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Investigating the transitional behaviour of tailings from a gold mine site in Australia

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Abstract

Tailing dams can be considered as fragile structures and often result in catastrophic effects when subjected to liquefaction. The existing stability and liquefaction analysis of tailings within the critical state framework explicitly assumes a unique critical state line (CSL). However, recent studies have highlighted the presence of non-convergent compression paths and non-unique CSLs in a diverse range of soils commonly referred to as transitional behaviour. An analysis was made of an extensive series of triaxial tests conducted on filtered tailings from a gold mine site. To examine the potential transitional behaviour based on the effect of texture tailings specimens were reconstituted using moist tamping and slurry deposition methods. The results have shown the features of transitional behaviour in the studied tailings with evidence of non-unique CSLs. The scanning electron microscopy-based fabric study revealed differences in the particle arrangement inherent in the preparation method which might be the primary cause of the transitional behaviour. This study further highlights the need for re-evaluation of effects of fabric in preparation of laboratory element test specimens for CSL determination.

Keywords: *critical state, moist tamped, reconstituted, slurry deposited, transitional*

1 Introduction

Tailings are by-products of mining processes and are mixtures of crushed rock, chemicals used in beneficiation processes and water. The mineralogies, gradations and particle morphologies of tailings generally vary significantly from natural soils due to the numerous extraction processes they undergo. The combination of the suspended constituents in the tailings is commonly deposited in the form of a slurry or filter cakes in impoundments called tailings storage facilities (TSFs). Due to the small particle size and the high water content, tailings show a high susceptibility to liquefaction induced failure either by static or dynamic loading making TSFs structures with a high risk of failure (Li et al. 2018).

The critical state soil mechanics (CSSM) framework is heavily employed nowadays to characterise tailings and assess their susceptibility to liquefaction (Been & Jefferies 1985; Bobei et al. 2009; Carrera et al. 2011; Fourie et al. 2001; Izadi et al. 2008; Jefferies & Been 2006; Lade & Yamamuro 2011; Li 2017). The critical state line (CSL) provides a robust line of reference to evaluate the tailings contractive and/or dilative responses independent of the initial state, fabric and stress history (Jefferies & Been 2016). However, several studies have recorded natural soils and tailings whose behaviour cannot be explained within the CSSM framework. The concept of a unique normal compression line and CSL is not applicable to such soils (Ferreira & Bica 2006; Li & Coop 2019; Mmbando et al. 2023; Nocilla et al. 2006; Ponzoni et al. 2014; Shipton & Coop 2015; Velten et al. 2022; Xu & Coop 2017) and they are termed ‘transitional soils’ (Nocilla et al. 2006). The key feature of the transitional behaviour is that compression and/or shearing is dominated by the initial density of the soil at its creation and hence the fabric which cannot be erased completely at large strains (Chang et al. 2011; Høeg et al. 2000; Nocilla et al. 2006; Shipton & Coop 2015).

The ambiguities in identifying a unique CSL is of prime concern in tailings engineering as the stability analyses are heavily dependent on identifying the CSL through laboratory testing of remoulded specimens (Torres-Cruz & Santamarina 2020) and also due to their significance in prominent failure investigations such as Morgenstern et al. (2016).

Moreover, there are contrasting arguments on deciding the ideal method to reconstitute low-plastic silts and tailings that can simulate the field behaviour. Although moist tamping (MT) is widely used for the reliable measurement of CSL in both academic and commercial laboratories (Reid et al. 2021b), it has been heavily criticised for resulting in non-uniform density profiles, undesirable volume changes during the saturation process, and unrealistic ('honeycomb') soil structure with non-uniform void ratio, compared to naturally deposited soils (Thomson & Wong 2008; Vaid & Sivathayalan 2000).

Despite being the focus of intensive research nowadays, the factors causing the transitional behaviour still remains elusive and complex. Several analytical techniques such as X-ray CT (computed tomography) scanning, scanning electron microscopy (SEM) and mercury intrusion porosimetry have been used extensively to characterise the soil structure and particle arrangement which is referred to as the soil texture (Carraro & Prezzi 2008; Chang et al. 2011; Fonseca et al. 2013; Hattab & Fleureau 2010; Todisco et al. 2018). However, one of the difficulties in examining the texture of transitional soils is that transitional mode of behaviour is evident in gap graded soils (Martins et al. 2001; Shipton & Coop 2015), well graded clayey silts (Ferreira & Bica 2006; Nocilla et al. 2006) as well as in well graded sands (Altuhafi & Coop 2011) making it challenging to clearly detect the textural elements at the scales of finer and coarser particles simultaneously.

Therefore, this paper aims to investigate the shearing behaviour of a mine tailings material and identify any transitional mode of behaviour present. In this study, two sample reconstitution methods, MT and slurry deposition (SD) were employed, and the effect of fabric was further assessed using SEM imagery.

2 Materials and experimental program

2.1 Materials

Mine tailings collected from a mine site in Australia were used in the current study. The TSFs that were the sources of samples used for the current study contained residue from gold ore processing from a single mine pit. Bulk samples were collected from shallow surface areas on the tailings beach of the TSFs close to the embankments and some Shelby–tube samples were also collected from selected depths at the same sampling locations. The index properties for the tailings are outlined in Table 1. The gradation for the two bulk samples used for this study determined from wet sieve analysis and hydrometer testing in compliance with the Australian standards are shown in Figure 1 along with a range of other soils exhibiting transitional behaviour.

Table 1 Properties of the studied gold tailings

Property		Value
Liquid limit	%	26.6
Plastic limit	%	19.4
Plasticity index	%	7.2
Fines content (<75 µm)	%	67
Mean particle size (D_{50})	µm	25
Specific gravity (G_s)	–	2.78

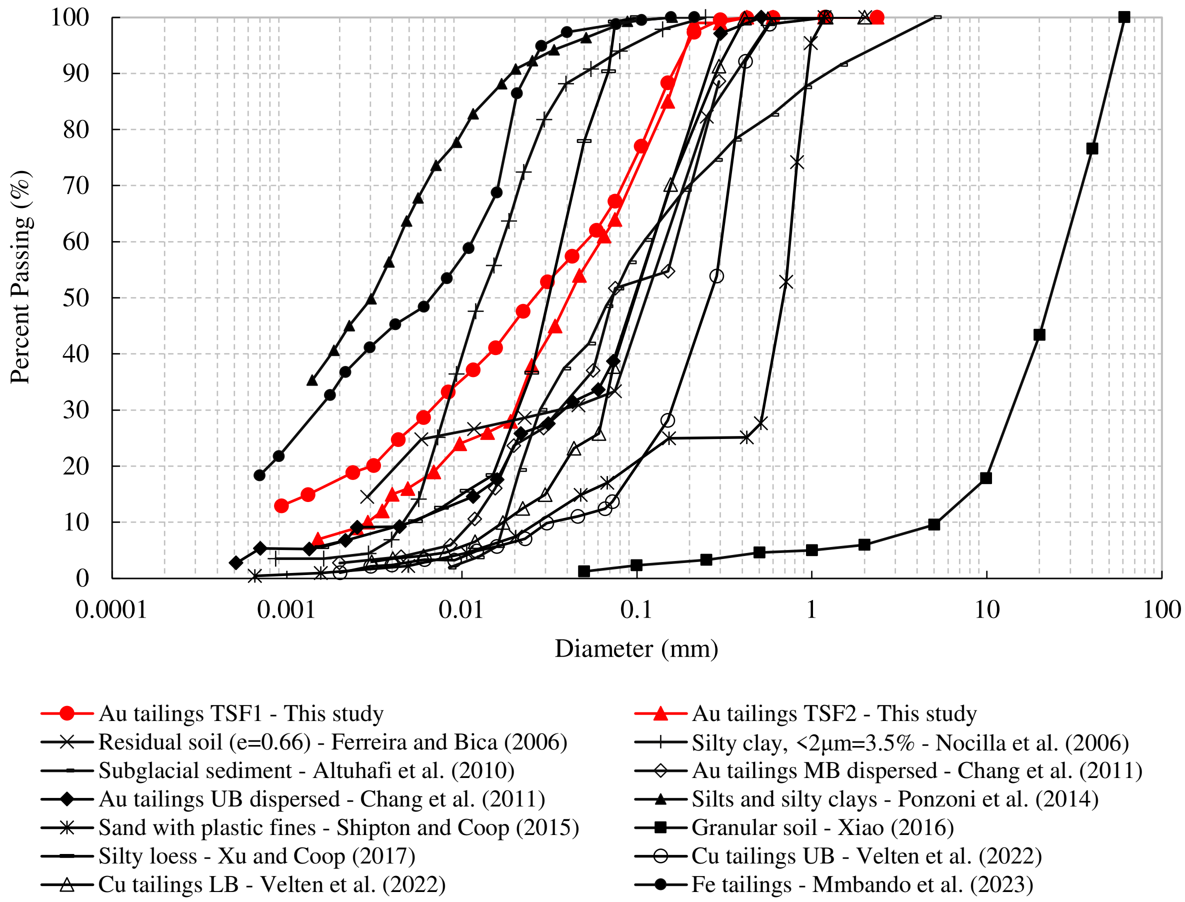


Figure 1 Particle size distribution of soils and tailings with transitional behaviour

2.2 Sample reconstitution and test methods

Prior to specimen reconstitution, oven dried tailings samples were gently crushed and sieved through a 1.18 mm sieve to minimise the effect of clods on any kind of testing carried out during this study.

The test program consisted of preparing a series of MT and SD samples using the composite materials to infer the location of CSL. All the samples were tested using a triaxial apparatus with a loading frame that can provide a maximum confining pressure of 700 kPa. Cylindrical samples of 63 mm in diameter and 126 mm in height were used for both MT and SD prepared samples.

For MT sample reconstitution, tailings with gravimetric water content (GWC) of approximately 8% was compacted in eight layers inside a 63 mm diameter membrane lined split mould using the 5% undercompaction method (Ladd 1978). The mass of dry tailings used for each sample was varied to control the void ratio of the specimens and samples were prepared as loose as practicable to promote uniform strain softening and to avoid shear localisations at large strains.

The SD samples were prepared with the intention of determining the uniqueness of CSL obtained from the two different sample reconstitution methods. The SD method comprises producing a thick homogeneous saturated slurry and then pouring or spooning it in the cavity prepared for the specimen placement (Bradshaw & Baxter 2007; Chang et al. 2011). The required amount of dry tailings was placed in a beaker and thoroughly mixed with deionised water to a GWC of 38–42%. Determining the amount of water content used for the slurry preparation is a crucial factor in in ensuring saturation and non-segregation of particles when pouring the slurry into the split mould. Thicker slurries with low water content pose issues related to saturation due to air entrapment during mixing and pouring whereas thinner slurries with higher water contents promote segregation of fines from coarse particles. A GWC of 38% allowed preparing the thickest consistency which can be poured and additional measures were taken to avoid entrapment of air bubbles as follows.

Once the tailings were mixed with de-aerated water, the tailings slurry was kept inside a vacuum desiccator (-75 kPa) for 24 hours to remove entrapped air. Saturated slurry was then poured into the vacuum split mould cavity (126 mm height, 63 mm diameter) on which a special extension collar of 80 mm was placed. Slurry was initially allowed to consolidate under self-weight with a 20 kPa vacuum gradient for two hours followed by incremental one-dimensional loading to reach 40 kPa over a period of 24 hours. The vertical effective stress imposed by the weights was always kept below the desired effective minimum consolidation pressure of 50 kPa.

At the end of initial slurry consolidation, the extension collar was carefully removed and the excess material above the split mould was trimmed using a wire saw. Once the top cap was placed, a suction of 30 kPa was applied to the samples to enhance the uniformity of the specimen as well as to avoid any bulging or tilting of the specimen when the split mould is removed. Several studies have emphasised the importance of applying a suction to the specimen to minimise the side friction that develops between the membrane liner and the consolidating tailings (Izadi et al. 2008; Wang et al. 2011). Finally, the split mould was removed to obtain a saturated slurry deposited specimen for triaxial testing. The SD method adopted here closely follows the works of (Reid & Fanni 2022; Soysa 2021).

All triaxial test samples were first flushed with CO_2 to accelerate the process, followed by water percolation. Finally, back pressure increments were applied until a B-value greater than 0.95 was achieved. Samples were then isotropically consolidated across a range of suitable mean effective stresses. Drained and undrained tests were sheared at approximate rates of 0.5% and 2% per hour, respectively. The void ratio of specimens used in this study was calculated using the end-of-test soil freezing method which is the current best practice for accurate measurement of void ratio (Jefferies & Been 2016; Sladen & Handford 1987) and the post-saturation volume changes were calculated using the values recorded by the back pressure pump.

Extracts from MT, SD and tube samples collected from the site (referred to as intact samples) were analysed under an SEM to get an idea about the textural differences.

3 Results and discussion

3.1 Stress paths and critical states

Figure 2 presents the state plot for the MT tests along with the CSL fit based on a semi-logarithmic interpretation ($e = \Gamma - \lambda \ln(p')$), where Γ is the void ratio when p' = 1 kPa and λ is the slope of the CSL as no significant curvature of the CSL was identified. The end points of the shearing tests define a very clear unique CSL with a R^2 value 0.99. The critical state friction ratio, M_{tc} from the stress paths in q-p' plane is 1.37 with an angle of shearing resistance at critical state, ϕ'_{cs} equal to 34°.

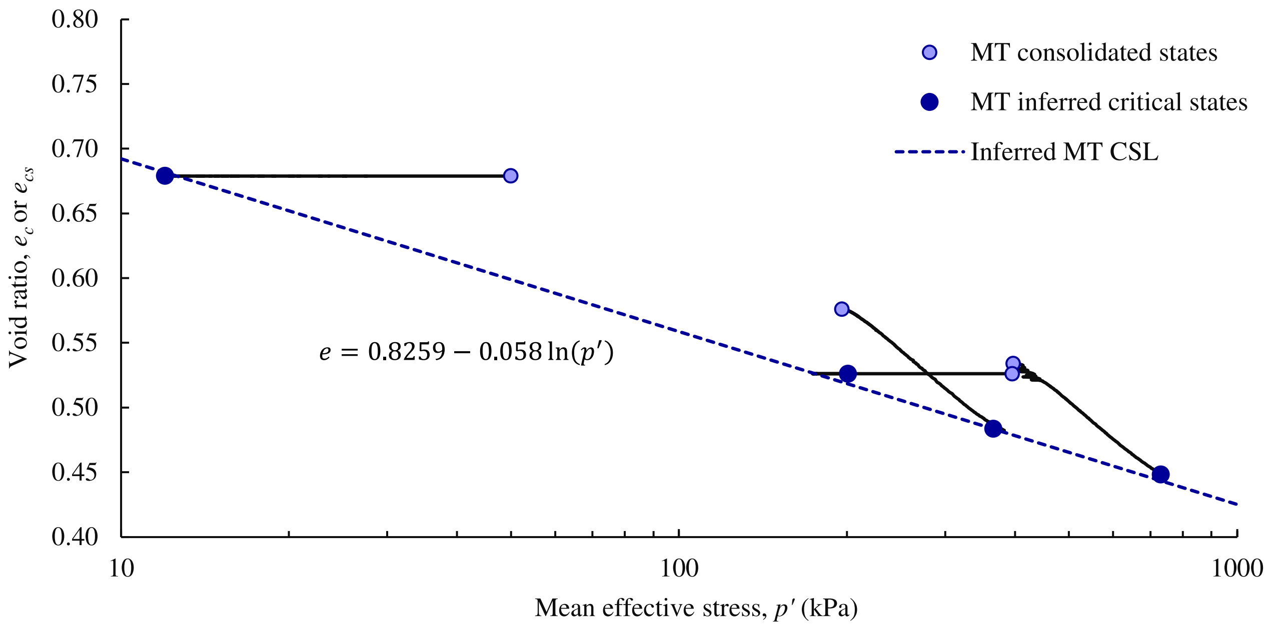


Figure 2 Test paths and critical state line for moist tamping tests

If the CSL was estimated in the same way as for MT CSL solely based on the average of all SD tests by employing the end-of-test method (Ghafghazi & Shuttle 2006), it results in a critical state friction ratio Mtc of 1.42 and an angle of shearing resistance at critical state, φ'cs, 35°. The φ'cs values observed for the studied tailings are relatively higher than the values that has been reported for clean sands (Jefferies & Been 2006). Murthy et al. (2007) presented an increase in φ'cs with increasing silt content. Such trend was attributed to the contribution of the wedging effect of angular silt particles to the shear strength of the flow fabric of the sand developed at critical state. The more angular the silt particles are, the higher the effect of silt on the φ'cs and this is presumed to be the reason for the higher φ'cs in this case.

The SD test paths are then plotted in a state diagram in Figure 3 with the MT CSL for comparison. As observed in a majority of similar studies (Reid et al. 2021a), looser states were formed by the MT method compared to SD samples. Interestingly, the consolidated states achieved by both MT and SD specimens in the present study are relatively consistent in terms of the consolidated stresses. It was seen that a unique CSL based on SD test results can be plotted with a R2 value of 0.99 which indicates non-significant scatter of the points. However, if one assumes no transitional behaviour is present for the material tested and fit the CSL based on all MT and SD tests, a best fit line with R2 with 0.96 will still be achieved with a maximum deviation of only 0.02 in terms of void ratio (not shown here). This value is smaller than the differences seen in the range of CS states identified using the end-of-test freezing method by different academic and commercial laboratories as discovered during a recent round robin program (Reid et al. 2021b) and also the scatter seen when fitting the CSL in e-ln(p') plane in some research studies (Bedin et al. 2012; Li et al. 2018).

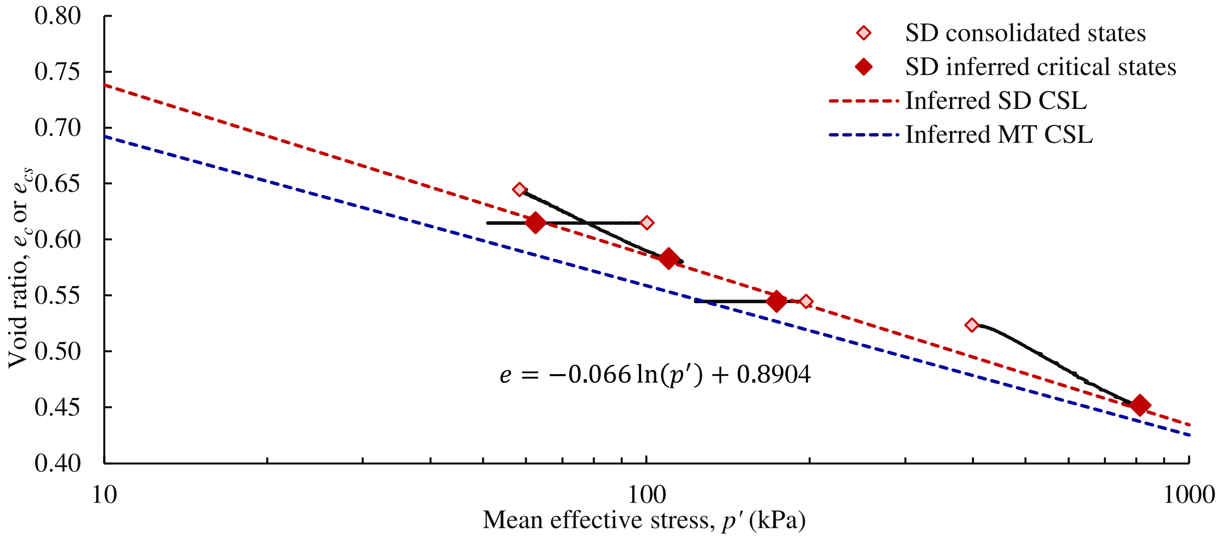


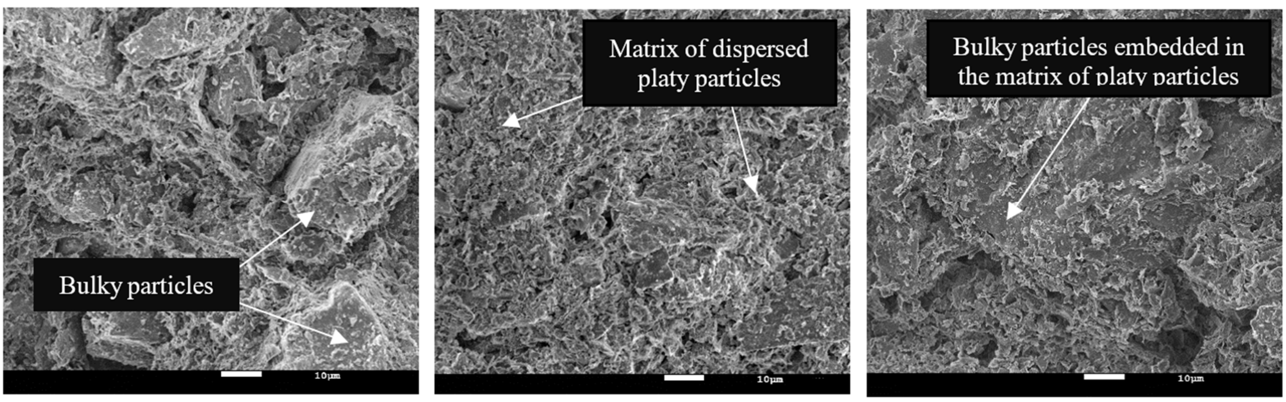
Figure 3 Test paths and critical state line for slurry deposition tests

However, it was decided to interpret data for the current study with two unique CSLs identified with the values of λ equal to 0.058 and 0.066 and corresponding Γ values of 0.8259 and 0.8904 for MT and SD tests, respectively. This was based on the facts that (i) the two separate CSLs provide better R^2 values than fitting a single CSL for all tests and (ii) the presence of transitional behaviour in compression (not shown here), which means there is a seat for transitional behaviour during shearing as well.

However, it is also clear that the MT and SD CSLs can converge at higher stress levels as evident in Figure 3. That is, any residual differences remaining after compression in aspects of fabric and/or associated void ratios arising can be erased by shearing at high stresses. For the current study, such differences originating from different sample preparation methods are not completely erased by shearing at mean effective stresses below 1000 kPa (Ferreira & Bica 2006; Mmbando et al. 2023; Shipton & Coop 2015).

3.2 Microstructure and texture

A robust comparison of the fabrics between different specimens should be done prior to the shearing stage if the effect of fabric in shearing needs to be investigated. A comparison of fabrics of MT, SD and intact specimens from tube samples obtained from the field which underwent saturation and consolidation phases is presented in Figure 4. The MT specimens showed a pronounced flocculated and aggregated structure and the bulky particles are embedded in the fine grained flocks with a large amount of pore space. Apart from the flocs among the bulky particles, some dispersed platy particles also exist as seen from Figure 4a.



(a) (b) (c)

Figure 4 Scanning electron microscopy micrographs of fabric specimens (a) Moist tamping; (b) Slurry deposition; (c) Intact

However, the SD structure is dominated by the dispersed fabric where bulky particles are deeply embedded in the platy matrix and similar to the fabric of pond tailings studied by Chang et al. (2011) with relatively finer particle gradation. The gradation of the gold tailings studied in the current work is similar to that of the middle beach (MB) tailings of Chang et al. (2011) and MT specimens of this study have a texture closer to their undisturbed and slurry deposited MB tailings. The flocs originated from MT are a well-established feature in their texture study and deemed to provide the primary support to the soil structure during shearing. However, in the current study, bulky particles are not in contact with each other and the matrix of fine particles should provide the primary support. The intact specimen microstructure is more biased towards a dispersed fabric where platy particles are dispersed around and in between the bulky particles. Therefore, it can be concluded that the dispersed structure resulting from SD is closer to the intact specimen microstructure than is the MT structure and SD can be put forwarded as the reconstitution method providing a texture closer to the in situ texture of the deposited tailings. However, identifying any obvious particle orientations was was not easy.

4 Conclusion

A series of triaxial tests on a primarily silt low-plastic gold ore tailings have been carried out. The tailings were extruded from push tubes to obtain intact samples. Bulk tailings were reconstituted using MT and SD. Comparisons were made across the mechanical response of reconstituted and intact tailings. The main outcomes of the current study are summarised as follows:

- The work highlighted that the mechanical response of tailings shows a weak transitional mode of behaviour in compression (not shown here) and shearing. The transitional behaviour is evident within the tested stress range and is dependent on the method of preparation. The gold ore tailings used in this study also has a gradation similar to other geomaterials exhibiting the transitional behaviour.
- Similarly, two distinct critical state lines were found for the MT and SD methods. However, the two lines seems to converge at higher stress levels suggesting the complete destructuring of the initial fabric when sheared to larger strains at high stress levels, i.e. any fabric effects from the sample preparation method seems to be erased more easily by shearing than by compression.
- The SEM-based fabric study revealed the preparation method induced differences which were similar to the findings of previous studies. The MT produced an aggregated structure while slurry deposited specimens had a fabric where bulky particles are heavily embedded within a matrix of platy particles. Although the texture of slurry deposited specimens is much closer to that of intact tailings, it is clear that neither MT nor SD methods can fully replicate the microstructure of the undisturbed gold tailings.

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