings as assets, the long-term behaviour of these unconventional geomaterials under realistic environmental conditions must be assessed. This paper focuses on the effects of the environmental conditions on the behaviour of tailings from tungsten mining by experimentally determining their major physical and mechanical properties for three different conditions: twenty-months-aged undisturbed samples and reconstituted samples, with the latter being fresh and three months. The results confirm that twenty-months-aged undisturbed and fresh reconstituted tailings have significantly different mechanical behaviour, while three-months-aged reconstituted samples show an in-between behaviour as if the material regenerates and improved its behaviour with time due to physical and chemical processes. These ageing processes are experimentally confirmed by measuring the electrical conductivity in the samples. The results confirm that optimising the design of tailing storage facilities and using these geomaterials in sustainable geotechnical applications must consider the existing environmental conditions and the potential tailings' mechanical changes due to ageing.

**Keywords:** tailing characterisation; mechanical behaviour; sustainability



**Citation:** Oliveira, J.P.; Araújo Santos, L.; Ribeiro, J.; Coelho, P.; Pedro, A.M.G. Influence of Environmental Conditions on the Behaviour of Tailings from Tungsten Mining for Sustainable Geotechnical Applications and Storage. *Sustainability* **2024**, *16*, 10987. <https://doi.org/10.3390/su162410987>

Academic Editor: Cun Zhang

Received: 11 November 2024

Revised: 9 December 2024

Accepted: 12 December 2024

Published: 14 December 2024



**Copyright:** © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

## 1. Introduction

The production of mine tailings is closely related to societal demands and is currently being boosted by technological advances and the exploitation of metals essential for high-tech industries, such as those used in batteries, electric vehicles, and renewable energies. The United States Agency for International Development (USAID) estimates that the total mineral demand will increase between 2 and 4-fold between 2020 and 2040 for, respectively, the “Stated Policies” and the “Sustainable Development” Scenarios, allowing for the Paris Agreement goals to be met [1]. Any of these scenarios imply that a proportionally greater amount of tailings will be produced by the mining industry in the near future. Furthermore, according to the World Mining Congress report, global mining, which includes precious metals, copper, iron, and others, is expected to grow by an average of three per cent a year until 2030 [2]. This expansion means that more tailings will be produced, as the proportion

of waste relative to the extracted ore remains very high. Currently, most of the mine tailings are deposited in tailing dams or other tailing storage facilities, which are often a cause of distress due to the potential risks involved, including catastrophic failures, as in the cases of Mariana and Brumadinho in Brazil [3,4]. Following these tragic events, the need for safer and optimum storing and reutilisation of tailings in different applications became a global priority and led to the development of different strategies for its valorisation [5,6].

However, its direct application is not simple as mine tailings vary greatly in their physical, chemical, and mineralogical characteristics, depending on the type of ore and the separation and beneficiation processes employed. Mine tailings can also contain toxic elements such as arsenic, cadmium, lead, and acidic conditions, which can improve dissolution and make their way into the environment, potentially causing contamination of adjacent soils and watercourses [7]. Moreover, when exposed for a long period of time to environmental conditions such as rain, temperature, and oxygenation, these geomaterials undergo various physical and chemical processes, including consolidation, cementation, and oxidation, which increase their heterogeneity and complexity [8,9]. Temperature and freeze–thaw cycles alter the rate of chemical reactions and physical stability of the tailings, while their exposure to rainwater and oxygenation accelerates oxidation [10,11]. In fact, when exposed to oxygen and water, the sulphide minerals, which are very common in tailings from ore mining, suffer oxidation reactions that result in the formation of sulphuric acid and iron hydroxide precipitates [10,12]. This process, known as acid drainage (AD), not only alters the chemical composition of the tailings but also their physical and mechanical properties [10,12]. This physico–chemical transformation is accompanied by the precipitation of secondary minerals, such as iron oxyhydroxides and sulphates, which can promote the cementation of tailing particles, increasing their mechanical resistance and creating a hardened layer on the surface. This layer can reduce surface permeability, slow water infiltration and restrain the migration of contaminants while at the same time increasing, at least temporarily, the structural stability of the tailings deposit [10].

Previous investigations have demonstrated that the precipitation of secondary minerals may cement tailing materials due to oxidation of primary minerals and reactions with pore-water [13]. These secondary phases that cement solid particles in tailings are a complex and extremely variable mixture that depends on the primary mineral assemblage in tailing materials (which varies over time during mining operations and ore beneficiation) and on environmental conditions (e.g., pore-water composition, *pH*, redox potential, precipitation). Previous studies related to secondary minerals formation in tailings from a W-rich deposit [14], which is the case of the Panasqueira deposit, pointed out that the oxidation of sulphide minerals leads to the formation of sulphates, secondary sulphides, iron-oxyhydroxides, and changes in the concentrations of aqueous species. Some of these secondary precipitated species are easily solubilised in water.

An attempt to indirectly evaluate the degree of these physico–chemical alterations can be performed by measuring the *pH* and the electrical conductivity (EC) of run-off and percolation water, as these parameters provide information regarding the acidity and the amount of dissolved ions [15–17]. According to the Portuguese Environmental Agency [18], the reference value of EC for non-contaminated soils is below 570  $\mu\text{S}/\text{cm}$ . The Portuguese legislation for natural waters [19] also recommends that the maximum value of EC is 1000  $\mu\text{S}/\text{cm}$ , and that *pH* should be between 5.5 and 9.0 to ensure the quality of surface freshwater intended for the production of water for human consumption after treatment.

The physical and chemical reactions occurring over time after the deposition of tailings, usually referred to as ageing processes, play a significant role in the mechanical behaviour of tailings, as highlighted by some studies. The study conducted by Troncoso et al. [20] shows that older deposits of mining tailings present a higher resistance to liquefaction than newly deposited ones. This increase in resistance was justified by the formation of bonds between the particles, which strengthen over time, improving the rigidity and stability of the geomaterial. Cyclic triaxial tests carried out on samples of tailings from dams in El Cobre, Chile, by Troncoso and Garcés [21], showed that the cyclic resistance of the tailings

increased over the time of deposition. An increase in cyclic resistance by factors of 3.5, 2.4, and 2.0 was observed in samples deposited for 30, 5, and 1 years, respectively, when compared to freshly deposited samples. In this context, proper characterisation of the long-term behaviour of tailings is essential for the sustainable management of tailings storage facilities, which require optimum design and further implementation of the circular economy principles.

One of the most common applications of tailings is in producing construction materials such as cement and bricks, using silica and alumina-rich tailings to replace natural aggregates and reduce the exploitation of virgin resources [5,22]. Moreover, mine tailings have also been used to stabilise soils and build road pavement bases [22,23]. Another relevant application is the recovery of valuable elements through new processing technologies, transforming tailings into secondary sources of raw materials [24,25]. In most of these applications, the previous destructurement of tailings is often required, implying that the characterisation must focus not only on the undisturbed tailings but also on the reconstituted geomaterial, which, despite having identical mineralogical content, can behave substantially differently. In soils, particularly in those with significant fines content, it is well known that reconstituted samples can present a poorer mechanical behaviour with much smaller strength and stiffness than the undisturbed samples, with the difference increasing with the ageing (overconsolidation ratio) of the soil [26–28]. In the case of tailings, the differences between undisturbed and reconstituted geomaterials can be even higher, being potentiated by the physical and chemical processes that occur over time [29]. However, although some studies highlight the importance of the reconstitution technique employed [30,31], the mechanical behaviour variations with the ageing of the reconstituted geomaterial are very limited and have not been fully understood [32,33]. Still, this aspect of the problem is of paramount importance since it can compromise the safety and sustainability of projects involving the use of these geomaterials. Furthermore, understanding the transformation of reconstituted tailings over time is crucial to the development of techniques for treating and reusing these geomaterials.

In this context, this article aims to evaluate the behaviour of mine tailings using physico–chemical and geotechnical tests, focusing on identifying and explaining the evolution of the mechanical characteristics of the reconstituted geomaterial over time. To this end, tungsten tailings from a Portuguese mine were analysed, allowing the detailed characterisation of these geomaterials and the identification of possible merits and risks associated with their use or disposal. The fact that the variation of the mechanical behaviour of the samples with time is assessed through advanced triaxial tests and oedometer tests, and that the origin of the ageing effects is discussed based on physico–chemical tests, provides original and valuable insights into this problem.

## 2. Materials and Methods

### 2.1. Panasqueira Mine Tailings

The tailings from tungsten ore mining considered in the present study were collected from the Panasqueira mine, which is located in north-central Portugal, integrating the municipalities of Covilhã and Fundão in the district of Castelo Branco and Pampilhosa da Serra (district of Coimbra). Apart from tungsten, small amounts of copper are also extracted in this underground mine [34]. The mineralogical composition of the tailings from the Panasqueira mine is very diverse, reflecting the complexity of its paragenesis. The main minerals include oxides and silicates such as quartz, wolframite, and cassiterite, which were formed in the early stages of the deposit. There is also a significant quantity of sulphides such as pyrite, chalcopyrite, arsenopyrite, pyrrhotite, and blende. The alteration of pyrite gives rise to minerals such as marcasite and siderite. In the later stages, carbonates such as dolomite and calcite were also deposited [34,35]. These minerals not only reflect the hydrothermal evolution of the mine but also directly influence the stability and management of the tailings. Table 1 shows a set of sixty-five minerals present in the Panasqueira mine deposits, grouped into eleven mineral groups based on their chemical

composition [35]. As mentioned previously, some of these minerals oxidise when in contact with atmospheric oxygen and water, triggering chemical reactions that produce sulphuric acid and mobilise heavy metals such as iron, copper, arsenic, zinc, and manganese, which can be released into the environment [36]. The oxidation of pyrite and the consequent generation of AD is one of the most significant reactions observed in the Panasqueira mine. Tests performed in the mine in areas directly impacted by AD reveal extremely low  $pH$  values. Candeias et al. [16] indicate that the  $pH$  of the tailings' drainage water varied between 2.9 and 3.2, reflecting highly acidic conditions that favour the solubilisation of metals. According to Dinis et al. [17], even lower  $pH$  values were determined in samples collected at the surface of tailings, with values ranging between 1.4 and 2.5, due to the intense oxidation of the minerals in that area. The deeper samples showed a slightly higher  $pH$ , between 2.5 and 3.6, but were still highly acidic. According to Ávila et al. [15], the analysis of drainage water indicated  $pH$  values between 3.0 and 3.9, also showing an acidic environment that facilitates the mobility of toxic metals.

**Table 1.** Mineralogy of Panasqueira deposit (adapted from Simão [35]).

Mineral Group	Mineral
Arsenates	Arseniosiderite, scorodite, and pharmacosiderite
Arsenides	Lollingite
Carbonates	Ankerite, calcite, dolomite, and siderite
Halides	Fluorite
Native elements	Antimony, bismuth, gold, and silver
Oxides	Cassiterite, goethite, hematite, magnetite, and rutile
Phosphates	Althausite, amblygonite, apatite, isokite, panasqueirite, thadeuite, vivianite, wagnerite, and wolfeite
Silicates	Beryl, bertrandite, biotite, chlorite, quartz, muscovite, topaz and tourmaline
Sulphates	Gypsum
Sulphides and Sulphosalts	Acanthite, arsenopyrite, bismuthinite, chalcocite, chalcopyrite, canfieldite, covellite, cubanite, freibergite, galena, gudmundite, mackinawite, marcassite, matildite, molybdenite, pavonite, pentlandite, pyrite, pyrrhotite, pyrargyrite, spharelite, stannite, stephanite, stibnite, and tetrahedrite
Wolframates	Hydrotungstite, scheelite, tungstite, and wolframite

In addition to  $pH$ , EC was also measured to infer the concentration of dissolved ions in situ. Candeias et al. [16] obtained EC values for drainage water ranging from 2000  $\mu\text{S}/\text{cm}$  to 4400  $\mu\text{S}/\text{cm}$  in areas close to the tailings, indicating high concentrations of ions, especially sulphates and dissolved metals, which corroborate the high acidity. Dinis et al. [17] also recorded high values of EC, between 350  $\mu\text{S}/\text{cm}$  and 3630  $\mu\text{S}/\text{cm}$ , with higher values near the tailings and in the AD treatment areas. This indicates the presence of metals such as copper and zinc, which are more mobile in low- $pH$  environments. In the same vein, Ávila et al. [15] obtained EC values ranging from 37  $\mu\text{S}/\text{cm}$  in less affected areas to up to 1088  $\mu\text{S}/\text{cm}$  in regions impacted by AD.

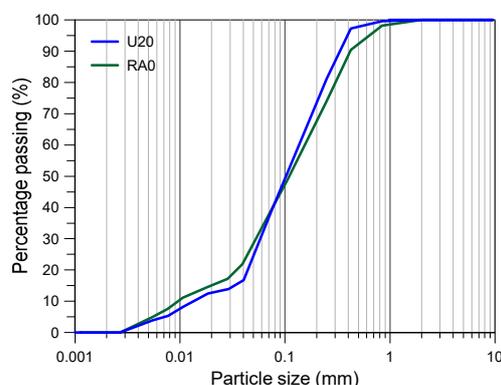
## 2.2. Sample Collection and Physical Characterisation

In order to characterise the behaviour of the mine tailings from the Panasqueira mine, undisturbed blocks were collected in October 2021 at the surface of the tailings dam in a location not far from the discharging point of the tailings. Those blocks were adequately packaged to avoid variations in the water content or any other damage during transportation to the Geotechnical Laboratory of the University of Coimbra, where they were stored in a climate control chamber with controlled temperature and humidity of 25 °C and 98%, respectively. From those blocks, several samples were trimmed to perform physico-chemical characterisation and advanced laboratory testing, including oedometer and triaxial tests.

The physical characterisation of the tailings was carried out according to Portuguese, British, and European standards, with the main results being summarised in Table 2. The Atterberg limits and phase relationships are similar to those obtained in similar tailings. The variation of the specific gravity ( $G$ ) agrees with the range of values proposed for mine tailings by Fourie et al. [37] and Hu et al. [38], the average value being significantly higher than usually found in common soils because of the presence of different metals and minerals in the tailings. The in situ void ratio ( $e_0$ ) varies between 0.62 and 0.75, and although this value may not be directly compared with other results since it depends on the deposition process, it is in agreement with the results published by Rodríguez et al. [39]. Regarding the Atterberg limits, they are also similar to others proposed for other mine tailings, namely iron ( $w_L = 28\%$  and  $w_P = 19\%$ ), copper ( $w_L = 28\%$  and  $w_P = 13\%$ ) [38], gold ( $w_L = 25\%$  and  $w_P = 18\%$ ) [40], silver, zinc, and lead ( $w_L = 21\%$  and  $w_P = 6\%$ ) [41]. The particle size distribution performed on the undisturbed samples (U20) revealed that Panasqueira's tailings are composed of 16% clay, 73% silt, and 11% sand, with the granulometric curve obtained displayed in Figure 1 with a solid blue line (U20). Based on the ASTM standard D 2487-06 [42], this material is classified as clayed sand (SC), corroborating Witte et al.'s [43] suggestion that mine tailings can be perceived as transition soils between sands and clays, with different densities and, consequently, different mechanical properties. Since mine tailings are non-conventional geomaterials, Witte et al. [43] presented an alternative size distribution-based classification, considering some factors that influence mine tailings' characteristics. According to that classification, Panasqueira's tailings are classified as granular tailings, resembling non-plastic silty sands.

**Table 2.** Physical properties of Panasqueira mine tailings.

$w_L$ (%)	Atterberg Limits		$I_P$ (%)	Particle Size Analysis			Phase Relationships		
	$w_P$ (%)			$D_{10}$ (mm)	$D_{50}$ (mm)	$C_U$	$C_C$	$G$	$e_0$
23–24	14–15		8–10	0.01–0.014	$\approx 0.10$	10.7–17.5	1.78–1.88	2.94–3.15	0.62–0.75



**Figure 1.** Particle size distribution curves of the undisturbed and reconstituted samples.

### 2.3. Undisturbed Samples

As shown in Figure 2, the undisturbed blocks retrieved at the Panasqueira mine were rigid and highly stratified, which made the process of trimming adequate samples challenging. However, with a meticulous preparation process, it was still possible to trim samples with suitable geometry for both oedometer and triaxial testing. The tests on the undisturbed samples were performed in June 2023, i.e., approximately 20 months after the collection and, consequently, these samples were denoted as U20 ("U" because they were undisturbed and "20" since that was the approximate number of months passed between collection and testing).



**Figure 2.** Undisturbed block retrieved at Panasqueira mine.

#### 2.4. Reconstituted Samples

The reconstituted samples were prepared through slurry deposition, following a methodology similar to that proposed by Carraro and Prezzi [44]. This methodology was adapted to avoid particle segregation, which is significantly encouraged when reconstituting tailing samples due to the differences in the grains' sizes (Figure 1) and, particularly, grains' densities ( $G$  in Table 1) [45]. To ensure repeatability during preparation, mechanical mixing equipment was developed to mix the tailings with tap water in order to obtain a homogeneous slurry. It was established that the ideal ratio of water to dry tailings corresponded to a slurry's water content of 27%. After two minutes of mixture with specially designed blades, the equipment was switched off, and the homogeneous slurry was immediately deposited by gravity into the mould via a tap located at the bottom of the vat. An essential feature of this equipment is its versatility, which allows the preparation of samples of different sizes and shapes, as required to test samples in regular oedometers, triaxial cells, and hollow cylinder apparatus [46].

As Qin et al. [47] demonstrated, the slurry deposition method leads to spontaneous densification of the sample in the moments after the deposition. To ensure homogeneity and repeatability of the sample, some additional procedures were established. Firstly, the settling time of the slurry was assessed by preparing samples in glass containers and recording their initial heights ( $H_0$ ). Surface settlement readings ( $dh$ ) were taken at several intervals for 24 h. The settlement variation with the time curve obtained was more pronounced in the first 30 m, after which the settlement tended to stabilise. Based on this result, a rest time of 1 h was adopted in all tests. The second procedure concerned the possible segregation effects during deposition. To observe this effect, different dummy samples were prepared and let to dry. Visual inspections and particle size distributions performed in three sections of the samples (bottom third, central third, and top third) confirmed that no segregation occurred throughout the height of the triaxial samples, which could be considered uniform. Unsurprisingly, the particle size distribution curve obtained was identical to that of the undisturbed samples (Figure 1).

To evaluate the ageing influence on the reconstituted geomaterial behaviour, multiple triaxial samples were produced and left to rest at ambient temperature and humidity. The first set of samples was tested immediately after its preparation and are therefore designated as RA0 ("R" from reconstituted, "A" from aged "0" for the number of months passed after the sample preparation). Another set of samples was tested after three months and is accordingly designated as RA3.

#### 2.5. Tests Performed

The tailings' behaviour characterisation discussed in the present study relies on mechanical (oedometer and triaxial compression tests) and physico-chemical tests (measurement of  $pH$  and EC). The test procedures were the same for each type of test, regardless of the sample type tested (undisturbed or reconstituted).

The  $pH$  and EC of the samples were determined according to the procedures described in ISO 10380 [48] and ISO 11265 [49], respectively. Even if these standards were created for

soils, they were considered the most suitable as there are no specific standard procedures to determine  $pH$  and EC in mining tailings. To determine the  $pH$ , each sample was mixed with deionised water (in a volume ratio of 1 soil–5 water). After stirring for 1 h and allowing the suspension to rest for another 1 h, the  $pH$  of the solution was measured. For the evaluation of the EC of each sample, a portion of the soil was mixed with deionised water (also in a ratio of 1:5) and stirred for 30 m. These measurements were performed with a calibrated multiparameter water quality meter (*Hanna Instruments*).

The one-dimensional compression tests were carried out using a standard oedometer apparatus. The dimensions of the samples were 19 mm in height and 69.6 mm in diameter. The test followed the normalised procedure [50], with the initial pressure applied being 15 kPa. The pressure was then increased by doubling the previous pressure applied in increments every 4 h (proven enough to stabilise the displacement–time curve and fully consolidate the sample) up to a maximum pressure of 7200 kPa. The tests also comprised one or two discharge stages, in which the pressure was reduced to one-quarter of the previous pressure applied in each unloading/reloading stage.

The conventional triaxial compression tests were performed on a Bishop and Wesley’s hydraulic triaxial apparatus [51] under undrained loading conditions after isotropic consolidation and followed the procedures established in standard BS 1377-8 [52]. The samples, with a height of 76 mm and 38 mm in diameter, were initially saturated to a minimum pore pressure coefficient (B-value) of 0.98 and then isotropically consolidated to one of two initial mean effective stresses ( $p'_0$ ): 200 kPa or 800 kPa. Once the initial mean effective stress was achieved, the sample rested for four hours to allow for the total dissipation of any excess pore water pressure generated during consolidation. The samples were then sheared until failure was achieved by applying a constant strain rate of 1.6%/hour in the vertical piston (increase in the vertical stress) while maintaining a constant value of the confining pressure in the cell (radial pressure did not change throughout the test). The conditions of each triaxial test performed are presented in Table 3. It should be noted that for evaluating the inherent variability of the tailings, two tests for each of the two initial consolidation pressures were performed on the undisturbed samples (U20). As for the reconstituted samples (RA0 and RA3), only one test was performed for each consolidation level since the repeatability ensured by the adopted reconstitution process was already demonstrated by Oliveira et al. [46].

**Table 3.** Conditions of the triaxial samples.

Sample Designation	Time After Collection (Month)	Time After Reconstitution (Month)	Type	Consolidation			Shearing	
				$\sigma_v; \sigma_r$ <sup>1</sup> (kPa)	$u$ <sup>2</sup> (kPa)	$p'_0$ <sup>3</sup> (kPa)	Type	Drainage
U20-200_1	20	–	Isotropic	800	600	200	Compression with increase in the vertical stress	Undrained
U20-200_2	20	–		800	600	200		
U20-800_1	20	–		1400	600	800		
U20-800_2	20	–		1400	600	800		
RA0-200	–	0		800	600	200		
RA0-800	–	0		1400	600	800		
RA3-200	–	3		800	600	200		
RA3-800	–	3		1400	600	800		

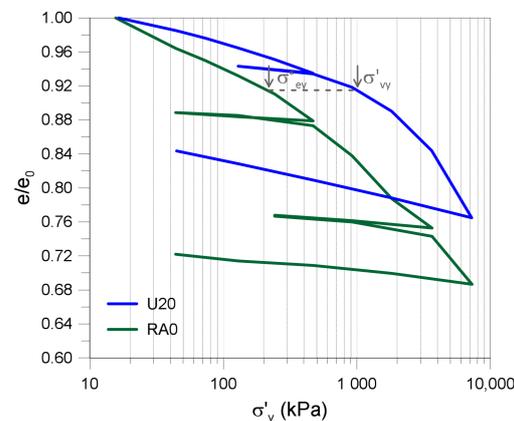
<sup>1</sup>  $\sigma_v; \sigma_r$ —vertical total stress and radial total stress applied in the outside of the sample. <sup>2</sup>  $u$ —backpressure in the inside of the sample. <sup>3</sup>  $p'_0$ —initial mean effective stress.

### 3. Results and Discussion

#### 3.1. Influence of the Structure on the Mechanical Behaviour of Tailings

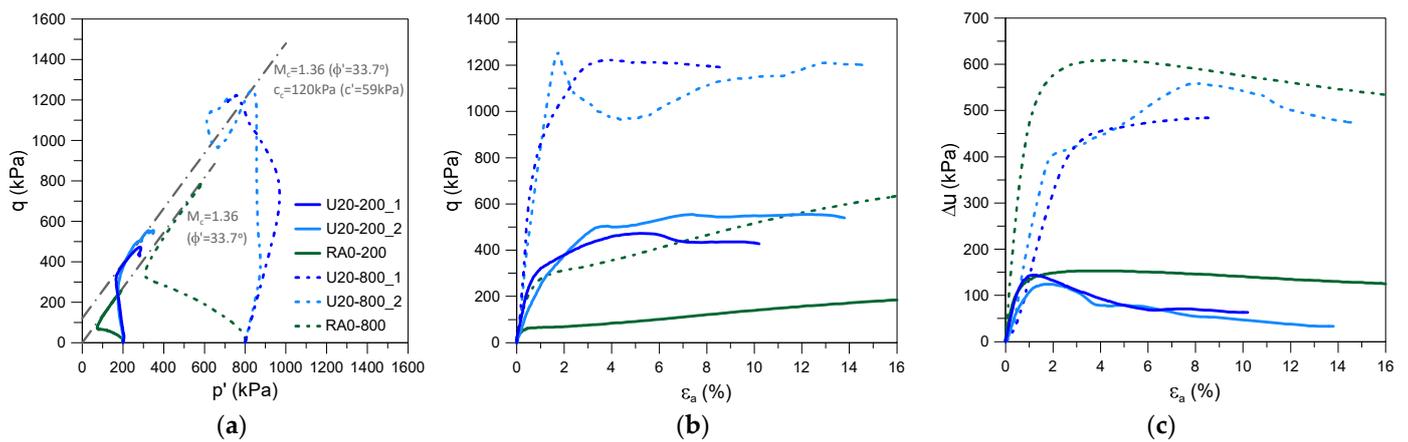
The evaluation of the structure of the tailings developed as a result of ageing was performed by comparing the results of the undisturbed (U20) and unaged reconstituted

(RA0) samples. The results obtained from the oedometer tests performed are presented in Figure 3. To facilitate the comparison between curves, the void ratio ( $e$ ) was normalised by its initial value ( $e_0$ ). As expected, there is a clear difference between the behaviour of the samples, with the undisturbed sample exhibiting much smaller deformations than the reconstituted sample for the same stress levels applied. It is also visible that the reconstituted sample presents a more uniform decrease in the normalised void ratio with the logarithmic increase in the vertical effective stress, while in the undisturbed sample, a more complex behaviour is observed. In fact, in this case, after an almost linear decrease in the void ratio up to a vertical effective stress of about 1000 kPa ( $p' \cong 625$  kPa estimated using Jaki's [53]  $K_0$  proposal), a progressively steeper decrease in the void ratio is observed for further stress increments. The behaviour exhibited by both undisturbed and reconstituted tailing samples resembles that observed by Burland [26] in clays, revealing that the undisturbed tailings, despite being deposited relatively recently in the dam and ageing only for 20 months in the laboratory, have acquired some structure. Naturally, that structure is completely destroyed by the reconstitution process, but also, if large stresses are applied, with the results suggesting that the effect of the structure is gradually reduced for mean effective stresses above 625 kPa. It also appears that, for large stresses, both curves tend to converge in a single isotropic compression curve, as is typically observed in clays [26].



**Figure 3.** Behaviour of undisturbed and unaged reconstituted samples in one-dimensional compression.

The stress–strain behaviour obtained in the triaxial tests performed on both undisturbed and reconstituted samples is depicted in Figure 4. The samples consolidated for a mean effective stress of 200 kPa are represented in solid lines, while the samples consolidated for 800 kPa are shown in dashed lines. The results of the two tests per stress level performed on the undisturbed samples (light and dark blue solid and dashed lines) show that despite the heterogeneity observed in the tailings, the stress–strain behaviour of the samples can be considered identical for each pair of tests. The undisturbed samples exhibit mainly strain hardening (Figure 4b) and an almost vertical stress path in the  $p'$ - $q$  plane (Figure 4a), which indicates the generation of positive excess pore water pressures in every sample (Figure 4c), due to their tendency to contract when sheared. This behaviour becomes less evident with the increase in the consolidation pressure, with inclusively the mean effective stress surpassing its initial value. As for the reconstituted samples, represented by the green solid and dashed lines, the stress–strain curves confirm that these samples are much softer than the corresponding undisturbed samples. Also in this case, a typical strain hardening behaviour is observed (Figure 4b) with the development of significant positive excess pore water pressures (Figure 4c) that considerably reduce the mean effective stress until yielding occurs (Figure 4a). After that point, the stress path inverts and follows a very well-defined critical state line until the end of the test is reached.



**Figure 4.** Influence of the structure in the stress–strain behaviour: (a)  $p'$ - $q$  stress path; (b) stress–strain curves; (c) generation of excess pore water pressures.

Despite the limited number of tests, some considerations regarding the strength of the materials can be established. Superimposed in Figure 4a are also the failure envelopes (grey dashed-dot lines) predicted for both materials, which confirm that the undisturbed tailings have higher strength. It is interesting to note that the envelopes of both materials have approximately the same inclination with a  $M_c = 1.36$ , which corresponds to an angle of shear strength ( $\phi'$ ) of  $33.7^\circ$ . This result confirms that the frictional strength mobilised between particles is identical in both materials, which could be expected, as the reconstitution process should not alter the characteristics of the particles (see Figure 1). The difference in strength between both materials is due to the cohesive component, which in the case of the unaged reconstituted samples is zero, confirming the destructuration induced by the reconstitution process, and in the case of the aged undisturbed sample corresponds to about 59 kPa, confirming that the undisturbed tailings tested exhibit some structure.

An attempt to quantify the structure of the tailings can be performed by applying the framework initially proposed by Terzaghi [54] for clays. This framework relies on the determination of the sensitivity, which is expressed as the ratio between undisturbed and reconstituted parameters determined in laboratory tests. Naturally, a higher sensitivity value indicates a more pronounced soil structure, while a sensitivity of 1 corresponds to the absence of structure in the soil. According to Cotecchia and Chandler [55], it is possible to determine the stress sensitivity ( $S_\sigma$ ) based on the oedometer results.  $S_\sigma$  can be determined by Equation (1), where  $\sigma'_{vy}$  corresponds to the vertical effective stress where the yield is first observed in the undisturbed sample and  $\sigma_{ey}^*$  is the equivalent (for the same void ratio) vertical effective stress in the reconstituted sample (as illustrated in Figure 3).

$$S_\sigma = \frac{\sigma'_{vy}}{\sigma_{ey}^*} \quad (1)$$

Based on the undrained triaxial tests, it is also possible to determine the so-called strength sensitivity ( $S_t$ ), which corresponds to the ratio between the undrained strengths measured in the undisturbed ( $s_u$ ) and reconstituted samples ( $s_u^*$ ), as expressed in Equation (2) [55].

$$S_t = \frac{s_u}{s_u^*} \quad (2)$$

The results of the sensitivity determined for the oedometer and for the two stress levels of the triaxial tests are presented in Table 4. Despite the differences observed, the sensitivity determined in both tests can be considered medium according to Mitchell and Soga [27]. These results confirm that the aged undisturbed tailings have relevant bonds between particles that confer an increased strength in comparison with the reconstituted geomaterial.

**Table 4.** Sensitivity of the tailings tested in different conditions (aged undisturbed—U20 and unaged reconstituted—RA0).

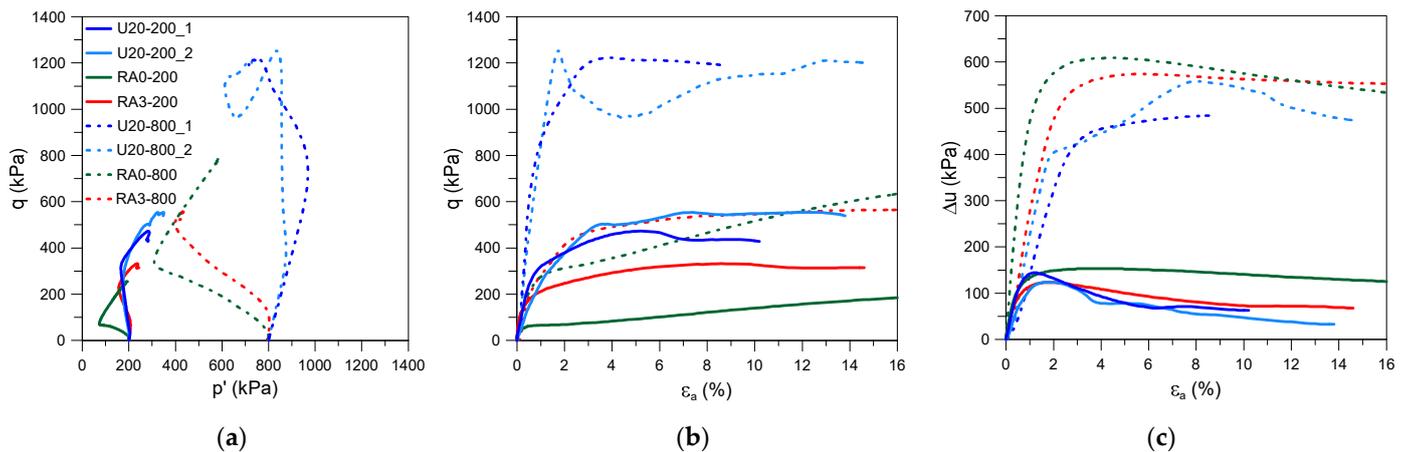
Test	U20	RA0	Sensitivity
Oedometer	$\sigma'_{vy} = 1000$ kPa	$\sigma_{ey}^* = 220$ kPa	$S_\sigma = 4.6$
Triaxial <sup>1</sup>	$p'_0 = 200$ kPa	$s_u^* = 45$ kPa	$S_t = 3.7$
	$p'_0 = 800$ kPa	$s_u^* = 185$ kPa	$S_t = 3.2$

<sup>1</sup> Undrained strength was determined in the moment when the stress path first touches the failure envelope.

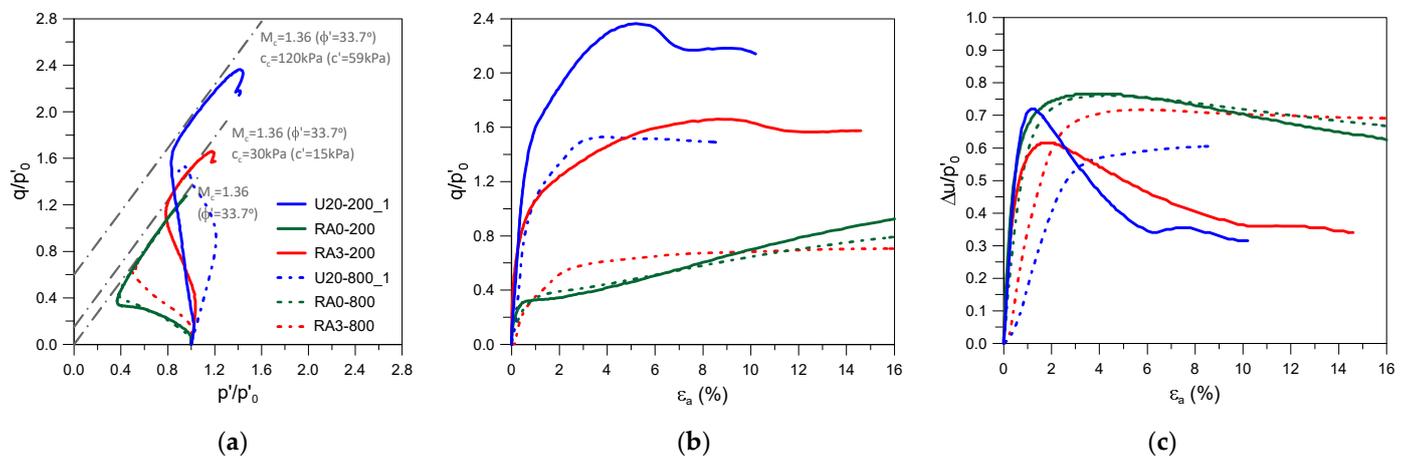
### 3.2. Assessment of the Ageing Process

As mentioned previously, part of the reconstituted samples was reserved for later testing. After a period of three months, the aged reconstituted samples (RA3) were tested in the triaxial apparatus to evaluate the influence of the ageing processes and evolution with time. The results of the triaxial tests performed are represented by the red solid (200 kPa) and dashed (800 kPa) lines in Figure 5. For clarity of interpretation, only one test of the undisturbed samples is represented in the figure. The results show that the aged samples have a behaviour in-between the unaged reconstituted (RA0) and the aged undisturbed samples (U20). However, it is interesting to observe that the behaviour is strongly affected by the initial consolidation level. For the smallest mean effective stress considered, RA3-200, the stress path (Figure 5a) is very similar to that observed in the aged undisturbed samples, with the main difference being the maximum deviatoric stress reached, which is smaller in the sample RA3. When consolidated to 800 kPa, the behaviour of the RA3-800 sample resembles that verified in the unaged reconstituted sample RA0-800. In this test, the stress path also bends significantly to the left due to high excess of water pressure generated and, although yielding occurs at a higher deviatoric stress, the post-yielding trajectory is identical to that observed in the reconstituted sample. This distinct behaviour due to the initial stress level is even clearer in Figure 6, where the results of the triaxial tests are normalised by the mean effective confining stress. It becomes evident from the stress path (Figure 6a) that, after yielding is reached, the sample consolidated to 200 kPa (RA3-200) follows a failure envelope parallel (with the same  $M_c = 1.36$ ) but in-between the envelopes determined for the undisturbed and the reconstituted samples. In the case of RA3-200, an effective cohesion of 15 kPa can be estimated, which compares with the 59 kPa determined for the aged undisturbed samples and with the absence of cohesion obtained in the unaged reconstituted samples. In contrast, the sample consolidated to 800 kPa (RA3-800) yields in the envelope defined for the unaged reconstituted samples, presenting just a slightly higher undrained strength at failure. These results suggest that the ageing process allow for some regeneration of the structure in the reconstituted geomaterial, with some bonds being created between particles that improve the performance of the geomaterial. However, these bonds are relatively fragile, at least when formed during an ageing period of only 3 months, and are destroyed when higher levels of stress are applied.

This behaviour resembles, to some extent, that observed in the oedometer tests (Figure 3). Consequently, it is reasonable to assume that, for the only three-months-aged reconstituted samples, the bonds created between particles are relatively fragile and get destroyed for even smaller stress levels. This might justify why the RA3-200 sample behaves more similarly to the undisturbed sample and the RA3-800 to the reconstituted sample. This result is confirmed by comparing the undrained strength measured in all tests. As can be seen in Table 5, a significant increase in the undrained strength is measured in the RA3 samples, with the RA3-200 test exhibiting a substantial increase of 178% in comparison with the equivalent RA0-200 test, while on RA3-800 a still relevant but much smaller 41% increase was determined.



**Figure 5.** Influence of the ageing process in the stress–strain behaviour: (a)  $p'$ - $q$  stress path; (b) stress–strain curves; (c) generation of excess pore water pressures.



**Figure 6.** Normalised stress–strain behaviour: (a)  $p'$ - $q$  stress path; (b) stress–strain curves; (c) generation of excess pore water pressures.

**Table 5.** Undrained strength measured in the triaxial tests.

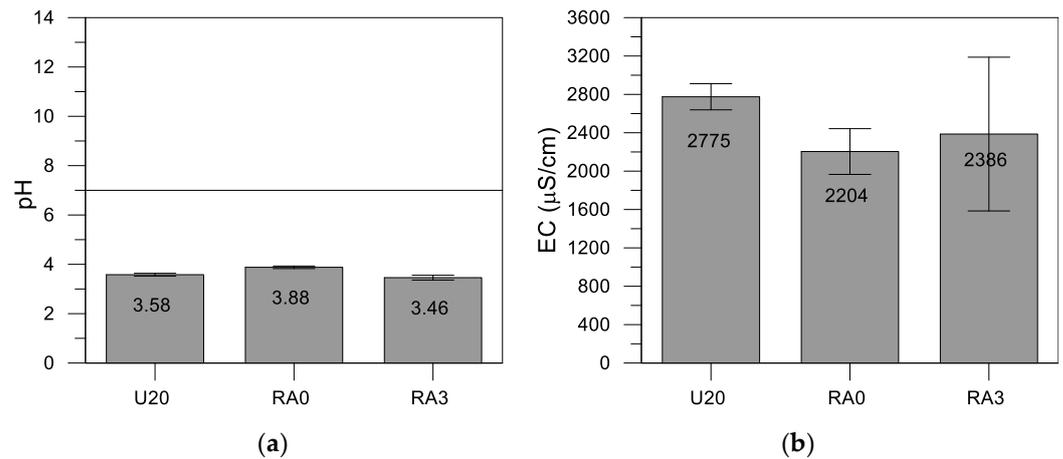
Test	U20	RA0	RA3
Triaxial <sup>1</sup>			
$p'_0 = 200$ kPa	165	45	125 (↑178%) <sup>2</sup>
$p'_0 = 800$ kPa	600	185	260 (↑41%) <sup>2</sup>

<sup>1</sup> Undrained strength was determined in the moment when the stress path first touches the failure envelope. <sup>2</sup> Values in parenthesis correspond to the percentage of the undrained strength of the RA3 tests in comparison to the RA0 values.

### 3.3. Correlation of Ageing with Physico–Chemical Tests

In order to evaluate if the increase in strength observed over time in the tailings tested could be correlated with easier-to-determine physico–chemical parameters, a set of tests was performed. In total, 24 tests, 8 for each type of sample, were carried out to evaluate both the  $pH$  and the EC as these parameters are usually measured to assess the tailings' environmental impact. In Figure 7, the average results and the corresponding standard deviations obtained for each parameter and for each sample are presented.

The results of the  $pH$  are consistent and show that all samples are highly acidic, having an average  $pH$  value of about 3.5, which agrees with the results published in the literature [15–17]. As a result,  $pH$  does not seem to be influenced by either the reconstitution process or the ageing of the samples, with the addition of tap water (with a  $pH$  of about 7) to prepare the reconstituted samples having a minor impact on the  $pH$  value measured.



**Figure 7.** Results of the physico-chemical tests for all the tailing samples: (a) pH; (b) EC.

As for the CE (Figure 7b), the results appear to be related to the cementation of the samples. The highest CE corresponds to the undisturbed samples (U20), while the reconstituted samples (RA0) have the lowest value, which seems to reflect the precipitates present in aged undisturbed samples that promotes the cementation developed during the ageing process. Despite some scatter, the CE in the aged samples (RA3) has a value in-between, which is consistent with the conclusions of the evolution of the mechanical behaviour of reconstituted samples with time. In fact, RA3 samples show signs of ageing effects that include bonds between particles that were inexistent in RA0 samples but remain more fragile than those found in U20 samples. Since the CE values increase in the reconstituted samples with ageing, from RA0 to RA3, and increase further in the aged undisturbed samples, it seems that there is a link between the cementation of the samples and the CE. This potential link, which should be further confirmed by additional tests with different ageing periods, might simplify the process of evaluating the strength of the reconstituted tailings and its evolution with time. In any case, these results suggest that the secondary mineral phases that seem to be formed as a result of the ageing processes appear to be water soluble and depend on the existence of conditions favourable for the precipitation processes to occur.

#### 4. Conclusions

More sustainable and safer management of tailing storage facilities strongly depends on the ability to fully understand the behaviour of tailings under different environmental conditions, including the development of ageing effects induced over time due to the reactive potential of tailings. In fact, whether the aim is to optimise the design of large tailings storage facilities or to reuse tailings in sustainable geotechnical applications applying the concept of circular economy in practice, the evolution of tailings' behaviour over time is fundamental to suitably establish the technical solutions while maintaining the environmental risks under control. Considering the current and future industry requirements and societal demands, this is a most needed advance in the understating of tailings' behaviour.

The experimental work presented herein indicates the following regarding the tested tailings produced by a tungsten mine:

- The mechanical behaviour changes over time, due to ageing effects that can be totally reversed if full destructuration of the material is carried out;
- Undisturbed samples aged for about twenty months show, when compared to unaged reconstituted samples, a significant stiffness increase under one-dimensional compression, up to large values of vertical effective stresses ( $\approx 1000$  kPa);
- Undisturbed samples aged for about twenty months show, when compared to unaged reconstituted samples, a very significant increase in the shear strength observed in

- undrained triaxial compression, which tends to reduce with the increase in the effective confining stress, similarly to the behaviour observed in one-dimensional compression;
- Reconstituted samples aged for three months show an in-between behaviour in undrained triaxial compression, which suggests that an ageing process is also developed but the bonds between tailing particles remain more fragile when compared to those found in the aged undisturbed tailings;
  - The sensitivity calculated for the aged undisturbed samples in comparison to the unaged reconstituted samples clearly shows the important effects of ageing for the different loading conditions imposed on the samples and also the relevant effects of the effective confining stresses on ageing-induced effects;
  - The  $pH$  measured remains low in all cases, showing no influence of ageing or of tailing destructuration, which needs to be taken into account when considering alternative use of these geomaterials in environmentally safe applications;
  - Higher CE reflects the ageing effects that improve the mechanical performance of tailings with time, which is attributed to the precipitation of secondary mineral phases that bind particles and are easily water soluble.

Overall, the results suggest that considering the improvement of the mechanical performance induced by ageing effects in tailings may further optimise the design of tailing storage facilities and further enhance the use of these unconventional geomaterials in sustainable geotechnical applications. From the practical point of view, controlling the possible improvement of the mechanical behaviour of tailings due to ageing would potentially increase the safety of existing tailing storage facilities and/or reduce the safety requirements for new infrastructures of these types and thus optimise their design in the future. On the other hand, if ageing effects can be controlled in the field, this would promote the implementation, in current design practice, of circular economy solutions based on the use of tailings in large geotechnical projects that would combine environmental sustainability, economic efficiency, and social benefit.

However, tailings are not common geomaterials, and their reactive potential must also be accounted for in sustainable geotechnical design. In fact, the  $pH$  and CE values observed in the samples require that field applications may be limited to conditions where these parameters can be controlled and, consequently, the AD phenomenon; they also require systematic field monitoring to ensure that truly sustainable solutions can be achieved. In addition, the evolution of the mechanical behaviour of tailings and its stability with time, under field conditions, should also be confirmed.

**Author Contributions:** Conceptualisation, J.P.O. and L.A.S.; methodology, J.R., P.C. and A.M.G.P.; validation, P.C. and A.M.G.P.; writing—original draft preparation, J.P.O. and L.A.S.; writing—review and editing, J.R., P.C. and A.M.G.P. All authors have read and agreed to the published version of the manuscript.

**Funding:** This work was partly financed by FCT/MCTES through national funds, namely project GeoSusTailings, PTDC/ECI-EGC/4147/2021.

**Institutional Review Board Statement:** Not applicable.

**Informed Consent Statement:** Not applicable.

**Data Availability Statement:** The raw data supporting the conclusions of this article will be made available by the authors upon request.

**Conflicts of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as potential conflicts of interest.

## References

1. De Jong, T.; Sauerwein, T.; Wouters, L. *Mining and the Mining and the Green Energy Transition: Review of International Development Challenges and Opportunities*; United States Agency for International Development: Washington, DC, USA, 2021.
2. Federal Ministry of Agriculture, Regions and Tourism World Mining Data 2020. World Mining Congress 2020. Available online: <https://www.world-mining-data.info> (accessed on 11 December 2024).

3. Rubio, F.R.; Kleinmann, B. Introduction to This Special Issue on Tailings Storage: Challenges and Technologies. *Mine Water Environ.* **2021**, *40*, 1–5. [[CrossRef](#)]
4. Garcia, F.F.; Camilo Cotrim, C.F.; Caramori, S.S. Mine Tailings Dam's Failures: Serious Environmental Impacts, Remote Solutions. *Environ. Dev. Sustain.* **2024**, 1–23. [[CrossRef](#)]
5. Araujo, F.S.M.; Taborda-Llano, I.; Nunes, E.B.; Santos, R.M. Recycling and Reuse of Mine Tailings: A Review of Advancements and Their Implications. *Geosciences* **2022**, *12*, 319. [[CrossRef](#)]
6. Adiansyah, J.S.; Rosano, M.; Vink, S.; Keir, G. A Framework for a Sustainable Approach to Mine Tailings Management: Disposal Strategies. *J. Clean. Prod.* **2015**, *108*, 1050–1062. [[CrossRef](#)]
7. Duarte, E.B.; Neves, M.A.; Oliveira, F.B.; Martins, M.E.; Oliveira, C.H.R.; Burak, D.L.; Orlando, M.T.D.; Rangel, C.V.G.T. Trace Metals in Rio Doce Sediments before and after the Collapse of the Fundão Iron Ore Tailing Dam, Southeastern Brazil. *Chemosphere* **2021**, *262*, 127879. [[CrossRef](#)]
8. Araújo, B.D.; Maia, R.A.; Barbosa, M. Effects of Mining Tailings on Soil Quality and Performance of Two Native Atlantic Forest Species: Implications for Restoration. *Water Air Soil Pollut.* **2024**, *235*, 687. [[CrossRef](#)]
9. Redwan, M. Geochemical and Mineralogical Characteristics of Some Gold Mine Tailings in Egypt's Eastern Desert. *Front. Earth* **2022**, *16*, 906–915. [[CrossRef](#)]
10. Lindsay, M.B.J.; Moncur, M.C.; Bain, J.G.; Jambor, J.L.; Ptacek, C.J.; Blowes, D.W. Geochemical and Mineralogical Aspects of Sulfide Mine Tailings. *Appl. Geochem.* **2015**, *57*, 157–177. [[CrossRef](#)]
11. Li, C.; Jin, J.; Wu, P.; Xu, B. Effect of Freeze–Thaw Cycles on Shear Strength of Tailings and Prediction by Grey Model. *Minerals* **2022**, *12*, 1125. [[CrossRef](#)]
12. Lu, X.; Wang, H. Microbial Oxidation of Sulphide Tailings and the Environmental Consequences. *Elements* **2012**, *8*, 119–124. [[CrossRef](#)]
13. Sapkota, B.; Verbuyst, B.; Bain, J.; Ptacek, C.; Blowes, D.; Al, T. Geochemical and Mineralogical Investigation of Cemented Crusts in the Tailings Cover at Long Lake Gold Mine, Sudbury, Canada. *J. Hazard. Mater.* **2023**, *451*, 131192. [[CrossRef](#)]
14. Petronic, B.M.; Al, T.A.; Weaver, L.; Hall, D. Identification and Characterization of Secondary Minerals Formed in Tungsten Mine Tailings Using Transmission Electron Microscopy. *Appl. Geochem.* **2009**, *24*, 2222–2233. [[CrossRef](#)]
15. Ávila, P.F.; Silva, E.F.; Salgueiro, A.R.; Farinha, J.A. Geochemistry and Mineralogy of Mill Tailings Impoundments from the Panasqueira Mine (Portugal): Implications for the Surrounding Environment. *Mine Water Environ.* **2008**, *27*, 210–224. [[CrossRef](#)]
16. Candeias, C.; Ávila, P.F.; Silva, E.F.; Ferreira, A.; Salgueiro, A.R.; Teixeira, J.P. Acid Mine Drainage from the Panasqueira Mine and Its Influence on Zêzere River (Central Portugal). *J. Afr. Earth Sci.* **2013**, *99*, 705–712. [[CrossRef](#)]
17. Dinis, M.L.; Fiúza, A.; Futuro, A.; Leite, A.; Martins, D.; Figueiredo, J.; Góis, J.; Vila, M.C. Characterization of a Mine Legacy Site: An Approach for Environmental Management and Metals Recovery. *Environ. Sci. Pollut. Res.* **2020**, *27*, 10103–10114. [[CrossRef](#)]
18. APA. Portuguese Environment Agency Contaminated Soils—Technical Guide. In *Reference Values for Soil*; APA: Lisboa, Portugal, 2019.
19. Ministry of the Environment Decree-Law N° 236/98 1998. (In Portuguese). Available online: <https://files.diariodarepublica.pt/gratuitos/1s/1998/08/176a00.pdf> (accessed on 11 December 2024).
20. Troncoso, J. Ageing Effects on Cyclic Shear Strength of Tailings Materials. In Proceedings of the Ninth World Conference on Earthquake Engineering, Tokyo-Kyoto, Japan, 2–9 August 1988.
21. Troncoso, J.H. Ageing Effects in the Shear Modulus of Soils. *Soil Dyn. Earthq. Eng.* **2000**, *19*, 595–601. [[CrossRef](#)]
22. Segui, P.; Safhi, A.M.; Amrani, M.; Benzaazoua, M. Mining Wastes as Road Construction Material: A Review. *Minerals* **2023**, *13*, 90. [[CrossRef](#)]
23. Djellali, A.; Laouar, M.S.; Saghafi, B. Evaluation of Cement-Stabilised Mine Tailings as Pavement Foundation Materials. *Geotech. Geol.* **2019**, *37*, 2811–2822. [[CrossRef](#)]
24. Mancini, S.; Casale, M.; Tazzini, A.; Dino, G.A. Use and Recovery of Extractive Waste and Tailings for Sustainable Raw Materials Supply. *Mining* **2024**, *4*, 149–167. [[CrossRef](#)]
25. Zhang, Y.M.; Wang, L.N.; Chen, D.S. A Method for Recovering Iron, Titanium and Vanadium from Titanomagnetite Containing Vanadium. *Int. J. Miner. Met. Mater.* **2018**, *25*, 131–144. [[CrossRef](#)]
26. Burland, J.B. On the Compressibility and Shear-Strength of Natural Clays. *Géotechnique* **1990**, *40*, 329–378. [[CrossRef](#)]
27. Mitchell, J.K.; Soga, K. *Fundamentals of Soil Behavior*; John Wiley & Sons: Hoboken, NJ, USA, 2005; Volume 3, p. 558.
28. Hight, D.W.; Jardine, R.J.; Gens, A. The Behaviour of Soft Clays. In *Embankments on Soft Clays*. *Public Work. Res. Cent.* **1987**, *2*, 33–158.
29. Wu, S.; Liu, Y.; Southam, G.; Robertson, L.; Chiu, T.H.; Cross, A.T.; Dixon, K.W.; Stevens, J.C.; Zhong, H.; Chan, T.S. Geochemical and Mineralogical Constraints in Iron Ore Tailings Limit Soil Formation for Direct Phytostabilization. *Sci. Total Environ.* **2019**, *651*, 192–202. [[CrossRef](#)] [[PubMed](#)]
30. Reid, D. Slurry Deposition Preparation Method for Tailings Characterisation—History, Debates, Techniques and Benefits. In Proceedings of the Tailings 2022, Online Conference, 6–8 July 2022.
31. Viana da Fonseca, A. The Mechanics of Iron Tailings from Laboratory Tests on Reconstituted Samples Collected in Post-Mortem Dam I in Brumadinho. *Soils Rocks* **2022**, *45*, e2022001122. [[CrossRef](#)]
32. Huang, Y.; Wang, G.; Rao, Y.; Liu, W. Mechanical Properties and Damage Mode of Cemented Tailings Backfill in an Acidic Environment. *J. South. Afr. Inst. Min. Metall.* **2021**, *121*, 317–324. [[CrossRef](#)]

33. Igwe, O.; Chukwu, C. Evaluation of the Mechanical Properties and Critical Slope Parameters of Mine Tailings in Enyigba, South-East Nigeria. *Int. J. Geo-Eng.* **2018**, *9*, 7. [[CrossRef](#)]
34. Antunes, S.M.P.B. Survey of the State of Contamination of the Lamas Dam and the Panasqueira Mine Slag Heap. Master's Thesis, University of Porto, Porto, Portugal, 2010.
35. Simão, F.C.S.V. Evaluation of the Potential in Critical Metals in the Fine Tailings Dams of the Panasqueira Mine (Barroca Grande, Portugal). Master's Thesis, University of Coimbra, Coimbra, Portugal, 2017.
36. Neiva, A.M.R. Geochemistry of Cassiterite and Wolframite from Tin and Tungsten Quartz Veins in Portugal. *Ore Geology Reviews.* *Ore Geol. Rev.* **2008**, *33*, 221–238. [[CrossRef](#)]
37. Fourie, A.; Reid, D.; Ayala, J.; Russell, A.; Vo, T.; Rahman, M.; Vinod, J. Improvements in Estimating Strengths of Loose Tailings: Results from the TAILLIQ Research Project. *Proc. Mine Waste Tailings* **2021**, 207–217.
38. Hu, L.; Wu, H.; Zhang, L.; Zhang, P.; Wen, Q. Geotechnical Properties of Mine Tailings. *J. Mater. Civ. Eng.* **2016**, *29*, 04016220. [[CrossRef](#)]
39. Rodríguez, R.; Muñoz-Moreno, A.; Caparrós, V.A. How to Prevent Flow Failures in Tailings Dams. *Mine Water Environ.* **2021**, *40*, 83–112. [[CrossRef](#)]
40. Islam, S. A Study on the Mechanical Behaviour of Three Different Fine-Grained Mine Tailings. *J. King Saud Univ. Eng. Sci.* **2021**, *35*, 335–341. [[CrossRef](#)]
41. Malekzadeh, M.; Lovisa, J.; Sivakugan, N. Consolidation of Cannington Mine Tailing at Its Liquid Limit. In Proceedings of the 12th Australia New Zealand Conference on Geomechanics, Wellington, New Zealand, 22–25 February 2015.
42. ASTM. *Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) D 2487*; American Society for Testing and Materials: West Conshohocken, PA, USA, 2006.
43. Witte, A.; Ekman, K.; Diaz, C. Mine Environment Neutral Drainage Project. MEND Report 2.50.1 Study of Tailings Management Technologies. In Proceedings of the 24th Annual BC MEND Metal Leaching / Acid Rock Drainage, Vancouver, BC, Canada, 29 November 2017; Klohn Crippen Berger: Vancouver, BC, Canada, 2017.
44. Carraro, J.; Prezzi, M. A New Slurry-Based Method of Preparation of Specimens of Sand Containing Fines. *Geotech. Test. J.* **2008**, *31*, 1–11. [[CrossRef](#)]
45. Coelho, P.; Camacho, D. The Experimental Characterization of Iron Ore Tailings from a Geotechnical Perspective. *Appl. Sci.* **2024**, *14*, 5033. [[CrossRef](#)]
46. Oliveira, J.P.; Coelho, P.; Araújo Santos, L. Application of the Slurry Deposition Method to the Reconstitution of Samples of Wolframite Ore Tailings. In Proceedings of the XVIII ECSMGE, Lisbon, Portugal, 26–30 August 2024.
47. Qin, J.; Zheng, J.; Li, L. An Analytical Solution to Estimate the Settlement of Tailings or Backfill Slurry by Considering the Sedimentation and Consoli-Dation. *Int. J. Min. Sci. Technol.* **2021**, *31*, 463–471. [[CrossRef](#)]
48. *ISO 10380*; Soil Treated Biowaste and Sludge—Determination of pH. International Organization for Standardization: Geneva, Switzerland, 2021.
49. *ISO 11265*; Soil Quality—Determination of the Specific Electrical Conductivity. International Organization for Standardization: Geneva, Switzerland, 1994.
50. British Standards Institution. Soils for civil engineering purposes. In *Part 5: Compressibility, Permeability and Durability Tests*; British Standards Institution: London, UK, 1990; p. 40.
51. Bishop, A.W.; Wesley, L.D. Hydraulic Triaxial Apparatus for Controlled Stress Path Testing. *Géotechnique* **1975**, *25*, 657–670. [[CrossRef](#)]
52. British Standards Institution. Soils for civil engineering purposes. In *Part 8: Shear Strength Tests (Effective Stress)*; British Standards Institution: London, UK, 1990; p. 38.
53. Jaky, J. The Coefficient of Earth Pressure at Rest. *J. Soc. Hung. Archit. Eng.* **1944**, 355–358.
54. Terzaghi, K. Ends and Means in Soil Mechanics. *Eng. J.* **1944**, 608–615.
55. Cotecchia, F.; Chandler, R.J. A General Framework for the Mechanical Behaviour of Clays. *Geotechnique* **2000**, *50*, 431–447. [[CrossRef](#)]

**Disclaimer/Publisher's Note:** The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.