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Hydrogeological behaviour of stabilised paste and filtered tailings cover systems under extreme climate conditions

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Abstract

Tailings cover systems represent a promising strategy for mine site reclamation, particularly in areas with limited access to natural resources, as they help to control acid mine drainage (AMD) generation. However, their long-term durability can be compromised under extreme climatic conditions. Processes such as cracking and pore size redistribution often indicate internal structural changes that reduce the hydraulic performance of the cover. Cyclic events, including prolonged droughts and freezing temperatures, are among the main climatic stressors that accelerate such degradation.

The initial solid content strongly influences the structural stability and hydrogeological response of cover systems. Lower solid content increases the susceptibility to internal changes. For instance, paste tailings tend to develop wide cracks shortly after deposition due to rapid water loss by evaporation and drainage. In contrast, filtered tailings more commonly exhibit finer fissures associated with settlement, low density or inadequate compaction procedures, effects that are amplified under cyclic extreme climatic conditions.

To overcome these limitations, this study investigates slag–cement stabilised tailings as an alternative cover system. Column tests were conducted under controlled laboratory conditions to simulate extreme climatic cycles and evaluate the hydrogeological behaviour of stabilised paste and filtered tailings. Results show that the slag–cement stabilisation effectively limited structural variations after curing. Furthermore, stabilised paste tailings exhibited superior performance in maintaining a high degree of saturation, suggesting enhanced resilience to cyclic climatic stresses.

Keywords: *paste, filtered, tailings, stabilisation, cover system, freezing-thawing, wetting–drying*

1 Introduction

Sulphide minerals (e.g. pyrite and pyrrhotite) present in mine tailings oxidise when exposed to oxygen, producing acid mine drainage (AMD) and releasing heavy metals that can persist for centuries after deposition. These contaminants pose serious risks to terrestrial and aquatic ecosystems as well as local and regional surface water and groundwater flow (Environment-Canada 2009). A widely applied practice to mitigate AMD generation and metal leaching is the use of cover systems that limit oxygen ingress to acid-generating tailings. The design of such covers must be adapted to site-specific conditions, including material availability, climate, hydrogeological settings, and waste reactivity (Aubertin et al. 2016). The effectiveness of cover systems depends on the properties of the materials used to limit oxygen ingress, particularly fine-grained soils with low hydraulic conductivity.

Most cover system designs rely on natural fine-grained materials as oxygen and water barriers, due to their low saturated hydraulic conductivity (k_{sat}) and high air-entry value (AEV), which help retain porewater and thereby reduce infiltration and oxygen diffusion. However, the use of these materials is often limited by their availability near mine sites (Aubertin et al. 2016). As an alternative, the use of tailings in cover systems has

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gained increasing attention, since they are also classified as fine-grained materials and can act as effective oxygen and water barriers provided that they remain highly saturated (Bussière et al. 2004; Dublet-Adli et al. 2021; Kalonji-Kabambi et al. 2017). Tailings themselves can serve as fine-grained barriers, but their structural behaviour varies depending on the initial solids content and deposition method.

Tailings are commonly disposed of as slurry or paste with relatively low solids content (i.e. high water content), which makes them structurally weak and susceptible to internal changes, especially densification and cracking linked to the rapid loss of water (Martin 2018). These characteristics also pose significant management risk (Bruschi et al. 2025). For example, slurry and paste tailings often develop wide cracks shortly after deposition (Figure 1a) due to rapid water loss through evaporation and drainage leading to oxygen and water fluxes through preferential flow paths that reach reactive tailings.

In recent years, filtered tailings deposition has emerged as an alternative, whereby tailings are stored in dry stacks, thereby reducing the risks associated with conventional disposal methods (Masengo et al. 2023). Nevertheless, filtered tailings are not exempt from structural instabilities, as they frequently develop fissures (Figure 1b), probably caused by settlement of underlying layers, low density, or inadequate compaction.

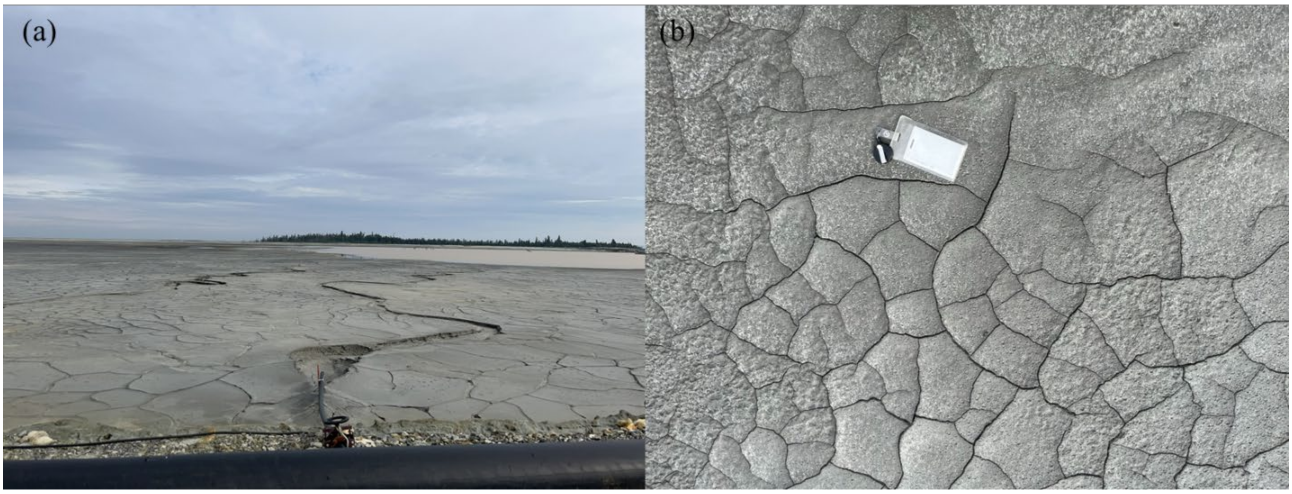


Figure 1 Desiccation cracks in (a) slurry and (b) filtered tailings

Structural instabilities in tailings cover systems are often worsened by cyclic extreme climatic conditions (e.g. prolonged droughts, and very low temperatures) which can increase oxygen fluxes beyond design targets or hinder water recharge after infiltration, ultimately compromising overall performance (Boulanger-Martel et al. 2015; Lieber et al. 2021). Wetting–drying cycles (WDC) typically induce increases in porosity, pore size redistribution, and the expansion, interconnection and propagation of microcracks (An et al. 2022; Xu et al. 2022). In contrast, during freezing–thawing cycles (FTC), porewater undergoes a phase change from liquid to solid, expanding by ~9% in volume. Upon thawing, the soil skeleton reorganises, resulting in a new pore size distribution and further volume changes (Nyameogo et al. 2020; Tian et al. 2019). Given these weaknesses, strategies to improve the durability of tailings covers are essential, and cementitious stabilisation has emerged as a promising approach.

In the first hours after deposition, tailings undergo evaporation and self-weight consolidation, which remove excess water and cause micro and macro structural variations. These instabilities are further amplified under repetitive WDC and FTC (Yilmaz et al. 2014). Stabilisation with cementitious additives has been shown to enhance durability of tailings by promoting the formation of cementitious bonds between particles. Although hydration reactions begin within minutes of mixing, the development of strong interparticle bonds typically requires more than 28 days, as the process is governed by the progressive formation of hydrates that promote solidification, increase strength and reduce porosity (Gartner et al. 2001).

Building on conventional cement stabilisation, the incorporation of slag provides further long-term improvements due to its prolonged hydration and residual reactivity, particularly over the long-term, because the hydration process can continue for up to 100 days, as long as enough capillary water is available (Berodier & Scrivener 2015; Scrivener & Nonat 2011). Moreover, due to the slow reactivity of slag, a substantial amount of unreacted particles can persist for several years, contributing to residual improvements in the material (Huang et al. 2014). For instance, stabilisation of tailings cover systems has been shown to increase long-term strength, to reduce permeability (Bruschi et al. 2025) and control the release of heavy metals through hydration-driven precipitation processes (Ahn et al. 2011).

Despite these advantages, the performance of slag–cement-stabilised tailings under cyclic extreme climatic conditions have not been fully assessed, particularly for paste and filtered tailings. The present study addresses this gap by investigating the long-term performance of slag–cement stabilised tailings covers in controlled laboratory column tests. The objective is to assess the effects of WDC and FTC on the hydrogeological behaviour of stabilised tailings.

2 Methodology

This study was conducted through a combination of laboratory column tests and complementary specimen testing to evaluate the hydrogeological behaviour of slag–cement-stabilised tailings under WDC and FTC. The methodology is divided into three main parts:

- description of the materials, including the tailings and stabilising agents
- experimental setup of column and specimen tests
- data collection and analysis procedures.

2.1 Materials

Tailings were sampled from the LaRonde mine site, located in western Québec, Canada (Figure 2). The region receives an average annual precipitation of ~885 mm, with rainfall events alternating with short dry intervals. The driest period occurs from May to July, when only about 6 days per month record precipitation greater than 5 mm. During winter, temperatures fall below 0°C, with average minima around -20°C, while the mean temperature during the rest of the year is approximately 15°C. These climatic conditions naturally generate WDC and FTC.

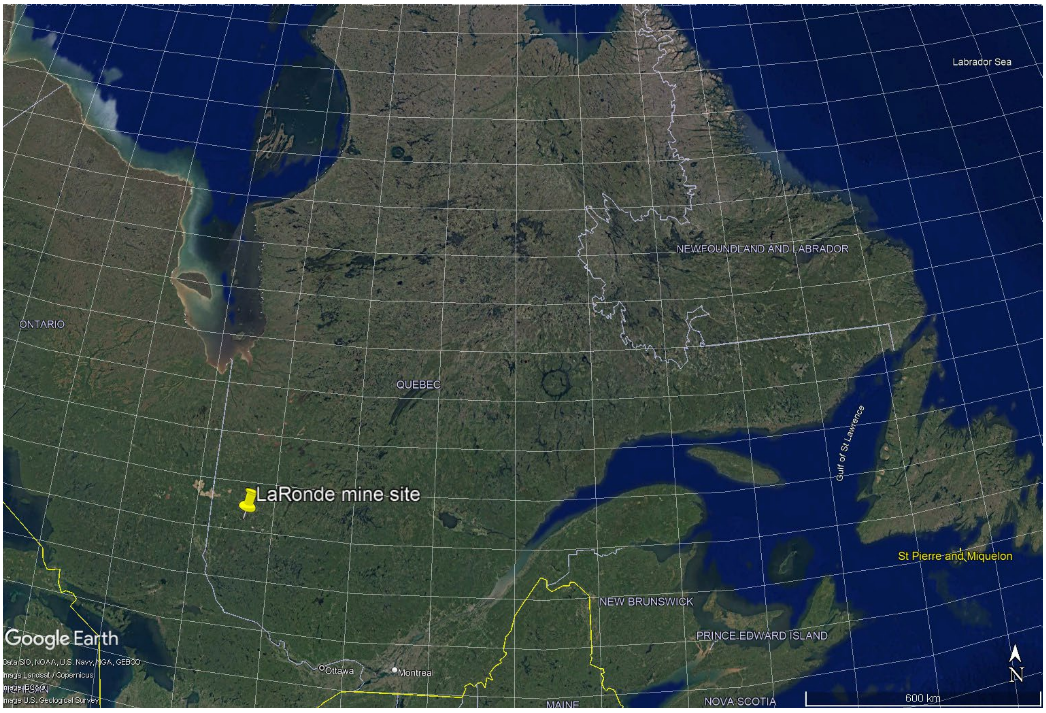


Figure 2 LaRonde mine site location

The sampled tailings originated from the processing of gold, copper, zinc and silver ores. They were collected in a fresh state directly from the concentrator after filtration and prior to disposal in the tailings storage facility. Mineralogical composition is predominantly quartz (~57%), albite (~14%), gypsum (~10%), pyrite (~8%), and muscovite (~6%). The tailings are classified as potential acid generators with a net neutralisation potential of approximately −277 kg $CaCO_3$ eq/t due to the abundance of sulphide minerals and absence of carbonates.

Physically, the material is a non-plastic-fine-grained soil with particle size characteristics of d_{10} = 20 µm and d_{60} = 53 µm, and a coefficient of uniformity (C_u) of 2.6. The specific gravity (G_s) is 3.05. Since the sampled tailings contained less water than typical paste tailings, they were rewetted in the laboratory to achieve a more fluid consistency. After homogenisation, tailings were mixed with 7% of granulated blast-furnace slag and general use (GU) cement blend, at a ratio of 80% slag and 20% GU cement.

2.2 Experimental setup

Four column tests constructed: 2 to simulate WDC and 2 to simulate FTC, using rigid PVC tubes with an internal diameter of 30 cm. The columns were filled with stabilised tailings in 5 cm lifts until a total height of 50 cm. Filtered tailings were compacted manually, achieving a compaction effort comparable to standard Proctor energy, while paste tailings were poured in small batches until reaching the target height. Each column consisted of 20 cm of non-stabilised tailings base layer and 30 cm stabilised tailings cover layer. The main properties of the stabilised material are presented in Table 1.

Table 1 Tailings cover system properties during assembling

Type	Solid content (%)	Dry density (g/cm^3)	Porosity
Filtered	83	1.54	0.49
Paste	74	1.42	0.54

The tops of the columns were left open and a fan was positioned above each column to accelerate evaporation. At the base, a ceramic plate was installed to enable the application of suction to simulate a water table depth of 5 m. Suction was applied using a vacuum line connected to a small vacuum reservoir (bottle with release valve), maintaining around 50 kPa (± 10 kPa). Volumetric water content (VWC) and suction were monitored with Teros 12 and Teros 21 sensors, installed 10 cm above and below the bottom and the top of the cover layer. Sensor readings were logged every 15 minutes. A schematic of the column setup is shown in Figure 3.

A curing period of 28 days under laboratory conditions was imposed before applying WDC or FTC:

- WDC: tap water was added at the top of the columns to increase porewater content, followed by drainage and evaporation. Each cycle lasted 7–10 days, and 10 cycles were performed on each column. After a final extended drying period, the upper 15 cm of each column was sectioned for sensor calibration. Gravimetric water content was determined by incrementally adding water and weighing the material, allowing calibration equations to be developed between VWC measurements and raw data.
- FTC: columns were placed in a freezing chamber programmed to decrease temperature at 16°C/h until reaching −20°C. This stage was followed by ~48 h at constant temperature. Thawing occurred at 2.5°C/h until reaching +20°C, where temperature was again maintained constant for ~48 h. Each FTC lasted ~5 days, and 10 cycles were applied.

In addition, small cylindrical specimens (7.5 cm diameter × 12.5 cm height) were prepared and cured in a controlled humidity chamber. These were used to determine saturated hydraulic conductivity (k_{sat}) before and after the cycles. The specimens were subjected to the same WDC and FTC as the large columns. k_{sat} was measured following ASTM D5084 (ASTM International 2023) using a flexible wall permeameter in a triaxial chamber.

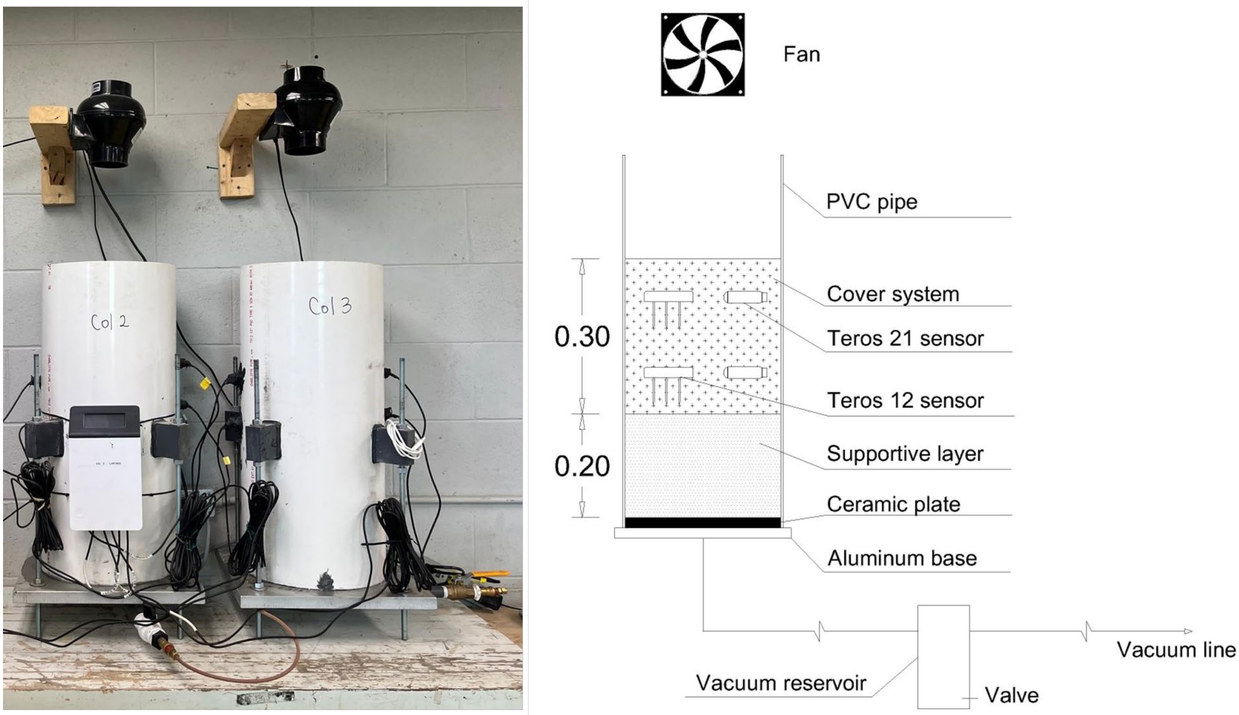


Figure 3 Column test setup

2.3 Data collection and analysis

Raw VWC data were converted to volumetric units (m^3/m^3) using the calibration equation derived for each material. Small gaps were interpolated using linear methods. Data were organised by sensor position (top or bottom) and smoothed with a rolling mean filter to reduce high-frequency noise.

Suction values below 0.1 kPa, outside the operational range of the Teros 21 sensor, were excluded to avoid skewing the data. Datasets were visually inspected for consistency and segmented into cycles based on temporal trends, following the procedure described by Rosales et al. (2025). The cycle-based classification enabled to conduct a more robust statistical analysis and facilitated the identification of underlying trends.

The processed datasets and laboratory measurements were then analysed to evaluate changes in the hydrogeological behaviour, including VWC and suction. These results are presented and discussed in the following section, with emphasis on the effects of WDC and FTC conditions on the long-term performance of stabilised tailings.

3 Results and discussion

After consolidation, stabilised paste tailings achieved higher density and lower porosity, which remained relatively stable throughout the tests, similar to the behaviour observed for stabilised filtered tailings (Table 2). Salt precipitation at the surface was evident in both materials subjected to WDC and FTC, a phenomenon commonly reported in pyrite-rich tailings (Sapkota et al. 2023). This precipitation was likely enhanced by the elevated evaporation rates under laboratory conditions (Simms et al. 2007) and during thawing phases in the freezing chamber. As a result, a crust formed at the surface of the tailings due to salt accumulation. This crust influenced drying pathways and their spatial uniformity across the surface, while also affecting evaporation dynamics and the underlying water content (Simms et al. 2007, 2019). It has been found that a thin salt crust has a great evaporation resistance, even in wet soils, due to its dense structure. Salt precipitation can also decrease the tailings temperature due to an increased albedo (Li et al. 2022; Li & Shi 2021).

Table 2 Basic properties of stabilised tailings cover system after testing

Type	Solid content (%)	Dry density (g/cm^3)	Porosity
Filtered	82	1.54	0.49
Paste	84	1.59	0.49

Before the onset of WDC, following the initial settlement, a major radial crack was observed on the surface of paste tailings, along with minor cracks along the column borders. These features were attributed to rapid water loss through evaporation and percolation. Such behaviour is more common in paste tailings which generally exhibit a looser internal structure than filtered tailings (Ichrak et al. 2016; Qin et al. 2021; Simms et al. 2019). No cracks were observed in filtered tailings at the beginning of the test (Figure 4), which contrasts the cracking behaviour of non-stabilised fine-grained soils, which tend to develop higher crack indices after compaction that can worsen over time (Yesiller et al. 2000).

By the end of the WDC, surface cracks in paste tailings had not significantly widened or deepened, suggesting that stabilisation limited crack propagation after the initial curing period. Similarly, both paste and filtered tailings subjected to FTC exhibited only minor shrinkage at the column borders, with little change over the course of the cycles. The stabilising efficiency after curing has also been reported by Xu et al. (2020), who found that longer curing times more effectively controlled crack development, expansion and propagation. However, the scale of the column tests relative to field conditions may limit the development of representative cracking patterns, highlighting the need for caution when extrapolating these results to field applications (Wang et al. 2025).

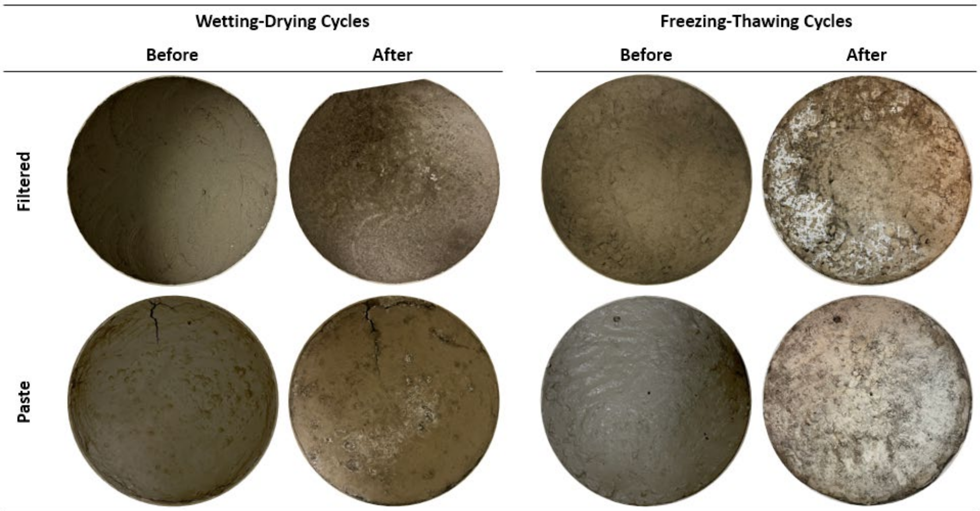


Figure 4 Surface condition of filtered and paste tailings before and after wetting–drying and freezing–thawing cycles

Before exposure to WDC or FTC, the specimens exhibited similar k_{sat} values (Table 3). However, after the cycles, the paste tailings showed k_{sat} values approximately one order of magnitude lower than those of filtered tailings, whose k_{sat} remained close to the initial values. Previous studies have shown that k_{sat} in tailings decrease during the first curing days and then stabilise (Yilmaz et al. 2015), a trend consistent with the filtered tailings in this study.

The k_{sat} reduction observed in both materials can also be attributed to the higher and sustained water content throughout the cycles (Figure 5), which favours long-term hydration reactions, particularly in paste tailings. These conditions promote the formation of additional hydration products and precipitation of secondary minerals, leading to a denser cemented matrix with partially clogged pores that reduce k_{sat} (Faraji & Fall 2024; Godbout et al. 2007). Moreover, it has been reported that the ice formation generates a high surface pressure on the particles, causing their breakage and the creation of finer particles, which can migrate and clog the pore throats, thereby decreasing k_{sat} (Xu et al. 2020).

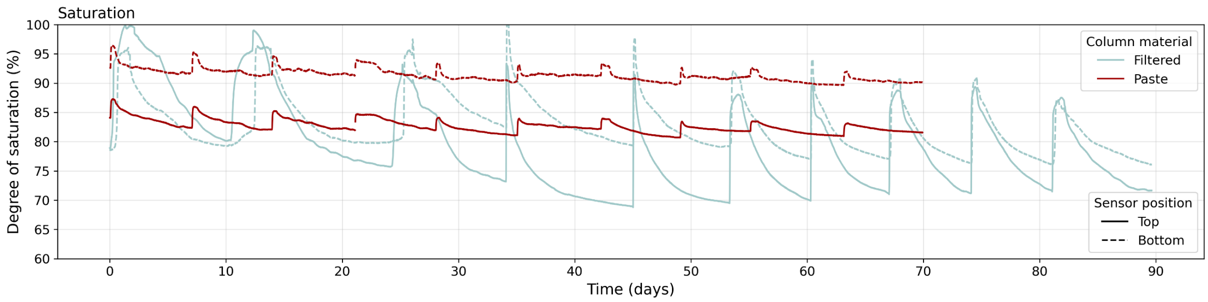
Table 3 Saturated hydraulic conductivity before and after wetting–drying cycles (WDC) and freezing–thawing cycles (FTC)

Type	Porosity	k_{sat} initial (m/s)	k_{sat} WDC (m/s)	k_{sat} FTC (m/s)
Filtered	0.49	4.0×10^{-7}	4.8×10^{-7}	7.8×10^{-7}
Paste	0.49*	3.9×10^{-7}	5.2×10^{-8}	6.0×10^{-8}

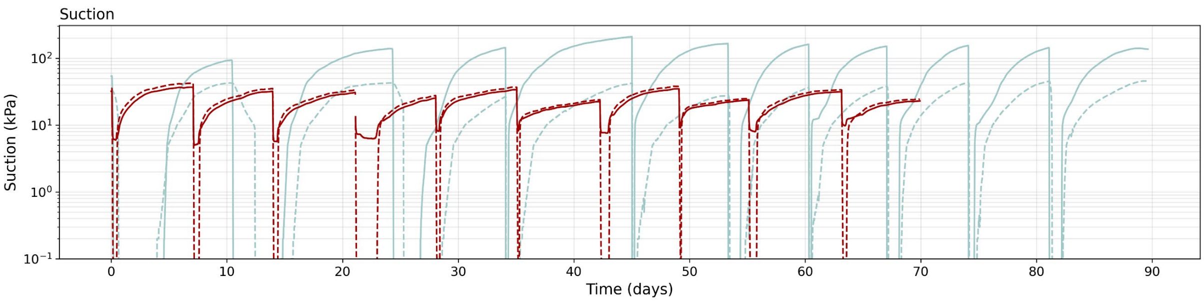
* Calculated after consolidation

The analysis of the sensor-based data from the column tests (Figure 5) allowed the identification in each cycle of a sharp increase in saturation (decrease in suction) which indicates a wetting phase followed by a gradual decrease in saturation (increase in suction) that indicates a drying phase. Drying curves showed a rapid initial drainage followed by a slower decrease. The top sensors in filtered tailings (Figure 5) showed stronger saturation oscillations (~70–100%), indicating they are more exposed to evaporation and infiltration, while the bottom sensors remain more stable (~80–95%), acting as a buffered zone with smaller fluctuations. At the same time, the top shows much higher suction values (>100 kPa), consistent with stronger drying stresses near the exposed surface, while the bottom remained below that of about 30 kPa, showing that the water retention and capillarity dampen the fluctuations at depth. Over successive cycles, saturation at the bottom shows a slight downward trend, while the top continues oscillating strongly.

The results demonstrated that stabilised filtered tailings maintained relative lower degrees of saturation under repeated WDC, which fall below the recommended good performance threshold of 85% (Aubertin et al. 2016). The top layers were vulnerable to strong fluctuations, leading to high suction stresses and potential desaturation.



(a)



(b)

Figure 5 For filtered and paste tailings: (a) Degree of saturation; (b) Suction timeseries

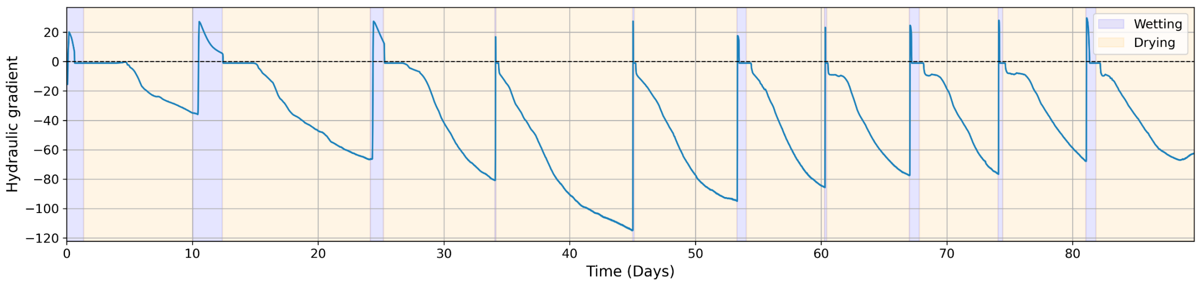
The results for stabilised paste tailings show that the top of the column remains consistently less saturated than the bottom. Saturation at the top starts around 83–86% at the beginning of each cycle, then gradually decreasing, while the bottom remains around 91–95%, with smaller drops. This behaviour indicates that during recharge, water redistributes from top to bottom with the bottom acting as a water storage zone that maintains a high saturation before drainage occurs. During drying, suction increases progressively, reaching values of about 30–40 kPa which is less than the applied suction at the bottom of the column (50 kPa). This response can be attributed to the low permeability and limited pore connectivity of paste tailings (Li et al. 2019), which delay the rapid transmission and redistribution of the suction through the sample.

When comparing stabilised filtered and paste tailings, clear differences in hydraulic response were observed. Paste tailings had a stronger ability to retain water and a buffering effect in which the bottom of the column acted as a storage zone. In contrast, filtered tailings results exhibit larger oscillations in saturation can be attributed to their higher permeability and lower water-holding capacity.

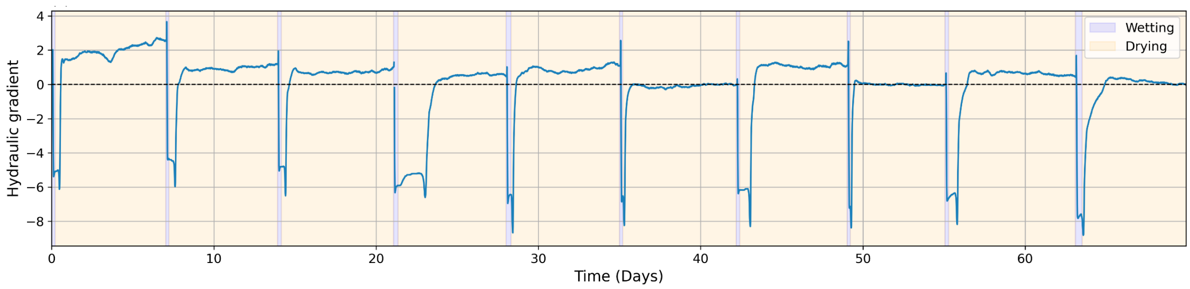
Additional insights emerge from the hydraulic gradient measured between the top and bottom sensors across the cycles (Figure 6). In the filtered tailings, the gradient fluctuated widely, from about +10 down to −120. This indicates a much stronger driving force, with water drawn upward during drying (negative gradient) toward the evaporating surface, before the gradient returns toward zero or positive during wetting. After the fourth WDC, the gradient became less negative and progressively stabilised, likely reflecting partial clogging or a pore size redistribution toward finer pores.

In contrast, paste tailings showed smaller gradients, mostly between +2 and −8. Their finer pore structure promoted greater water retention, so suction gradients were less steep, and water redistribution is slower. Consequently, flow is more buffered against evaporation, implying better resistance to drying stresses. Gradients in the paste tailings tend to stabilise after the fifth cycle in both wetting and drying phases; during drying, the system approaches a near-equilibrium (quasi-steady) state.

These gradient magnitudes were consistent with the imposed high suction and enhanced evaporation in both materials. From a cover system design perspective, however, large negative gradients lead to strong upward driving forces that can release moisture to the atmosphere and reduce long-term performance (Pabst et al. 2018). Nevertheless, despite the fact that this behaviour can cause water fluxes towards the upper part of the cover, the very low hydraulic conductivity should control these water movements.



(a)



(b)

Figure 6 Hydraulic gradient for (a) filtered and (b) paste tailings

4 Conclusion

After consolidation, stabilised paste tailings reached a higher dry density due to the rapid loss of water during the first hours of curing. However, the absence of strong interparticle bonds made them more susceptible to the development of desiccation cracks, which tended to be wider and deeper. Once a drier state was achieved, the paste tailings adopted a more stable condition, similar to filtered tailings, which showed only minor variations throughout the cycles as a result of the slag–cement stabilisation.

Salt precipitation and the formation of surface crusts could probably influence the evaporation process and the spatial distribution of water loss by creating a thin, dense layer that limited water loss. This phenomenon should be further investigated to better quantify its impact on the hydrogeological response of the cover.

Overall, stabilised paste tailings offered superior performance in maintaining higher degrees of saturation, with the bottom portion of the cover acting as buffering zone that helped regulate water redistribution. Although paste and filtered tailings share similar physical characteristics, the high density and packing of the stabilised paste tailings resulted in lower k_{sat} and higher AEV values that restricted water losses by drainage and evaporation. In contrast, the filtered tailings were more prone to desaturation, particularly near the surface.

The results show that stabilisation of paste tailings could offer a better performance compared to filtered tailings in limiting water and oxygen fluxes when exposed to WDC due to the k_{sat} and the sustained high degree of saturation in the cover. However, more characterisation is needed to understand how FTC could affect the overall performance of the stabilised cover systems.

While the column tests provided valuable insights into the microstructural behaviour of slag-cemented tailings cover systems, the laboratory scale of the experiments may have underestimated the extent of cracking and the full capacity of stabilisation in mitigation macrostructural variations under field conditions.

Acknowledgement

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