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A geotechnically derived screening method to assess the filterability of tailings

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Abstract

International Commission on Large Dams (ICOLD) Bulletin 181 (ICOLD 2021) has classified tailings into five broad types depending on their physical properties (e.g. particle size, plasticity, consolidation). The classification system has been recognised as a valuable framework for predicting the general behaviour of tailings. For this study, the authors have undertaken an extensive literature review of geotechnical parameters reported for filtered tailings studies. The literature review included the digitisation of various tailings parameters reported and compared against the ICOLD classification system. The comparison allowed it to establish how the filterability and filtration rates were achieved from the historical reports. The benchmark process allowed for the development of filterability boundaries inspired by the classification system. The charts developed for the study are proposed as a first-pass screening tool to understand the filterability of the tailings at hand, charts proposed herein are not envisioned to provide a yes or no suitable for filtration outcome. Conventional soil classification test results are often readily available from most tailings storage facilities, making the charts an attractive tool. The charts can also be used to compare, at a high level, which tailings from a range of potential alternative sites are the most suitable for filtration. Three anonymous iron ore sites are used to trial the system. The study concludes with a summary of limitations and opportunities to consider when adopting the proposed screening methods.

Keywords: *screening, filterability, tailings classification, dry stack, tailings management*

1 Introduction

While a single root cause for each historical tailings dam failure has not been identified, a recurring factor that causes the severity of such failures is the management and behaviour of water within these facilities. The finding has led the industry to consider alternatives to traditional tailings storage methods. These alternatives include pre-deposition dewatering techniques (MEND 2017).

This paper introduces a geotechnical screening methodology for assessing the filterability of tailings, based on the classification system outlined in the International Commission on Large Dams (ICOLD) Bulletin 181 (ICOLD 2021). This system categorises tailings according to physical properties such as particle size, fines content, settling rate and geotechnical index properties. It is acknowledged as a potential tool for predicting the filtering behaviour of tailings.

The methodology involves a comprehensive literature review focusing on the geotechnical properties of filtered tailings. This includes the digitisation and analysis of various tailings parameters from existing literature, followed by their comparison with the ICOLD classification system. Notably, the methodology is progressively tested against the dataset from the Karara iron ore mine (Amoah et al. 2018) which represented, in 2023, the largest filtration operation globally (currently being upgraded to produce

45,000 tonnes per day). The approach integrates technological advancements and innovations with established best practices; a synergy expressed by Williams (2020).

The outcome of this research intends to establish filterability boundaries influenced by the ICOLD criteria, that resulted in the creation of diagnostic charts. These charts are designed as preliminary screening tools to evaluate the filterability, utilising readily available soil classification test results from existing tailings storage facilities (TSFs) utilising different upstream dewatering technologies. Additionally, they provide a mechanism for comparing the filtration suitability of various tailing types or sites at a broad level.

2 The ICOLD classification system

Tailings materials have characteristics similar to unconsolidated natural soils. However, processing, transport, deposition, and geochemical properties can give tailings distinct characteristics (ICOLD 2021). The ICOLD classification system, based on Fell et al. (2005) and Vick (1990), categorises tailings by granulometry (see Table 1). The system established the following groups:

- Coarse tailings (CT): cohesionless, angular, suited for materials with medium to high shear strength. Properties can be influenced by the type of material, such as salt or coal. Examples of minerals/ore are salt, mineral sands, coarse coal rejects, iron ore sands.
- Hard rock tailings (HRT): often derived from igneous and metasedimentary rocks, characterised by good shear strength and variable hydraulic conductivity related to particle grading. Examples of minerals/ore are copper, massive sulphide, nickel, gold.
- Altered rock tailings (ART): formed from altered rocks with significant clay content, moderate shear strength and settling characteristics. Examples of minerals/ore are porphyry copper with hydrothermal alteration, oxidised rocks, bauxite, leaching processes.
- Fine tailings (FT): silt-dominated, with varying amounts of clay, showing a range in both plasticity and shear strength. Examples of minerals/ore are iron ore fines, bauxite (red mud), fine coal rejects, leaching processes, metamorphosed/weathered polymetallic ores.
- Ultra fine tailings: characterised by high plasticity and very low hydraulic conductivity, requiring long consolidation times. Examples of minerals/ore are oil sands (fluid fine tailings), phosphate fines, some kimberlite and coal fines.

Table 1 Overview of the tailings properties in the ICOLD classification system (after ICOLD 2021)

Tailings type	Composition	Plasticity	Shear strength	Hydraulic conductivity	Specific considerations
CT	Silty sand	Non-plastic	Medium-high	High	Varies with material type; salt may reduce conductivity due to solubility effects
HRT	Sandy silt	Non to Low	Good	Varies with grading	Angularity from igneous/ metasedimentary rocks; finer fractions can alter overall properties
ART	Sandy silt with trace clay, bentonitic clay content	Low	Moderate, dependent on clay content	Moderate	Settling characteristics and shear strength influenced by quantity and type of clay
FT	Silt with trace to some clay	Low to Moderate	Variable	Variable	Dominated by silt, may contain clay-sized ‘rock flour’ without clay-like properties
UHT	Silty clay	High	Low	Very low	Long consolidation period, defined by finest clay fraction

The ICOLD framework delineated various analytical categories, each pivotal in elucidating the potential mechanical behaviours extrapolated from geotechnical parameters measured in tailings. The paper utilised the ICOLD framework and extrapolated it as a geotechnically-derived screening method to offer insights into the potential behaviour of filtered tailings.

The overview into tailings management and the ICOLD Bulletin (2021) sets the stage for subsequent discussions on the significance of understanding index properties for tailings classification. These characteristics assessed are summarised in Table 2. Notably, the proctor compaction test, widely used in geotechnical engineering, has been identified as a tool to inform target moisture content during filtration. However, the test has been excluded from this work. A separate study on tailings compaction is presented in this conference proceedings.

Table 2 Overview of filtered tailings tests and properties

Criteria	Description	Recommended lab test	Insights
Atterberg limits	Determines filtration moisture content relevant to geotechnical design, typically at the plastic limit (PL) of the material and below the liquid limit (LL)	Fall cone test (preferred over Casagrande Cup for low plasticity materials)	Analysis of filtration moisture content in relation to PL and LL; assesses the influence of climate variability
Clay mineralogy	Identifies fine-grained phyllosilicate minerals (<2 µm)	Cation exchange capacity testing; X-ray diffraction analysis; QEMSCAN	Swelling clays can affect filtration rates due to moisture absorption
Compressibility of material	Evaluates volume compressibility and consolidation behaviour under load	Oedometer testing for various PSDs; constant rate of strain consolidation testing	Key to understanding water release during settling; insight into active consolidation water release
Particle size distribution (PSD)	Examines how tailings react to filtration systems	Hydrometer testing or laser diffraction for fines gradation	Identifies fine particle content and its effect on cake formation; notes how water absorption and adsorption increase with finer particles (e.g. clays), affecting filterability
Settling tests	Evaluates settling rate, filterability, reagent effects, consolidation, and density of tailings. Drained and undrained settling tests for various PSDs	Standard jar tests with specified beaker dimensions; Extended duration tests (up to five days) for various clay content levels; Tests should use process water for an accurate representation	Provides analysis of settling time and density specific to tailings type; includes determination of non-segregating boundary. Provides insight into the water balance in the tailings storage facility and the effect of clays and process reagents on recovery rates

3 Literature review

The literature review began with an analysis of particle size distribution (PSD) for various types of tailings. The particle size is a crucial factor in understanding how the material will interact with a filtration system. Finer particles may cause problems in cake formation and drainage during filtration processes.

As a preliminary assessment tool, PSD has been utilised to evaluate suitability, necessitating additional testing as part of a comprehensive evaluation. Figure 1 presents a review of the PSD literature, wherein the data is benchmarked against filtration rate criteria proposed by (Pyle et al. 2019). Pyle et al. stated that tailings with less than 15% of particles passing a 10 µm size filter at high rates can achieve low moisture levels in filter cakes. Similarly, tailings with a higher fines content, exceeding 30% passing 10 µm, tend to have poor filtration rates and high moisture content, requiring significantly extended filtration durations.

The PSD literature data includes successful filtered tailings (AMEC 2010), iron and lithium tailings (Grosso et al. 2021), typical gradation curves for dry-stack (Crystal & Hore 2018), gold tailings (Burden 2021), graphite tailings (Moshi et al. 2019), polymetallic tailings from Hecla Creek TDF (Erickson et al. 2021) and iron ore tailings from two different sites (Costa et al. 2021; Amoah et al. 2018).

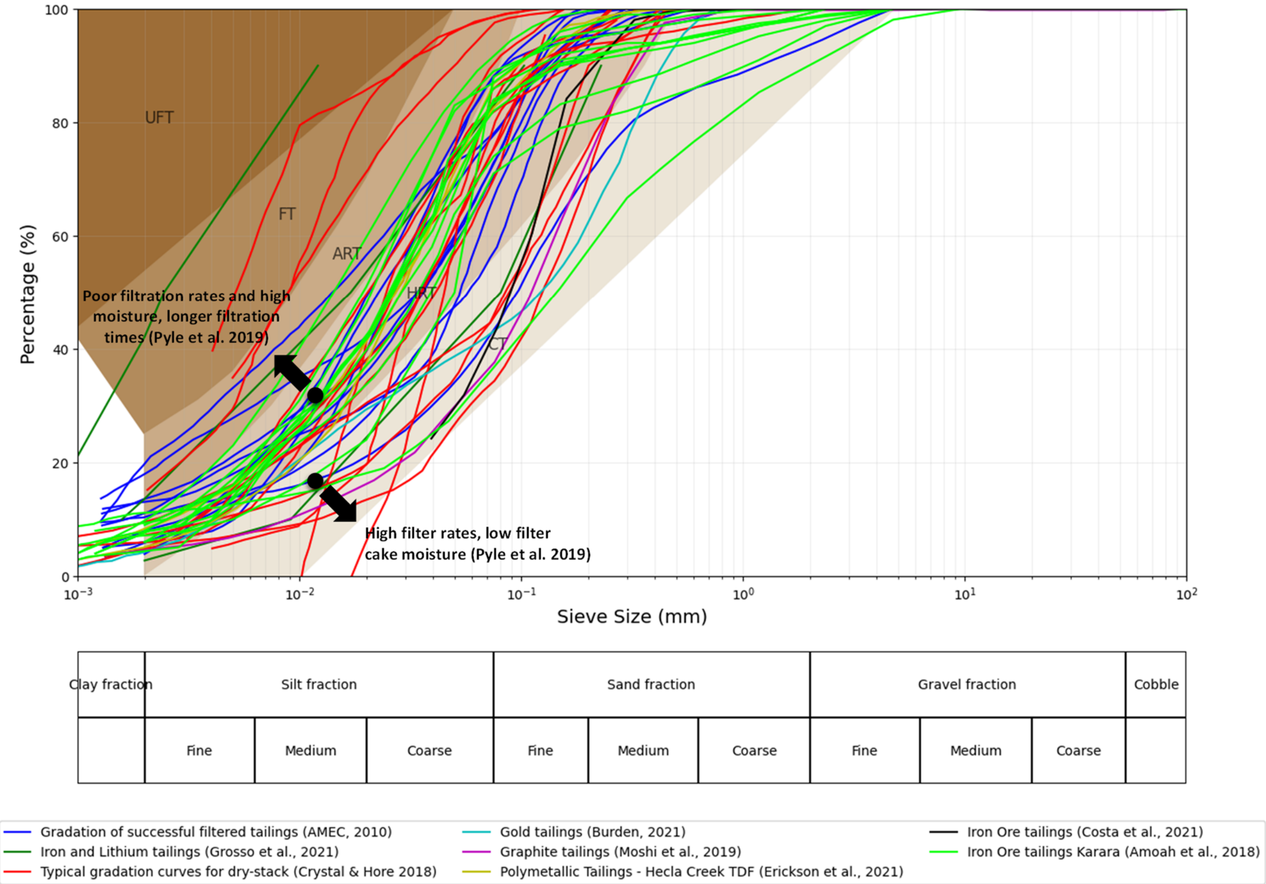

Figure 1 ICOLD classification and literature review regarding particle size distribution

Subsequent to the data analysis, the results from ICOLD were categorised into a ‘traffic light’ system. This approach enables quick interpretation and efficient assessment of the feasibility of dewatering processes. The ‘traffic light’ system is visually represented in test result figures through shadings:

- Green: test results fall within the ideal region, suggesting high filtration rates. Care must be taken because coarse material, arguably easier to dewater, can impact the durability of filter clothes.
- Amber: test results are within the transitional region, indicating potential, or limited data availability precluding a definitive classification.

- Red: test results may be problematic, not necessarily precluding dewatering, but indicating potential issues that should be addressed in the project.

It should be noted that the red traffic light may carry the connotation of unsuitable filtration. The authors acknowledge that there are applications for which pressure filters do not work. Filtration for some of those materials may take longer and run at lower rates, however, can usually still produce a friable cake.

Figure 2 illustrates the classification approach applied here, using a PSD chart. The regions were developed in accordance with ICOLD bulletins. The positioning of data within the coloured regions aids in assessing material behaviour. However, data alignment within a specific region is not conclusive; it serves as a guideline rather than a definitive rule. PSD information from four sites has been plotted in Figure 2. Karara (Amoah et al. 2018) and three anonymous iron ore sites from work completed by the authors. The information from the sites was shortlisted to present:

- Site 1: with a PSD similar to that of Karara
- Site 2: broadly plotting within the red region in the PSD plot
- Site 3: presenting a broader range of expected PSD with several PSDs plotting close to the green region.

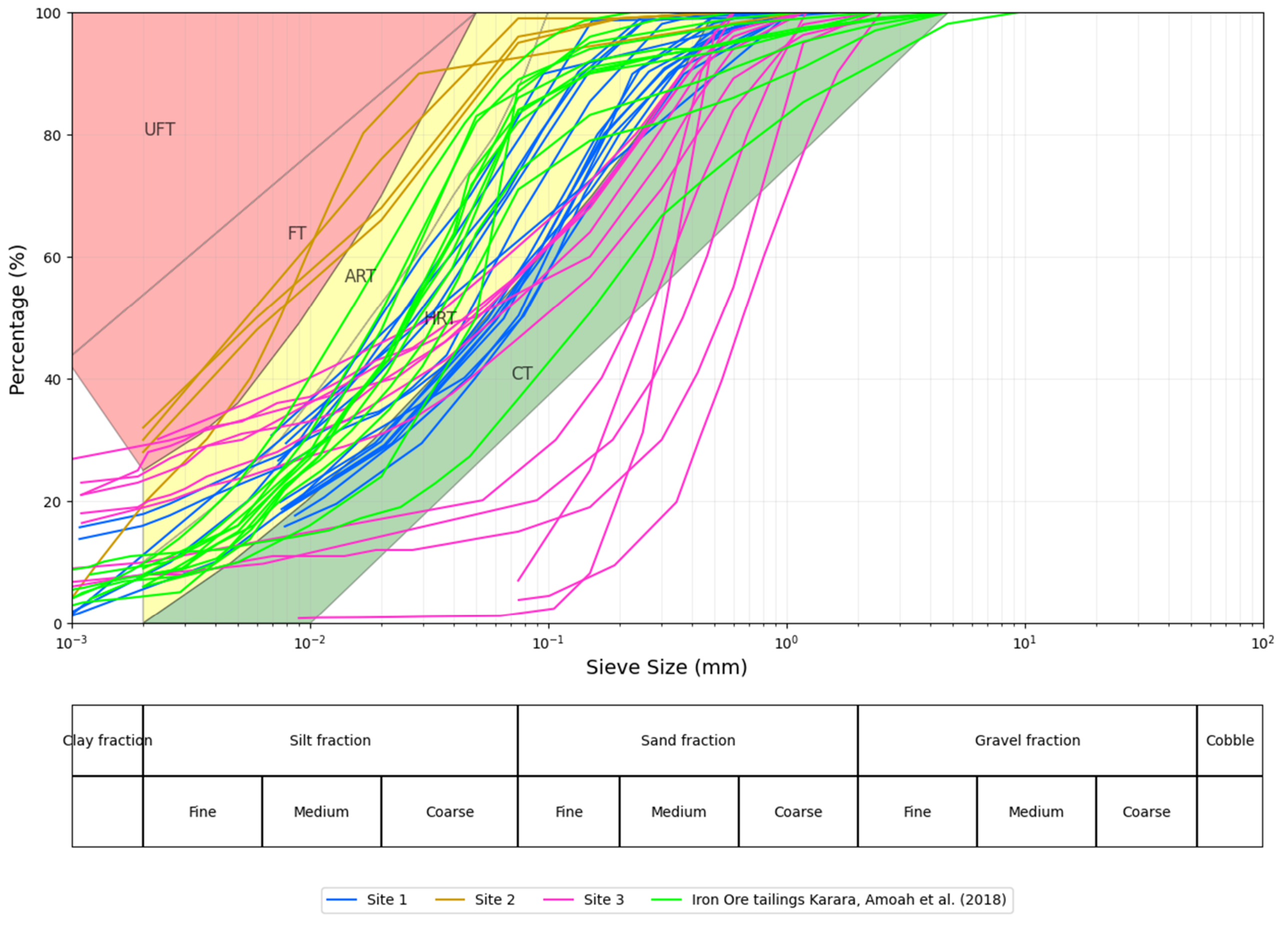

Figure 2 Particle size distribution screening dewatering tailings method

4 Tailings classification and assessment

The analysis in this section focuses on the classification and assessment of dewatered tailings, guided by the proposal screening framework. It leverages the methodologies and criteria established by the ICOLD as a foundational reference. This approach allows for the extrapolation of these principles to encompass various geotechnical aspects found in dewatering systems. Additionally, the analysis includes benchmarking against practices observed at specific sites such as Karara (iron ore) and three anonymous iron ore sites, providing a practical context to the theoretical underpinnings.

4.1 Plasticity index

The concept of plasticity in tailings materials, especially its relation to clay minerals, is a critical aspect in the field of tailings management. ANCOLD (2012) emphasises that the permeability of tailings is highly dependent on particle sizes, degree of segregation, the density along with the time and the quantity and type of clay minerals present. This is because clay minerals have the capacity to store water within their molecular structure. Tailings dewatering is indeed a mechanism that depends, among others, on hydraulic conductivity and plasticity. High plasticity in tailings, due to significant clay content, is indicative of poor settling and consolidation parameters, as well as low hydraulic conductivity, as reported by ICOLD. High plasticity directly translates into a need for increased mechanical energy to extract water from the clay's microscopic structure during filtration processes.

Atterberg limits analysis is a fundamental variable during the geotechnical assessment of structures. The role of Atterberg limits is relevant for defining the behaviour and classification of fine-grained soils and tailings management. It involves two key parameters:

1. Liquid limit (LL): the water content at which soil transitions from liquid to solid-like state (from a geotechnical standpoint). Typically, the LL is understood as the water content at which the undrained shear strength (or yield strength as described by other disciplines) is around 1.7 kPa.
2. Plastic limit (PL): the water content at which the soil changes from ductile to brittle, indicating a significant shift in mechanical properties.

The plasticity index (PI) is the difference between LL and PL. High PI is indicative of a significant presence of clay minerals, resulting in poor filtration performance due to the additional energy required to remove water from the clay's structure. Conversely, low plasticity suggests better filtration characteristics. Meiring (2021) highlighted that the Atterberg limits, when compared against cake moisture content, provide vital insights into the characterisation of filter cake. For instance, Meiring reported that a friable cake (low PL) with a solids concentration higher than the plastic limit (> 72% solids) is easily handled. In contrast, an intermediate phased plastic material with solids concentration between the plastic and LLs (56–72% solids), or a flowable material with a concentration less than the LL (< 56% solids), can be challenging to handle. Figure 3 shows that the Atterberg limits can cover a wide range and as such, specific studies for each site must be always undertaken.

In TSF design, the focus has often been on maintaining the operational water content near the PL (which is often found to be similar to the optimum moisture content measured in the standard proctor test), ensuring it stays below the LL. The study presented herein proposes to use a plasticity chart, juxtaposed with PSD's data, and the colour code scheme inspired by ICOLD guidelines (Figure 3). Pyle et al. (2019) indicated that higher LL and PI often correlate with high plasticity materials or clays, which can significantly affect the efficiency of dewatering processes. These observations are aligned with the plasticity chart proposed in Figure 3.

An analysis of the four sites selected for this study reveals that most data points measured for Karara and Site 1 plot within the amber region, see Figure 3. The similarity between Karara and Site 1 observed in the PSD chart (see Figure 2) is loosely maintained in Figure 3. Site 2 is observed to plot within the amber region in Figure 3 but close to the amber/red boundary. Site 3 shows a wide variation in plasticity from non-plastic to high plastic.

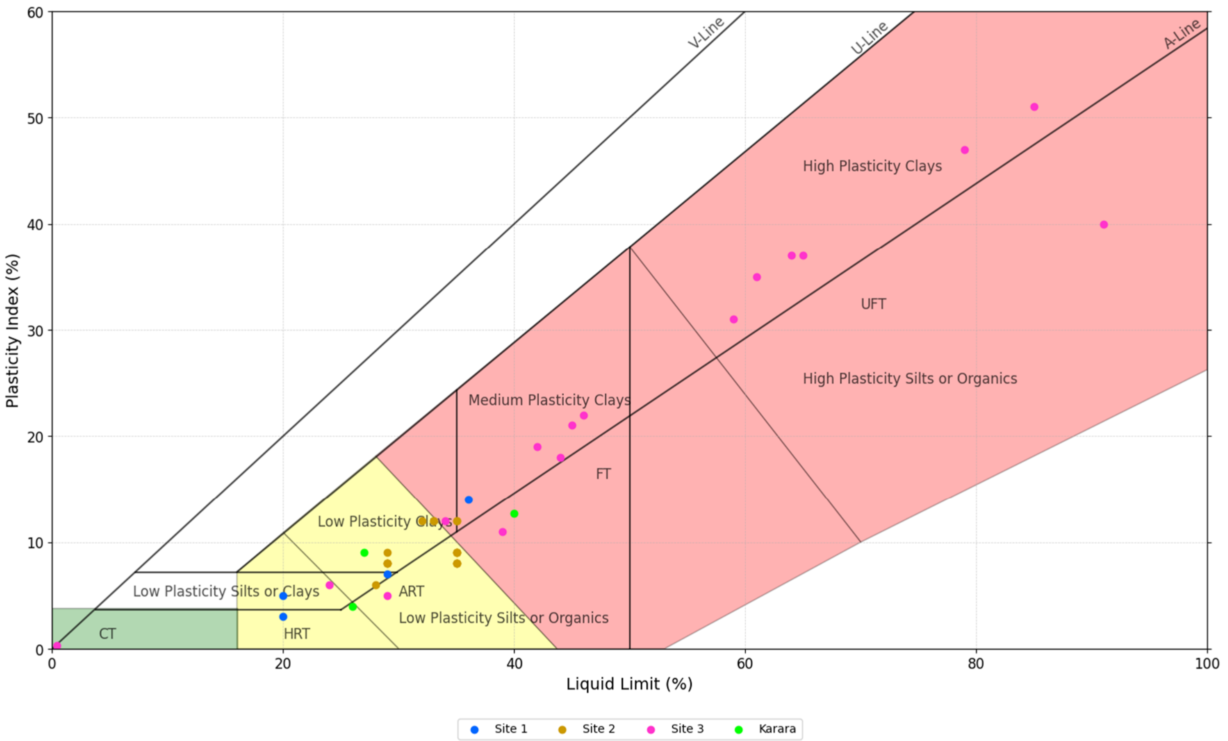

Figure 3 Atterberg limit screening dewatering tailings method

4.2 Clay fraction

Morrison (2022) points out the importance of understanding the PSD in tailings, especially the finer fractions, which are generally more impacted by the presence of fines. Clay fraction in geotechnical engineering is often defined as particles with sizes of less than 2 µm. These finer portions of the PSD are crucial in determining how a material behaves during dewatering processes, whether by sedimentation or filtration. High concentrations of clay minerals in these fine fractions can notably affect the flow-through the cake (Kujawa et al. 2019) leading to reduced dewatering efficiency and increased requirements for flocculants and equipment.

The concept of clay activity, as defined by Skempton (1953), is a measure of its colloidal activity, directly related to its PI and clay fraction content. This is calculated as a ratio of the PI to the percent of clay-size. The activity index helps to determine the swelling potential of expansive clays. A clay with an activity index below 0.75 is considered inactive, while clays with an index above 1.25 are active and have swelling potential.

Grosso et al. (2021) provide a characterisation of clay minerals in the context of filtration studies. According to Grosso et al., clay minerals consist of silicate tetrahedral (T) and alumina octahedral (O) layers, which form various structures that define their physical and chemical properties (Figure 4). Notably, clay minerals like kaolinite, smectite, and chlorite differ in their layer arrangements, influencing their interaction with water and other substances. Upon wetting, water molecules arrange themselves within these clay structures. Clay minerals are noteworthy for the capacity to absorb moisture and swell, while simultaneously resulting in a negative impact on moisture transfer rates. These mechanisms can impact filtration rates negatively.

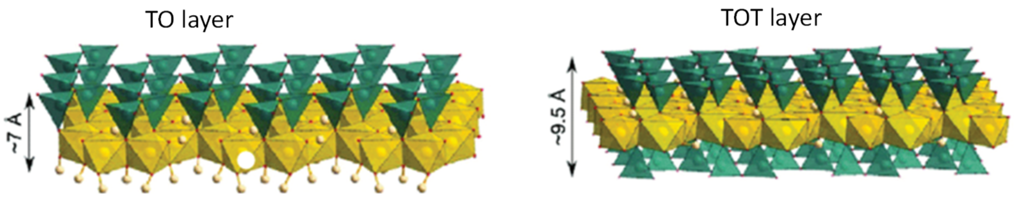

Figure 4 Example of clays packing in tetrahedral–octahedral (TO) and tetrahedral–octahedral–tetrahedral (TOT) layer (Tournassat et al. 2015)

Fine particles, such as clay-size tend to embed themselves within filter cloth fibres, causing clogging. This problem is further intensified because these particles also exhibit high plasticity, increasing their likelihood of adhering themselves to the cloth.

These observations can be quantified in the clay activity chart defined by Skempton (1953) and recommended by ICOLD. The presence of fine particles, reflected in higher clay activity index, necessitates the consideration of dewatering strategies, as indicated by ICOLD. Clay presence is in general an undesired characteristic in tailings considered for filtration. As such, the result is the elimination of the green region (indicating optimal conditions). Figure 5 correlates the PSD of particles smaller than 2 µm's data and the 'traffic light' scheme proposed herein.

Karara and Site 1 overall plots within the amber region. Karara results indicate illite minerals and Site 1 kaolinite minerals. Site 2 plots between the amber and the red region following the kaolinite mineralogy trend. Site 3 plots within the amber region in close vicinity with the red region and follow the trends defined by montmorillonite and illite minerals.

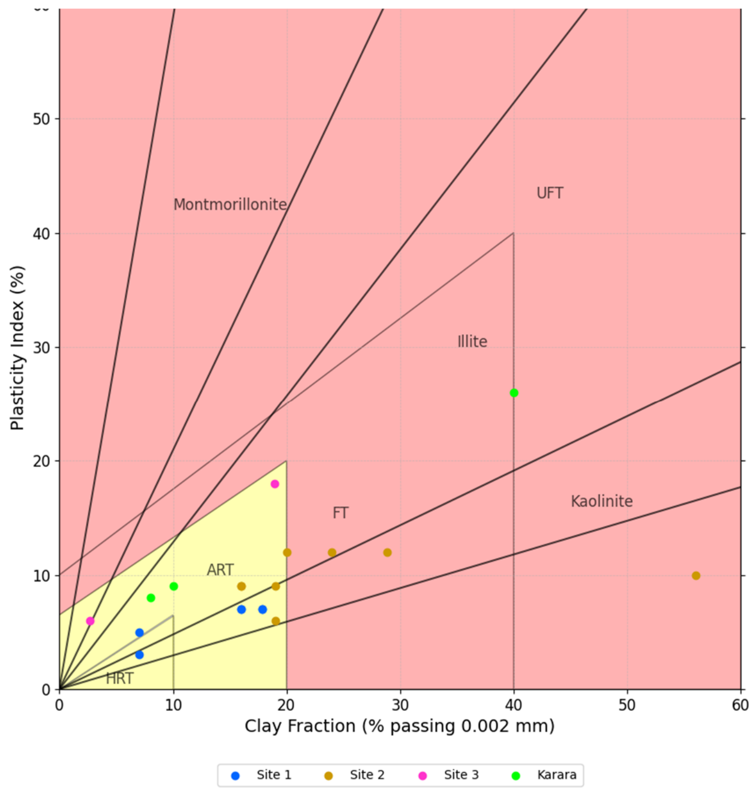

Figure 5 Clay activity screening dewatering tailings method

4.3 Settling tests

The process of settling and consolidation in tailings management is a complex phenomenon influenced by various factors, including initial solids concentration and the presence of fine particles within the tailings. These factors play a critical role in understanding the behaviour of tailings after deposition and during water recovery processes. In conventional tailings management, settling tests offer insights into the density of the settled material and are useful in predicting the tailings' post-deposition behaviour. Settling tests are also used to inform the site water balance. The minimum amount of water reporting to the decant pond is a key factor, influenced by aspects such as clay fraction and the tolerance of the process to fines.

Kujawa et al. (2019) describe a notable relationship between filtration rates and settling rates. Higher filtration rates necessitate the selection of equipment with faster cycle times and lower mechanical times, resulting in a higher efficiency in dewatering. As feed solids increase, the quantity of liquid requiring removal diminishes, consequently leading to reduced filtration cycle times. This relationship highlights the importance of adapting filtration strategies based on the characteristics of the feed.

Fast settling indicates particles that are more efficient to dewater, while slow settling implies reduced filtration efficiency.

According to ICOLD, these tests simulate the initial sedimentation process, emphasising the importance of accurate simulation methods such as jar settling tests with specific dimensions to minimise sidewall friction. Figure 6 shows the integration of settling test data, along with the colour-coding schemes based on ICOLD standards. Settling test results from Site 1 plot within the green and amber regions. Settling test results from Site 2 plot between the red and amber region. Settling test results from Site 3 plot within the amber region.

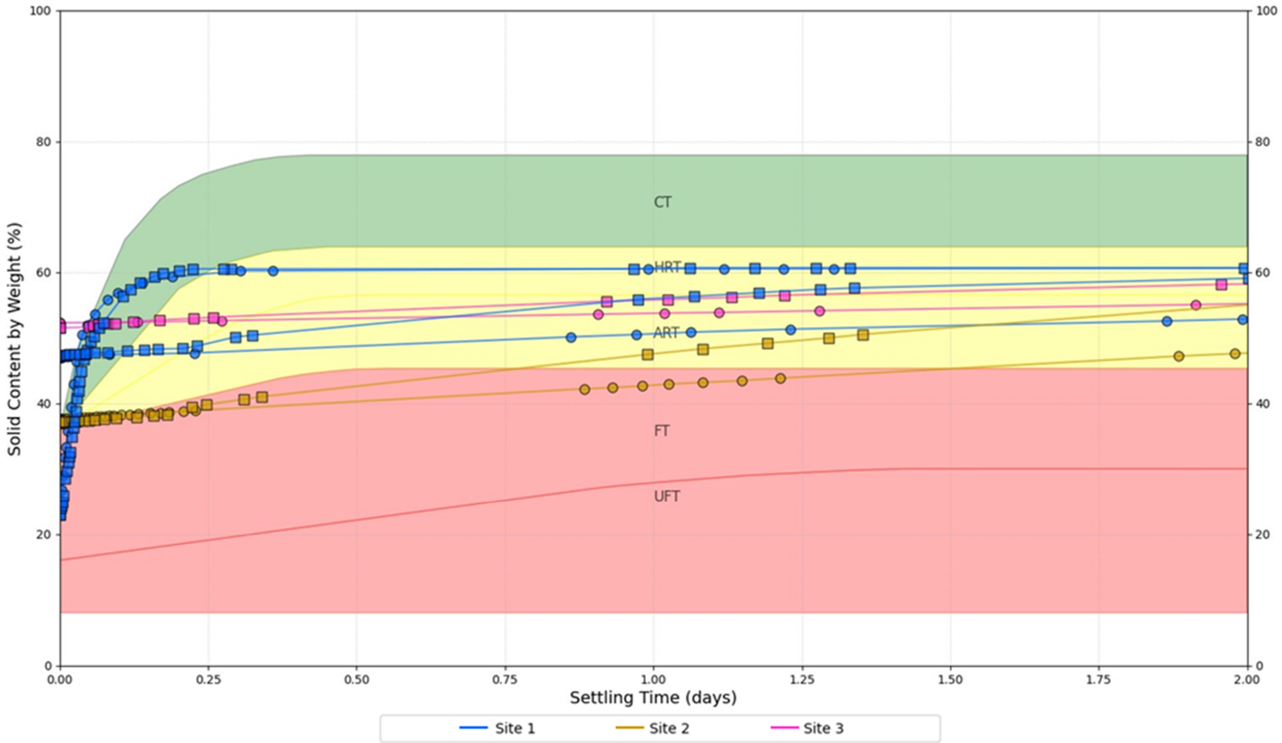

Figure 6 Settling tests screening dewatering tailings method

4.4 Compressibility

Research by Robinson & Allam (1998) on the compressibility of different clay minerals, such as kaolinite, illite, and montmorillonite, demonstrates the dependence of consolidation behaviour on the mechanical properties of the solid grains and the lubricating effect of the pore fluid.

Consolidation mechanics in geotechnical engineering involve subjecting soil samples to constant loads and observing their settlement over time. The oedometer test, a standard in geotechnical engineering, is used to determine the compressibility or void ratio reduction versus the vertical effective stress of a soil sample. Additionally, the permeability or void ratio versus hydraulic conductivity is determined. As void ratio decreases, the permeability decreases and the dewatering process is expected to be influenced negatively.

Meiring (2021) highlighted that tailings plasticity directly impacts handling and deposited geotechnical properties. High plasticity is associated with decreased permeability and shear strength, increased compressibility, and swell potential, as demonstrated in their results. A plot by Meiring shows the variation between total moisture and total pressure, which is equivalent to the compressibility plot widely used in geotechnical engineering. Meiring's work shows the interval of total stress applied by different dewatering technologies. The total stress range lies between 200 kPa and 2 MPa approximately (see Figure 7).

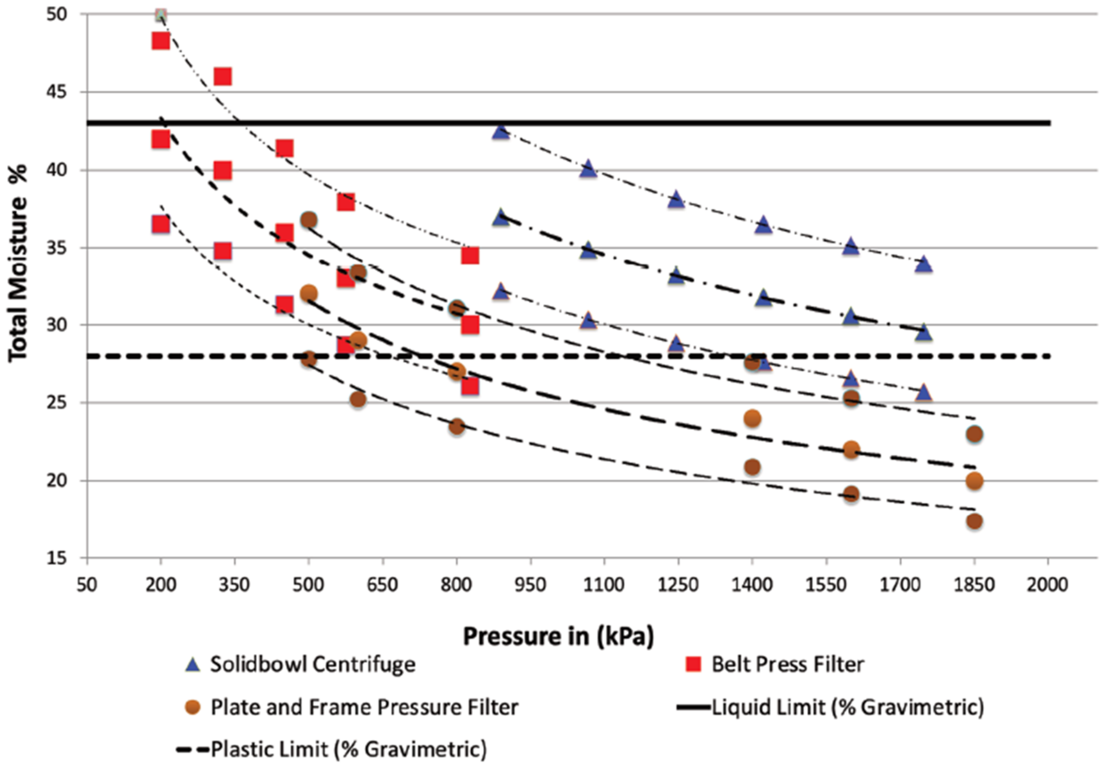

Figure 7 Indicative moisture range versus applied pressure (Meiring 2021)

Pressure filtration is a sophisticated, accelerated consolidation mechanism. This process aids in achieving moisture content near optimal levels for efficient compaction. These presses encompass variants such as plate and frame pressure filters, membrane pressure filters, and belt pressure filters. A geotechnical compressibility plot is a practical analogue to the filtration process

The mechanics of a filter press operate under a principle similar to conventional consolidation tests, but with a markedly more aggressive approach. Although the oedometer test applies loads gradually, a filter press exerts mechanical force to compress tailings. The high compressibility of certain tailings types implies that substantial pressure is necessary to achieve significant void ratio (i.e. volume) reduction. Tailings filtration can be understood as accelerated mechanically induced consolidation, thus reducing the volume and moisture content of tailings to reach a state conducive to disposal or further processing. Low compressibility (flat line slopes in Figure 8) is favourable for dewatering processes. Conversely, high compressibility (higher line slopes in Figure 8) is unfavourable to dewatering processes.

The data presented in Figure 8 exemplify the properties of tailings during consolidation. The colour code scheme adopted in the figure follows a draft version of the ICOLD Bulletin 181 and is adopted herein. Steep slopes in the compressibility plot represent high compressibility. Conversely, flat slopes represent lower compressibility, which is favourable for filtration. The results from the sites analysed herein indicate that Karara tailings and Site 2 plot well within the green region. Site 1 plots within the green and amber boundaries. Site 3 plots within the red and amber boundaries show a wide spectrum of compressibility behaviour. This was expected from Site 3 because previous characterisation information, such as PSD and Atterberg limits, indicated wide ranges. Figure 8 covers a stress range of between 1 kPa to 10 MPa vertical effective stress, not to be confused with the total stresses shown in Figure 7.

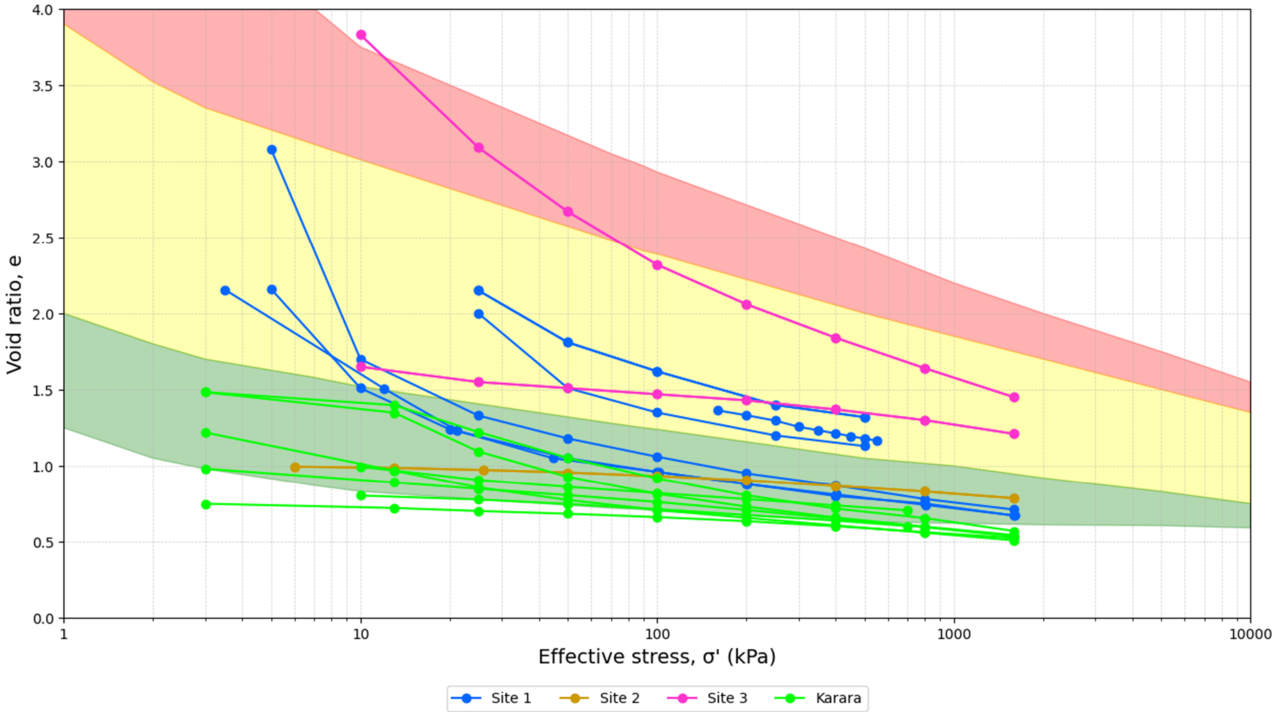

Figure 8 Consolidation tests screening for tailings dewatering

5 Discussion

Karara's benchmark site reveals a PSD and PI in the amber zone, indicating potential filtration challenges due to water-retaining illite clay minerals. An operational focus on balancing particle size and plasticity is thus essential for efficient filtration, particularly for the presence of illite, indicating the need for advanced filtration strategies due to its moisture absorption and potential swelling properties. Despite the lack of specific settling test data, Karara's tailings benefit from lower compressibility, which facilitates effective filtration.

Similarly to Karara, Site 1's tailings fall within the amber region for PSD, PI, and clay fraction, but are dominated by kaolinite minerals. This indicates that it may experience issues with moisture transfer and potential filter cloth clogging due to the plastic nature of the clays. Site 1's settling test results indicate generally favourable and fast sedimentation and dewatering conditions. Site 1 compressibility shows variability under pressure. This suggests that effective dewatering is possible, though adjustments in filtration pressure might be needed to accommodate the compressibility differences.

In contrast, Site 2 presents a more complex challenge. Its PSD is in the red region and its PI and clay fraction are close to the red boundary, indicative of significant issues in filterability. Clay fraction at this site has been found to present a wide variability. The presence of kaolinite minerals, which are known for their swelling and moisture absorption properties, further complicates the filtration process. Site 2's test results, despite plotting well within the green region for compressibility, reflect a significant challenge aligning with the problematic PSD, high plasticity, and challenging clay fraction, indicating a trend towards poor filtration performance.

Site 3, while displaying a favourable PSD close to some Karara test results, reveals a variable clay fraction with montmorillonite and illite minerals which can contribute to challenging dewatering process due to their high swelling potential and moisture absorption. The variation in the clay fraction may impact the dewatering negatively, as seen in the compressibility tests.

Table 3 summarises the analysis using the proposal screening method.

Table 3 Overview of tailings filterability based on geotechnical principles

Criteria	Karara	Site 1	Site 2	Site 3
Particle size distribution	X (yellow)	X (yellow)	X (red)	X (green) X (yellow)*
Atterberg limits	X (yellow)	X (yellow)	X (yellow)	X (red)
Clay activity	X (green)	X (yellow)	X (yellow) X (red)*	X (yellow)
Settling tests	NA	X (green) X (yellow)	X (red)	X (red)
Compressibility of material	X (green)	X (green) X (yellow)	X (green)	X (yellow) X (red)*

* Denotes high variability, which is an undesired feature for a potential tailings dewatering operation
Double symbols in the table denote a transition or boundary behaviour

6 Conclusion

This work expects to contribute towards the rationalisation of geotechnical concepts within the field of tailings management specifically focusing on the feasibility and efficacy of implementing dewatering processes of iron ore tailings. Anchored in a literature review and laboratory data analysis, the study aligns with ICOLD (2021) to offer a structured approach. The comprehensive examination of PSDs, Atterberg limits, and clay activity proposes a screening method to evaluate the filterability of tailings with a particular emphasis on potential filtration rates. This methodology highlights the importance of conventional soil classification tests, commonly available in TSFs, for assessing tailings behaviour and filterability.

The establishment of filterability boundaries, based on the ICOLD classification system, is an initial screening tool. This screening methods for different types of tailings provide a comparative analysis of their filtration potential. The red traffic light may be indicative of materials that cannot be filtered into a cake but the rate and hence cost are impacted by these criteria. Karara's test results are used to benchmark the framework. Karara is currently the largest filtration operation in the world being upgraded to produce 45,000 tonnes per day as of 2023. A key limitation to the wider adoption of dewatering strategies has been the scale at which filtration plants can operate. The benchmarking against Karara is expected to contribute towards the consideration of mechanical dewatering at similar or greater scales. For example, the plots described in this work can help to identify parameters whereby tailings separation could be used to enhance filterability.

The study underscores the necessity for continuous research. Future work should focus on refining the screening methods, considering more advanced geotechnical parameters. Future work will also include laboratory scale filtration test results to provide a more comprehensive assessment. The methods presented and described here are material characterisation considerations. Indeed, there are other technical assessments such as water balance, long-term tailings management plan, tailings volume and material handling, among others. The decision to adopt mechanical dewatering strategies is multifactorial and requires a comprehensive consideration, including other disciplines complementary to geotechnical engineering.

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