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The Experimental Characterization of Iron Ore Tailings from a Geotechnical Perspective

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Featured Application: Iron ore tailings are amongst some of the most common and widely available types of mining waste. This paper focus on the geotechnical characterization of these materials in order to promote their potential applications as building materials in more sustainable geotechnical works, namely in embankments, employing the concept of circular economy.

Abstract: The mining industry produces large amounts of tailings which are disposed of in deposits, which neglects their potential value and represents important economic, social and environmental risks. Consequently, implementing circular economy principles using these unconventional geomaterials may decrease the wide-ranging impacts of raw material extraction. This paper presents an experimental characterization of iron ore tailings, which are the most abundant type of mining waste. The characterization includes various aspects of behavior that are relevant to different types of use as a building material, including physical and identification properties, compaction behavior and stress–strain properties under undrained monotonic and cyclic triaxial loading. The tailings tested can be described as low-plasticity silty sand materials with an average solids density of 4.7, a maximum dry unit weight close to 3 g/cm^3 and a higher angle of friction and liquefaction resistance than common granular materials. The experimental results highlight the particular features of the behavior of iron ore tailings and emphasize the potentially promising combination of high shear resistance and high density that favors particular geotechnical applications. Overall, the conclusions provide the basis for promoting the use of mining wastes in the construction of sustainable geotechnical works and underpin the advanced analysis of tailings storage facilities' safety founded on an open-minded geotechnical approach.

Keywords: iron ore tailings; geotechnical characterization; grain size distribution; plasticity; permeability; compaction behavior; shear strength; cyclic liquefaction

Citation: Coelho, P.; Camacho, D. The Experimental Characterization of Iron Ore Tailings from a Geotechnical Perspective. *Appl. Sci.* **2024**, *14*, 5033. https://doi.org/10.3390/app14125033

Academic Editor: Syed Minhaj Saleem Kazmi

Received: 3 May 2024
Revised: 5 June 2024
Accepted: 6 June 2024
Published: 9 June 2024

1. Introduction

Modern societies need increasing amounts of metal and mineral resources to sustain their development in a context of a growing and increasingly environmentally conscious global population, with the aim of achieving a conversion to a so-called low-carbon economy. However, clean energy technologies tend to use significantly more mineral and metal resources, which will necessarily intensify the demand for these commodities in the future. In fact, some experts consider that, to accomplish the desired global energy transition, the demand for metals such as nickel and cobalt may be almost 20 times higher in 2040 compared to 2020 [1]. But the case of iron ore is particularly relevant, as it is currently the most massively mined commodity, with its global production reaching about 2400 Mt in 2021 [2]. Furthermore, in 2019, iron ore accounted for almost 94% of all metals produced by the mining industry in the world, with 98% of which being used for steelmaking [3], making it the ideal mining waste to study from a circular economy perspective.

Unfortunately, the mining industry produces large amounts of waste, usually in the form of tailings that are disposed of in massive tailings storage facilities where their potential value as a construction material is neglected and which frequently pose important economic, social and environmental risks. In fact, the rock-to-metal ratio, which is an important measure of mining environmental impacts, is usually extremely high, with values in the range 10^5 to 10^6, in the case of gold, and values in the order of 10 in the case of iron ore often being reported [4]. Moreover, the metallic ore grades exploited through mining show an evident global tendency to decrease, because the higher-grade reserves have already been almost completely exploited [5]. As a result, the number and magnitude of tailings storage facilities in the world are expected to rise further. Consequently, an increase in the number of accidents involving these massive geotechnical structures has been observed during the last few decades, particularly in the case of the more failure-prone tailings dams. This problem is particularly serious in the case of iron ore tailings, with different failure mechanisms being identified from past events [6]. According to data collected by WMTF [7], which compiles the number of failures that have occurred in the past, at least 30 serious or very serious tailings dam failures are predicted to occur in the current decade (Figure 1). This distressing forecast suggests that the volume of mining waste produced must be reduced and that the safety of tailings storage facilities must be enhanced.

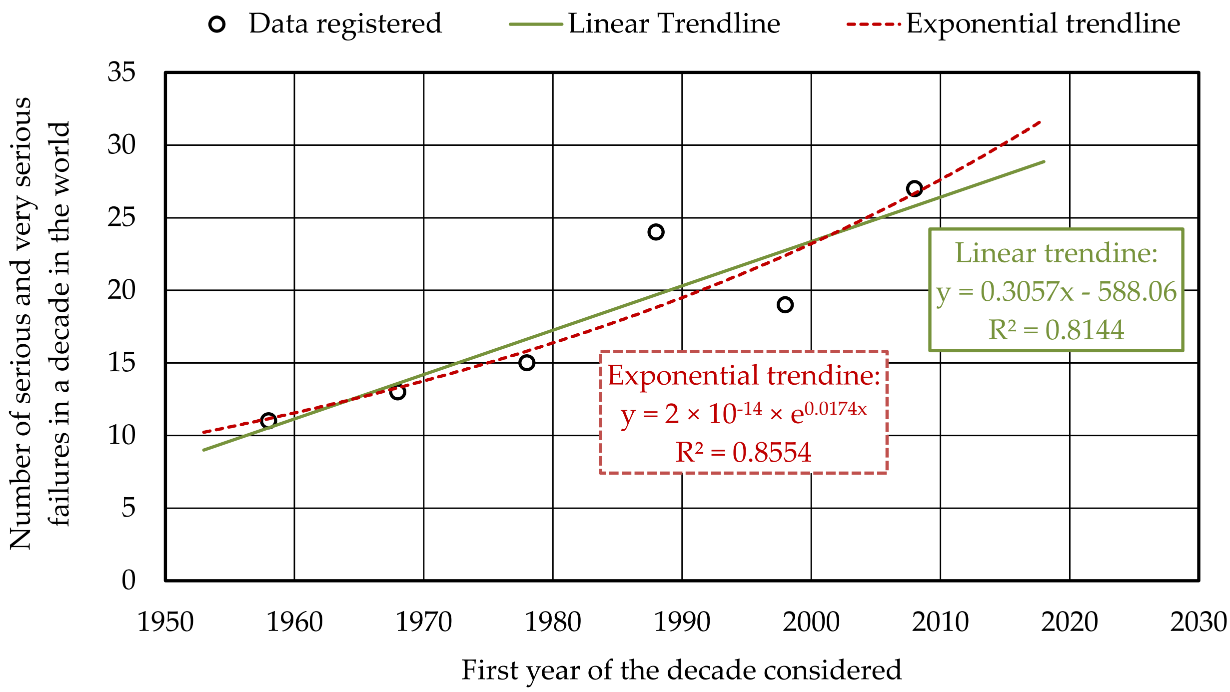

Figure 1. The number of serious and very serious tailings dam failures observed in the past in the world and predictions of similar failures in the future, based on data from WMTF [7].

Considering the volume of mining waste that is currently being generated, different principles of the circular economy could be applied to enhance mining waste management sustainability, including re-treating tailings within mine processing to enable the reuse and regeneration of materials [8]. This may be achieved in practice through the use of these unconventional geomaterials in geotechnical works in order to decrease the wide-ranging impacts of raw materials' extraction. In fact, the UN urges for further research on innovations in tailings' reuse, namely with respect to the potential to reuse at least part of the mining waste as an alternative to natural aggregates in construction [9]. Some attempts have been made to reuse tailings in construction, namely those resulting from iron ore mining, with the experimental results suggesting promising applications for the waste analyzed, which was processed by briquetting [10]. Using iron ore tailings in geotechnical works can be even more attractive, due to the large volume of materials that are often required to build embankments, land reclamation works, etc. Yet, sustainable geotechnical applications require control of the environmental safety of the applications, namely through suitable physicochemical and ecotoxicological analysis that must be carried out, similarly to other unconventional geomaterials used in construction [11,12].

On the other hand, the safety of tailings dams and other tailings storage facilities must be enhanced in order to protect human life, the environment and the economy. In fact, as mining is currently trying to cope with falling ore grades, increasingly larger projects are required to manage growing amounts of tailings. This creates continuous pressure in tailings management, namely with respect to stability to avoid catastrophic failures and other short- and long-term problems [2]. Also, there is increasingly growing pressure from society to avoid the consequences of dramatic failures such as the 2019 Brumadinho tailings dam collapse, which is believed to be the most serious social and environmental disaster that affected Brazil [13]. In addition, at least three different outstanding international teams reached inconsistent conclusions with respect to the causes of failure [14–16], which suggests that the mechanical behavior of tailings is still poorly understood. But even if the Brumadinho tailings dam collapse did not seem to be caused by earthquake loading, many of these structures are built in seismically active areas and are prone to earthquake-induced liquefaction [17]. This complex phenomenon can cause dramatic failures in granular saturated geomaterials due to the reduction in effective stress induced by large excess pore pressure generation, with its analysis and mitigation requiring proper mechanical characterization [18] and advanced modeling tools incorporating the intricate nature of local earthquakes [19]. But even if excess pore pressure generation induced by static or cyclic loading plays a role in major failures of tailings dams [20], the behavior of tailings still requires further clarification due to their rather peculiar man-made origin [21].

Considering the relevant problem faced by the mining industry regarding the reduction in the volume and the enhancement of the safety of tailings storage facilities in a challenging environment, this paper focus on the experimental characterization of iron ore tailings, which are the most abundant type of mining waste produced in the world. Iron ore samples representing real tailings and compacted tailings were tested to assess the most relevant physical, identification and mechanical properties governing their performance under different conditions that may exist in the field, namely when used as a building material. The tailings tested can be described as low-plasticity silty sand materials with average solids density of 4.7, a maximum dry unit weight close to 3 g/cm^3 and an angle of friction and liquefaction resistance exceeding the values usually found in common granular materials. The experimental results highlight the particular features of the behavior of iron ore tailings and emphasize the potentially promising combination of high shear resistance and high density that favors particular geotechnical applications. The research outcome should contribute to improving our current understanding of the behavior of this unconventional geomaterial so that safer tailings storage facilities can be designed and alternative uses for iron ore tailings can be found in the field of geotechnical engineering.

2. Materials and Methods

The experimental characterization of iron ore tailings was carried out using a selected representative material from a Portuguese iron mine and by employing different tests to characterize the behavior of the material from diverse relevant geotechnical perspectives.

2.1. The Moncorvo Iron Mine

This research was based on tailings collected from an old tailings storage facility created during the operation of the Torre de Moncorvo iron mine, which lasted until the 1980s. The mine, whose activity was recently revived, is located in the NE region of Portugal (Figure 2).

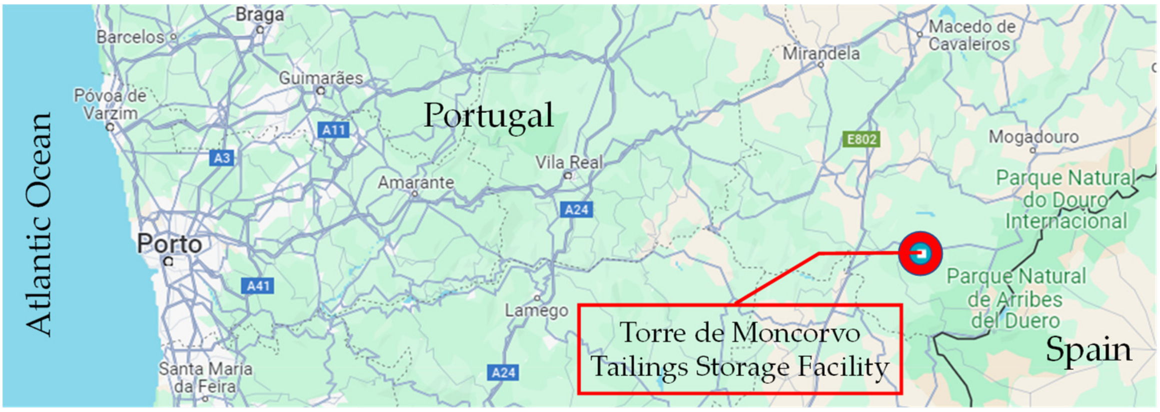

Figure 2. Location of Torre de Moncorvo iron mine tailings storage facility (northeast Portugal).

Disturbed iron ore tailings were collected in order to prepare compacted and slurry-based reconstituted samples for geotechnical testing, as described below. The material was selected because it represents the most abundant type of mining waste available in the world and also because its properties are typical of other iron ore tailings storage facilities found in the world. Thus, the iron ore tailings selected were consistent with the research aims.

2.2. Experimental Methods

2.2.1. Sample Reconstitution to Replicate Tailings' Field Behavior

To more truthfully reproduce tailings' field depositional conditions and obtain uniform samples showing realistic geotechnical behavior under different testing conditions, the samples aiming to replicate the tailings' field behavior were prepared using the "slurry deposition method"—SDM [22]. The SDM was adapted to the material tested, using a water content that facilitated uniform mixing of the slurry while avoiding particle segregation, which was significantly encouraged by the differences in the sizes and densities of the grains found in the iron ore tailings. Sample reconstitution, carried out with a water content of 23%, involved 3 stages (Figure 3): (A) preparing a slurry with the particles forming the iron ore tailings, aleatorily selected using a riffle sample divider, with the desired water content (23%); (B) placing the slurry in a rigid mold, with a diameter of 11.5 cm and a height of 30 cm; (C) consolidating the slurry in a rigid mold, acting as a consolidometer, to the desired effective vertical stress (50 kPa) by successively increasing the vertical load by 10% every two days. In the end, samples were easily cut from the block to the required dimensions for testing, provided that vibrations were strictly avoided.

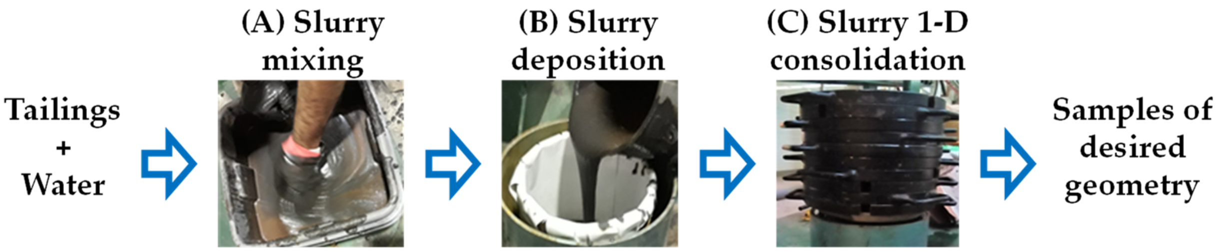

Figure 3. Slurry-based reconstitution method used to prepare the iron ore tailings samples, involving the following stages: (**A**) slurry uniformization through hand mixing at the desired water content; (**B**) the deposition of the slurry in a suitable mold; (**C**) slurry consolidation under the selected vertical load.

2.2.2. Physical and Identification Tests

The physical and identification tests were carried out on the tailings selected following mostly the ASTM standards, namely the Standard Test Method for Particle-Size Distribution of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis [23] (ASTM D7928-21), the Standard Test Method for Specific Gravity of Soil Solids by the Water Displacement Method [24] (ASTM D854-23) and the Standard Test Methods for Plastic Limit of Soils [25] (ASTM D4318-17^{e1}). Because the iron ore tailings used in the research had low plasticity, the determination of the liquid limit was carried out using the BS standards, namely BS 1377-2:2022 [26], as the determination was based on the cone penetrometer method (definitive method). In fact, this method is more suitable to determine the liquid limit of low-plasticity materials such as those used in this research.

2.2.3. Modified Proctor Test

The modified Proctor test was carried out following the ASTM standards relative to this test [27]: Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort—ASTM D1557-12(2021). This test was selected in order to assess the behavior of the unconventional geomaterial considered in the research, namely to verify if the material showed a compaction curve similar to the curves shown by conventional geomaterials and also to prepare a sample for testing under undrained triaxial compression. The results also shed further light on the opportunity of using the material as a building material in the construction of embankments and other geotechnical works.

2.2.4. Undrained Monotonic Triaxial Tests

The undrained monotonic shear stress–strain behavior of the iron ore tailings tested was determined through undrained monotonic triaxial compression tests carried out in accordance with the ASTM standards, namely the Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils—ASTM D4767-11 [28]. All the samples tested were cylindrical with a height-to-diameter ratio of 2:1. The samples prepared by the SDM had a height of 76 mm and the samples prepared by compaction had a height of 200 mm.

2.2.5. Undrained Cyclic Triaxial Tests

The undrained cyclic shear-stress–strain behavior of the iron ore tailings tested was determined through undrained cyclic triaxial compression tests carried out in accordance with the ASTM standards, namely the Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil—ASTM D5311-11 [29]—adapted to the characteristics of the triaxial equipment available, which only permits low-frequency tests that are completely suitable to test the response of liquefiable materials under undrained cyclic loading. The samples tested were prepared by the SDM and had a cylindrical shape, with a height-to-diameter ratio of 2:1 and a height of 76 mm.

3. Results

Following the tests carried out, the results obtained are presented and discussed in this section, which is organized in accordance with the previous section, which defines the details of the tests carried out.

3.1. Sample Reconstitution to Replicate Tailings' Field Behavior

The iron ore tailings samples' reconstitution procedures resulted in a series of uniform samples with the required geometry for testing, as shown in Figure 4. After progressive consolidation of the slurry for a total of almost 3 weeks, the samples prepared through the SDM were relatively straightforward to remove from the consolidometer (Figure 4a) and cut to the desired geometry (Figure 4b). In fact, provided that the samples were not submitted to any form of vibration that would induce liquefaction, the samples were fairly consistent. The different samples were tested at different locations with respect to the grain size distribution, plasticity and specific gravity of soil solids, which confirmed that the reconstituted samples prepared with the described method had uniform compositions and coherent behavior at different locations [30].

Figure 4. Results of the sample reconstitution: (**a**) final aspect of the reconstituted block; (**b**) final aspect of a sample cut from the block and ready for testing in a triaxial cell.

3.2. Physical and Identification Properties

The most relevant physical and identification properties of the reconstituted samples of iron ore tailings considered in this research were determined using the methodologies described in Section 2.2.2. The average values shown were obtained from 24 tests carried out for each of the properties determined.

3.2.1. Grain Size Distribution

Figure 5 represents the grain size distribution curve for the reconstituted iron ore tailings samples with sieve and sedimentation analysis, which is representative of the 24 tests performed. The results show that the tailings are composed of silt (51%) and sand (49%) in similar proportions, which is consistent with the results of similar tests carried out on samples collected from similar tailings storage facilities around the world. For example, the average values of D_{10} and D_{50}, which are close to 0.0145 mm and 0.059 mm, respectively, are within the intervals observed in the Yuhezhai iron ore tailings. In fact, in these iron ore tailings, the values of D_{10} and D_{50} were determined in the ranges of 0.005 to 0.051 and 0.030 to 0.120 for D_{10} and D_{50}, respectively [31]. The results also suggest that the grain size distribution of the tailings tested is fairly uniform, with a coefficient of uniformity (C_u) of 4.07. This value is also consistent with the range (3.11~8.82) observed in similar materials [31].

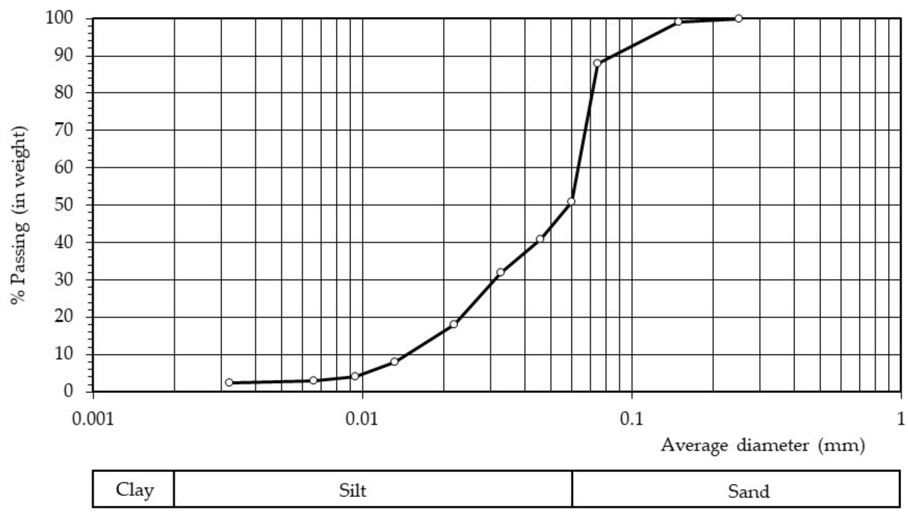

Figure 5. Grain size distribution curve of the reconstituted iron ore tailings samples.

3.2.2. Specific Gravity of Soil Solids

The specific gravity of soil solids (G) relative to the iron ore tailings tested was experimentally determined through the water displacement method [24]. The average value obtained (G ≈ 4.7) is significantly higher than the values commonly obtained in conventional geotechnical materials (G ≈ 2.6~2.7), which is due to the fact that tailings still contain variable but significant amount of metals and minerals. In this case, the fact that iron particles have a density close to 8 results in a much higher value of G for the tailings particles, which also indicates that the tailings tested still incorporate significant amounts of iron. The fact that in some cases the values of G reported for similar materials are not so high derives from the fact that the efficiency levels of the methods used to separate the iron vary a lot amongst different mines. E.g., for the Yuhezhai iron ore tailings, the values of G reported are in the range 3.08 to 3.23 [31], which suggests a more efficient recovery of the iron ore. It should be noted that the tailings tested were produced about 50 years ago, in many cases involving manual selection of the natural rock during the beneficiation stage, which was undoubtedly an ineffective selection process.

3.2.3. Plasticity

The plasticity characteristics of the iron ore tailings tested, namely the plastic (w_P) and liquid (w_L) limits and the plasticity index (PI), were experimentally determined. The soil plastic limit was assessed through the soil hand rolling procedure defined by the ASTM standards [25]. The liquid limit was assessed through the cone penetrometer method (multipoint) defined by the BS standards, which is a more reproducible method that should not yield significant differences when compared to the alternative method employing the Casagrande apparatus [26].

The results obtained (Table 1) show that the tailings tested are slightly plastic, with a plasticity index of just 5%. These results are consistent with the grain size distribution and composition of the tailings tested but also with the values observed in other iron tailings storage facilities. For example, the values obtained fit into the ranges for the plastic (0∼19%) and liquid (0∼28%) limits, as well as for the plasticity index (0∼9%), measured in the Yuhezhai iron ore tailings [31].

Table 1. Average plasticity characteristics experimentally determined for the iron ore tailings tested.

Plastic Limit—w_P (%) [1]	Liquid Limit—w_L (%) [2]	Plasticity Index—PI (%)
15	20	5

[1] ASTM D4318—17e1 [25]; [2] BS 1377-2:2022 [26].

3.3. Modified Proctor Test

The compaction curve relative to the modified Proctor test for the iron ore tailings tested (Figure 6) was obtained following the procedures established by the ASTM standards [27]. The values of the optimum water content and the maximum dry unit weight were established as 8.95% and 2.99 g/cm^3, respectively.

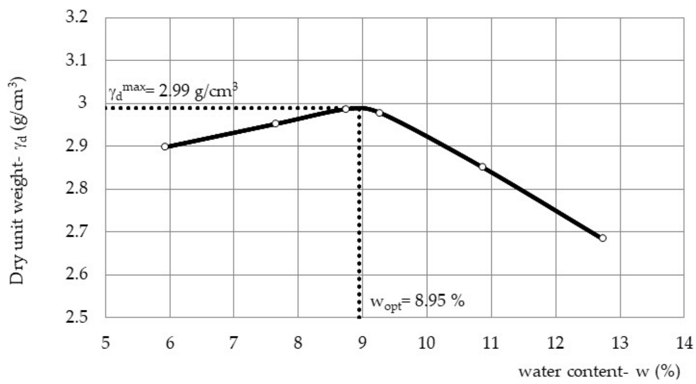

Figure 6. Compaction curve obtained for the iron ore tailings tested using the energy defined for the modified Proctor test.

The shape of the compaction curve, obtained with the modified Proctor test, is similar to the compaction curves usually found in conventional geomaterials, namely for those commonly employed in embankment construction. In fact, a peak is clearly defined in the curve relating the water content used in the compaction with the resulting dry unit weight. Also, the value of the optimum water content, which is about 60% of the plastic limit, is in line with the values observed in conventional geomaterials. For example, the optimum water content (w_{opt}) can be correlated with the liquid limit (w_L) as follows [32]:

$$w_{opt} = 0.3802w_L + 2.4513 \quad (1)$$

Equation (1), where w_{opt} and w_L are given in %, predicts a value of 10.1% for the optimum water content (w_{opt}) of a geomaterial with a liquid limit (w_L) of 20%, which is fairly close to the value experimentally determined.

On the contrary, the value obtained for the maximum dry unit weight is much higher than the values commonly found in conventional geomaterials. For example, employing the database that was used to establish the correlation shown in Equation (1), the maximum dry unit weight (${\gamma_d}^{max}$) can be correlated with the liquid limit (w_L) as follows [32]:

$${\gamma_d}^{max} = 2.116 - 0.01008w_L \quad (2)$$

Equation (2), where ${\gamma_d}^{max}$ is shown in g/cm^3 and w_L is given in %, predicts a value of 1.91 g/cm^3 for the maximum dry unit weight (${\gamma_d}^{max}$) of a geomaterial with a liquid limit (w_L) of 20%, which is much lower than the value experimentally determined. However, it should be noted that the large database (126 different soils with different plasticity and grain size compositions) used for establishing these correlations is only composed of conventional geomaterials, with specific gravity of soil solids (G) varying between 2.58 and 2.85. However, the iron ore tailings tested have a much higher value of the specific gravity of soil solids (G), which is much higher than the range of values exhibited by the materials included in the database. As a result, the values cannot be directly compared and the correlation proposed in Equation (2) is not applicable to the unconventional material tested in this research.

3.4. Undrained Monotonic Triaxial Compression Tests

The stress–strain shear resistance response in the undrained monotonic triaxial compression (UMTC) of reconstituted samples representing field behavior, reconstituted through the SDM, was assessed through the behavior of isotropically consolidated samples to effective confining stresses of 50 and 200 kPa (Figure 7). The stress paths described by both samples (Figure 7a) under undrained triaxial compression indicate that, during the early loading stages, the samples show a tendency to contract until reaching a common line passing through the origin.

The so-called phase transformation line (PhTL) observed in Figure 7a marks the instant where the samples change from a contractive to a dilatant tendency, with the stress paths curving to the right-hand side of the plane p′-q and progressive shearing causing an increase in the effective confining stresses (p′). For a certain level of axial strain, the stress paths tend to follow another common line passing through the origin, which may possibly coincide with the so-called critical state line (CrSL).

During shearing, the stress–strain responses of the two samples also show similar features (Figure 7b). Until they come near to the PhTL, there is a fairly linear stress–strain response of the samples. But as the PhTL is crossed, the samples show decreasing stiffness and strains increase at a larger rate with the increase in shear stress. Finally, as the samples approach the CrSL, the samples show progressively increasing stiffness with strain. As expected, during all the described stages, the sample consolidated at higher effective confining stresses exhibits a stiffer response due to the well-known effect of p′ on the stiffness of soils [18]. In fact, this well-known effect of p′ on the stiffness of soils during shearing is also clear in the case of this unconventional geomaterial.

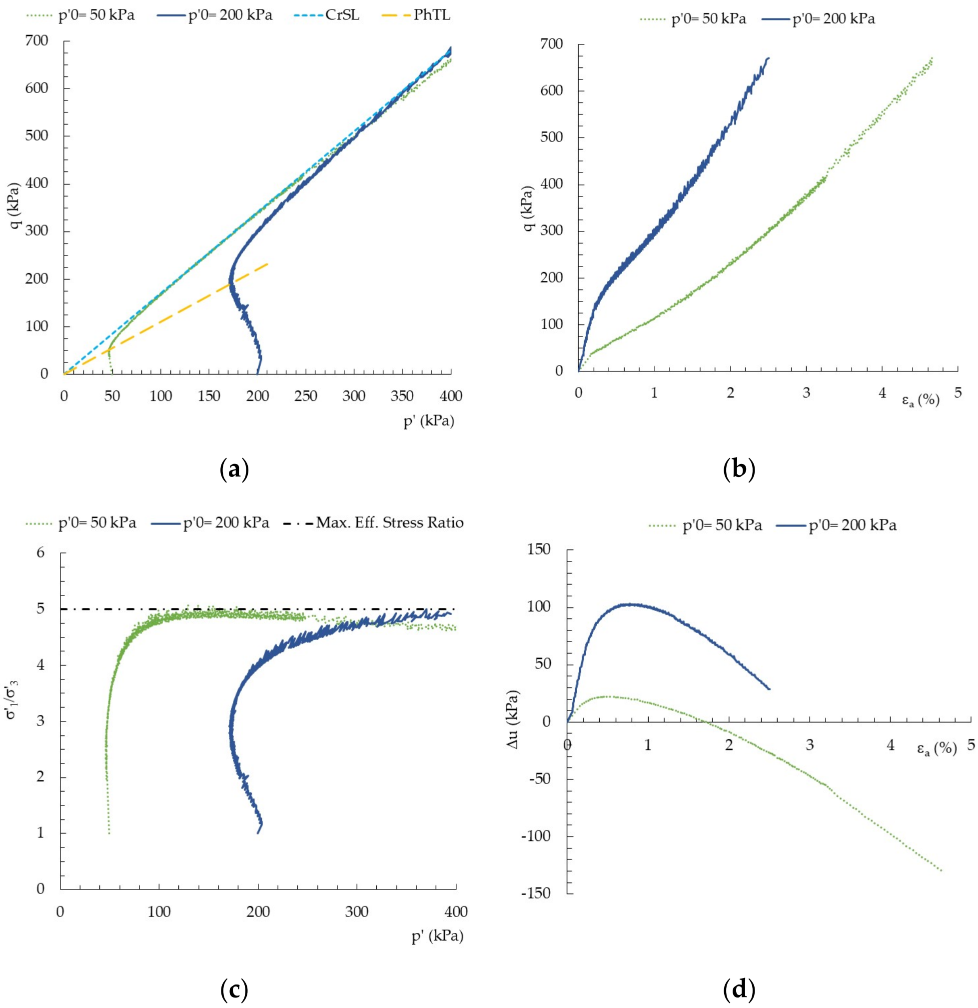

Figure 7. Stress–strain shear resistance response of slurry-based reconstituted samples isotropically consolidated to effective confining stresses of 50 and 200 kPa under undrained monotonic triaxial compression: (**a**) effective stress path; (**b**) stress–strain response; (**c**) variation in the effective stress ratio with p′; (**d**) variation in the excess pore pressure with axial strain.

Figure 7c reinforces some of the features of behavior previously described, namely with respect to the tendency for the effective stress ratio (σ′1/σ′3) to reach a similar and fairly constant value for the two samples tested, which is close to 5. This value corresponds to an effective friction angle of 42°, which is a fairly high value in comparison with a conventional soil with the characteristics of the tailings tested. Still, this value is within the range of values observed in the field, namely in Campo Grande iron ore tailings dam (Mariana/MG, Brazil), possibly due to the very important angularity of the grains formed by rock crushing and grinding, as shown by optical and electron microscope photographs [33]. It is also worth mentioning that the sample consolidated to a higher effective confining stress shows a higher initial tendency to contract, which results in a large reduction in p′ during the earlier loading stages. This is a feature that is also typical of the behavior of granular soils under undrained monotonic shearing, which also tend to show a larger contractive tendency (responsible for higher excess pore pressure generation) when consolidated under larger effective confining stresses.

Figure 7d emphasizes the tendency of the samples to change their behavior from contractive to dilative during monotonic shearing, which is another feature of behavior that is also commonly shown by granular soils [18]. In the case of the undrained monotonic triaxial compression tests carried out, this tendency can be observed through the variation in the excess pore pressure with the axial strain imposed to the sample. In fact, as the PhTL is crossed, both samples show an inversion of the initial tendency to generate positive excess pore pressure and progressive shear straining, inducing a significant reduction in the pore pressures to values that can be lower than the initial values. Once again, the effect of the effective confining stress on the behavior of the samples is notorious and similar to that observed in conventional granular geomaterials.

Overall, the qualitative response of the reconstituted iron ore tailings tested in undrained monotonic triaxial compression, representing the field behavior, is similar to that exhibited by other conventional geomaterials, namely granular soils. Still, the value of the effective friction angle observed in the tailings tested may exceed the values currently found in other geomaterials, possibly due to the significant angular nature of their industrially produced particles.

An additional triaxial test (Figure 8) was carried out to assess the stress–strain shear resistance response in the undrained monotonic triaxial compression (UMTC) of compacted samples, representing the behavior of the tested iron ore tailings, namely when used as a construction material for sustainable geotechnical works. The sample was compacted with the water content defined in Section 3.3, using the specific energy of the modified Proctor test. For the sake of comparison, the sample was isotropically consolidated to an effective confining stress of 50 kPa, which aimed to represent relatively shallow field conditions of iron tailings when used as a construction material, namely in embankment construction.

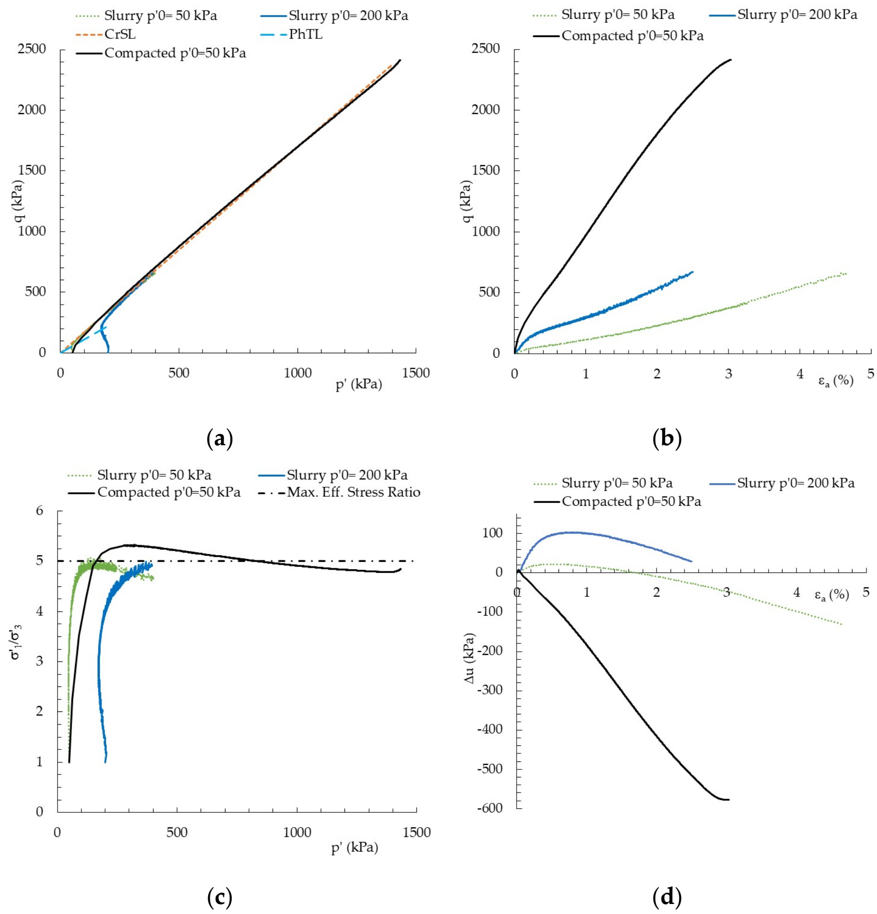

Figure 8. Stress–strain shear resistance response of isotropically consolidated compacted iron ore tailings and slurry-based reconstituted samples under undrained monotonic triaxial compression: (**a**) effective stress path; (**b**) stress–strain response; (**c**) variation in the effective stress ratio with p′; (**d**) variation in the excess pore pressure with axial strain.

The major features of behavior described with respect to the stress–strain shear resistance response of reconstituted samples representing field behavior (Figure 7) remain qualitatively valid when the behavior of the compacted sample is observed (Figure 8). However, similarly to what is shown by conventional geotechnical materials under comparable conditions, significant differences can be observed when a compacted tailings sample is sheared in undrained monotonic triaxial compression. In fact, the compacted sample tends to exhibit a clear dilatant tendency from an early stage, as shown by the effective stress paths (Figure 8a) or by the variation in the excess pore pressure with the axial strain (Figure 8d).

But the most relevant and interesting aspect of behavior exhibited by the compacted tailings sample, from a geotechnical perspective with the aim of using tailings as a construction material, is the significant increase in the stiffness of the sample during undrained triaxial compression (Figure 8b). This is evident when comparing the stress–strain behavior of the compacted and slurry-based reconstituted samples isotopically consolidated for the same effective confining stress (50 kPa). In fact, the former sample shows very large reductions in the axial strains induced by shearing. These reductions in axial strain mount up to 94% and 89%, corresponding to increases in the deviatoric stress of 100 and 500 kPa, respectively. It is also noticeable that the maximum value of the effective stress ratio observed in the reconstituted samples ($\sigma'_1/\sigma'_3 \approx 5$) is exceeded for smaller strains in the compacted sample (Figure 8c).

3.5. Undrained Cyclic Triaxial Tests

The stress–strain-shear resistance response of reconstituted samples, prepared with the slurry-based method, in undrained cyclic triaxial compression, was assessed through the behavior of an isotropically consolidated sample to an effective confining stress of 200 kPa tested under cyclic shear loading of Δq = ±200 kPa (Figure 9).

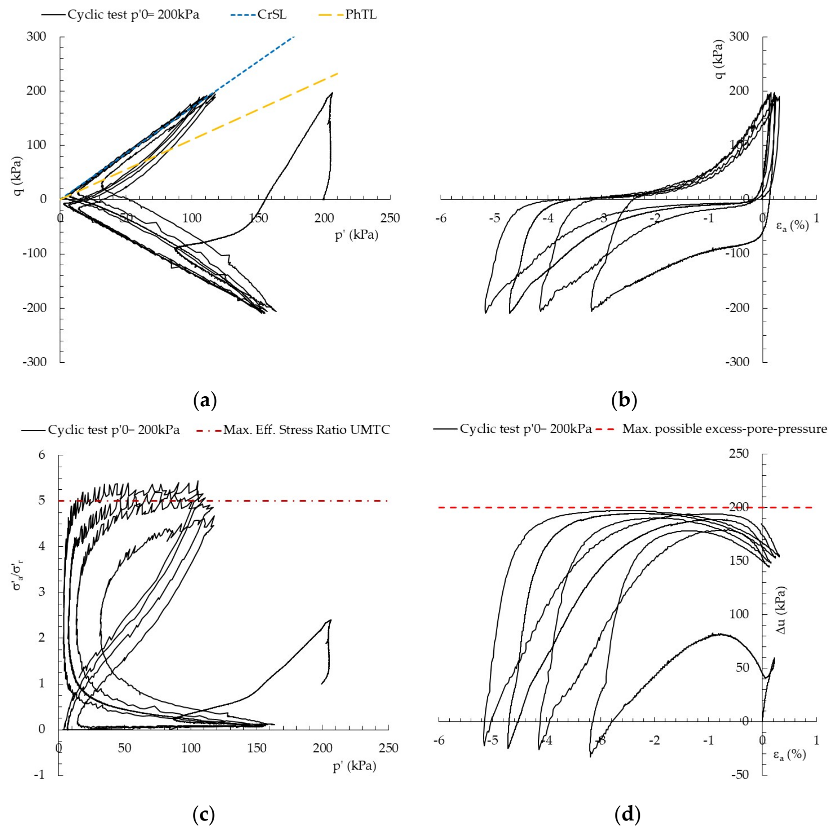

Figure 9. Stress–strain shear resistance response of a reconstituted sample isotropically consolidated to an effective confining stress of 200 kPa under undrained cyclic triaxial loading with Δq = ±200 kPa: (**a**) effective stress path; (**b**) stress–strain response; (**c**) variation in the effective stress ratio with p′; (**d**) variation in the excess pore pressure with axial strain.

The cyclic stress path described by the sample (Figure 9a) under undrained cyclic triaxial loading indicates that a very large tendency to contract is observed during the first cycle, due to the fact that the cyclic loading imposed is large and the stress path comes near to the PhTL. Like in undrained monotonic triaxial compression (Figure 7a), this line marks the instant where the sample changes from a contractive to a dilatant tendency in each loading cycle, with the stress path curving to the right-hand side of the plane p′-q with progressive shearing. And as cyclic loading progresses, the stress path defines a so-called butterfly shape that indicates the occurrence of cyclic liquefaction ($p' \approx 0$), as commonly observed in conventional geotechnical materials, especially in granular soils. The CrSL governs the position of the stress paths at this loading stages, namely in compression loading.

The stress–strain response of the sample during undrained cyclic shearing is also similar to that observed in conventional granular geomaterials (Figure 9b). In fact, as liquefaction looms, large axial strains accumulate in each cycle, namely in extension, and the progressive degradation of the iron ore tailings sample's stiffness occurs, even if during the initial parts of the unloading and reloading stages the stress–strain response is fairly rigid.

Another relevant aspect of stress–strain behavior (Figure 9b) is the large damping observed as cyclic loading progresses and liquefaction is observed, which reflects the substantial amount of energy dissipated in each cycle at this stage, as also commonly observed in conventional granular geomaterials.

Figure 9c reinforces some of the features of behavior previously described, namely with respect to the tendency for the effective stress ratio (σ'_a/σ'_r) to reach a similar and fairly constant value in specific parts of the loading stages in every cycle after liquefaction occurs. This value of σ'_a/σ'_r is in fact similar to the value observed in undrained monotonic triaxial compression, which is also close to 5. On the other hand, during other parts of the loading cycles, this ratio is close to zero, which results from the fact that, in this particular case, the value of σ'_a is close to zero. In other parts of the cycle, this ratio varies significantly while p′ is practically zero.

Figure 9d highlights the tendency of the sample to change its behavior from contractive to dilative in each cycle, even if, overall, the excess pore pressure tends to increase during the cyclic test until reaching its maximum possible value, which is equal to the initial effective confining stress of the sample (200 kPa). This is another feature of behavior that is also commonly shown by granular soils, with the fact that the maximum excess pore pressure value was achieved so quickly being determined by the fact that the first peak loading cycle resulted in a close approach to the PhTL, which has a significant detrimental effect on the liquefaction resistance of more conventional geomaterials [19]. It should also be noted that the reversion of the contractive to dilatant tendency in each cycle occurs when the PhTL is crossed, which is also typically observed in conventional granular geomaterials.

Overall, the response of the iron ore tailings tested in undrained cyclic triaxial loading is similar to that exhibited by other conventional geomaterials, namely granular soils, with the PhTL and CrSL governing the behavior during most of the test, namely after liquefaction ($p' \approx 0$) is achieved.

The stress–strain shear resistance response of slurry-based reconstituted samples during the undrained cyclic triaxial compression of an isotropically consolidated sample to a similar effective confining stress of 200 kPa but tested under a significantly lower value of cyclic shear loading ($\Delta q = \pm 60$ kPa) is shown in Figure 10.

The major features of behavior previously described for the sample tested under a larger cyclic shear loading of $\Delta q = \pm 200$ kPa (Figure 9) remain valid, the main difference being the number of cycles required to reach liquefaction (Figure 10a). As expected, a significant reduction (70%) in the cyclic shear loading applied under similar conditions results in a significant increase in the number of cycles that the sample can sustain before reaching a state of near-zero effective stress, inducing large cyclic axial strains in each cycle.

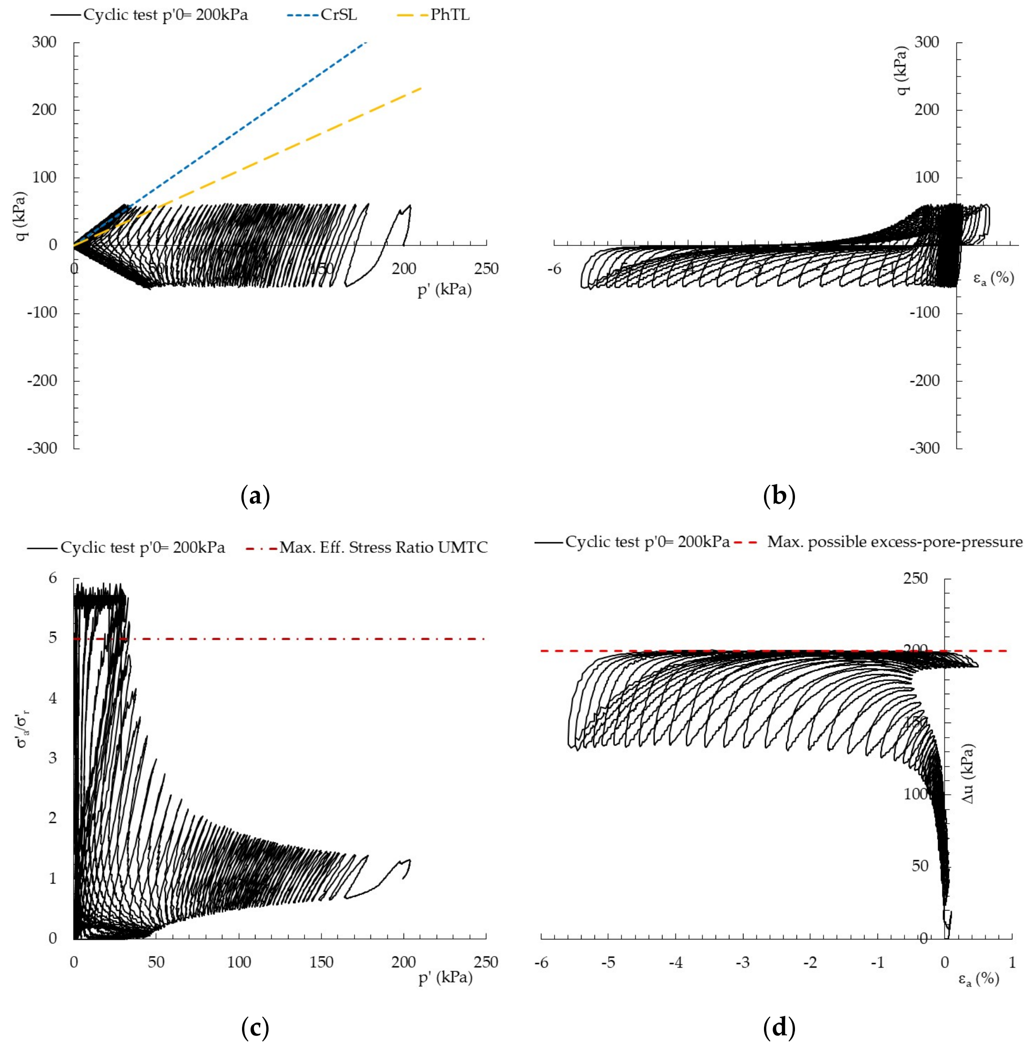

Figure 10. Stress–strain shear resistance response of a reconstituted sample isotropically consolidated to an effective confining stress of 200 kPa under undrained cyclic triaxial loading with Δq = ±60 kPa: (**a**) effective stress path; (**b**) stress–strain response; (**c**) variation in the effective stress ratio with p'; (**d**) variation in the excess pore pressure with axial strain.

In addition, the progression of cyclic axial strains in each cycle is considerably smaller, even after a state of near-zero effective stress is reached (Figure 10b). As the cyclic loading progresses and a state of near-zero effective stresses is reached, the maximum value of the effective stress ratio observed in each cycle increases up to values close to the maximum values observed in UMTC conditions. The fact that the maximum value previously observed is slightly exceeded may be due to the fact that the effective stress values compared are in some cases extremely low for significant periods of the loading/unloading stages, as clearly shown by the variation in the excess pore pressure with the axial strain (Figure 10d).

It can also be observed that, due to the smaller value of cyclic shear loading applied in this test (Δq = ±60 kPa), the temporary dilation periods observed in each cycle (Figure 10d) never cause a reduction in the excess pore pressure as large as in the test (Figure 9d) where a larger value of cyclic shear loading was applied (Δq = ±200 kPa). In fact, in this latter case, transient negative values of excess pore pressure were observed, namely at the peak of the extension stages in each loading cycle (Figure 9d).

4. Discussion

The results presented in detail in the previous section highlight the most relevant aspects of behavior of the iron ore tailings tested, which were collected from a Portuguese iron mine located in Torre de Moncorvo. These tailings should be, at least qualitatively, representative of other iron ore tailings present in the world, as the extraction, beneficiation and depositional procedures used in iron mining around the world are fairly comparable.

Firstly, reconstituted samples were prepared based on the slurry deposition method, which tends to more effectively replicate the field depositional conditions observed in many tailings storage facilities, namely in tailings dams. Because these geotechnical structures are usually the most prone to failure, it was reasonable to select this reconstitution method to address tailings' mechanical properties, namely those that depend more on the conditions and structure of the samples and/or that are more relevant to stability analysis. In fact, this method results in uniform reconstituted samples that truly replicate field behavior [30], provided that the correct amount of water is used during reconstitution to avoid segregation. In addition, its use has been proven successfully, namely when preparing reconstituted samples with complex geometry [22], which is another advantage of the method.

With respect to the physical and identification properties, the iron ore tailings tested can be described as a transitional uniform material composed of very similar percentages of silt and sand, exhibiting limited but non-negligible plasticity (IP = 5). It is in fact the plasticity of these tailings that supports the use of the slurry deposition method. But because the difference between the liquid and the plastic limits is relatively small, the liquid limit could only be assessed using the cone penetrometer method (multipoint) defined by the BS standards [26]. But the most remarkable feature of the iron ore tailings tested is the unusually high values observed for the specific gravity of soil solids ($G \approx 4.7$), which considerably exceed the values commonly observed in conventional geotechnical materials ($G \approx 2.6$~2.7). Even if these values can vary more or less significantly depending on the amount of iron left in the tailings, which reflects the particular efficiency of the beneficiation process during mining that depends on the mine and on the historical period, the values of the specific gravity of soil solids and other index properties of iron tailings that are directly correlated (unit weight, e.g.,) tend to show values that are often much higher than those commonly found in soils. The value of G obtained in this case reflects the fact that the tailings tested were produced about 50 years ago and using fairly primitive manual selection procedures. Overall, the values obtained for the samples tested are comparable to those found in other mining sites, e.g., in Yuhezhai iron ore tailings [31]. Furthermore, except for the values of G, the values obtained fit into the ranges commonly observed in conventional geotechnical materials. This suggests that the experimental characterization of iron ore tailings should be established based on a geotechnical perspective, without overlooking the particular features of tailings' compositions.

But if iron ore tailings are to be used as a construction material in geotechnical works, the tailings are expected to be compacted in order to improve their mechanical behavior, except in very specific conditions of application. The results obtained show that the shape of the compaction curve is similar to that observed in the vast majority of conventional geomaterials, with the possible exception of uniform sands. In fact, the existence of a peak in the compaction curve defining the optimum water content (w_{opt}) and the maximum dry unit weight ($\gamma_d{}^{max}$) is clearly observed. In addition, the value of w_{opt} obtained (≈9%) is consistent with the ranges for conventional geotechnical materials with similar plasticity characteristics. That said, it is important to emphasize that the value of $\gamma_d{}^{max}$ resulting from the modified Proctor test (≈3 g/cm^3) is much higher than that commonly observed in conventional geomaterials. This should not be understood as an experimental error nor as a sign of an extremely dense material, as, in fact, the value obtained would be physically unacceptable if the density of solid particles (G) would be in the usual range. But as previously described, iron ore tailings can have G values much higher than usual (4.7, in this case), which justifies the higher values of $\gamma_d{}^{max}$ in compacted iron ore tailings.

Irrespective of the need to consider a particular use of iron ore tailings as a building material for geotechnical works or, as an alternative, to assess the stability of tailings storage facilities, the shear resistance of tailings, namely under undrained conditions, must be established. This is true both for static and cyclic loading conditions, with the latter being particularly important when tailings storage facilities are built in seismically active regions, where earthquake loading can have dramatic consequences. Overall, the undrained monotonic and cyclic behaviors observed in the triaxial tests carried out as part of this research suggest that tailings observe the basic features of behavior established for conventional granular materials. In fact, the principles of CrSL and PhTL govern the undrained response of iron ore tailings under monotonic and cyclic triaxial loading.

In particular, in undrained monotonic compression carried out on samples prepared through the slurry-based method and potentially representing field conditions of some traditional tailings storage facilities, the effects of the effective confining stresses are clear both with respect to the increase in the contractive tendency during the early shearing stages (resulting in positive excess pore pressures in undrained tests) and also in the increase in the stiffness of the material at every loading stage. But even if in a fairly loose condition, both of the samples tested show a tendency to dilate as soon as the PhTL is reached. All these features of behavior are typically observed in sandy materials under similar loading conditions [18]. For larger axial strains, both samples follow stress paths corresponding to an effective angle of friction close to 42°, a value that exceeds what is commonly observed in conventional geomaterials but is within the values observed in iron ore tailings in the region of Minas Gerais, Brazil, where values between 26 and 45 were reported [33]. Once again, to explain this value, the particular characteristics of tailings must be examined in detail. In fact, natural soil particles with dimensions comparable to those found in tailings are created naturally and tend to suffer long processes of weathering that result in near spherically shaped particles. In contrast, tailings result from the mechanical crushing and grinding of rocks that tend to form particles with a much more angular shape, as observed in optical and electron microscope photographs, which justifies the fairly large value of effective angle of friction found in the experiments and in other tailings storage deposits in the world [33].

When compacted in order to simulate the conditions of tailings used as a building material or in alternative tailings storage facilities (dry stacking, e.g.,), the tailings' behavior is qualitatively comparable to that of the reconstituted samples in similar conditions. But, as observed in conventional geomaterials, the stress–strain response of the compacted tailings is much more rigid, at least partially as a result of the much clearer tendency to dilate from earlier loading stages. In fact, the axial strains induced by deviatoric stress increases that would be expected in the field under conceivable undrained loading conditions ($\Delta q \approx 100$~500 kPa) are considerably smaller. As a result, the undrained Young's Modulus (E_U) measured in the compacted sample rises from 11.6 to 252.1 MPa for a deviatoric stress increase of 100 kPa and rises from 13.3 to 119.0 MPa for a deviatoric stress increase of 500 kPa when compared to the non-compacted reconstituted samples.

Similarly, under undrained cyclic triaxial loading, the features of behavior are also typically observed in sandy materials under comparable loading conditions. In fact, not only does every cycle cause increasing excess pore pressure, but also, as p' approaches near-zero values, the typical butterfly shape shown by the cyclic effective stress patch is established. Once again, the cyclic behavior of the material is governed by the same lines observed in undrained monotonic loading: the CrSL and the PhTL. In addition, the level of cyclic loading applied in each cyclic test strongly affects the response of the material, namely with respect to the number of loading cycles needed to reach liquefaction. The stress–strain response of the sample during undrained cyclic shearing also fits the typical behavior of conventional granular geomaterials, with large axial strains accumulating in each cycle, namely in extension, as liquefaction occurs.

The behavior of the iron ore tailings tested under undrained cyclic loading can also be assessed through the progressive degradation of shear stiffness and variation in the damping ratio with increasing shear strain (Figure 11).

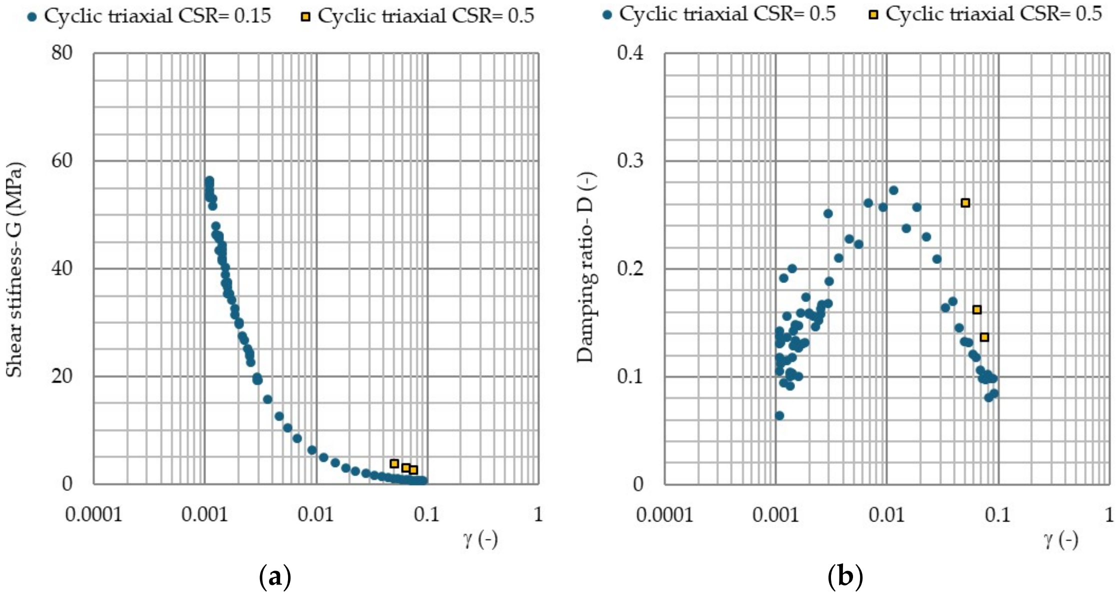

Figure 11. Analysis of the undrained cyclic triaxial tests on iron ore tailings with CSR values of 0.15 and 0.5: (**a**) shear stiffness degradation with shear strain; (**b**) damping variation with shear strain.

As observed in conventional geomaterials, significant degradation of the shear stiffness and large damping variations can be observed as the shear strain progressively increases with cyclic loading. The shear stiffness degradation with shear strain (Figure 11a) shows behavior similar to that observed in common geomaterials, namely in sands, where cyclic-induced liquefaction causes a progressive but massive reduction in the shear stiffness with shear strain. With respect to the damping variation with shear strain (Figure 11b), the initial behavior is consistent with that observed in common geomaterials, with a progressive increase in damping being observed in each cycle. But as shear strains increase above around 2%, the shapes of the hysteretic shear stress–shear strain curves deviate from the common shape used to calculate damping based on elastic considerations, and the damping values obtained show significant reductions. Clarification of whether this is a specific feature of tailings or results from an inappropriate estimation of real damping values due to the shape of the stress–strain curves requires further testing and analysis.

When assessing the liquefaction resistance of conventional granular geomaterials, when cyclically loaded in undrained conditions, it is common to represent the variation in the number of cycles required to reach liquefaction ($N_{Liquefaction}$) against the cyclic stress ratio (CSR = τ/σ'_{v0}) applied during the test, often assuming that liquefaction occurs when the double-amplitude axial strain measured in a cycle reaches 5% (5%DA). The results of the liquefaction resistance of the samples of iron ore tailings tested are plotted in Figure 12, with the results being compared with the liquefaction resistance of mineral sand tailings [34] and a natural sand, namely Sile sand [35], tested under fairly comparable conditions. The results show that the iron ore tailings tested have a liquefaction resistance that exceeds that of the mineral sand tailings presented for large values of CSR, but the resistance increase with decreasing CSR values is less pronounced. In addition, both tailings show higher liquefaction resistance than natural sands, including Sile sand (Figure 12), possibly due to the uncommon shape of non-natural tailings particles. Overall, the behavior observed, namely in terms of liquefaction resistance, is closer to that of sands, despite some plasticity of the tailings tested. This signals the need to address the possibility of earthquake-induced liquefaction occurrence in iron tailings, eventually considering energy-based methods that tend to more effectively explain the behavior of conventional granular geomaterials [19].

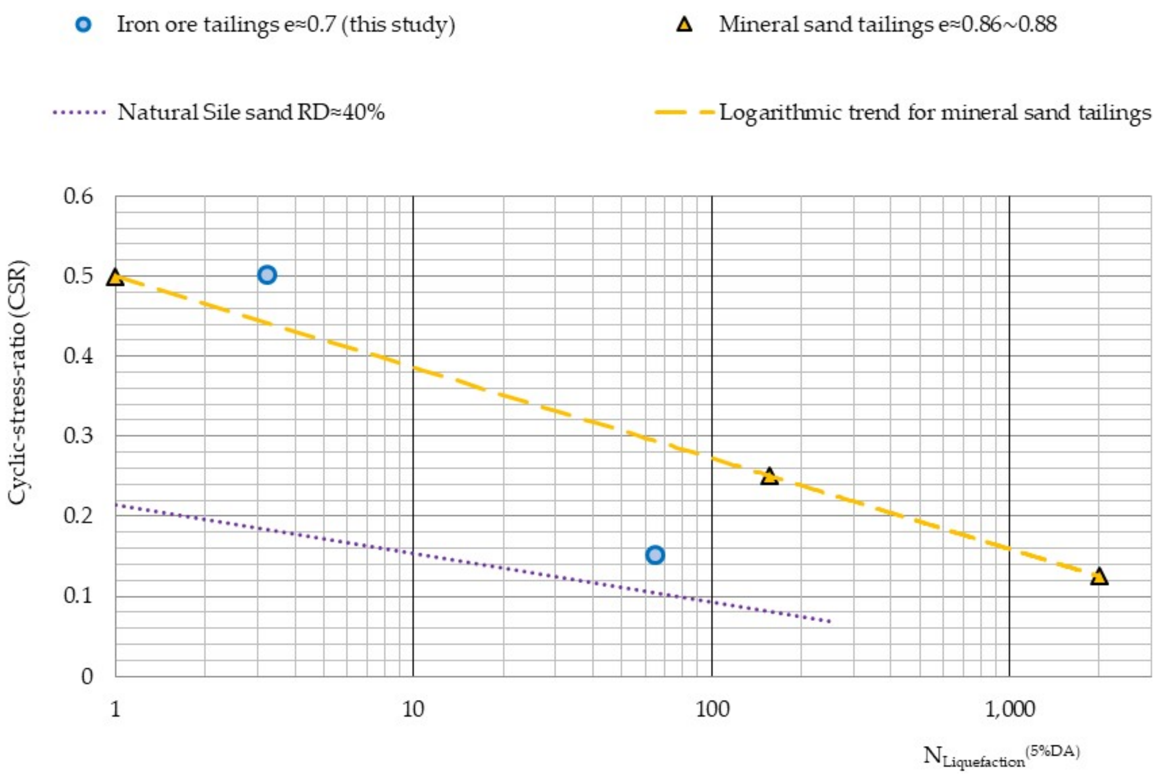

Figure 12. Liquefaction resistance (5%DA) of the tailings tested in comparison to other mineral sand tailings [34] and natural Sile sand [35].

Based on the results obtained, iron ore tailings seem to have promising behavior for application as a building material in the field of geotechnical engineering. In fact, the effectiveness of compaction in increasing the stiffness of tailings in undrained monotonic compression is quite promising and should be accompanied by a significant increase in the liquefaction resistance, similarly to what is observed in granular soils, where densification is a valuable liquefaction resistance measure [36]. In addition, the further light shed on the behavior of the tested unconventional geomaterial will support the more accurate analysis of existing and new tailings storage facilities, which will enhance the safety of these massive structures and reduce the possibility of dramatic consequences that result from their failure. But if tailings need to be assessed from a geotechnical perspective, they are not natural soils. Actually, a true understanding of tailings' behavior requires the solid and openminded interpretation of the results, where the specific nature of tailings must not be ignored, namely with respect to the composition and shape of its grains. In this case, apparently, too-large values of the effective angle of friction or the maximum dry unit weight look more reasonable when a detailed understanding of the particular features of tailings is achieved.

Nevertheless, a final but important recommendation must be issued, namely when considering the use of iron ore tailings as a sustainable building material. Indeed, sustainable geotechnical solutions can only be achieved when using unconventional geomaterials, particularly waste, if the environmental impacts of using these materials are fully under control. Therefore, real applications of iron ore tailings and other similar types of waste require previous analysis of their physicochemical and ecotoxicological properties to confirm the environmental safety of their use in the particular projected conditions [10,11].

5. Conclusions

The mining industry produces large amounts of valueless tailings with significant economic, social and environmental risks to society. Ensuring the safety of massive tailings storage deposits and implementing the principles of circular economy by using these unconventional geomaterials in geotechnical works to reduce this problem and the wide-ranging impacts of raw materials' extraction is therefore a critical goal of the mining industry. This paper focuses on the experimental characterization of iron ore tailings, which are the most abundant type of mining waste produced in the world.

The results presented highlight the most relevant aspects of behavior of iron ore tailings, which behave as follows:

- They qualitatively behave like other conventional geomaterials with similar grain size composition, in the range of silts and sands, and low plasticity;
- They are distinct from natural soils, with the composition and shape of the grains more or less significantly affecting the values of some relevant properties;
- They exhibit compaction characteristics typical of conventional geomaterials, with large dry unit weights being a consequence of unusually high G values that result from the remaining presence of iron particles;
- They considerably benefit from the improvement induced by compaction, namely with respect to the stiffness and straining-induced dilation observed in undrained monotonic triaxial compression, with intrinsic shear resistance (ϕ') being high in any case;
- They present large shear stiffness degradation and large damping variations under undrained cyclic loading causing liquefaction, with the behavior strongly depending on the cyclic stress ratio applied;
- They show liquefaction resistance similar to other comparable tailings and possibly larger than natural sands.

Overall, iron ore tailings can be described as granular materials, with a significant silty component that is responsible for the low plasticity observed, combining higher effective shear resistance and very high maximum dry unit weight after compaction with some susceptibility to earthquake-induced liquefaction, as a result of the following characteristics of tailings particles:

- Large resistance which is due to the fact that tailings result from the mechanical crushing and grinding of rocks, which tend to form particles with an angular shape that considerably differs from the spherical shape of natural soils particles, as observed in optical and electron microscope photographs;
- Larger than expected values of the maximum dry unit weight which result from the presence of iron particles in the tailings.

The outcome of this research suggests that the characterization of iron ore tailings' behavior requires a geotechnical approach that does not overlook the particular and singular features of tailings particles shape and composition. Based on the results obtained, iron ore tailings seem to have promising behavior for applications as building materials in the field of geotechnical engineering. In fact, the consequences of the singularity of iron ore tailings grains with respect to the higher effective shear resistance and very high maximum dry unit weight after compaction should be explored for specific geotechnical applications where these unique properties are relevant. This includes applications where, namely after compaction, the following aspects apply:

- High shear resistance and stiffness, at least partially due to the uncommon shape of tailings particles, are required (e.g., embankments);
- Large unit weights, due to the presence of iron particles that result in unusually high G values, can be an advantage (e.g., sea shore protection).

Still, a note of caution must be issued with respect to the potential issues related to the earthquake-induced liquefaction susceptibility of these materials and the potential negative environmental impacts of their use as a building material. In fact, sustainable geotechnical solutions involving unconventional geomaterials, particularly waste, must be preceded by proper analysis to assess the environmental safety of their use in the particular projected conditions.

Author Contributions: The individual contributions to this paper were as follows: conceptualization, P.C.; methodology, P.C. and D.C.; software, P.C. and D.C.; validation, D.C.; formal analysis, P.C. and D.C.; investigation, D.C.; resources, P.C.; data curation, D.C.; writing—original draft preparation, P.C.; writing—review and editing, P.C. and D.C.; visualization, P.C. and D.C.; supervision, P.C.; project administration, P.C.; funding acquisition, P.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by FCT—Foundation for Science and Technology—through the research grant PTDC/ECI-EGC/4147/2021.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author.

Acknowledgments: The authors acknowledge the contribution made to this research by the company responsible for Torre de Moncorvo's iron mine, Aethel Mining, Ltd., by providing access to the tailings storage facilities and authorizing sample collection.

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Komnitsas, K.; Lazos, I.; Eerola, T. Energy Transition Metals: Future Demand and Low-Carbon Processing Technologies. *Mater. Proc.* **2023**, *15*, 56. [CrossRef]
2. Mudd, G.M. Assessing the Availability of Global Metals and Minerals for the Sustainable Century: From Aluminium to Zirconium. *Sustainability* **2021**, *13*, 10855. [CrossRef]
3. Bhutada, G. All the Metals We Mined in One Visualization, Visual Capitalist. 2021. Available online: https://www.visualcapitalist.com/all-the-metals-we-mined-in-one-visualization/ (accessed on 20 April 2024).
4. Nassar, N.T.; Lederer, G.W.; Brainard, J.L.; Padilla, A.J.; Lessard, J.D. Rock-to-Metal Ratio: A Foundational Metric for Understanding Mine Wastes. *Environ. Sci. Technol.* **2022**, *56*, 6710–6721. [CrossRef] [PubMed]
5. Norgate, T.; Jahanshahi, S. Low grade ores-smelt, leach or concentrate. *Miner. Eng.* **2010**, *23*, 65–73. [CrossRef]
6. Otieno, F.; Shukla, S.K. An insight into failure of iron ore mine tailings dams. *Int. J. Min. Reclam. Environ.* **2022**, *37*, 127–147. [CrossRef]
7. WMTF. Estimate of World Tailings Portfolio, Data from the Organization World Mine Tailings Failures. Center for Science in Public Participation, Bozeman, Montana, USA. Available online: https://worldminetailingsfailures.org/ (accessed on 20 April 2024).
8. Zhou, L. Towards sustainability in mineral resources. *Ore Geol. Rev.* **2023**, *160*, 105600. [CrossRef]
9. Franks, D.M.; Keenan, J.; Hailu, D. Mineral security essential to achieving the Sustainable Development Goals. *Nat. Sustain.* **2023**, *6*, 21–27. [CrossRef]
10. Ardelean, E.; Socalici, A.; Lupu, O.; Bistrian, D.; Dobrescu, C.; Constantin, N. Recovery of Waste with a High Iron Content in the Context of the Circular Economy. *Materials* **2022**, *15*, 4995. [CrossRef] [PubMed]
11. Bandarra, B.S.; Mesquita, C.; Passos, H.; Martins, R.C.; Coelho, P.A.L.F.; Pereira, J.L.; Quina, M.J. An integrated characterisation of incineration bottom ashes towards sustainable application: Physicochemical, ecotoxicological, and mechanical properties. *J. Hazard. Mater.* **2023**, *455*, 131649. [CrossRef]
12. Bandarra, B.S.; Monteiro, L.; Veloso, G.; Abreu, P.; Sousa, H.; Martins, R.C.; Pereira, J.L.; Coelho, P.A.L.F.; Quina, M.J. Evaluation of MSW incineration bottom ash for environmentally safe geotechnical applications. *Constr. Build. Mater.* **2024**, *427*, 136011. [CrossRef]
13. Rotta, L.H.S.; Alcântara, E.; Park, E.; Negri, R.G.; Lin, Y.N.; Bernardo, N.; Mendes, T.S.G.; Filho, C.R.S. The 2019 Brumadinho tailings dam collapse: Possible cause and impacts of the worst human and environmental disaster in Brazil. *Int. J. Appl. Earth Obs. Geoinf.* **2020**, *90*, 102119. [CrossRef]
14. Robertson, P.K.; Melo, L.; Williams, D.; Wilson, G.W. Report of the Expert Panel on the Technical Causes of the Failure of Feijão Dam I, Vale, S.A., Brazil, 2019; 71p. Available online: https://bdrb1investigationstacc.z15.web.core.windows.net/assets/Feijao-Dam-I-Expert-Panel-Report-ENG.pdf (accessed on 20 April 2024).
15. CIMNE. *Computational Analyses of Dam I Failure at the Corrego de Feijao Mine in Brumadinho*; Final Report; International Centre for Numerical Methods in Engineering: Barcelona, Spain, 2021; 561p.
16. Zhu, F.; Zhang, W.; Puzrin, A.M. The slip surface mechanism of delayed failure of the Brumadinho tailings dam in 2019. *Commun. Earth Environ.* **2024**, *5*, 33. [CrossRef]

17. Verdugo, R.; Sitar, S.; Frost, J.D.; Bray, J.D.; Candia, G.; Eldridge, T.; Hashash, Y.; Olson, S.M.; Urzua, A. Seismic Performance of Earth Structures during the February 2010 Maule, Chile, Earthquake: Dams, Levees, Tailings Dams, and Retaining Walls. *Earthq. Spectra J.* **2012**, *28* (Suppl. 1), S75–S96. [CrossRef]
18. Azeiteiro, R.J.N.; Coelho, P.A.L.F.; Taborda, D.M.G.; Grazina, J.C.D. Critical State–Based Interpretation of the Monotonic Behavior of Hostun Sand. *ASCE J. Geotech. Geoenviron. Eng.* **2017**, *143*, 04017004. [CrossRef]
19. Azeiteiro, R.J.N.; Coelho, P.A.L.F.; Taborda, D.M.G.; Grazina, J.C.D. Energy-based evaluation of liquefaction potential under non-uniform cyclic loading. *Soil Dyn. Earthq. Eng.* **2017**, *92*, 650–665. [CrossRef]
20. Ishihara, K. Liquefaction and flow failure during earthquakes. *Géotechnique* **1993**, *43*, 351–415. [CrossRef]
21. Carrera, A.; Coop, M.; Lancellotta, R. Influence of grading on the mechanical behaviour of Stava tailings. *Géotechnique* **2011**, *61*, 935–946. [CrossRef]
22. Tastan, E.O.; Carraro, J.A.H. A New Slurry-Based Method of Preparation of Hollow Cylinder Specimens of Clean and Silty Sands. *Geotech. Test. J.* **2013**, *36*, 811–822. [CrossRef]
23. *D7928-21*; Standard Test Method for Particle-Size Distribution of Fine-Grained Soils Using the Sedimentation (Hydrometer) Analysis. ASTM: West Conshohocken, PA, USA, 2021.
24. *D854-23*; Standard Test Method for Specific Gravity of Soil Solids by the Water Displacement Method. ASTM: West Conshohocken, PA, USA, 2023.
25. *D4318-17^{e1}*; Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. ASTM: West Conshohocken, PA, USA, 2018.
26. *BS 1377-2:2022*; Methods of Test for Soils for Civil Engineering Purposes—Classification Tests and Determination of Geotechnical Properties. BSI: London, UK, 2022.
27. *D1557-12(2021)*; Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort. ASTM: West Conshohocken, PA, USA, 2021.
28. *D4767-11*; Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils. ASTM: West Conshohocken, PA, USA, 2011.
29. *D5311-11*; Standard Test Method for Load Controlled Cyclic Triaxial Strength of Soil. ASTM: West Conshohocken, PA, USA, 2011.
30. Coelho, P.A.L.F.; Camacho, D.; Gobbi, F.; Araújo Santos, L. Sample reconstitution for evaluating the cyclic liquefaction resistance of iron ore tailings. In Proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering, Sydney, Australia, 1–5 May 2021.
31. Hu, L.; Wu, H.; Zhang, L.; Zhang, P.; Wen, Q. Geotechnical Properties of Mine Tailings. *ASCE J. Mater. Civ. Eng.* **2017**, *29*, 04016220. [CrossRef]
32. Günaydın, O. Estimation of soil compaction parameters by using statistical analyses and artificial neural networks. *Environ. Geol.* **2009**, *57*, 203–215. [CrossRef]
33. Becker, L.D.B.; Cavalcanti, M.D.C.R.; Marques, A.A.M. Statistical Analysis of the Effective Friction Angle of Sand Tailings from Germano Dam. *Infrastructures* **2023**, *8*, 61. [CrossRef]
34. Cartwright, A. Investigating Cyclic Liquefaction in Transitional Tailings. Ph.D. Thesis, Department of Civil, Environmental & Geomatic Engineering, University College London, London, UK, April 2022.
35. Zeybek, A. Experimental and Empirical Studies to Evaluate Liquefaction Resistance of Partially Saturated Sands. *Appl. Sci.* **2023**, *13*, 81. [CrossRef]
36. Coelho, P.A.L.F.; Haigh, S.K.; Madabhushi, S.P.G. Centrifuge modelling of liquefaction of saturated sand under cyclic loading. In Proceedings of the International Conference on Cyclic Behaviour of Soils and Liquefaction Phenomena, Cyclic Behaviour of Soils and Liquefaction Phenomena, Bochum, Germany, 31 March–2 April 2004; pp. 349–354.