Geomechanical Behaviour of an Iron Ore Tailings under High-Stress Levels for Disposal by Dry Stacking

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Abstract

Recent upstream tailings dam failures have driven, around the world, research for alternative and safer methods for mining tailings disposal. Dry stacking disposal with compacted tailings after the previous filtering (dry) process, instead of the traditional hydraulic disposal methods with successive upstream dam heightening, is being recently considered. In addition, the critical state soil mechanics (CSSM) approach is essential to understand the tailings' geomechanical behaviour under high-stress levels in order to design the maximum height of these stacking structures. Thus, this paper presents results of drained and undrained triaxial diversified stress path tests, that aimed to evaluate the behaviour of an iron ore tailings from the area known as 'Quadrilátero Ferrífero' (Minas Gerais State, Brazil), when subjected to mean effective stress levels (p') to represent confining pressures until 6400 kPa, value that exceeds the maximum design stresses involved in the highest stacking embankment. The results showed a relevant non-linearity in the critical state line (CSL) of the material for higher p' levels, which, given the importance of the critical state parameters for the material response pattern to different stress paths, can condition changes in their mechanical response during shearing, raising the need for further research about the microstructural properties (at particles level) that can explain this non-linearity of CSL.

Introduction

Recent tailings dam failures (Mt. Polley, Cadia, Fundão, and B1 in Brumadinho) have highlighted the particularity of the geomechanical behaviour of tailings deposited in these geotechnical structures and emphasized the importance of studying these peculiar materials in order to design safer tailings storage facilities (TSF). Although the structure design plays a major role, the nature of the tailings itself makes this material particularly sensitive to instability by liquefaction triggering. The characteristics of this type of material are highly influenced by its anthropic production, with none or hardly any chemical weathering, resulting in predominantly non-plastic silty or silty-sandy artificial soils. Together with the high-water content of the deposited material by conventional hydraulic disposal methods, tailings are highly susceptible to flow liquefaction.

Considering the difficulty of safely designing and maintaining upstream tailings dams, their construction and operation was recently banned in Brazil (ANM, 2019). The dry stacking disposal, with compacted tailings after the previous filtering process to ensure unsaturated tailings close to the optimum moisture content (OMC) from Proctor compaction standards (but not completely dry), appears as an alternative capable of better using the landform, as less storage space is required. However, the proper stacking design requires the knowledge of the geomechanical response of compacted filtered tailings under a variety of stress states, especially considering the high-stress levels to which the materials can be subjected, conditioning possible changes in its behaviour as the stress state increases.

The 'Quadrilátero Ferrífero' (‘Iron Quadrangle’, from Portuguese) is a mineral-rich region in the state of Minas Gerais, in Brazil known for its extensive deposits of minerals like gold, diamonds, and iron ore. Its long history of mining results in a large number of purpose-built TSF. In 2020, the National Mining Agency in Brazil registered 221 tailings dams in Minas Gerais.

The current paper will disclose an extensive and advanced laboratory program undertaken to investigate a non-plastic silty-sandy iron ore tailings from the region. This material is being studied for disposal by dry stacking. In this paper are presented the results of triaxial tests, allowing the definition of fundamental parameters for the entry of adequate constitutive models, based on the critical state soil mechanics (CSSM) framework, from a wide range of stress states (until 6400 kPa) and initial conditions of the material.

Background

Several researchers have studied the influence of stress states on the geomechanical behaviour of mining tailings (Schnaid et al., 2013; Viana da Fonseca et al., 2022).

From the CSSM, voids ratio (e) is recognized as a key parameter - together with stress state (mean effective stress, p', and deviator stress, q), which defines the mechanical behaviour of soils by means of the state parameter, Ψ (Jefferies & Been, 2016):

$$\Psi = e_0 - e_{cv} \tag{1}$$

where, e_0 and e_{cv} are respectively the current/initial void ratio and the critical state void ratio (at constant volume shearing) for the same stress level; this one is an intrinsic value for each type of soil and stress, independent of the loading condition (Schofield & Wroth, 1968).

The conventional CSSM framework defines a unique and straight critical state line (CSL) in both Cambridge $p' - q$ and $e - p'$ planes, given respectively by:

$$q = Mp' \tag{2}$$

and

$$e = \Gamma - \lambda \ln p' \tag{3}$$

where the constants M (critical state friction ratio), Γ (void ratio at reference pressure of 1 kPa) and λ (slope of the CSL) represent basic soil-material properties (Schofield & Wroth, 1968).

Several authors (Verdugo & Ishihara, 1996; Li & Wang, 1998) recognise that for cohesionless granular materials, a unique but curved CSL provides the best fit in the $e - \log p'$ plane, given by a power-law:

$$e = A - B(p'/100)^C \tag{4}$$

where A, B and C are fitted to match laboratory test results and 100 is the reference pressure taken as 1 atm ($\approx$ 100 kPa).

The CSL shape combined with the initial state of the material controls the static liquefaction potential. From undrained triaxial tests under axisymmetric stress conditions it is theoretically possible to evaluate the state of instability where to the onset of flow liquefaction induces sudden increases in strain and pore water pressure (PWP). The ratio of shearing at the instability line (η_{IL}) using the $p' - q$ plane is compared to in-situ conditions (η_0) in the same plane to ensure that:

$$\eta_0 < \eta_{IL} \tag{5}$$

with $\eta = q/p'$ as the stress ratio, where $q = \sigma'_1 - \sigma'_3$ and $p' = (\sigma'_1 + 2\sigma'_3)/3)$; in which σ'_1 is the major effective principal stress and σ'_3 is the minor effective principal stress (confining pressure in the triaxial cell).

A flat trend of curved CSL in the $e - \log p'$ plane is usually observed at low stress levels and it is related to flow instability due to a loss of stiffness and strength of soils, which are characterized by effective stress close to zero (Yamamuro & Lade, 1998) or, in some cases, these differences can originate from compliance issues during testing, like unappropriated transducers for specific strain and stress levels that may induce significant errors in the test results (Figure 1a) (Viana da Fonseca, Cordeiro & Molina-Gómez, 2021).

Cohesionless materials, like mining tailings, will be prone to instability by flow liquefaction whenever the void ratio is above the CSL on its lower stress range. However, if the material has a lower void ratio, there will be a dilative response with increasing shear strain that inhibits a pronounced loss of strength under undrained shear loading.

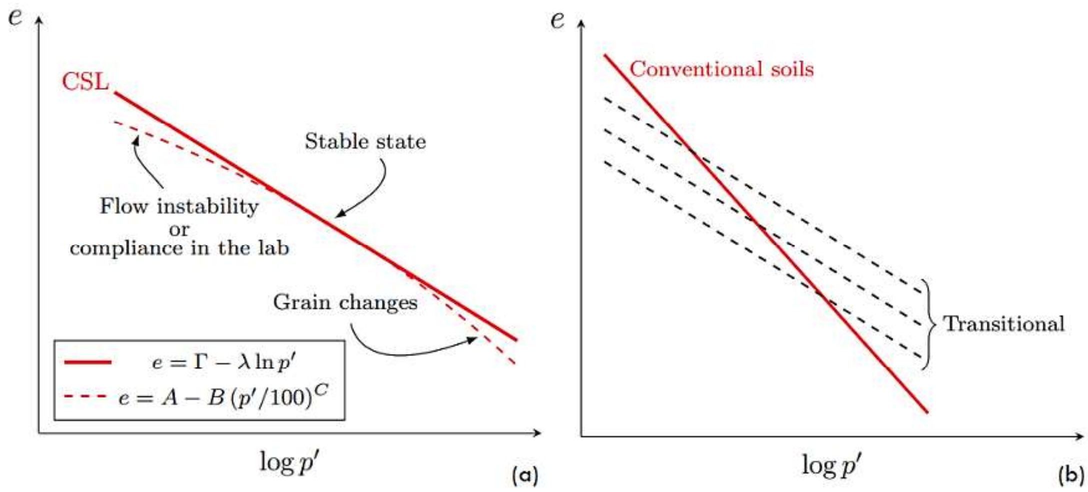


Figure 1: Schematic illustration of (a) non-linearity of CSL and (b) the transitional soil behaviour (Viana da Fonseca, Cordeiro & Molina-Gómez, 2021)

Marques et al. (2020) presented studies with iron ore tailings from the 'Quadrilátero Ferrífero', whose CLS presented a pronounced non-linearity for initial mean effective stress (p'_0) < 200 kPa, implying a higher brittleness of the material at low stresses under undrained shearing. Soares & Viana da Fonseca (2016), by extensive laboratory studies, shown similar behaviour for natural sands.

For high-stress levels, eventually, it was also possible to verify an increase in the non-linearity of CSL, which may be associated with particle breakage or with a relevant morphological particles' evolution (Figure 1a) (Schnaid et al., 2013; Soares & Viana da Fonseca, 2016) by changes in sphericity, angularity and/or superficial texture of individual soil particles (Delgado et al., 2022).

This microstructural approach (at particles level) can contribute to the understanding both the non-linearity of CSL and the transitional behaviours, characterized by non-unique, straight or curved, CSL (Figure 1b) their locations being highly dependent on the e_0, observed by some researchers (Coop, 2015; Velten et al., 2022) mainly for mixed grading and structured soils and less common for mining tailings.

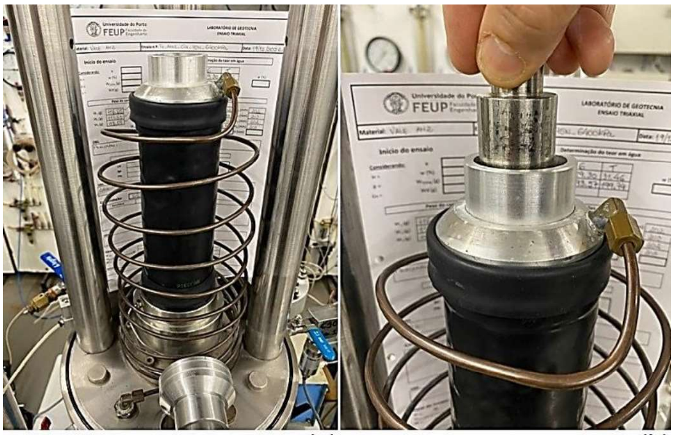
Viana da Fonseca et al. (2022) studied some iron ore tailings from the B1 Dam in Brumadinho ('Quadrilátero Ferrífero') after dam failure, and showed a relevant non-linearity of CSL in the $e - \log p'$

plane at higher stress levels for the studied materials. This non-linearity was related by the authors to the material grading changes by morphological particles' evolution. This evolution behaviour was verified for p'_0 > 800 kPa. The CSL slope changes at higher stress level associated with increased grain angularity has also been reported by Soares & Viana da Fonseca (2016) and Lashkari et al. (2020). Further research, by quantification of morphological changes during laboratory tests and discrete element method (DEM) simulations, could help to validate this stress-strain behaviour at macro-scale.

Methodology

The material studied is a silty-sandy filtered tailings from iron ore processing of the 'Quadrilátero Ferrífero' to be disposed by dry stacking, here called AM3 (designation related to the origin in the mine). The mining tailings have a specific gravity (G_s) of 2.85 and its particle size distribution (PSD) curve will be show in the results section. The studies carried out aim to raise the knowledge level about the material as well as subsidize the dry stacking embankment design.

The Figure 2a shows one specimen prepared for one of the carried out triaxial tests (note the neoprene membrane and the copper pipes drainage to withstand the high pressures) and Figure 2b shows the detail of the embedded top-cap guided ram connection used in the tests.



(a) (b)

Figure 2: (a) Specimen for triaxial test and (b) Detail of the embedded top-cap guided ram connection

The triaxial compression tests were conducted at the Laboratory of Geotechnics (LabGeo) at the Faculty of Engineering of the University of Porto (FEUP), under saturated conditions, according to advanced laboratory procedures, such as: local internal instrumentation, embedded top-cap guided ram connection, oversized lubricated end platens, end-of-test soil freezing, etc. Such procedures, in current use at LabGeo/FEUP, and their importance for the determination of geomechanical parameters are widely discussed by Viana da Fonseca, Cordeiro & Molina-Gómez (2021).

The specimens were molded using two different effort levels from Proctor compaction standards with four degrees of compaction (75%, 97%, and 100% Standard Effort, 75N, 97N, 100N respectively, and 100% Modified Effort, 100M). Table 1 presents the different triaxial tests carried out and some results obtained from the tests.

Table 1: Triaxial compression tests (set-up and some results)

Test	p'_0 (kPa)	e_0	e_f	η_p	η_f	S_u/σ'_{vo}	State
Tx_AM3_CID_75N_200kPa	200	0.82	0.76	1.39	1.33	-	Loose
Tx_AM3_CID_75N_400kPa	400	0.82	0.73	1.38	1.37	-	Loose
Tx_AM3_CID_75N_800kPa	800	0.79	0.68	1.34	1.33	-	Loose
Tx_AM3_CID_75N_1600kPa	1,600	0.76	0.63	1.36	1.35	-	Loose
Tx_AM3_CID_75N_3200kPa	3,200	0.72	0.61	1.37	1.35	-	Loose
Tx_AM3_CID_75N_6400kPa	6,400	0.68	0.49	1.44	1.44	-	Loose
Tx_AM3_CID_100N_75kPa	75	0.63	0.69	1.74	1.52	-	Dense
Tx_AM3_CID_100N_150kPa	150	0.61	0.68	1.72	1.50	-	Dense
Tx_AM3_CID_100M_100kPa	100	0.60	0.67	1.79	1.48	-	Dense
Tx_AM3_CID_100M_200kPa	200	0.61	0.68	1.69	1.43	-	Dense
Tx_AM3_CIU_75N_400kPa	400	0.81	0.81	0.59	2.16	0.19	Loose
Tx_AM3_CIU_75N_1600kPa	1,600	0.75	0.75	0.66	1.35	0.20	Loose
Tx_AM3_CIU_75N_3200kPa	3,200	0.71	0.71	0.76	1.37	0.21	Loose
Tx_AM3_CIU_75N_6400kPa	6,400	0.66	0.66	0.83	1.44	0.24	Loose
Tx_AM3_CIU_97N_400kPa	400	0.67	0.67	1.39	1.30	2.33	Dense
Tx_AM3_CIU_97N_800kPa	800	0.64	0.64	1.41	1.33	1.70	Dense
Tx_AM3_CIU_97N_1600kPa	1,600	0.63	0.63	1.36	1.34	0.93	Dense
Tx_AM3_CIU_97N_3200kPa	3,200	0.62	0.62	1.39	1.32	0.57	Dense
Tx_AM3_CIU_97N_6400kPa	6,400	0.62	0.62	1.14	1.36	0.42	Dense

Note: Tx: Triaxial compression test; CID: Consolidated Isotropically Drained; CIU: Consolidated Isotropically Undrained; e_0: initial void ratio; e_f: final void ratio; η_p: peak shearing ratio; η_f: final shearing ratio; S_u/σ'_{vo}: undrained strength ratio, where S_u: undrained strength and σ'_{vo}: initial vertical effective stress.

Results and Discussion

From the results, it was possible to obtain a single CSL on the $p' - q$ plane (non-transitional behaviour) as shown in Figure 3, where all stress paths can be observed. It is noted that some specimens, as expected, went into flow liquefaction, given their initial state (Tx_AM3_CIU_75N_400kPa and Tx_AM3_CIU_75N_1600kPa). With the increase of the stress state and degree of compaction (initial state) an increase of stability under undrained condition was observed. The M parameter obtained was 1.42 with the friction angle at critical state, ϕ'_{cv} = 35°.

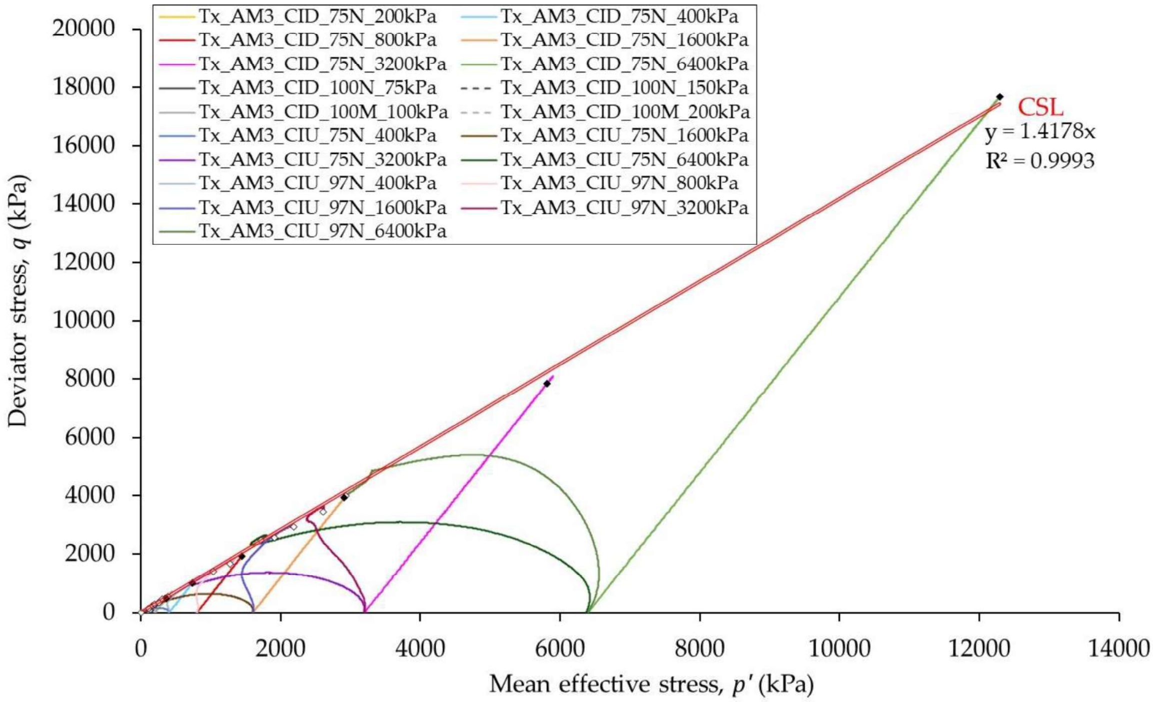


Figure 3: Triaxial compression tests results: stress paths and CSL in the $p' - q$ plane

Figure 4 shows the CSL fitted by a power-low given by Equation (4) just for loose specimens due to the best fiting, because for dense ones the formation of shear bands was observed making it difficult to accurately determine the critical state, together with an isotropic Normal Consolidation Line for 75% standard effort from Proctor compaction (NCL_{75N}) parallel to CSL. The triaxial tests' color code is the same from Figure 3. The parameters for the CSL fitted by power-law are A = 0.8291, B = 0.0494 and C = 0.4012.

The results showed a relevant non-linearity in the critical states line of the material in the $e - \log p'$ plane at higher stress levels (mainly observed from Tx_AM3_CID_75N_6400kPa test), which, given the importance of the critical state parameters for the material response pattern to different stress paths, raising the need for further research about the microstructural properties at particles level for explain this non-linearity behaviour (Viana da Fonseca et al., 2022). The Tx_AM3_CIU_97N_3200kPa test apparently did not reach the critical state and is certainly interfering slightly in the critical state parameters definition of the material, so it will be repeated.

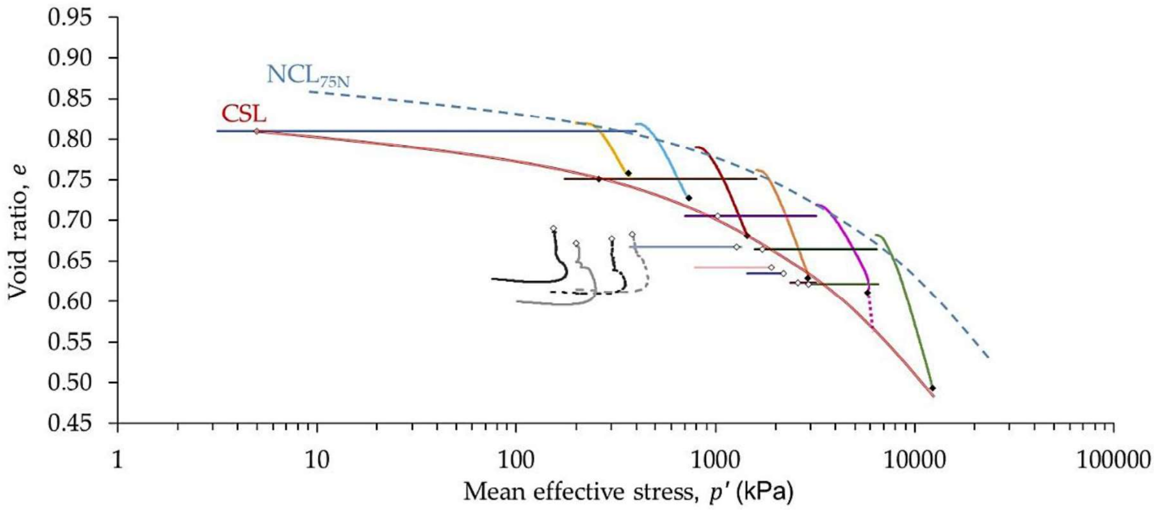


Figure 4: Triaxial compression tests results: CSL and NCL$_{75N}$ in the $e - \log p'$ plane

Figure 5 shows the original PSD curve of the material, as well as the PSD curves obtained after tests under high-stress levels (above 1600 kPa) making it possible to evaluate possible grain size evolutions due to particle breakage and/or morphological changes.

A considerable grain size evolution was noted, as expected, mainly for higher stress levels with specimens with a lower degree of compaction under drained shearing (Tx_AM3_CID_75N_3200kPa and Tx_AM3_CID_75N_6400kPa), which in the long-term could compromise the performance of the structure if it were subjected to at such stress levels, since changes in the state parameter, from dilatant to contractive behaviour (under drained shearing), can increase the susceptibility to liquefaction (in case of solicitations that induce stress-strain in undrained conditions). This possibility of liquefaction by state changes of the materials under high-stress levels should be studied during design and re-analyses while in construction by appropriate stress-strain constitutive models and numerical simulations.

Therefore, the filtered tailings mechanical behaviour under high-stress levels needs to be further investigated at the microstructural level (at the particle level), to try to understand more precisely what may be conditioning this non-linearity of CSL or its evolution, if transitional characteristics are envisage.

Conclusion

It could be concluded that the stress state increasing can impose uncertainties about the geomechanical behaviour of compacted filtered iron ore tailings due to a possible particle breakage and/or with relevant morphological particles' evolution, which added to the possibility of state changes under high-stress levels for stacking embankment. This investigation about non-linearity of CSL associated with evolution behaviour at the particles level should be an aspect to be considered and carefully studied during the design step.

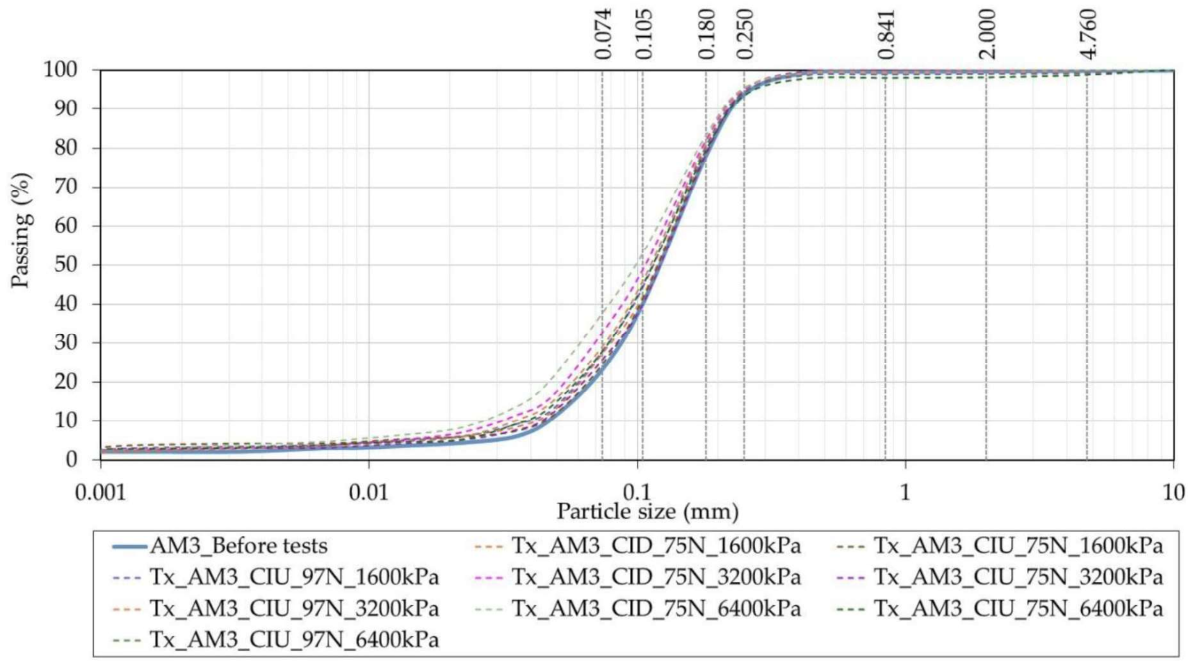


Figure 5: PSD curves before and after some triaxial tests

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