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Why accelerated mechanical consolidation delivers equal or greater benefits to other tailings management solutions

O Santiago *Phibion, Australia*

R Menezes *Phibion, Chile*

W McAdam *Phibion, Australia*

D Smirk *Phibion, Australia*

Abstract

The International Council on Mining and Metals (ICMM) and members have created a roadmap that outlines significant improvements in the reduction and improvement of tailings management. Key aspects of tailings management under the ICMM improvement plan are to:

- *Achieve safer management of tailings facilities*
- *Remove moisture from and strengthen tailings*
- *Reduce or eliminate the generation of tailings waste.*

All these improvement initiatives and additional benefits can be achieved by the implementation of in situ tailings management methodology termed accelerated mechanical consolidation (AMC™) on new and existing facilities.

Australia-based company, Phibion, has been successfully deploying and implementing in situ mechanical dewatering (AMC) with a customised advanced Archimedes screw tractor, MudMaster®, which works over-saturated material to overcome hindered settling and consolidation, expediting the transition from slurry to solid. The process is primarily delivered through enhancing the particle packing density through repeated passes of the MudMaster (mechanical aid) to influence drainage and consolidation. The physical properties of the tailings and when combined with sequenced tailings deposition and ploughing of a predetermined layer thickness accelerates the dewatering rate and increases the final density that can be achieved which is not significantly impacted by rainfall nor dependent on evaporation. When executed with purpose-built machines, consolidation is delivered orders of magnitude faster than self-weight processes and is highly predictable. In situ mechanical dewatering operations, utilising mechanical aid, are currently the preferred and best available technology used by a range of mining/processing operations including commodities such as copper, rare earth metals, nickel, zinc, bauxite and alumina among others.

This paper provides a deep understanding on how in situ mechanical dewatering has provided equal or greater benefits and added value when compared with other tailings management solutions (i.e. thickening, filter press and dry stacking) to a zinc refinery and smelter tailings in Brazil. In situ mechanical dewatering applied with a specialised tractor has demonstrated a methodology for this operation to prolong the life of the refinery complex by extending the tailings storage facility's (TSF) storage capacity, improving tailings dewatering, reducing water accumulation, aligning customer with ICMM objectives for tailings management and allowing for earlier than expected TSF closure, thus reducing liabilities and uncertainties in the process.

Keywords: *in situ mechanical dewatering, accelerated mechanical consolidation, zinc, tailings management solution*

1 Introduction

International Council on Mining and Metals (ICMM) signatories are working on the advancement of safe and responsible management of tailings dams (ICMM 2022, 2021a). To fulfill this purpose, global standards, compliance protocols, good practice guides and a roadmap for the implementation of safe and responsible management have been developed. By 2023, signatories to the ICMM aimed to strengthen operational performance for the design, operation and closure of tailings facilities. Among the ambitious goals is the need to remove moisture and increase tailings strength through the implementation of cost-effective scale-up technologies which can process tailings by 2028. Finally, the goal for 2033 is to reduce or eliminate the generation of tailings which contemplates the use of alternative methods that recover mineral or metals without generating mining waste (ICMM 2021b, 2021c).

Technologies and methods for tailings dewatering are increasing not only with the singular goal of reclaiming water trapped in tailings, but also to enable safe and responsible tailings dam management that can reduce moisture, increase strength and prepare tailings dams for closure (McPhail et al. 2019; Chaedir et al. 2021). These technologies challenge the standard used in the industry and the methodology of how tailings have been managed to date. However, most technological advancements are deterministic and present issues including implementation, capital and operational costs, adaptation, scaling in high production rates, and no impact on legacy of existing tailings impoundments (McPhail et al. 2019; Chaedir et al. 2021; Cacciuttolo Vargas & Marinovic Pulido 2022).

One of the emerging technologies which has been tested, implemented and scaled, and significantly improves tailings management issues in new and existing dams, is in situ mechanical dewatering (AMC™) methodology using an advanced and customised tractor equipped with Archimedean screws (Smirk et al. 2022; Munro & Smirk 2018, 2012). The use of mechanical aid (MudMaster®) combined with a detailed work methodology and controlled sequential deposition of tailings ensures that the saturated material can be dewatered at a higher rate and significantly increase the tailings' surface density much higher than traditional extraction practices in dams. Both in situ dewatering and mechanical aid have been selected several times as one of the best practices for tailings management by the International Alumina Institute (IAI 2014, 2016, 2022; Smirk & Jackson 2010). This methodology and technology is currently used for a variety of tailings deposits including minerals such as copper, rare earth metals, nickel, zinc, bauxite and alumina among others.

2 Site description and problem definition

The zinc mines, refinery and smelter are operated by one of the largest producers in the world. The tailings storage facility is northwest of Sao Paulo, Brazil. The climate is tropical semi-humid with an average annual temperature of 16.5°C and rainfall of 1,442 mm. The smelter produces about 163 kt of metallic zinc and 40 kt of zinc oxide, generating around 520,000 dry tonnes of tailings per year. Tailings are disposed in two facilities; one of them (TSF B) already at capacity with an area of 27 hectares, while the other facility (TSF A) has less than two operational years of life with a total area of 21 hectares but is filling quicker than expected. Both facilities are fully lined with high-density polyethylene (HDPE) liner acting as an environmental control to mitigate potential seepage to local groundwaters (Figure 1).

The mine operator has been under pressure since permitting for construction of a wall raise or new facility and construction work was forecasted to go beyond the expected time to exhaust the capacity of TSF A, leading to a potential early closure of the zinc complex. The operator reviewed a range of options to prolong the life of the complex with technologies such as tailings thickeners and filtration; however, these solutions were consider unviable as they required permitting/approvals of areas designated to stacking filtrated material in addition to high capital/operational cost. Despite all operational efforts to improve natural consolidation, TSF filling rates indicated that the refinery would be required to stop in less than two years with no alternative or backup tailings storage available in time. Often measures taken by trained practitioners are directed to improve filling rate which might not directly address the root cause of the problem. Often these initiatives have significant costs and engineering associated while only returning marginal benefits.

While TSF A required a strategic solution to increase available storage, TSF B was in need of a cost-effective closure alternative. Both initiatives are equally important to progress and extend the life of the zinc complex.

(a) (b)

Figure 1 (a) TSF B at capacity; (b) TSF A operational

The most common practices in tailings management, which were utilised at this site, included self-weighted consolidation, natural drainage, and evaporation of water (solar drying) from the wet surface of the material. These practices can be impacted by external and intrinsic factors of the material reducing their effectiveness, such as:

- Excessive deposition depth inhibiting natural consolidation and drying process
- Low to non-existing beach angle
- Physicochemical properties that interfere with drainage and evaporation of water such as rapid generation of surface crust
- Poor ability to recover water, large and unfavourable location of decant pond, and defective deposition system.

Although all the above variables could be controlled by adjustments in operation, the natural consolidation process presents a deficiency that makes the handling and management of tailings conditional on an unpredictable process, incredibly slow and a large area of operation compared to some established technologies for tailings dewatering. In most cases, the only way to improve tailings management and handling to maximise effectiveness of the operation and meet dam design objectives is to increase the rate of consolidation, which is largely influenced by tailings characteristics (Williams 2014; Cacciuttolo et al. 2014). These factors have a direct impact on the storage density and ultimately on the capacity to store additional material. Furthermore, alternative technologies that improve the pre-deposition density often do not increase the in situ density of existing facilities regardless of the material intrinsic consolidation rate.

3 Tailings characterisation and AMC methodology

The site-specific tailings have a specific gravity averaging 2.78 (1.00 g/cm^3 water), discharged into the facility at approximately 1.15 t/m^3 (bulk density) or 20% solids (w/w). Particle size distribution indicates the material is made up of largely silt (80%), equal clay and sand (<10% each) like particles with a D60 = 14.5 µm. The United States Department of Agriculture (USDA) soil classification categorises this material as silt to silt loam. This indicates that material has a moderate draining ability and a potential to increase in situ density with consolidation. It was estimated, given the deposition intensity and filling rates, that the overall storage dry density was about 0.47 t/m^3 (dry) or 36% solids (w/w) which required a storage capacity of 1,100,000 m^3/year (Figure 2). Any reduction in the in situ stored density would require additional capacity extending the life of the facility and zinc complex.

(a) (b)

Figure 2 (a) Active discharge of tailings into TSF A; (b) MudMaster conducting AMC recovery work on TSF A

To increase the rate of consolidation of tailings, a load must be applied to the surface so that water interstitially trapped in the material matrix is released and removed. In principle, this is the theory used for self-weighted consolidation; however, the load is relatively low and, in some cases, ineffective, causing the tailings to dry out and develop a crust that retains large amounts of water trapped between deposition layers that is difficult to extract with conventional methods. Low consolidation rates in TSFs can generate the need to prematurely increase the height of the facility or create the need to build new dams to sustain the mining operation with significant financial consequences for operating companies. Under the scenario in which there is excess water contained in tailings, this can have major implications which could affect the stability of dam walls, increasing the potential for tailings liquefaction, low tailings resistance, infiltrations, high watertable etc.

To solve these operational problems experienced in this zinc complex, Phibion implemented the in situ mechanical dewatering methodology using a tractor as a robust and effective alternative process for the management and integrated handling of tailings that enables the dewatering and consolidation of deposited tailings. The in situ dewatering process has two operational stages – recovery and production. Recovery operation of the tailings surface seeks to consolidate an initial layer serving as a substrate or base for subsequent tailings depositions. This initial layer provides benefits such as greater traction for the machine, increasing operational speed and area coverage by the equipment, providing favourable conditions for the next stage and successive discharges of material. The production stage is where the equipment and tailings operation work together to maximise consolidation and dewatering in shorter periods of time, which results in sustained and predictable operation improving tailings' density and strength while simultaneously recovering water.

The in situ mechanical dewatering process makes use of a fleet of machines that travel a certain number of times in a straight line from the discharge points to the decant pond or water collection point following a detailed work plan established by the type and behaviour of the tailings under consolidation, pond geometry and beach angles. The work plan must guarantee the achievement of maximum density and drainage of the tailings. The dewatering process and progress is measured against in-field undrained shear stress data obtained from vane shear instruments and laboratory derived density of undisturbed tailings. Aerial topography is also used to track the volumetric change obtained by consolidation.

4 Outcomes from successful in situ mechanical dewatering implementation

To optimise and accelerate the natural rate of dewatering and consolidation, in situ mechanical dewatering was used to apply a cyclic and concentrated load over the tailings surface, which increases surface pore pressure, producing a rapid dewatering effect and accelerating the dewatering process. In addition to dewatering, the mechanical aid (tractor) provides compaction of the material enabling effective packing of the material which progressively increases material density, thus indirectly improving material strength (South32 2023; McPhail et al. 2021). Both dewatering and density or strength properties have a direct effect on volume reduction due to consolidation and compaction. Monitoring consisted of fortnightly aerial survey to determine volumetric changes within the perimeter of the facility, and comprehensive in situ testing of undrained shear strength at two depths (0.2 and 0.5 m) across the extent of the in situ dewatering operations.

4.1 Recovering TSF storage capacity through consolidation and compaction

The in situ mechanical dewatering was applied to both TSFs A and B under two different purposes; although storage capacity was improved for both facilities. The mechanical dewatering plan for TSF A consisted of recovering storage capacity in the shortest time frame to guarantee continuity to the zinc operation complex and to demonstrate extension of the life of the asset by consistently delivering tailings at a higher density and in turn increasing the life expectancy of the TSF. The total storage capacity recovered during four months of continuous mechanical dewatering was 125,202 m^3 (Figure 3) which is equivalent to 5,962 m^3/Ha. Storage recovery was achieved with an average tailings undrained shear strength over 40 kPa at 0.5 m deep, which could sustain low-ground pressure equipment and substantially improve traction of the MudMaster in subsequent consolidation of fresh layers.

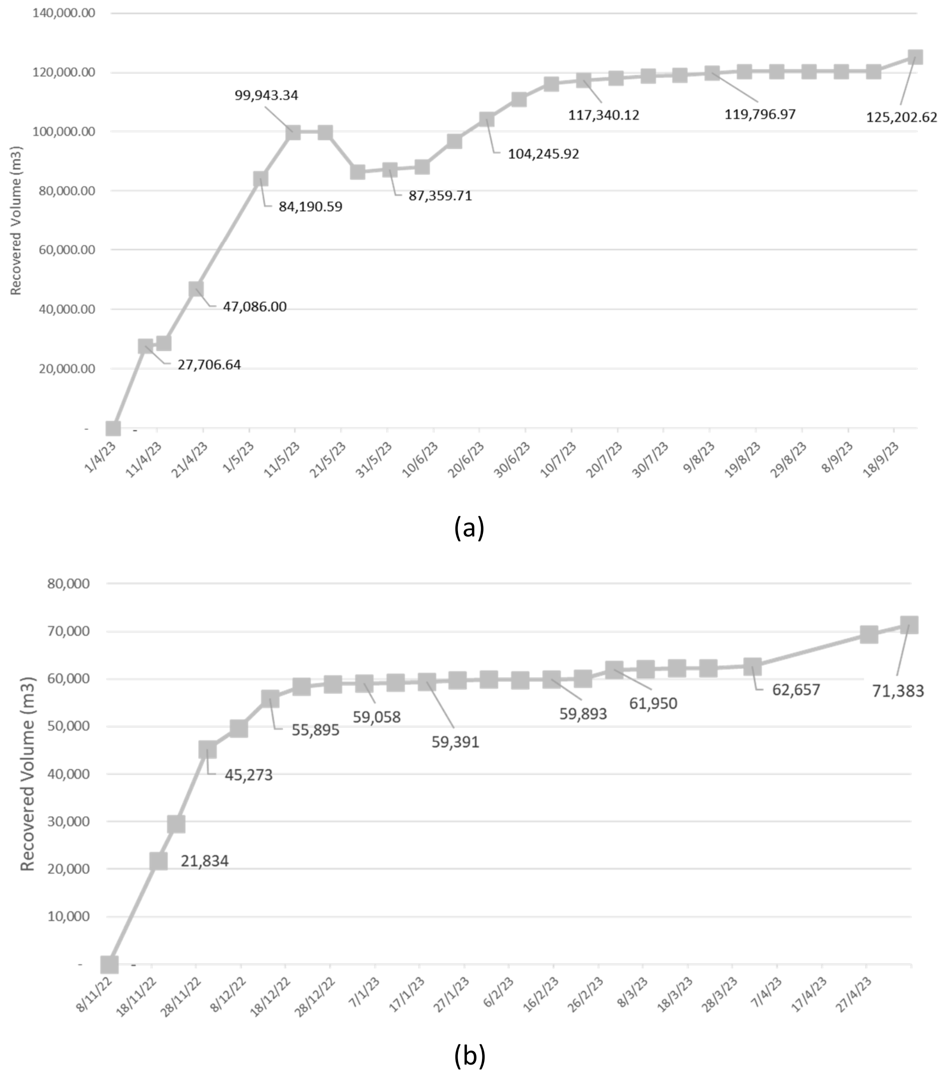


Figure 3 Recovered storage capacity measured as cumulative volumetric change for (a) TSF A and (b) TSF B. Note TSF A presented a change in the trend between 21/5/2023 and 10/6/2023 due to emergency deposition of fresh material, also demostrating the versatility of the AMC process in active facilities

On TSF B, in situ mechanical dewatering was applied over a period of four months in order to achieve maximum surface strength so closure works could be brought forward. Nonetheless, both tractor and dewatering methodology with a detailed plan created an additional storage of 71,383 m^3 which is equivalent to 2,643 m^3/Ha. This additional volume at TSF B was generated with tailings developing a minimum shear strength of >50 and >70 kPa at 0.5 and 0.2 m depth respectively. This volume reduction was achieved despite the last deposition cycle at TSF B occurring seven years prior to commencing works.

The combined results from TSF A and B over nine months of in situ dewatering recovered a total storage capacity of 196,585 m^3 or equivalent to 4,095 m^3/Ha of TSF. The estimated annual recovered storage capacity is over 235,902 m^3 which suggests that tailings can be stored at 65% solids or 1.1 t/m^3 dry density. This means that the actual tailings storage requirements for a year decreased from 1,100,000 to 470,000 m^3 which represents a 57% reduction in storage year-to-year with the potential to consolidate further the existing tailings in inferior layers. This represents a significant improvement in stored density that can extend the life of the zinc complex and TSF for at least another 3.5 years without the need for raising the TSF or developing a new facility and extends the approval period required for these works.

4.2 Improving tailings surface strength with in situ mechanical dewatering

Tailings surface strength is a critical path towards closure and generation of stable stored tailings in dams during continuous operation. In situ mechanical dewatering campaigns at TSFs A and B demonstrated superior results when compared with years of natural consolidation on TSF B, and even more satisfactory results on fresh tailings on TSF A. The dewatering cycle under normal continuous operation is considered complete when shear strength is >35 kPa since it could sustain low-ground pressure equipment. Closure works require that mechanical dewatering deliver higher shear strength (>50 kPa) to enable traffic of conventional civil machinery required for closure works.

In situ strength testing results follow a direct relationship with application of in situ mechanical dewatering increasing incrementally from an initial strength of 0 to over 50 kPa for TSF A. Figures 4 and 5 show the results obtained from different testing campaigns in TSF A which are represented as points for specific locations and heat maps which represent general strength found from site survey. As expected, material strengthening during the first tractor passes do not have major improvement since material is rapidly draining excess water that later will aid in developing strength. After excess trapped water is removed, strengthening starts in the vicinity of the spigots since those locations present higher dewatering rates due to the beach angle formed around the deposition points. In addition, further application of in situ mechanical dewatering homogenises the strength around the spigots and overall surface until it reaches the desired strength (Figure 6).

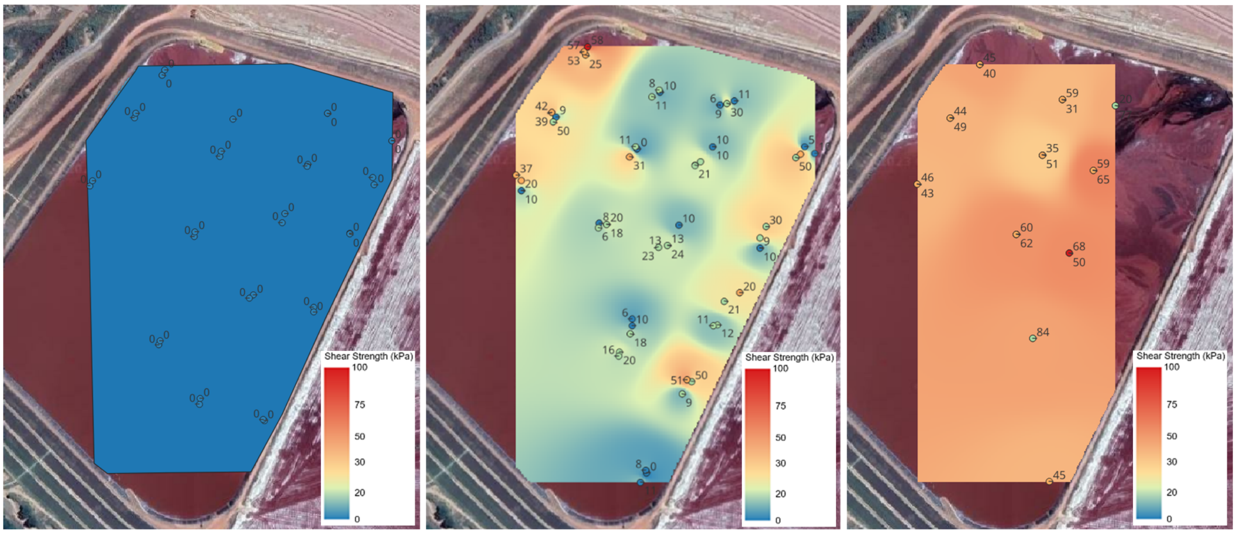


Figure 4 TSF A shear strength at 0.5 m deep. (a) First survey completed early May 2023; (b) Testing completed over July 2023; (c) Testing during September 2023. Note gradual improvement of shear strength characteristic of a recovery type operation where material and the whole facility surface undergoes AMC. Final strength after recovery corresponds to the foundation of subsequent fresh layers that require consolidation.

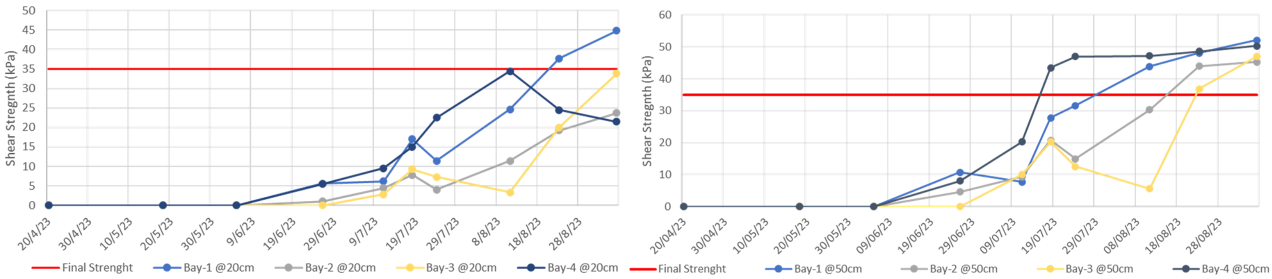


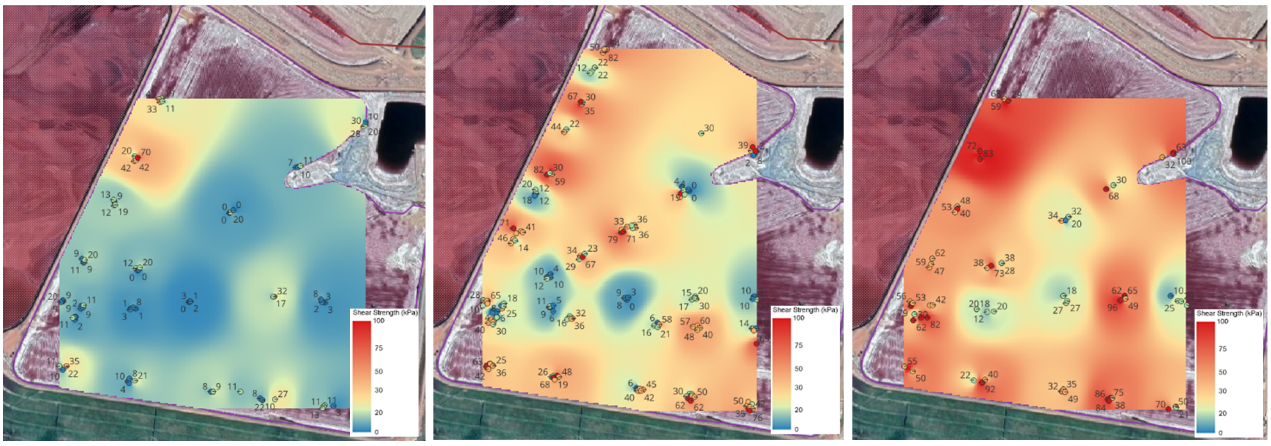
Figure 5 Average shear strength (kPa) per operating AMC bay and cycle on TSF A. (a) Results obtained at 0.2 m deep between May and August 2023 and (b) 0.5 m deep between May and August 2023. Note all the average results for TSF A bays at 0.5 m are above 40 kPa. First 0.2 m is still experiencing dewatering after August 2023 skewing average values. MudMaster delays the formation of surface crust

TSF B required a minimum surface strength to sustain closure works of >50 kPa. To achieve that outcome, the dewatering work plan consisted of several steps. The first phase consisted of shifting the decanting basin from the external wall to an internal wall by producing differential consolidation which created preferential surface flow towards the selected location. Secondly, the dewatering phase consisted of removing excess water towards the new decant basin and pumping infrastructure. The last stage of the work plan focused on progressively gaining surface undrained shear strength in preparation for civil equipment (Figure 7).

(a) (b)

(c) (d)

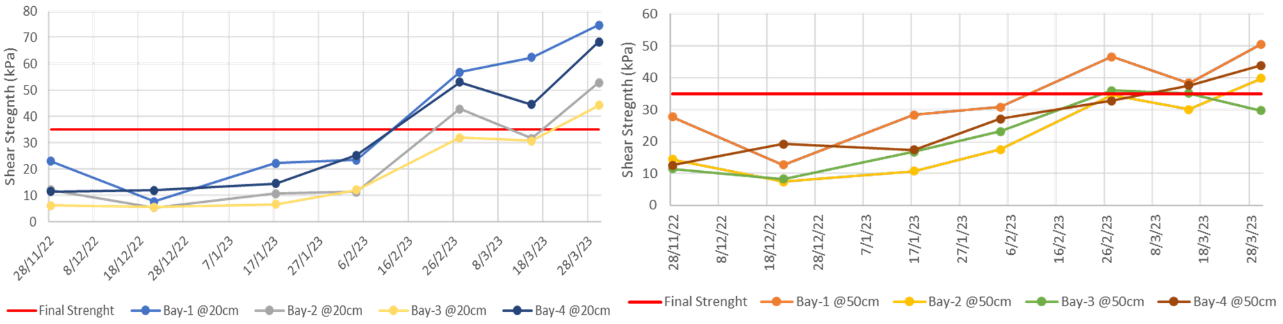
Figure 6 TSF A material strength improvement through AMC cycle. (a) MudMaster working tailings surface providing dewatering; (b) In situ inspection and testing on foot after shear strength is found to be over 40 kPa.; (c) and (d) Pictures during September 2023 with material strength >50 kPa



(a) (b) (c)

Figure 7 TSF B shear strength at 0.2 m deep. (a) First survey completed early January 2023; (b) Testing completed over February 2023; (c) Testing during March 2023. Note gradual improvement of shear strength to >50 kPa and spots with low strength areas in March 2023 where decanting pond was previously located

TSF B received the last deposition cycle of fresh tailings seven years prior to in situ mechanical dewatering, hence some areas presented a crust and ‘consolidated’ state. This is shown in the first survey completed at the end of November 2022 (Figure 8). However, most of the area exhibited a strength <10 kPa, which could not enable conventional civil equipment to traffic surface. After the first few weeks of work, the MudMaster broke through the crust allowing dewatering of underlying layers, provisionally reducing material strength. After dewatering, tailings material started to gain strength consistently reaching >40 kPa after the third month of operation. Achieving >50 kPa across the whole surface for the first 0.2 m required the MudMaster to concentrate on areas with poor drainage due to relocation of the decant pond. At the end of March 2023, shear strength was >50 kPa with large areas achieving >80 kPa. Figure 9 shows TSF B prior to and after mechanical dewatering, and the progressive closure development.



(a) (b)

Figure 8 Average shear strength (kPa) per operating AMC bay and cycle on TSF B. Results obtained at both depths (a) 0.2 m and (b) 0.5 m show, in first instance, surpeficial crust with low strengths that progressively increases to reach >50 kPa across the whole surface of the facility

(a) (b)

Figure 9 Aerial imagery of TSF B taken (a) December 2022 and (b) June 2023. Note image from June 2023 with active closure execution project

5 Discussion

Tailings management and governance has increased with the introduction of additional tools and improved industry practice to raise the standard and performance of storage facilities. Nonetheless, adaptive management of tailings throughout the whole facility lifecycle will remain an essential part of the mining industry despite improved technologies, new innovations and other ore mining improvements. Hence the need for a sustainable, long-term and cost-effective manner to dewater, safely store and minimise tailings will remain. Currently, tailings practitioners preferentially suggest technologies to dewater tailings such as thickening, filtration and dry stacking which require a substantial investment, ongoing operational costs that might be cost prohibitive to some mining operations, and often have scaling issues due to technical operational limits. While these technologies might be seen as a solution to 'solve' the issues facing tailings storage facilities, they do not independently improve management of mining waste and, more importantly, do not tackle legacy or existing facilities. Additionally, disposal areas required for 'dry' stockpiling typically involves additional land clearing and associated permitting, which also need a degree of management and capital cost often ignored in the evaluation of technology and realised during implementation.

There is sufficient justification to improve and enable continuous operation of mining operations with a cost-effective tailings management solution such as AMC. Phibion has implemented AMC providing mine operators with a flexible and practical methodology to safely store tailings in dams or storage facilities, making them smaller and improving life of asset. Implementation of in situ mechanical dewatering into a new or existing facility is rapid with minimum to no changes to infrastructure but requires full integration with operational processes of the facility. This means that mine operators are not required to commit to costly infrastructure or processing hardware since mechanical dewatering is applied to existing facilities that will be used at their maximum capacity which, in return, brings cost savings and, in the long-term, utilises the TSF's life as expected or even extend it. All of this enables mine operators to have safe storage, stable material, reduced operational risk and support closure of facilities.

Results shown in Section 4 demonstrate some of the benefits that in situ mechanical dewatering brings to tailings operations restoring and improving storage capacity of the dam while making the tailings safe by providing consistent material strength. In situ mechanical dewatering has demonstrated a number of times to be the preferred technology by mine operators to avoid large capital and operational costs often related with implementation of other tailings management options while delivering outstanding results on existing and new facilities (South32 2023). Besides, results clearly provide an effective alternative for reducing stored tailings volume, existing and future, and increasing surface strength and density that enables a sustainable operation and subsequent closure of the TSF, which supports a safe and responsible management of tailings consistent with the purposes of ICMM and its members.

6 Conclusion

Application of the AMC on zinc tailings have been shown to improve density of stored tailings, thus improving the capacity of the dam by 4,095 m^3/Ha on average after the first cycle – a trend that is likely to continue after subsequent deposition and dewatering cycles. Surface density improved across the surface of the dam validating that material can be stored at >65% solids by weight, which represents an extension of the life of the dam from material being stored at <36% solids by weight. Gain in density from old tailings and efficient storage from fresh layers of material doubled the operational capacity of the facility without extensive capital investment.

In situ mechanical dewatering provides an alternative for closure fast tracking consolidation and compaction of the tailings surface providing a consistent and competent material strength for safe operation of civil equipment and other ancillary works required for closure. It was shown that shear strength is developed in large areas using MudMaster in a relatively short amount of time when compared with natural consolidation. Undrained shear strength for tailings treated with in situ mechanical dewatering could well develop over 80 kPa which can sustain a range of heavy machinery for safe operation.

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