NORTHERN PLAINS
RESOURCE COUNCIL

July 18, 2022

Robert Grosvenor
Gardiner Ranger District
PO Box 5
Gardiner, MT, 59030

Craig Jones
Montana Department of Environmental Quality
PO Box 200901
Helena, MT 59620-0901

RE: Public Scoping Comments on the EIS for Stillwater Mining Company's Tailings and Waste Rock Expansion Proposed as East Boulder Mine Amendment 004.

Dear Mr. Grosvenor and Mr. Jones:

Cottonwood Resource Council, Stillwater Protective Association and Northern Plains Resource Council (the Councils) appreciate the opportunity to provide scoping comments related to the Environmental Impact Statement (EIS) for Sibanye-Stillwater Mining Company's (SMC) proposed Major Amendment 004 at East Boulder Mine for the construction and operation of the Lewis Gulch Tailings Storage Facility (LGTSF) and Dry Fork Waste Rock Storage Area (DFWRSA).

The Councils have participated in the development and review of the East Boulder Mine expansion design process with Stillwater Mining Company (SMC) as parties to the Good Neighbor Agreement (GNA). The GNA is a legally binding contract between the Councils and SMC, which has been successfully implemented for over 20 years. The GNA includes objectives to minimize mine related impacts to our land and water resources while allowing for responsible economic development of the East Boulder and Stillwater Mine operations. The GNA established a process for the Councils to regularly meet with company representatives and obtain professional technical advice to work to proactively address and prevent problems related to mining impacts prior to the permitting process. Our participation has included involvement of GNA Technical Advisors, Jim Kuipers P.E. and Sarah Zuzulock M.S., P.E., as members of SMC's Technical Review Committee in discussions and meetings with SMC and their contractors, the agencies and the TSF Independent Review Panel (IRP).

The proposed waste management facilities and associated infrastructure represent a significant expansion of the East Boulder Mine which would nearly triple the area permitted for disturbance from 249 acres to 723 acres, and extend the projected life of mine for more than 20 more years. Under the heading “Expected Impacts” the EIS scoping notice identifies the following “preliminary impacts” for analysis in the EIS:

*Surface Water and Groundwater* – Construction and operation of mine infrastructure may impact water quality and quantity.

*Public Health and Safety* – Public health and safety could potentially be impacted throughout the life of the mine.

*Wildlife* – Construction activities and operations could affect wildlife species and habitats including fish such as Yellowstone cutthroat trout.

The Councils concur with the preliminary impacts disclosed in the scoping document, and appreciate your consideration of the following comments related to the proposed action and analysis of potential impacts.

<u>*Surface Water and Groundwater*</u> - The EIS should describe current water quality conditions, including water quality changes in groundwater and surface water over the life of the East Boulder Mine, and ongoing mitigation measures that have been implemented to reduce mine related water quality impacts. The EIS should disclose that discharges of nitrogen from mine waste management facilities resulted in exceedances of applicable groundwater standards not predicted to occur in the previous environmental analyses for the project. Further, this EIS should disclose that the primary point of discharge of mine influenced groundwater to the East Boulder River has been determined to be five miles downstream from the mine site, which is inconsistent with the original analysis and predicted impacts.

The Councils would like to see this environmental review analyze the ongoing groundwater and surface water quality impacts associated with the discharge of nitrogen from currently permitted East Boulder Mine operations and proposed new operations. Over the past 10 years, and as part of the GNA, the Councils have been involved in the identification, monitoring, and mitigation of mine nitrogen discharges to groundwater. Those efforts first involved working with SMC to identify explosives residuals from the waste rock used as TSF embankment fill as the source of water quality degradation. Subsequent efforts to mitigate this discharge through source control have been undertaken for short periods of time in the past, including the use of explosives containing less nitrogen and underground washing of waste rock in the muck pile after blasting.

Those source control efforts were implemented with limited success, and in 2014-2015 the Councils were involved in the decision for SMC to place a liner below the embankment waste rock beginning with TSF Stage 3 as a measure to reduce nitrogen discharges to groundwater from the material below the liner, and to capture seepage from waste rock above the liner which is disposed of in the TSF where it subsequently goes to treatment to reduce nitrogen levels prior to reuse or discharge. This liner system has captured large amounts of nitrogen in a lined collection pond; however, nitrogen concentrations in groundwater downgradient of the TSF, and in the East Boulder River (at the campground) remain elevated. This suggests approaches such as a double-liner with a leak detection and/or evacuation system should be preferred wherever technically and economically feasible, as leaks always occur whether due to design, installation, operations or maintenance failures.

The Councils are concerned with the potential cumulative effects on water quality from additional nitrogen loading from the proposed LGTSF and, in particular, the DFWRSA mine facilities. As currently designed and proposed, the construction and operation of these mine waste disposal facilities have the potential to result in additional loading of nitrogen to groundwater and surface water in the upper East Boulder watershed that could result in water quality degradation and loss of beneficial uses in an area of the watershed that is not currently impacted by mine operations. The Councils want to see this EIS consider impacts from nitrogen loading to the environment, and identify mitigations to allow for these waste management facilities be permitted and operated in a way that is protective of baseline water quality. As described in more detail below, this environmental review should fully analyze an alternative design for the LGTSF that utilizes filtered tailings technology, and also analyzes an alternative for the DFWRSA that utilizes rinsing nitrogen residuals from waste rock prior to disposal on the surface. These alternatives are important to consider in this environmental review to prevent further water quality impacts associated with waste management facilities at the East Boulder Mine.

*Effects to Human Health and Safety* – Human health and safety would potentially be negatively impacted as a result of TSF failure. The EIS should consider the risk of failure for the LGTSF in comparison to the currently permitted TSF through Stage 6. The potential for a compounded failure caused initially by the failure of the already permitted TSF should be considered, both throughout mine operations, closure and post-reclamation. The Councils recommend that the EIS analyze the potential for long-term stability given the ultra-fine/slimes nature of SMC's tailings. Montana's Metal Mine Reclamation Act (MMRA) requires mine impacted lands to be returned to a usable and stable landform. The metrics required to achieve a stable landform of a TSF should be considered and defined in this environmental review.

The EIS should take note of the level of effort that has been undertaken by SMC to minimize the risk of failure as a result of adoption of both industry best practice and the requirements of SB409 which modified MMRA. It should also take note that in the event of a failure, SMC performed an inundation analysis and has undertaken efforts to inform the local first response agencies such as the Sheriff's Office and Disaster Response Coordinators, in addition to the public, as to Emergency Response Plans developed in that event.

The EIS should also consider the increased level of independent review of the existing TSF that has been undertaken as a result of this expansion, and the recommendations that have been provided by the IRP and addressed or otherwise incorporated by the Engineer of Record (Knight Piésold) and SMC. The EIS should describe that all of these combined efforts result in a significant reduction in the risk to human health and safety, however there still is potential for failure of the TSF that could result in the loss of human life.

A TSF failure could also result in impacts to land resources as well as damage to critical infrastructure such as bridges and roadways. The recent storm events in Sweet Grass and Stillwater Counties serve as a prime example of the type of damage in terms of movement of the river channel that could cause a TSF failure. However, a TSF failure with a facility containing slimes as opposed to whole tailings, would be even more severe and have even greater potential for loss of human life.

*Mitigation of long-term potential for TSF failure* – SMC is discharging a particularly fine tailing product into the TSF as a result of both finer grinding to accomplish a metals recovery rate, and separation of the sand fraction of the tailings for underground mine backfill resulting in primarily slimes tailings being stored in their TSFs. As a result, and as recently discussed with respect to closure of the Nye TSF at the Stillwater Mine, closure of these TSFs containing primarily slimes tailings is more complicated because those materials are more difficult to consolidate and prevent liquefaction, when compared to closure of TSFs containing whole tailings. In order to reduce both the potential for, and effect of a TSF failure post-reclamation over the long-term, several additional measures have already been incorporated or are under consideration. This includes plans for additional tailings characterization, use of geotextile material in establishing a waste rock cover, and use of an average of four feet of waste rock cover, or potentially more, over a five-year period in establishing an initial reclamation cover consistent with closure objectives. Additionally, discussions are presently being undertaken to address the potential advantage of adding additional waste rock together with the use of wick drains, or other means, to further consolidate the upper 30-40 ft of tailings, and as a result reduce the risk of long-term failure and the impacts if such a failure were to occur by making the tailings less fluid.

The EIS should address modification of the proposed plan for the LGTSF to include aspects similar to these as potential mitigations that could reduce the long-term risk and impact of TSF failure, and increase opportunities for reclamation success.

*Mitigation of potential for reclamation failure* – The EIS should address the potential for long-term failure of reclamation as a result of erosion, cover loss, vegetation loss due to drought or fire, weed invasion, and storm and other events in exceedance of design parameters that are likely to occur to the TSFs and DFWRSA over the long-term following initial reclamation. The need for various levels of long-term monitoring and maintenance as well as other potential actions resulting from the Lewis Gulch TSF and waste rock pile should be identified and addressed as well.

The Councils and SMC have worked to further consider how to reclaim the TSF and other site features at the East Boulder Mine to meet objectives of “stable landform closure” and “geomorphic landform design.” Consistent with the recommendations of the Mount Polley Independent Engineering Review Panel and Canadian Dam Association, the Councils’ goal is to ensure that TSF closure results in a stable landform. A key part of our discussions has been to consider how to define and specify “stable closure,” and to realize the limitations that may exist given the ultra-fine nature of SMC’s tailing material as well as the presence of the liner system. The concept of geomorphic design, or landform architecture design, is intended to allow for design, construction and closure of TSFs and other waste management facilities that mimic natural geology and hydrology and consider the long-term evolution of reclaimed mine features. The Councils would like to see this concept considered in the EIS as an alternative with potential to reduce or mitigate predicted impacts (aesthetics, long-term stability, etc.).

*Climate Change* - The EIS must address anthropogenic driven climate change and how it might result in more frequent or more extreme storm events and overall changes to precipitation, snowpack and evaporation patterns, and how those might impact the LGTSF and DFWRSA in terms of erosion, stability, discharge of mine pollutants to the environment, fires, revegetation, and other potential impacts.

*Socioeconomic Impacts* – This environmental review is likely to result in an additional 20 years or more of mine life, and the ongoing and reasonably foreseeable impacts to the surrounding communities and infrastructure should be analyzed and disclosed.

Alternatives for Consideration in the EIS

*TSF Method and Design* - SMC’s proposed LGTSF would utilize a downstream paddock type dam to store slurry tailings. The rationale for selecting the alternative proposed (explained in a study appended to the TSF Design Report), is primarily based on a technical feasibility study completed in 2018 together with 30+ years of demonstrated success with this method at SMC’s facilities as compared to filtered tailings. The use of filtered tailings is complicated by technical considerations related to the extremely fine nature of SMC’s slurry tailings stored on the surface, which is the product of prior sand/slimes separation to allow use of the coarse sand fraction as underground backfill.

Filtered tailings have been in use at similar sized underground mines such as the Greens Creek Mine and Pogo Mine, both located in Alaska. The primary difference is that those mines utilize paste backfill of whole tailings and as a result filter whole tailings, which are easier to filter than tailings with the sand fraction largely removed. However, the filtration of finer tailings is still technically feasible by providing greater filter area.

Significant advances have been made in filtered tailings technology since this study was completed in 2018. It is widely recognized by the mining industry that filtration technology has improved with the Engineering and Mining Journal recognizing in May 2020 “The past 18-24 months has seen the commercial availability of next-generation pressure filters that can handle extremely high throughputs and achieve very low residual moisture content in filter cakes (as low as 5%) safely and economically. And, this has been a game changer.” (Exhibit 1) And as noted by Furnell et al (2021) (Exhibit 2), social and environmental concerns warrant that filtered tailings technology, or stacked tailings, technology and application be moved forward. The

Councils would like to see this EIS fully analyze an alternative for the LGTSF that utilizes filtered tailings.

As the agencies are aware, SMC is working on a new feasibility study based on current technology to evaluate the application of filtered tailings at the East Boulder Mine, and this information can be used to justify whether or not to develop an alternative for the EIS. A filtered tailings alternative has the potential to reduce impacts associated with the construction, operation and closure of the LGTSF when compared to the proposed slurry alternative including: reduced potential risk for catastrophic failure of the TSF, increased disposal capacity for mine waste within the same footprint, potential for co-disposal of tailings and waste rock eliminating the need for construction of the DFWRSA, reduced water quality impacts from seepage, application of geomorphic reclamation principles and the ability to achieve a stable landform at closure, and others. The Councils strongly recommend that the agencies fully analyze a filtered tailings alternative in this EIS, and consider the feasibility study currently being performed by SMC.

*Waste Rock Rinsing Prior to Disposal* – This EIS should acknowledge and disclose that nitrogen residuals from blasting practices remain on the waste rock at the time of disposal, and are the primary source of nitrogen-related water quality impacts associated with the currently permitted East Boulder Mine facilities. SMC has been proactive with the proposed design for the DFWRSA, including a double-liner and leak detection system, in an effort to mitigate impacts and minimize infiltration of mine-influenced water to surrounding water resources. While these efforts are to be commended, it is important to understand that all liners leak to some extent. SMC's most recently constructed waste rock disposal facility at Stillwater Mine's Benbow Portal included a liner system that did not work as designed, and resulted in an unintended discharge of nitrogen to groundwater. The design proposed for the DFWRSA includes a double-liner and leak detection and evacuation system at the base of the pile, which is an improvement when compared to the Benbow waste rock facility liner design. Despite best efforts to mitigate anticipated impacts, the Councils remain concerned with impacts to water resources from the DFWRSA. The liner system proposed, in particular the shingled liner installation along the steep hillside behind the pile, has not been proven to be an effective mitigation measure to prevent water quality impacts through collection and management of seepage generated from the waste rock pile. As presently designed and proposed, the DFWRSA poses a potential for impacts to the water quality, especially when considering the shallow depth to groundwater and close proximity to the East Boulder River.

The Councils and SMC have discussed the concept of rinsing waste rock as a source control measure to reduce nitrogen compounds that are associated with present waste rock disposal practices at the East Boulder Mine. In addition to the elimination of nitrogen from the waste rock pile, this rinsing alternative could provide additional benefits that reduce the need for long-term water management and treatment at the time of mine closure, and also minimize long-term monitoring and maintenance requirements. The Councils would like to see this EIS consider waste rock rinsing prior to disposal, or other applicable source control measures, as an alternative to SMC's proposed action for the DFWRSA. The Councils and SMC are working collaboratively to continue technical development and economic consideration of this approach.

This environmental review should also include consideration of groundwater mitigation alternatives to protect the East Boulder River from potential impacts, in the event the double-liner and leak detection system proposed for the DFWRSA were to fail and nitrogen reaches groundwater.  An option could be a slurry wall, or similar *in situ* barrier, in conjunction with pumpback of captured groundwater, constructed between the DFWRSA and East Boulder River.

The Councils appreciate your consideration of these comments in the upcoming environmental review for Stillwater Mining Company's Major Amendment 004. If you have any questions, or would like to meet to discuss this further please do not hesitate to contact the GNA Manager, Michael Skinner, at Northern Plains Resource Council (406.248.1154).

Sincerely,

Betsy Baxter
GNA Task Force Chair

Exhibit 1

# How to Make Filtered Tailings Feasible

May 2020 | Features

The technology and drivers required for dry-stack tailings are all there, so why are mines still wary of high-performance filters, and how can we overcome the current inertia?

By Carly Leonida, European Editor

To dewater or not to dewater tailings? That is a question many mining companies are grappling with at the moment, and it's a tricky one to answer given the huge number of unique factors that can influence the business case at each site.



Dewatering to create thickened tailings, paste or filter cakes for dry stacking removes residual process water from the tailings making it less risky and bulky to store. It allows process water to be returned to the concentrator for reuse, helping mines drive down their operating costs and, it opens up multiple options for tailings storage including backfill and dry stacking.

Dewatering technologies have existed for years in the form of thickeners, cyclones, centrifuges, vacuum filters, belt presses etc., and these have been widely applied at high-grade, lower throughput operations and at mines in water stressed areas. However, until relatively recently, aside from the cost of water, there has been little incentive for high-throughput, lower-grade operations such as copper or iron-ore to dewater their tailings. So, what has changed?

Firstly, filtration technology. The past 18-24 months has seen the commercial availability of next-generation pressure filters that can handle extremely high throughputs and achieve very low residual moisture content in filter cakes (as low as 5%) safely and economically. And, this has been a game changer.

The industry has been talking about the potential benefits of dry stacking tailings for years. However, applications have been few and far between, mainly due to limitations in the performance of technologies and the associated capital cost. Now that filters that can handle 30,000 metric tons per day (mt/d) and more have been proven, we should,

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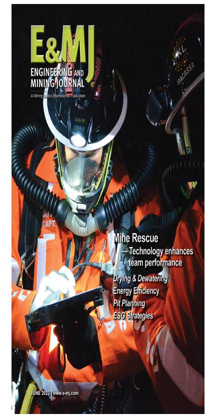


technically, see the first full-scale implementations within the next 1-3 years.

Secondly, up until 18 months ago, in the majority of cases – bar water stressed operations like those in northern Chile, and in countries where dewatering is mandated i.e., Brazil – the business case for dewatering tailings at most high throughput operations just wasn't strong enough.

The past 10 years have seen a string of high-profile tailings dam failures including Mount Polley, Samarco and, most recently, at Brumadinho in January 2019. The last event in particular prompted stakeholders at all levels to take greater notice of mining practices, good and bad.



If designed or managed poorly, wet tailings storage facilities (TSFs) can pose a significant risk to human life, to the environment and to businesses and, as such, investors and governments are now leaning heavily on miners to consider more sustainable storage options for tailings.

The benefits of dewatering tailings to whatever degree are clear. However, despite the necessary technology being available and, despite almost unilateral agreement from equipment suppliers, engineering firms and mining companies that dry stacking is the most promising and widely applicable method of tailings storage going forward, the industry is at something of a stalemate.

Most of this inertia can be attributed to executive and investor's suppressed appetite for risk. There are a huge number of factors that can influence the operational and economic success of high-performance dewatering technologies. It takes time to properly evaluate and understand these, and this, coupled with a wariness of being the first to buy into a "new" technology, means the industry has yet to see a full-scale dewatering/dry stacking solution at a high-throughput operation.

It is only a matter of time, but until this hurdle is overcome, the industry cannot move forward with creating a truly sustainable sector, one that can stand up to stakeholder scrutiny and reap the benefits of the green economy.



Understanding the Risk/Payback Balance

To get a handle on where the industry is at technology wise, and how mines can navigate the economic/operational/logistical maze in front of them, E&MJ turned to two of the biggest providers of mineral processing solutions: FLSmidth and Metso.

Todd Wisdom, director of tailings at FLSmidth, began by explaining the evaluation process.

"First, we try and answer a bunch of technical and commercial questions with the client, ranging from what's the cost of water at their site, because that's going to determine how much money they spend on dewatering, what's the cost of electricity and manpower... those kinds of things.

"We look at the operational costs, in terms of spare parts, maintenance, and consumables. And we need to understand other constraints around the mine, aside from the commercial ones, like what altitude is the site at? What's the particle size distribution and mineralogy of the tailings material, which we'll confirm based upon the samples they send us.

"We do a desktop study to understand those constraints, and then we need to know what their TSF looks like. Is it an existing mine? If so, what was the original mine life plan? Are they getting toward the end of it? If it's an existing mine, we'll evaluate a sample of tailings and discuss how many years of life they're looking to get.



"A big filtered tailings solution probably needs around 10 years to be competitive and pay back the investment in the conveyors and filtration equipment. And for large concentrators that are looking at big pressure filters, like in Chile, the cost of water needs to be more than $3 a cubic meter ($m^3$) for it to start making economic sense or they need to be very near the end of life on their current TSF. So, we can use some high-level rules of thumb to say whether we think particular technologies are applicable or not."

Wisdom said one of the biggest misconceptions that accompanies high-performance dewatering equipment at present, is that mines need to implement an "all or nothing" approach. However, this is definitely not the case. A partial solution where mines dewater 20% or 30% of the tailings stream offers a good way to get familiar with the technology and can help minimize associated risks.

"Even engineers and OEMs can fall into that trap," he said. "If a mine has only a couple of years of life left and you can put in a process that's going to add another five years of life to the current TSF. And you're only going to dewater, say, 20% or 30% of the tailings, that does a lot for the mine. That allows them more time to find a longer-term solution if they think the mine life will be extended.



"It allows them to de-risk a higher performance dewatering tailing solution. One of the big issues, especially with large mines that are looking at filtered tailings, is they view it as a risk, because there's nothing bigger than 30,000-mt/d filtered tailings operating right now — Karara in Western Australia is the largest installation.

"A 100,000-mt/d mine might look it and say 'Ok, it's possible, the technology is there, but we're going to give it a really high-risk factor' and the project never makes it across the line. If they dewater just a portion of the tailings stream, then they're not betting the whole farm on what is, at this scale, a new technology. And it allows them to de-risk the project and get something off the ground that is beneficial for them."

And, at that scale, the amount of water and power saved by dewatering 20% or 30% of a tailings feed is significant. The operational savings can, quite quickly, help to offset the high capital cost associated with new filtration technology and a conveyor system. It also drives down the cost of tailings storage by reducing the number of lifts required; at large facilities each lift can cost hundreds of millions of dollars, so even a partial dewatering solution can provide significant benefit.



On the flip side, if a mine chooses to dewater 100% of its tailings using filtration technology, there is a need to factor in some redundancy so that, if the system goes down, the entire mine isn't held up.

"That's pretty easy to do on the dewatering, filtration and pumping side because you, typically, have multiple pieces of kit," Wisdom explained. "But on the conveying side, it can be more problematic. Typically, there's only one overland conveyor, and the TSF can be anywhere from 1 km to 20 km away from the mine.

"Whereas, if you're implementing a partial dewatering solution and there's an issue with the conveyor, say it's down for a few days, then instead of having a completely redundant system, you can just use the original TSF. But that also requires the mine to make the decision early enough that they've got some capacity left."

Finding the First Partners

Where is FLSmidth at with its filtration technology?

“The Colossal filter was designed to handle 10,000 mt/d, and we did a demonstration plant with Escondida in Chile that looked at that,” Wisdom said. “They eventually decided, I think it was partly due to the high-risk factor, to put in another desalination plant.

“Then we had the EcoTails Project that we worked on with Goldcorp. That developed a whole new filter that was able to handle 30,000 mt/d.”



That filter, which is yet to receive a catchy name, has been dubbed the “5 x 3.” FLSmidth held an event in Nevada last year to showcase the technology which is now commercially available. However, there aren’t any full-size units in operation yet. The test filter, that was demoed at the event is a demonstration model — it only has two chambers — and was designed to test samples of tailings to help companies build a business case before purchasing the technology at full scale.

“The filter itself is engineered. It could be sold if there was a client for it,” Wisdom said. “Goldcorp and FLSmidth were looking at creating a consortium to build that first demonstration plant at Peñasquito in Mexico and prove the 5 x 3 filter and associated technology.

“We’re still looking for partners. It really depends on how fast different miners come forward."

It all comes back to the old adage that miners prefer to be first to be second (or third) when it comes to selecting new technologies. And, to a degree, that's understandable. Most mining projects carry a fair amount of risk at the front end, so to create additional risk at the backend by throwing a new technology into the mix isn't an option for many companies... Unless of course the cost of water is so high that there will be a huge ROI or if there's regulatory pressure.

Wisdom thought for a moment, "I would say, especially with engineers, it's the risk factor that concerns them. They want to see more than one example of a technology installed and operating for that particular type of tailings," he said.



"There are two things we have to prove: the mechanical reliability and the process performance. The mechanical reliability can be proven at any site. The process performance, we need to prove that and scale it up based upon smaller tests. I think all of the vendors have pretty much shown that they can scale up the equipment.

"We've spent quite a bit of money trying to alleviate as much risk as we can. We can't alleviate that last step, somebody is going to have to step up and actually install one [a 5 x 3 filter], but we're trying to get as close as we can without making that last big investment."

Supply and Demand

“I would say every mine that I’ve been involved with, both new and existing, in the last few years, is evaluating filtered tailings,” Wisdom said. “Because there aren’t a lot of big new mines being built, probably, the biggest market is mines that are extending their operational life and are looking to increase the life of their TSF.

“Gold mines tend to be smaller, in the 10-15,000 mt/d range. And, I would say that for those smaller mines, filter technology is very well accepted. They’re not only evaluating it but very seriously considering it for every project.



“There’s a couple of drivers there technically and around profit margins. With big open-pit mines, they’re usually big and open pit because they’re low grade. And low-grade mines don’t usually have a lot of profit margin between what it costs them to produce a ton of metal, and what they make on that ton of metal. There’s very little margin for variation in equipment before it impacts on the ROI.

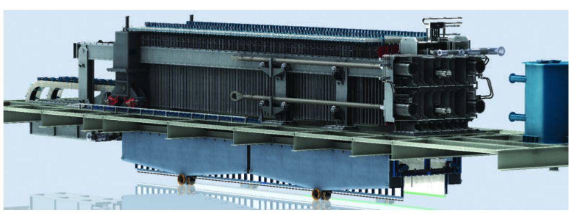
“Smaller high-grade mines usually have more bandwidth to play with. And, if they’re underground, they’re probably also looking at solutions like backfill. Once you start to dewater material to put it back underground, you’ve got most of the infrastructure there to dewater all of the tailings and surface-dispose the rest of it.”

Wisdom’s biggest piece of advice for companies that are evaluating dewatering is not to see it as an all or nothing solution.

"Especially when looking at existing mines, don't do an all or nothing solution, because I think the optimum, in terms of payback and lowest risk, is to partially dewater the tailings stream," he said.

"Make sure you look at all of the technologies. Don't get pigeonholed into 'I think this is what's going to work' because that's the only equipment the vendor offers, or because you have a preconceived notion. Do a high-level conceptual study that looks at all of the options and then maybe get a more detailed study on two or three. That might potentially come out with a better solution for the mine."





A rendering of the 5 x 3 filter. FLSmidth developed this in collaboration with Goldcorp as part of the EcoTails project.

## Solutions as Well as Technology

Metso also has a high-performance pressure filter that is ready and waiting for full-scale deployment. The VPX was launched in June 2019. There are currently four models in the product range, but the use of modules and an electromechanical drive (rather than a hydraulic drive system) means that each filter can be shortened or lengthened depending on how difficult the material is to dewater and the necessary throughput. The pressure can also be adjusted to maximize energy efficiency in relation to the desired end moisture content.

According to research by Metso, only 5% of the tailings generated globally in 2018 were dewatered to create thickened tailings or paste, and less than 1% were filtered for dry stacking. However, the company estimates that by 2025 the share of generated tailings that are dewatered will increase to 13%.

Metso is so sure of the market that, in addition to launching a new product last year, it also created a business unit called Metso Tailings Management Solutions that is, as the name suggests, dedicated to advising mining clients on and creating solutions based around tailings management.



Rodrigo Gouveia is vice president of Tailings Management Solutions, and he provided an update on the company's activity.

"The VPX is a big success," he said. "We have about 20 firm proposals delivered for mines in Chile, Peru, Brazil, Australia and in India. There are discussions also in Africa and Russia. We're expecting the first order in the second quarter from a customer in South America."

Like FLSmidth, Metso quickly recognized the need for a test unit to help clients prove the technology and build their business case before committing to a full installation. The VPX10 is a mobile pilot plant that features all the sensors and control systems of the larger VPX models, but its miniature size allows it to be transported in a shipping container and installed at, or close to, a customer's site, complete with thickeners and hydrocyclones.

The unit has proven so popular that it has a waiting list and, to help meet demand for numbers, Metso just installed a full-size pilot plant at its own facility in Sorocaba, Brazil.

The 5 x 3 pilot plant that FLSmidth demonstrated in Nevada in late 2019.



"This machine is ready for tests on an industrial scale," Gouveia explained. "It's not a lab unit. We have completed tests for four customers in Brazil already and we have customers in Chile, Peru, Australia and India that will start sending samples to us very soon. However, that has been delayed a little due to the coronavirus.

"With the tests we are going to perform with the VPX10 in our facility in Sorocaba, we expect to have results for processing different tailings, like iron, copper and gold. That was why we decided to install the plant at our own facility, because it opens up the opportunity for us to test different material from different customers. It would be great to also install this pilot plant for one specific customer. However, we will be limited to that particular application.

"Having it inside Metso, we can easily transport 1,000 liters of pulp or slurry to our own facility and process it there. It's also a good opportunity for customers to see the filter in operation, to have the maintenance people see the electromechanical drive working, and how reliable this solution can be.

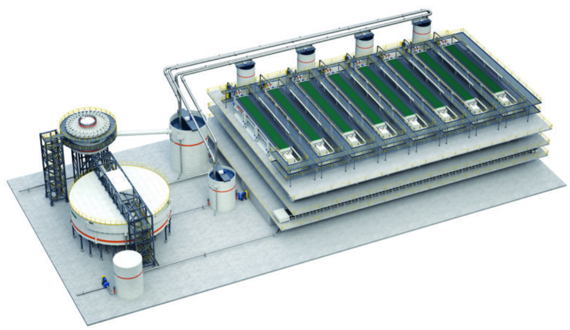


"We should have two more pilot units soon: one more in the pacific rim, to serve Chile and Peru, and another in Australia, to serve that part of the world."

Gouveia explained that the majority of inquiries have come from existing mines that are looking to expand or mines where TSFs are approaching their end of life.

"At this moment, what we are hearing most from customers and EPCs is concern on fresh tailings generation," he said. "There are a lot of TSFs today that are very close to maximum capacity without the option to be increased. Dry tailings are the best solution for those applications.

"Of course, it is of interest to new operations too with environmental licensing becoming trickier. But unfortunately, as an industry, we are not seeing many new projects coming through. For the few new large projects that are coming, dry tailings are definitely being considered."



A conceptual dewatering solution from Metso using high performance pressure filters amongst other technologies.

Water Scarcity PushesInnovation

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Again, the main concern that Metso is seeing regards the level of investment required for dewatering and dry stacking solutions, and their effectiveness.

"We all know that the mining industry is very conservative. It's difficult to make mining companies move on a new technology," Gouveia echoed Wisdom's words.

"All the studies that we have done so far show that dry tailings are the future. Not only because the risk related to tailing dams is eliminated, but also, we are seeing that with the new technology and all the cost involved with tailings management, the CAPEX and OPEX actually work out to be more efficient with dry tailings.

"New technologies like the VPX, they put a new perspective on the financial side of tailings management, because they can handle a much higher capacity.

That was the problem in the past. We had good equipment to reprocess or dewater tailings. However, the volume of water that could be recovered was low, so the cost became too high. A large number of filters were needed to cope with the volume of material but now, with these new technologies, it is very different."

Gouveia also emphasized the issue of water scarcity; something that is only going to get worse in the coming years, particularly in areas like northern Chile where many of the big copper mines are located. The region is currently experiencing its worst drought for more than 100 years, and the lack of water is leading many mines to reduce their operations or even consider halting them.



"If you ask me about the future, I'd say that it is the ability of us, of the OEMs, to offer solutions that can process even higher capacities than are already possible," Gouveia said.

"We are now seeing the big mines starting to prepare their long-term strategies for tailings with 100% of the stream dewatered. The volumes to be processed are huge, and existing technologies, they are able to perform the job, but the number of units required is also huge and expensive. Currently all our investments are related to developing equipment and solutions that can process a much higher volume of tailings at a lower cost.

"I think in the next 3-5 years, it will be possible to process 100% of such volume on a cost-efficient basis."

To help mines assess and evaluate potential solutions, Metso is currently developing a digital tool or "configurator." This value calculator allows mines to enter their main priorities i.e., energy efficiency, water consumption, footprint etc., as well as information on the volume and types of tailings they're producing and do a preliminary assessment on different circuit configurations. The tool can advise how many filters will be needed and even size the units.

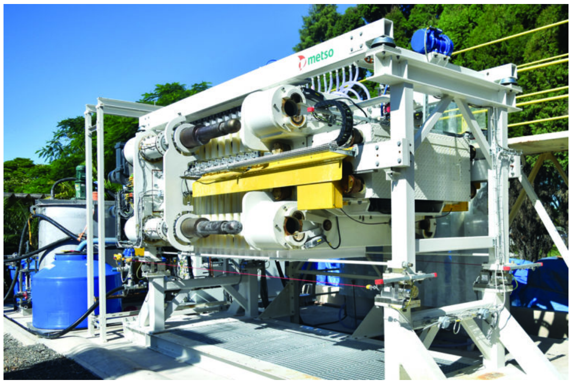


"It's going to be a great tool to help customers in the decision process for going to dry tailings. We are going to launch it in phases starting in June. It's really impressive what can be obtained with this configurator, and how quick we can respond to customer expectations," Gouveia added.

"The first phase will focus on dewatering and, later, we'll expand the tool to reprocessing and even other stages of mineral processing. We'll also connect it to our VPS configurator, which is already known in the market, for circuit simulations."

## What About Reprocessing?

Fresh tailings may be miner's main concern at present, but what about the hundreds of billions of tons of tailings currently sitting in dams, both operational and closed, around the globe?


Metso recently installs a VPX 10 filter at its facility in Sorocaba in Brazil to test the technology on different types of tailings and help customers to build a business case prior to purchase.

Select mines have been reprocessing high-grade tailings for some time, but now that the technology is available to do so at a large scale and, now that mining companies can no longer afford to turn a blind eye to TSFs after closure, interest must be growing.

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"I wouldn't say there's a lot of interest, but there's definitely some, especially from older mines that maybe didn't have as good separation technology or techniques early on in their mine life," Wisdom said. "There are definitely TSFs that they could look to reprocess and recover copper or gold or whatever is potentially still in those tailings."

Gouveia agreed, "There is great potential for reprocessing, mainly at older mines where the tailings were produced using older technologies, say, 30-50 years ago. Some of those tailings are really rich. Our studies indicate that metals obtained from reprocessed tailings can be up to three times cheaper than virgin ore. Some iron-ore mines have 50%-55% metals content in their tailings, which is amazing really. And there are copper operations with

0.5% of copper in their tailings which is higher than what's in the ground. It's just a question of dredging the material and floating the metal or using magnetic separation."

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Review

# Dewatered and Stacked Mine Tailings: A Review

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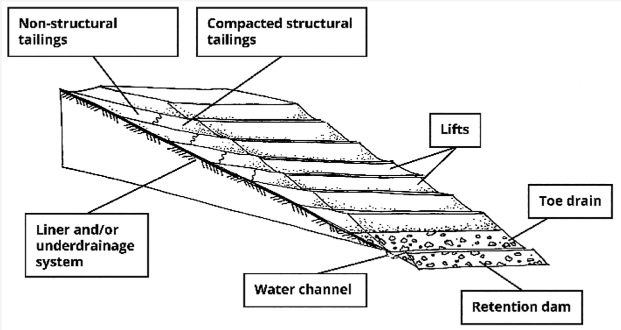


**ABSTRACT:** Tailings storage is a prescient issue in mining, representing a visible and destructive liability. Dewatering tailings to a paste-like consistency is a popular option to reduce tailings volumes and increase dam safety, but dewatering further to a bulk cake consistency has mostly been reserved for small operations in locations where seismicity or terrain prohibited the construction of dams. The recent high-profile failures of tailings dams such at Fundão and Brumadinho facilities along with the push toward socially conscious investing have generated renewed and urgent interest in tailings dewatering, including stacked ("filtered" or "dry-stack") tailings. While geochemistry and civil engineering topics relating to tailings in general are both extensively studied, very little academic literature is available specifically on stacked tailings, with discussion mostly confined to conference articles or extrapolation about the behavior of dewatered tailings. Furthermore, the nomenclature around and definition of this method of tailings storage is inconsistent, which can make researching the topic unnecessarily tedious and confusing and, in the worst case, can open the door to intentional misrepresentation of a tailings storage facility's safety as this is a technology still being scaled up. In this article, the term stacked tailings (ST) is introduced to describe what has been otherwise called filtered tailings or dry-stack(ed) tailings to remedy the inaccuracies with the two existing names and gather the existing literature in one place. Topics covered include the existing definitions of dewatered and stacked tailings; opportunities and barriers to adoption; and construction and general operation for such tailings storage facilities. These are supplemented by an overview of literature in geotechnical and geochemical topics relevant to tailings dewatering (ex. clays) and tailings storage facilities. Emerging dewatering technologies and innovations which might be useful in the scaling up of the technology are also discussed. The aim is to provide a thorough background on the topic for a general audience, outline gaps in the literature, and encourage further exploration of stacked tailings and tailings cake by furnishing a comprehensive list of sources. Stacked tailings are discussed in a rigorous way to make the topic a more approachable way to encourage standardization and adoption, scale up, and the development of associated technologies.

**KEYWORDS:** *dry stack, filtered tailings, unsaturated, stacked tailings, mine waste*

## 1. INTRODUCTION

Demand for commodity metals continues to grow as infrastructure and technology develop to meet consumer needs. The proliferation of specialized, portable, and often disposable goods requires an ever-widening range of metals, many of which are difficult to substitute in a given application.[1] Particular attention has been given to the electrification of transportation, a sector that accounts for approximately 23% of global $CO_2$ emissions.[2] Urgent demand for new electric vehicles is increasing the burden on mining, in particular for metals such as cobalt, lithium, nickel, and dysprosium.[2] Recycling programs, which recover diverse metals from traditionally discarded consumer goods, should be expanded as secondary metal supplies to help stabilize metal availability. However, mining is still necessary to replace the losses in recycling and to introduce additional metals into the market as regulations, consumer tastes, and infrastructure development drive demand.

As prices for a commodity increase, previously rejected deposits become economically viable to develop.[3] Geological exploration and resource reporting alone cannot accurately predict when critical metals will be depleted. The trend toward mining ever lower cutoff grades and deeper, remote deposits not only endangers ecosystems,[4] but it encourages bulk mining with low selectivity. Thus, more rock must be processed per unit metal extracted, leading to more mineral processing wastes (tailings) that must be managed indefinitely. Abandoned and grandfathered mines number approximately 558 000 in the

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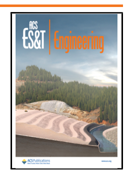

**Table 1. Geotechnical Definitions of Thickened, Paste, and Stacked Tailings from the Literature**

| Parameter | Thickened tailings | Paste tailings | Stacked (filtered) tailings | Ref |
|---|---|---|---|---|
| Physical characteristics | No grain-size segregation upon deposition; forms homogeneous slurry that must be transported as a turbulent flow at a minimum velocity to avoid sedimentation | Can be pumped in the laminar range without segregation; no terminal velocity; must have sufficient fines (>15% of less than 20 mm) | Only transportable by conveyor or truck | 23 |
| Typical solids content (mass of solids/total mass; %) | >65 | >70 | >77 | 23 |
| | - | - | 83–85 | 24 |
| | High-density: 60–70 | 70–75 | >75 | 25 |
| | Thickened: 40–60 | | | |
| | 50–70 | 70–85 | >70 | 26 |
| Water content for hard rock tailings (%) | <54 | 39 | <32 | 23 |
| | - | - | 18–22 | 24 |
| | 35–70 | 25–35 | <25 | 27 |
| | 30–100 | 20–30 | 10–20 | 26 |
| Yield stress during transport (Pa) | Generally, < 50 | >50 | >500; too high to be pumped economically | 23 |
| | 5–20 | >100 | >800 | 28 |
| | High density: <200 (range 100–300) | >200 (range 100–300) | - | 25 |
| | Thickened: <30 | | | |
| | 10–300 | 100–1000 | >1000 | 26 |
| Water recovery before deposition ($m^3$/t) assuming 50% solids slurry exiting mill | 0.45 | 0.60 | 0.68 | 23 |
| Water recovery (%) | 60–70 | 80–90 | >90 | 26 |
| Segregation | High density: medium | Low | Low | 25 |
| | Thickened: high | | | |
| Purpose | Homogeneous deposit with better strength characteristics at a given density; better water retention characteristics | Homogeneous deposit with better strength characteristics at a given density; better water retention characteristics | Higher strength at a given time after deposition; shorter time to trafficability and reclamation | 23 |



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United States[5] and over 10 000 in Canada.[6] To understand the impacts of increased tailings production, efforts have begun to collect data on tailings storage facilities (TSFs), namely, within the Global Tailings Dam Portal Project. However, the total amount of tailings being produced is extremely difficult to quantify due to inconsistencies in reporting. As participation in international councils and industry groups is voluntary, they cannot capture a comprehensive global picture.

Responsible tailings deposition methods should ensure that the tailings are (1) physically, chemically, and radiologically stable; (2) inert if they are to be interacting with the environment; (3) if they are not inert, geographically bound and managed with consideration of environmental and social conditions at each location; and (4) managed with the intent to reduce energy and water usage.[7] Conventional tailings storage and disposal techniques include impoundments, backfilling, and river or submarine disposal.[8]

If TSFs are not properly constructed, maintained, and monitored, both deterioration over time and acute climate change stress makes major dam failures increasingly more likely. Clarkson and Williams (2020) provide a critical review of tailings dam monitoring best practices.[9] TSF failures in recent years have had increasingly catastrophic consequences, and without changes in mine waste storage techniques or operational metrics, this trend is likely to continue.[10] Catastrophic or seepage failures can result in acid rock drainage (ARD) and metal leaching (ML) fluids contaminating the local environment, rendering the water unusable by affecting populations through direct toxicity, undesirable precipitates, and disruption of biotic mechanisms.[11]

TSF failure occurs when structural or foundational issues result in insufficient support of the tailings being retained. Seismic loading can lead to structural failure; therefore, the seismic activity of an area must always be considered during construction.[12] Mismanagement of water can lead to instability in several ways: (1) partial saturation of the dry structural area leading to a static failure, (2) failure to drain sufficient water leading to an excess of tailings beyond dam specifications, and (3) overtopping a dam with erodible structural material leading to weakening and failure.[8] Therefore, the trend in tailings management is to minimize the storage of water within the TSF.

Dewatering (or, more broadly, solid–liquid separation) techniques reduce the volume of TSFs and allow the recovered water to be reused in processing. Stacked tailings (ST; also known as "filtered tailings" or "dry-stack tailings") allow the maximum water recovery; slurry waste from flotation is dewatered to a cake-like consistency, allowing the TSF to be built in lifts. Because there is no standing water, problems such as dam overtopping, internal erosion, and liquefaction are mitigated. ST have gained traction in the past few decades, primarily in arid or seismically unstable regions, and they and merit more rigorous discussion in academia.

### 1.1. Climate Change Impact on Tailings Storage.

Unusual or extreme meteorological events are expected to increase due to climate change,[13,14] and these affect the mining industry, as noted by Pearce et al. (2011)[15] in their review. For example, warmer winters and earlier spring melts in the Northwest Territories, Canada, have led to transportation challenges requiring expensive supply fly ins. Warmer, drier summers have increased dust emissions from sand, limestone, and dolomite quarries in the province of Quebec that require expensive dust suppression techniques. Limited water availability has affected the water-intensive brining process at sodium sulfate mines in the province of Saskatchewan. Torrential rains in Yukon in 2008–2009 caused untreated water from the Minto Mine to be released into the Yukon River, resulting in environmental damage.[15] El Salvador has been forced to ban metal mining due to water shortages.[16] Flooding at the Ensham and Baralaba mines in Australia halted production for 4–6 months.[17] Melting ice caused increased ARD and ML from a coal mine waste-rock pile in Svalbard, Norway.[18] Increasing sea levels can flood coastal mines. Climate change has been estimated to cost the Greek mining sector US$800 million and more than 2000 direct jobs.[19]

The construction of conventional tailings dams was predicated on the assumption that climate conditions and the frequency and severity of extreme weather events would not change. However, in the face of climate change, global dam failure rates have increased by approximately 1.2% in the last century, with ∼20 failure events in the decade 1999–2010.[20] Tailings dam failures release an enormous volume of tailings containing hazardous chemicals and heavy metals into the surrounding area, contaminating nearby water sources, damaging the landscape, killing flora and fauna, and causing harm or death to those in nearby communities. The most devastating recent failure was the Brumadinho dam disaster in Brazil: fluidized tailings traveled over 10 km, covered 3.1 km$^2$ in mud, and killed 259 people.[21]

The risks associated with changing and extreme weather patterns provide urgent motivation to recycle process water during operations and to leave the most geotechnically stable structures behind, as they are effectively permanent constructions. Stacked tailings facilities are designed to avoid storing water and can be reclaimed faster, easing the burden on long-term active monitoring.

## 2. DEWATERED TAILINGS

### 2.1. Terminology.

Dewatered tailings are categorized into thickened, paste, or filtered (stacked) based on their water content. The term "dry-stack" is used informally and was initially adopted by designers and regulators to refer to facilities that store significantly dewatered tailings. However, this term is a misnomer because the tailings are not a bulk dry material but a moist cake of approximately 80 wt % solids. Therefore, the term "filtered tailings" is commonly used in research articles, but this may also be a misnomer because not all dewatering methods involve filtration (e.g., volute screw press is effective and efficient at dewatering; see Table 8). Due to the inaccuracies of both terms, this paper refers to tailings that have been dewatered to up to 80 wt % solids and are fully stackable as stacked tailings (ST).

Confusion is further compounded by the poorly defined limits between tailings with different water contents. Tailings can be dewatered to any desired specification, which affects the number of steps and equipment used for dewatering and leads to a "tailings dewatering continuum".[22] Several attempts have been made to precisely define each category along the continuum, but no consensus has been reached (Table 1). In addition, many definitions are based on the physical properties of the tailings material, leading to some overlap among definitions.

Thickened (40–70 wt % solids) and paste (70–75 wt %) tailings are both pumpable and, due to their low water content, do not require settling ponds (Table 2). To stabilize contaminants such as arsenic, binders like Portland cement

Table 2. Summary of Advantages, Disadvantages, Risks, and Costs of Each Tailings Storage Facility (TSF) Type[a]

| TSF Type | Advantages | Disadvantages | Geotechnical risk | Geochemical Risk | Costs |
|---|---|---|---|---|---|
| Conventional (impoundment) | Economical | Water-intensive | High during operations | High during operations and closure | Low capital and operational costs |
| | Applicable to wide variety of tailings | High risk of seepage | Loose, saturated tailings highly mobile in the event of a structural failure | ARD/ML seepage and runoff through pervious zones | High ARD and ML remediation costs |
| | High operational flexibility | Result of failure is catastrophic | | | High water management costs |
| | Saturated conditions help manage acid rock drainage | Large local environmental disturbance (footprint) | | | Failure is monetarily, environmentally, and socially expensive |
| | Well-known technology | High operational management costs during TSF life | | | |
| | | Active water management required with several contingencies | | | |
| | | Rehabilitation only possible after mine closure | | | |
| Thickened/paste | Low tailings volume | High capital and operational costs from thickening, pumping, etc. | High during operations and closure | High during operations and closure | High capital and operational costs |
| | High water recovery | Moderately water-intensive | Tailings potentially mobile if not fully contained | Large-scale operations have high risk of ARD and ML vs conventional TSFs | High ARD and ML remediation costs |
| | Failure from slumping restricted to local area 20x the stack height | Thickeners must be well maintained to produce optimal water content | | | Long closure period is costly |
| | Low risk of seepage due to less water | Beach slopes difficult to predict and maintain | | | |
| | Can be used for backfillingPumpable | Difficult to design for seasonal and weather events (erosion, runoff, etc.) | | | |
| | Do not require settling ponds | Long drying times | | | |
| | | Less well-known/implemented technology | | | |
| | | Rehabilitation only possible after mine closure | | | |
| Stacked | Low water use | High capital and moderate operational costs | High during operations | High during operations | High capital and moderate operational costs |
| | Eliminates catastrophic failure risk | Requires surface management to reduce dust generation and erosion | Material may not meet consistent construction requirements | Partially saturated tailings prone to ARD and ML | High ARD and ML remediation costs |
| | Less seepage | Filter plants require constant monitoring and maintenance to produce tailings with desired water content | | | Short closure period is cost-effective |
| | Diverse storage locations (steep slopes, small areas, etc.) | Variability in feed ore can impact dewatering and storage | | | Very low cost of failure |
| | Failure from slumping restricted to local area 10x the stack height | Difficult to scale to high tonnage rates | | | |
| | Easy to permit | Requires external water storage and runoff treatment | | | |
| | Do not require settling ponds | High energy usage (filter plants, transport, etc.) | | | |
| | Allow progressive reclamation | Difficult to manage ARD/ML of sulfidic ores due to low saturation | | | |

[a]ARD: acid mine drainage; ML: metal leaching.[8,25]



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may be added to paste tailings, although at lower proportions compared to underground paste backfill applications.[29] Thickened and paste tailings are shear thinning and, thus, are considered fluids during transit and under shear forces and solids or soils once they are beached and static. Therefore, an understanding of their rheological properties and soil mechanics is required for transport and deposition. Typically, thickened tailings are transported by centrifugal pumps, whereas paste tailings are transported using positive displacement pumps with high-pressure piping.[7] During pipeline transportation, when the tailings are subjected to pressure gradients, they must have sufficient fines to allow flow without particle segregation: the rule of thumb is 15% of the particles should have diameters < 20 $\mu$m.[23]

ST are classified as either "wet" cake (∼100% saturation) or "dry" cake (∼70−85% saturation). ST can be transported by conveyors or trucks and then spread, layered, and compacted onto drying pans to form unsaturated, dense, and stable stacks requiring a small dam or dike for retention. There is no need for a conventional TSF (Table 2), although there is often a water treatment facility for runoff. Another significant advantage of ST is the ease of progressive reclamation and closure. Reclamation can begin earlier in the project life cycle, which enables fugitive dust control and reduces the short- and long-term environmental impacts. ST reduce the risk of catastrophic failure releasing tailings into the environment and maximize water recovery. However, the need for alternative transport methods increases transportation costs.

**2.2. Tailings Storage Facilities: Advantages and Disadvantages.** Tailings dewatering before deposition improves their geotechnical stability, reduces the stored water volume, and minimizes the need to introduce new water into the processing circuit (Table 2). It can also lower dam construction, maintenance, and rehabilitation costs. Decreasing pore water and spaces can reduce the volume and potential toxicity of seepage and result in less reactive residual waste material. New and innovative ways to reduce tailings volume and repurpose tailings are being developed, providing significant opportunities to create value, reduce environmental damage and liability, and improve industry sustainability.

**2.3. Barriers to Stacked Tailings Adoption.** Effectively implementing ST, particularly at large scales, is mired in limitations and setbacks. As a concept and as a technology, ST have been around for decades, but their use has been limited. They are typically recommended for and adopted by sites with extreme restrictions imposed by water or storage space limitations or seismicity. An early adopter of ST, Greens Creek Mine, Alaska, began production in 1989. When operations began at this low-throughput operation with a short projected mine life,[30] geotechnical and space constraints and lower reclamation costs made ST substantially less expensive than a conventional tailings dam.

In Canada, tailings storage technologies are considered in prefeasibility studies and best available or achievable technology (BAT) assessments (Table 3). Following the Mount Polley tailings disaster in British Columbia in 2014, BAT assessments were encouraged by the Provincial Government for new projects, on top of the federally mandated tailings site selection reports needed for permitting.[31] Although they are only required on a case-by-case basis, BAT assessments provide insight into key decision-making considerations for industry. ST do not often make it past prescreening; the scores on BAT assessments are often disqualified based on costs associated with filtration and material handling.

Although industry assessments of technology alternatives overwhelmingly reject ST, social and environmental pressure continues to push ST technology forward. The high capital cost is commonly used as a reason for nonadoption, but water shortages and contested usage of local water sources have made conventional tailings management options more operationally expensive. Water scarcity and extreme weather in Chile, for example, have made alternative water sources such as desalination increasingly attractive, and regulators have been considering making this mandatory for mining companies since 2011.[38] Mines that upgrade ore using froth flotation are particularly water-intensive, with flotation requiring 3−7 t of water for every 1 t of ore.[39] Improving water reuse in mineral processing has positive material impacts for mines in water-sensitive regions.

A cost analysis for a mine in Chile found that the incremental cost of increasing ST throughput is much smaller than building additional dams and that the equipment needed to make ST can be reused, whereas conventional TSFs bury all infrastructure and represent entirely sunk costs.[40] East and Fernandez (2020) found that the lifetime cost of ST and thickened tailings are very similar but that careful consideration of filter efficiency, cloth life, energy costs, and safe placement is needed to plan ST projects.[24] Over the life of a hypothetical 40 000 t/d TSF, the ST facility showed a linear cost increase, and a thickened tailings facility showed step costs associated with introducing new cells to accommodate increased volumes as processing continued (Figure 1). Sensitivity analysis of inputs related to mine closure had the least effect on ST, which could be an asset worth considering in feasibility and planning stages for new mines.[41]

## 3. DESIGN AND CONSTRUCTION OF STACKED TAILINGS FACILITIES

**3.1. Tailings Dewatering and Transfer.** *3.1.1. Thickening and Filtration.* Tailings dewatering generally follows two steps, thickening and filtration, the latter usually informed by the technology used in the former. The technology and detailed design principles involved in both processes has been very well described elsewhere.[42,43]

Cylindrical tank thickeners can be categorized as conventional, high-rate, or paste thickeners (Table 4). The terms high-rate and high-capacity are often used interchangeably by manufacturers and usually refer to small thickeners, but they can be used to describe high throughput conventional thickeners.[43] Where space is limited, smaller diameter thickeners can be designed to process material faster through the addition of flocculants. However, the increased use of flocculants can make these high-rate thickeners expensive to operate and as such may not be suitable for all operations.[44] Paste thickeners use a deep bed which allows a deeper sediment layer and augmented thickening capacity. They typically generate higher solids content tailings, which may be beneficial as feed for the filtration stage.

The design and selection of thickeners is critical to tailings dewatering because while they are not able to achieve the required solids content for stacking, they are the last point at which buffering capacity can be included to accommodate fluctuations in process volume. Optimal performance of further dewatering and materials handling processes depends on a


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Table 3. Projects that Eliminated Stacked Tailings (ST) as a Storage Technology Based on Prefeasibility Studies and Recent Best Available Technology (BAT) Assessments[a]

| Project | Canadian province or territory | Planned mill throughput (t/d) | Report type | Tailings storage technology | Ranking | Notes |
|---|---|---|---|---|---|---|
| Yellowknife Gold Project[32] | Northwest Territories | 3000 t/d | Prefeasibility study | Slurry | Did not make it to detailed selection | Higher costs cited as reason for nonadoption of ST. |
| Red Mountain Project[33] | British Columbia | 1000 t/d | BAT assessment for feasibility study | Thickened | Third out of three alternatives | ST ranked last after cemented and thickened tailings, even with the economics excluded. |
| Ajax Project[34] | British Columbia | 65 000 t/d | BAT assessment for feasibility study | Thickened | Assessed but not selected as BAT | While ST can accommodate some off-spec material and the technology has been proven, it has not been implemented at high throughputs. Scaling up would likely incur too high costs. |
| Casino Copper–Gold Project[35] | Yukon Territory | 100 000 t/d | Tailings storage alternatives following up on prefeasibility study | Cyclone sand and fill embankment | Assessed out of three but not selected | Subaqueous tailings facility deemed necessary for potentially acid generating (PAG) material and as contingency storage. It is also the most expensive option. |
| Sisson Project[36] | New Brunswick | 30 000 t/d | Report required for Schedule 2 amendment of MMER | Slurry | Assessed out of three alternatives but not selected | ST disqualified in prescreening out of concern for isolating PAG material. |
| Blackwater Gold Project[37] | British Columbia | 60 000 t/d | Report required for Schedule 2 amendment of MMER | Subaqueous codisposal of slurry and PAG waste rock | Disqualified in prescreening | ST disqualified because high throughput, wet climate, and topography would require substantial works for water diversion and erosion control. |
| Magino Gold Project (SLR, 2016) | Ontario | 35 000 t/d | Report required for Schedule 2 amendment of MMER | Conventional or thickened | Disqualified in prescreening | Not carried forward because of cost, similar disposal sites, and lack of precedent. Environmental benefit deemed limited compared to other methods. |

[a]MMER: Metal and diamond mining effluent regulations.

consistent flow of materials. Thickener circuit design will be influenced by the ore characteristics, plant throughput,

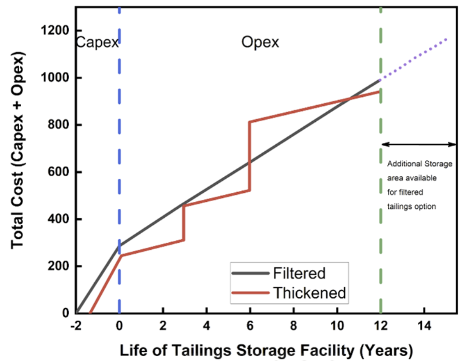


**Figure 1.** Projected capital (Capex) and operational costs (Opex) costs of a 40 000 t/d filtered (i.e., stacked) and thickened tailings facility. Adapted with permission from East and Fernandez (2020).[24] Copyright 2020 Springer-Verlag GmbH Germany.

**Table 4. General Feed and Underflow Properties of Typical Circular Thickeners[44,45]**

| Type of thickener | Feed particle size ($\mu$m) | Feed solids (% w/w) | Target underflow yield stress (Pa) | Underflow solids (% w/w) |
|---|---|---|---|---|
| Conventional | 0.1–500 | 20 | 20–30 | |
| High-rate/ high-capacity | 0.1–300 | <15 | 30–100 | |
| Paste | 0.1–300 | <15 | >100 | up to 70 |

thickener location and available footprint, and number of thickeners in series. Thickeners must achieve the optimal solids concentration of product to reduce the filtration energy required while also ensuring pumpability and reduced wear during transport to the filtration stage.

Filtration separates the slurry or paste into the "non-pumpable" filter cake (the residue) and the filtrate.[42] The slurry is forced through a porous bed or semipermeable membrane (the filter medium) to achieve high solid–liquid separation. Filtration without a cake exists (e.g., cross-flow filtration), but it is not discussed in this paper because dewatering for tailings storage explicitly aims for a bulk soil-like texture.[46] Filtration can be aided by (1) flocculants to aggregate fines and prevent "blinding" (clogging) of the filter medium and (2) surfactant filter aids, which changes the surface tension of the fluid or surface properties of particles of interest[42] to facilitate filtration. Filtration techniques can be broadly divided into continuous and batch processes (Table 5). Continuous processes typically employ belts or drums, and batch processes typically employ horizontal or vertical pressure filters with a membrane.

Plate and frame filter presses (a type of membrane pressure filtration) tend to achieve the highest water recoveries and are useful in high-altitude environments since they do not rely on local atmospheric pressure, unlike vacuum filters[46] (Figure 2). However, plate-and-frame pressure filtration is a batch process with a fixed volume; therefore, it is vulnerable to process upsets and inconsistencies. Blockage of the slurry inlet at high solids concentrations and leakage are issues, and filter cloth wear is a significant concern for filter presses with recessed frames. Filter plates rarely exceed 2 m × 2 m dimensions,[47] limiting


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Table 5. Aspects of Filtration Techniques[a]

| Type | Process | Heavy duty | Max. solids content[b] | Electricity consumption[c] | Critical design parameters |
|---|---|---|---|---|---|
| Vacuum Filtration | | | | | |
| Belt | Continuous | Yes | >75% | High | Belt speed, Layer thickness |
| Disk | Continuous | Limited[d] | >70% | | Rotation speed, Layer thickness |
| Drum | Continuous | Limited[d] | >70% | | Rotation speed, Layer thickness |
| Pressure Filtration | | | | | |
| Chamber | Batch[e] | Yes | >75% | Low | Cycle time, Dry matter content |
| Membrane | Batch[e] | Yes | >85% | | Cycle time, Dry matter content |
| Belt | Continuous | Limited[d] | >70% | | Belt speed, Layer thickness |

[a]Adapted with permission from Watson et al.[26] Copyright 2010 Australian Centre for Geomechanics, The University of Western Australia. [b]Dry matter content highly depends on the specific gravity of the material and other characteristics; the numbers here are representative. [c]Based on a feasibility study conducted by MWH Americas Inc. comparing tailings dewatering, tailings using horizontal belt filters, or membrane filter presses. [d]In general, rolling devices require more maintenance. [e]If multiple filter presses are installed, process can be considered continuous.

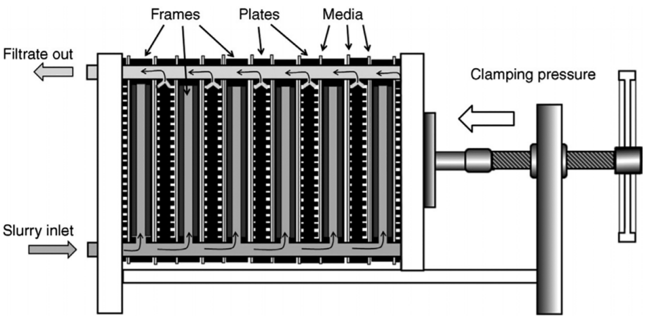


Figure 2. Cross-section of a plate and frame filter press. Reproduced with permission from Gupta et al.[47] Copyright 2016 Elsevier.

individual unit capacity and throughput, although larger units are being developed.[48]

*3.1.2. Dewatering Challenges.* High-energy grinding used to liberate entrained valuable minerals generates problematic fine solids which form gel-like stable particle networks that resist consolidation and trap process water, preventing water recycling.[49] Fine tailings require long settling times, resulting in larger TSFs that disturb large land areas and contain harmful substances that can be mobilized by wind, evaporation, and seepage. Fine particles (typically <2 $\mu$m) of phyllosilicate or clay minerals are common gangue minerals in low-grade ores that present significant challenges during flotation, transport, and dewatering. Phyllosilicates consist of stacked anisometric polymeric sandwiches of tetrahedral (T) and octahedral layers (O) in different proportions with relatively similar structures but different physical and chemical properties.[50] Layers with one tetrahedral and one octahedral sheet form the 1:1 (or TO) layer type; layers with two tetrahedral sheets on either side of an octahedral sheet form the 2:1 (or TOT) layer type (Figure 3). Variations in layer composition, order, and number lead to a wide variety of clay minerals.[51] In some clay minerals the interlayer space is occupied by cations (e.g., illite or montmorillonite) that compensate for the layer charge; other clay minerals do not contain counterions in the interlayer space (e.g., kaolinite). The cations can be solvated or nonsolvated leading to two swelling (e.g., smectites) and nonswelling (e.g., Illite) clays, respectively. The intercalated cation solvation leads to swelling of clay minerals in water to a volume several times the original dry volume, making the swelling clays useful for operations such as a drilling, and to plug leaks in soil, rocks, and dams.[52] However, in mineral processing operations, the

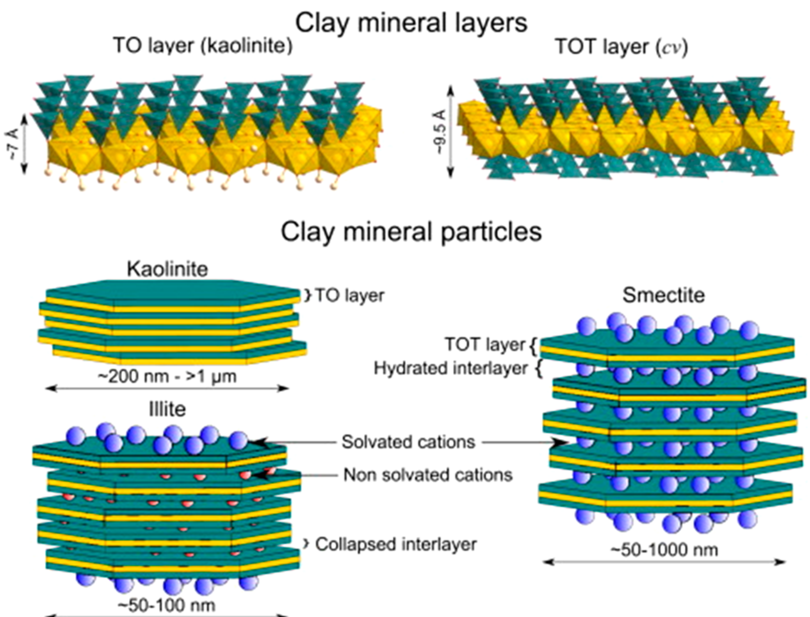


Figure 3. Structural schematic of clay mineral sheets and particles. Adapted with permission from Tournassat.[56] Copyright 2015 Elsevier.


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swelling of clay minerals is always deleterious, resulting in high viscosities even at low concentrations.[53−55]

Clay mineral particles are colloidal in nature and have a high surface charge, which renders them extremely stable and prevents settling in tailings suspensions; consolidation may take thousands of years. Clay minerals exhibit surface charge characteristics, which change from the octahedral face to the tetrahedral face and from faces to edges. Edges have a pH-dependent surface charge due to hydrolysis characteristics arising from the proton adsorption−desorption properties of broken and under-coordinated Al−O and Si−O bonds.[57−59] Face or basal plane surfaces were previously asserted to possess a permanent and non-pH dependent surface;[56,60,61] however, recent investigations have shown real mineral faces can also exhibit a pH dependent surface due to imperfect crystal structures and substitutions on the basal planes.[58,62−64] Anisotropic surface charge characteristics of clays permits control of coagulation behavior of clay tailings through manipulation of pH and/or ionic strength.[65] Changes in pH can lead to either dispersion or aggregation into various structures of the clay particles. For example, kaolinite has an alumina basal plane with an isoelectric point of ∼pH 6. Above this pH, kaolinite slurries have a very stable dispersed microstructure, which can only be aggregated at high ionic strengths which compress the electrical double layer.[66] Apart from coagulation through pH and ionic strength, polymeric flocculants can dewater tailings containing kaolinite clay minerals.

Different types of ores will occur alongside different gangue clay minerals. For example, sodium montmorillonite (Na-Mt), the main component of bentonite, is widely encountered in copper, gold, and other ore processing[54,67] and is extremely detrimental to mineral processing operations due to its high swelling nature and particle−particle interactions. Dewatering is extremely challenging in tailings having montmorillonite due to the presence of interlayer water molecules, which require high osmotic pressure to drain out.[68]

In low-grade nickel operations, instead of clay minerals, serpentine [$Mg_3Si_2O5(OH)_4$] is the main gangue mineral which is present in considerably large amounts in ultramafic nickel ores. It is found in three forms chrysotile, lizardite, and antigorite.[69] Serpentine particles are composed of two different surfaces, the basal plane composed of brucite and the bilayered edge surface having Si tetrahedral and Mg octahedral bonds. The basal plane has significantly different surface properties as compared to the bilayered edge plane. Although the basal planes of serpentine are electrically neutral, lattice defects such as vacancies and substitutions can cause pH-dependent charging. Conversely, the edge surfaces of serpentine are highly polar. Because of the anisotropic nature of serpentine and its nonspherical shape, the tailings slurry from ultramafic ore processing usually has a complex rheology and demonstrates high viscosity and yield stress.[70] Industries involved in the processing of aluminum-, phosphate-, and copper-bearing minerals do not always encounter phyllosilicates. However, their feed ore has high metal oxide content. These industries must contend with fine tailings[49] and devise innovative solutions to deal with dewatering challenges.

**3.2. Emerging Dewatering Technologies.** Dewatering to >70 wt % solids is extremely energy intensive and has high capital costs; therefore, the benefits of novel dewatering technologies cannot be neglected. Significant research effort has focused on improving dewatering technologies, and several promising options are outlined in Table 6.

*3.2.1. Volute Screw Press.* The volute screw press or volute dewatering press is a device based on the auger screw, with material being dewatered as it is pushed through a drum. The drum is made of alternating fixed and eccentric moving rings, which slide past each other as the auger screw rotates and pushes the mobile rings around. The motion of the moving rings between the fixed rings ensures that the inside of the screw press stays clean and can break up clumps of material to liberate more water.[71] A dewatered cake is pushed out at the end of the screw, while filtrate escapes between the rings, making up the barrel. Amcon Europe, a volute screw press manufacturer, estimates energy savings using this technology (∼0.8 kW/h) in comparison to belt and screw presses (1.2 and 2.0 kW/h, respectively).

The volute screw press is more commonly associated with organic sludges such as in sewage treatment but could find adoption in mining dewatering. A project to develop a dewatering process using volute screw presses in combination with flocculants in the management of fluid fine tailings successfully created a 55−60 wt % solids tailings cake.[72] While 60 wt % tailings cake is wetter than the target for most stacked tailings, the potential of a continuous process which avoids wear and tear on a membrane or pressure plate is an attractive pursuit. Further, a way to manage the finest tailings material is a pressing need for the industry, extending beyond the needs of oil sands where the experiment was conducted. Colloidally stable fines increase the surface area needed in conventional tailings facilities as well as the amount of water locked within them, so a way to manage them can directly impact the volumes projected for storage in conventional tailings facilities or make the filtration of coarser tailings easier if fines can be separated.

*3.2.2. Superabsorbent Polymers.* Superabsorbent polymers (SAPs) are hydrophilic, cross-linked polymer networks made of ionic monomers that are capable of absorbing and retaining huge amounts of water or aqueous solutions. The low degree of cross-linking allows them to absorb up to 1000 times their weight.[73,74] SAPs are synthesized from natural polymers like polypeptides and polysaccharides or synthetic monomers like acrylates or acrylamides.[74] Absorption occurs through a combination of physical entrapment of water via capillary forces in the SAP macroporous structure and hydration of SAP functional groups.[73] Performance depends on temperature, ionic strength, absorbent material, particle size, and pH. Above a critical pH, SAPs absorb water, and below a critical pH, SAPs release water.[75] Adsorption capacity can be increased by increasing the porosity or decreasing the SAP particle size.[76] Table 7 summarizes studies that have used SAPs and achieved target solids contents during dewatering of tailings.

Large-scale application of SAPs is limited because of high costs and difficulties in scaling up the technology. Preliminary work by Sahi et al. (2019) demonstrated that SAPs can be reclaimed and reused,[80] but desorbing the water incurs additional operating and equipment costs.

*3.2.3. Electrokinetic Dewatering.* When an electric field is applied across an aqueous suspension, cations within the suspension move toward the cathodes, along with bound water and surrounding free water through viscous forces.[81,82] Applying a DC current to geotextiles sandwiching saturated soils or to a filter press can accelerate electro-osmosis and electrophoresis. Electrokinetic dewatering has previously been


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Table 6. Summary of Emerging Dewatering Technologies

| Technology | Description | Advantages | Disadvantages |
|---|---|---|---|
| Volute screw press | Auger screw in drum made of alternating mobile and static rings. Filtrate escapes between the rings and the dewatered solids are discharged at the end of the drum. | Low energy requirements, low noise, accepts varied solids content inputs | Has not yet been scaled up, limited research in tailings filtration. |
| Superabsorbent polymers (SAPs) | Salt polyacrylate solids used to remove the liquid phase to be used in thickening processes | Effective: water can be desorbed for reusing SAPs | Twice the cost of existing dewatering technologies |
| Electrokinetic dewatering | DC current applied to geotextiles or filter plates in the field to remove interstitial water by migrating ions with bound water | Useful for removing interstitial water, consolidating clay-rich material | High energy cost and high capital cost of replacing corroded electrodes |
| Geotextile tubes | Large bags made of geotextile filled with tailings and consolidate as water escapes the bag | Low energy requirements, can be stacked vertically | Low volumes, low cost of geotextiles |

**Table 7. Examples of Superabsorbent Polymers and Their Dewatering Capabilities in Various Mineral Systems**

| Polymer | Mineral system | Initial solids content (%) | Final solids content (%) | Ref |
|---|---|---|---|---|
| Sodium acrylate/ acrylamide copolymer (ALCOSORB) | Coal | 70.6 | 86−88 | 75 |
| Cross-linked polyacrylate | Oil sands, mature fine tailings | ∼40 | ∼80 | 77 |
| Sodium polyacrylate | Na-montmorillonite and saprolitic nickel laterite slurries | 20 | 40−55 | 78 |
| Sodium polyacrylate homopolymer | Pyrite slurry | 16 | 82 | 76 |
| Polyacrylate | Refractive gold slurry | 20 | 70 | 79 |
| Sodium polyacrylate | Unspecified mine tailings | 7 | 21 | 80 |

studied as a ground consolidation method for clay-rich soils. It is effective at interstitial and vicinal water removal that cannot be achieved through mechanical dewatering techniques.[81] The zeta potential plays a key role in the success of electrokinetic dewatering. Fourie et al. (2007) suggested that fine particles with high zeta potential and in solutions of moderate salinity are optimal for this technique.[83] During electrokinetic dewatering, a pH gradient exists between the two electrodes due to the production of $H^+$ at the anode and $OH^-$ at the cathode, resulting in acidic and corrosive conditions at the cathode. Due to high energy and electrode replacement costs, electrokinetic dewatering is not widely applied. New electrode materials, such as graphite[84] and electrokinetic geosynthetics,[85] are being developed to optimize energy costs and operational conditions to make this technique widely viable. The use of electrokinetic dewatering, electrophoresis, electro-osmosis, and electromigration in dewatering sludge was reviewed by Mahmoud et al. (2010).[82]

*3.2.4. Geotextile Tubes.* Originally developed for shoreline protection, geotextile tubes filled with bulk sand or silt have been investigated for use in coal residual storage and sewage sludge and mine tailings dewatering. Geotextile tubes filled with slurries can be laid out and stacked on an impermeable pad where the filtrate can be collected. Like other dewatering processes, reagent addition has been investigated to improve the quality of the filtrate and facilitate consolidation of the solids.[86−88] Geotextile tubes offer the rare advantage of completely enclosing residues, protecting them from fugitive dusting in windy conditions.[89]

**3.3. Material Handling.** Material handling, which conveys the dewatered tailings to final storage, presents a throughput challenge and is a considerable sunk cost. Material handling and stacking processes must be specifically designed for each operation. Additionally, the material handling processes cannot buffer any extra or overflow material and must be designed as a series of continuous, linked operations.

The two main methods of bulk materials handling of ST are (1) a combination of loaders, trucks, and dozers or (2) a series of conveyors that are periodically moved as material is discharged onto the pad. Truck and loader operations tend to preserve moisture in the cake, while conveying dries the cake out, which can influence dusting and geotechnical stability over longer travel distances. Transport by truck is extremely flexible and convenient at the start of operations or over short


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distances. However, if the mine plan is fixed from the start and includes longer hauling distances for tailings, the upfront cost of conveyors and mobile stackers becomes increasingly justified. A summary of types of transport methods can be seen in Table S1.

Most of the conveying technology in use for moving tailings cake was originally developed for heap leach stacking and retains similarities with heap leach operations. Material handling systems contain a transfer point where the dewatering batch process is converted to a more continuous conveying process. Transfer points—typically fixed—are added as necessary between the mill and the pad. Several additional mobile transfer points on the pad are used for stacking. Multiple lifts can be stacked at once, and taller lifts are made possible by the upper end of mobile stacking equipment. This allows for higher volumes and more equipment availability, but a general trend toward more conservative heights has emerged for safety and ease of facility closure: shorter lifts are more geotechnically stable and are easier to reshape into more aesthetically pleasing landforms during reclamation.

Conveyor belts can increase transport distances and throughputs but are expensive and limited by conveyor belt speed and width. As material approaches a transfer point from one conveyor to the next, its trajectory is calculated to make sure the material lands predictably and without damage on the receiving conveyor belt. Conveyor speeds are limited to ∼3−5 m/s, because at speeds of 7−8 m/s the difficulty of loading the next conveyor is significantly higher. Longer, fixed conveyors are preferred as they are amenable to higher speeds. Conveyor belt width has a current maximum at ∼3 m. Wider conveyor belts can carry more material but require more power to operate, and the relative scarcity of components (e.g., rollers) for extra wide belts makes them especially expensive to maintain. Other common mechanical weak points include idlers wearing out or the belt ripping at the splice point. Preventive maintenance is extremely important in conveying systems.

Material segregation is a common issue during the transport of materials for heap stacking; however, it does not affect ST cake. The particle size distribution (PSD) is the percentage of each particle size fraction found in a material: a narrower PSD centered on smaller particles, combined with the usual minimum of three transfer points, allow the material to be adequately mixed.

**3.4. Geotechnical Considerations.** Geotechnical stability is foremost in the design of TSF because it reduces the risk of failure and reduces water discharge, which mitigates geochemical risk to the environment. A myriad of geotechnical properties need to be understood to predict how water will behave in the TSF and how it will interact with the tailings:[90]

1. Moisture content: ST contain the lowest moisture content among tailings types (15−30%; Table 1).
2. In-place density: traditional density metric (mass/volume).
3. Relative density: based on material gradation and packing structure after deposition.[90]
4. Permeability (hydraulic conductivity): a measure of how easily water can pass through a material; can be determined experimentally or estimated from the PSD. Depending on the way the material is deposited and its orientation, the permeability can change in the vertical and horizontal directions.[90]
5. Plasticity index: difference between the liquid and plastic limit; based on clay content. The higher the plasticity index, the more a material behaves like a “plastic” or clay; the lower the index, the more it behaves like a coarse-grained soil. ASTM D4318 is a method to determine the plasticity index for soils.[91]
6. Compressibility and consolidation: compressibility is a function of particle size and void ratio, and consolidation is the change in volume after a material has been loaded, which depends on its initial compressibility after deposition.[90] For example, a fine-grained material will pack tightly with a low void ratio; thus, it will have high compressibility and consolidation when loaded. In a coarser grained material, more void space between particles limits the compressibility and volume change when loaded (low consolidation). The standard (ASTM D698)[92] or modified (ASTM D1557)[93] Proctor methods are used to measure the compressibility of soils.
7. Shear strength: ability of a material to resist stress and potential failure. Unlike the previous characteristics, shear strength does not affect drainage or water flow, but it affects overall stability. The higher the shear strength, the more the material is able to resist stresses induced by increasing pore water pressures.[90] The shear strength of the soil can be determined based on consolidated undrained triaxial compression tests (ASTM D4767).[94]
8. The PSD is commonly measured using sieving (for larger particle sizes, ASTM D6913[95]) or microscopic analysis techniques (laser diffraction, dynamic light scattering, or image particle analysis).

Interactions among these features can be estimated by simulating the phreatic surface, that is, the elevation at which the tailings material is saturated with water. The key goal of TSF design is to prevent the phreatic surface from reaching the surface of the tailings and keep the level as low as possible toward the embankment face.[90] Traditional TSFs ensure a low phreatic surface by altering the permeability in specific regions in the embankment, either by installing lower permeability cores in the embankment or by having higher permeability areas downstream. The phreatic surface should not move, as changes to it affect the shear strength of the tailings.[90] Any factors that impact the phreatic surface directly also affect the stability of the entire TSF. During sudden precipitation events, water may accumulate on the top of the stack and lead to unpredictable changes in pore water pressures above the designed phreatic line, which can compromise its stability. Gradation and compaction can help limit water infiltration from precipitation events.[96] In the construction of ST facilities, depositional characteristics can be altered to achieve ideal conditions; for example, tailings placement and compressibility can be altered using machinery after deposition.[31]

Storage of ST has multiple advantages over storage of conventional tailings. The most important feature is the unsaturated nature of the tailings that arrive at the TSF. In general, unsaturated soils have higher resistance to cyclic loading and higher shear strength,[97] which reduces consolidation during operations and after closure. In ST that are both unsaturated and can be consolidated after deposition, liquefaction is not a primary concern.[90,97] A related advantage is that the hydraulic conductivity of ST is usually low, typically $<1 \times 10^{-6}$ cm/s.[96] Finite element modeling of the behavior of water through a ST facility showed that ST have limited


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seepage potential due to the low saturated permeability: the surface becomes saturated quickly, and water is prevented from penetrating the tailings under the surface.[98,99] The low saturated permeability also eliminates risks associated with internal erosion (e.g., piping) because the slow flow of fluids through it discourages the creation of internal channels. As there is no supernatant pond, any surface excess water will be susceptible to evaporation, and overtopping, as in conventional dams, is highly unlikely.[31,90]

Finally, unlike paste and thickened tailings, ST are not affected by shear thinning, allowing them to maintain their initial shear strength during transportation and potentially increase it after deposition through compaction, consolidation, and control of the hydraulic conductivity.[31,100]

ST facilities are still vulnerable to erosion—usually caused by rainfall—but with proper care and maintenance, this potential failure mode can be mitigated. Although an earthquake of high intensity may damage the stack,[101] ST have low mobility because they are unsaturated. Therefore, failures are localized, not catastrophic. Overall, ST have the best environmental performance in the event of a failure compared to other TSF types.

Although ST possess many geotechnical advantages, these benefits must not be overestimated, and the idea of a "dry" stack must not be misconstrued to give a false sense of security regarding potential failure modes and high stability. Although the ST material is not fully saturated like conventional and thickened tailings, it does contain water.[87] To design and construct a successful ST facility, full understanding of the deposit and the tailings material properties is required, as is compliance to design specifications.[31,96,100,101] If ST are not maintained within design parameters, the storage type may shift to thickened or paste tailings. If the delivered tailings do not meet the design specifications for PSD, moisture content, and hydraulic conductivity,[96,100] the use of secondary machinery after deposition may not render the material safe to stack if the shear strength is low.[92] A strategy to manage such material (e.g., stack zoning) is recommended, an example of which is indicated in Figure 4. Risks associated with conventional tailings dam failure modes are considerably reduced with ST, but these modes are still present under extreme environmental scenarios and if design specifications are not routinely met.[97]

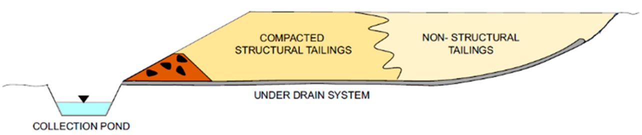


**Figure 4.** Schematic of a stacked tailings facility with zoned structural and nonstructural tailings areas with a water collection system, reproduced with permission from East and Fernandez.[24] Copyright 2020 Springer-Verlag GmbH Germany.

**3.5. Geochemical Considerations.** ST exposed to moisture and oxygen during storage have the potential to undergo chemical reactions that can release deleterious elements to the environment. Generally, tailings drainage may include ARD, ML, neutral mine drainage (NMD), and saline drainage. Drainage chemistry is controlled by mineralogy, geochemistry, microbiology, and hydrology. Monitoring and treatment of runoff and leachate requires comprehensive understanding of the geochemical properties of the ST, namely, (1) the chemical composition, (2) the mineral content and composition, (3) the exposed surface of area and texture of the mineral particles, and (4) the mineral reactivity and associations.[102] Most operational ST facilities tend use nonacid generating tailings due to the potential for environmental contamination.

The primary concern regarding TSFs is the ability for wastes to generate sulfuric acid ($H_2SO_4$) leachate and release heavy metals and sulfates into the environment. ARD/ML generation depends on the relative amounts of acid-generating sulfide (e.g., pyrrhotite, pyrite), neutralizing (e.g., carbonates), and heavy metal-releasing minerals[103] among other factors. ARD occurs when iron sulfide minerals are oxidized to sulfuric acid in the presence of oxygen and water. Pyrite ($FeS_2$) and pyrrhotite are the most abundant and reactive iron sulfide minerals, respectively; their oxidation generates $H^+$ ions as the acid source. When oxidized by oxygen and in water at circumneutral pH (pH > 5), pyrite releases two moles of $SO_4$, four moles of $H^+$, and one mole of Fe(III)-(oxy)hydroxide precipitate. Complete pyrrhotite oxidation can occur 20−100 times faster than pyrite oxidation. The amount of Fe(II) and $H^+$ ions generated depends on the iron content ($Fe_{1-x}S$, $0 \leq x \geq 0.125$). Partial pyrrhotite oxidation generates marcasite ($FeS_2$, different crystallography from pyrite) and Fe(III)-(oxy)hydroxide. $Fe(OH)_3(s)$ precipitation generates an additional 3 mol of $H^+$; however, these precipitates can reduce the oxidation rate and adsorb some of the heavy metal ions.[104] Under acidic conditions (pH $\lesssim$ 3), Fe(III) becomes the primary oxidant of pyrite and pyrrhotite, generating more $H^+$ ions, and accelerating the oxidation rate compared to atmospheric oxygen. Other iron sulfide minerals that bear heavy elements within their superstructure also dissolve to release iron, $H^+$, and heavy metals. Low pH water enhances desorption of metal ions from the mineral surface into the water. The reactivity of different minerals can also be accelerated by iron and sulfur oxidizing bacteria, such as *Acidithiobacillus ferrooxidans* or *A. thiooxidans*.

When neutral carbonate minerals within the tailings are depleted and lose their buffering capacity, ARD occurs. In alkaline tailings, water contamination can occur despite balanced dissolution of carbonate minerals, giving rise to NMD. NMD typically has a pH of 6−9 and contains elevated concentrations of $SO_4$, Ca, Mg, and other metals and metalloids. Under NMD conditions, some metals (e.g., Fe(II), Zn, and Cd) are hydrolyzed and (hydro)oxyanion-forming elements (e.g., As, Se, and Sb) are readily dissolved in the tailings.[105] Circumneutral conditions enhance the mobility for these sulfide-mineral oxidation products and cause greater downstream contamination. Additionally, the release of circumneutral effluent containing Fe(II) may lead to further oxidation and acid generation downstream.

Research on the geochemical behavior of ST facilities is limited. Lindsay et al. (2009) extensively investigated the geochemical, microbial, and mineralogical properties of NMD ST at the Greens Creek Mine in Alaska.[106] The pore water trace element concentration from seepage and runoff depended on the trace element content of primary sulfides, the mass of sulfides within the tailings deposit, and the extent of secondary reactions occurring following dissolution and oxidation.[106] The pore water was circumneutral and reducing, which limited the concentrations of aqueous Fe(III), Al, and Pb and elevated the concentrations of $SO_4$, Fe, Zn, Mn, and other trace elements. The concentrations of elements varied


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with depth within the deposit. For example, aqueous iron concentrations were at their highest approximately 50 cm below the surface, decreased at 50−100 cm where Fe(III)-hydroxides precipitated, and increased at 100−200 cm where conditions were reducing, and pore water was undersaturated. Concentrations of several elements, including Zn, Mn, and Ni, were attenuated via sorption and (co)precipitation with Fe(III)-hydroxide precipitates. Additionally, Na-isopropyl xanthate may have contributed to elevated dissolved organic carbon and $S_2O_3$ concentrations in the residual process water retained within the tailings. Bacterial activity seemed to be a localized phenomenon based on availability of electron donors and acceptors, not on depth.

ARD and NMD generate different types of leachates and runoff, requiring different water treatment systems—similar to systems to treat the seepage from conventional TSFs. However, Heikkinen et al. (2009) found that passive water treatment methods were effective for both ARD and NMDs.[107] Aerobic wetlands were able to remove iron through the formation of Fe-oxyhydroxides and decrease Ni concentrations through adsorption to Fe precipitates. Anaerobic bacterial reduction of $SO_4^{2-}$ was used after the removal of metals from the system. The seepage chemistry from the ARD mine was prone to significant fluctuation, requiring a series of passive treatment systems. ARD reactions are reviewed in detail by Egiebor and Oni (2007),[108] and methods of ARD and NMD treatment are reviewed by Tripathy (2014)[109] and Ben Ali et al. (2019).[110]

Assessment of minerology is important to understanding the acid generating behavior of ore and/or tailings. Several reviews and reference books present a wide variety of techniques to this end: Brough et al. (2013),[111] Jamieson et al. (2015),[103] Lindsay et al. (2015),[105] Parbhakar-Fox and Lottermoser (2015),[112] Dunne et al. (2019),[113] and St-Arnault et al. (2020).[114]

Bulk analytical techniques, such as optical microscopy, XRF (x-ray fluorescent), and XRD (x-ray diffraction), provide useful information for subsampling but are only surface-level techniques. Inductively coupled plasma techniques such as optical emission and mass spectroscopy provide high resolution and accurate information about the complete chemical composition of the ore and/or tailings but does not provide information on the composition of the minerals or their availability or reactivity.

More advanced analytical techniques, such as scanning electron microscopy, electron probe microanalysis, or synchrotron-based methods, can analyze individual grains and be used to investigate trace valuable minerals. These techniques can also analyze texture or roughness, which is important because porosity and surface area can affect mineral reactivity.[103] These techniques are often available through specialized consulting companies or universities. Jamieson et al. (2015) presented a comprehensive review of advanced analytical techniques that can be used in mineral identification and ARD/ML assessment.[103]

From a geochemical perspective, the most important consideration in designing a ST facility is the weathering behavior of the mine wastes, water infiltration into the stack, and resultant properties of the leachate and runoff. Typically, leachate and runoff are collected from around the ST facility and treated similarly to mine wastewater effluent from traditional operations. The design of ST from a geochemical perspective is rarely discussed in literature; therefore, this section discusses generally applicable recommendations for assessing the ARD/ML of any mine wastes, regardless of storage technique.

Assessing the geochemical behavior of tailings throughout their storage life requires consideration beyond testing the ore mineralogy. A few research groups have proposed testing flowsheets to robustly predict the ARD/ML behavior of ores.[111,112] Reliable tailings behavior assessment should consider the following steps:

1. Representative sampling at the mine site: sampling should be representative of all geological, lithological, and alteration units that affect the mine development plan. As sampling is critical for operational design choices it is its own field of discussion and is outside the scope of this review but is discussed elsewhere.[111,112]
2. Static geochemical tests and qualitative mineralogical assessment: Static ARD prediction techniques are critically reviewed by Parbhakar-Fox and Lottermoser (2015).[112] Acid−base accounting (ABA) is commonly used because it is rapid and cost-effective but has significant limitations and should only be used as a preliminary testing method.[112,115] Net acid generation tests provides an empirical estimate of the overall reactivity of the sample and is more representative of field conditions than the ABA test.[111] Acid buffering characteristic curve tests are recommended for nonacid forming samples.[116] Leachable metal testing (also known as deionized water leach testing) provides information on the short-term metal mobility within a sample. The amount of metal leached from mining and mineral processing wastes depends on the pH, reduction−oxidation potential, equilibration time, particle size, and liberation.[112] Several standard leach tests are used, including the Nevada Meteoric Mobility Procedure,[117] the U.S. EPA Toxicity Characteristic Leaching Procedure,[118] and the BS EN 12457 method.[119] Static geochemical tests only assess the potential of the ore or tailings for acid generation are not representative of any particular storage technique.
3. Kinetic geochemical tests and quantitative mineralogical assessments: kinetic ARD prediction tests simulate long-term weathering under accelerated laboratory conditions to indicate the rate of reactivity of minerals under conditions close to field conditions. The most widely recognized kinetic ARD prediction technique is humidity cell testing (ASTM D5744[120]). Others include kinetic net acid generation tests, Kappa tests, and column leach tests. Humidity cell testing might not reflect field conditions: leaching is conducted in regular cycles, and the leach cycles may remove reactive material that would not have been completely removed in the field.
4. Quantitative numerical modeling: QEMSCAN (quantitative evaluation of minerals by scanning electron microscopy) and mineral liberation analysis software programs can differentiate mineral grains based on their compositions even in fine-grained materials like tailings. Information like chemical composition, size, and shape is provided for each particle; as well, complex particles can be identified by their components. The use of automated mineralogy has significantly benefited the mining and mineral processing industry;[121] it is primarily used for

Table 8. Summary of Developing Technologies for Tailings Dewatering and Deposition and Their Current Technology Readiness Level (TRL)[123]

| Technology | Description | Current TRL |
|---|---|---|
| Gel membranes | Aluminum hydroxide polyhydrates act as secondary membrane on a retaining fabric; filtration achieved by mechanical straining and physical adsorption | TRL 3: Infancy: Proof of concept experiments |
| Superabsorbent polymers | Hydrophilic polymers that can adsorb fluids up to 1000 × their weight may be regenerated using a pH swing | TRL 3 and 4: Infancy: Lab-scale study and proof of concept<br>Cost is at least twice that of existing technologies[124]<br>More economic SAPs need to be synthesized for this technology to scale-up. |
| Volute screw press | Flocculated slurry flows into dewatering press under natural gravity conditions<br>Supernatant separation and sediment cake compression at the auger screw, which comprises volute plates<br>Axial compression obtained by circular end plate | TRL 5 and 6: Field tests |
| Electrokinetic dewatering | Application of electric field to aqueous suspension causes charged particles to move to electrodes of opposite polarity | TRL 6: Development phase: Scale up and field demonstrations Electrode corrosion remains a setback for application |
| Larger filter-presses | Addresses the limited filter plate area of most vertical filter press units by making the filter plates larger | TRL 6: Demonstration of a 3 m × 5 m filter plate performed in 2019[125] |
| Geotextile tubes | Flow of wastewater through long, cylindrical textile bags results in retention of solid particles inside the bag and allows clear water to pass out of the bag | TRL 7 and 8: Mature: Field trials and implementation stage. |
| Co-disposal and comingling | Include both waste rock and ST in the same storage facility, either by mixing before deposition or alternating layers of waste rock and tailings | TRL 8 and 9: Technologies such as mixed EcoTails currently being scaled up<br>Alternating layers of waste rock and tailings already in use |
| Flocculants | Particle aggregation via addition of organic polymers or other macromolecules | TRL 9: Technology proven in operational setting |
| Progressive reclamation | Landforms rehabilitated faster by beginning revegetation and cover of completed lifts during ST facility construction | TRL 9: Technology proven in operational setting |

mineralogy and metallurgical analysis but can also be of great benefit to ARD prediction. Dold (2017) recommended the use of QEMSCAN over static ARD prediction techniques due to their many problems and drawbacks.[115] Parbharkar-Fox (2017) has also recommended the use of QEMSCAN or mineral liberation analysis for ARD prediction.[122]

Developing a robust treatment strategy would be informed by the mineralogy of the ore body being mined, variations within the ore body, the processing methods and chemicals used, and the tailings storage method. Understanding the mineralogy and the ARD and ML potential and how this may affect the runoff and leachate is a well-established practice. However, the treatment required for each mine will be very site-specific, making it difficult to recommend design strategies that can be broadly applied.

## 4. FUTURE TRENDS AND NEEDS

**4.1. Emerging Needs.** ST technology has been in use for decades, but each site that has adopted the technology has devised their own solution, with little standardization or communication within the industry. While it has been proven at smaller scales, comprehensive and cost-effective solutions that accommodate larger throughputs are rare. To make ST feasible and accessible to companies, dewatering technology must be pushed forward, and the benefits for long-term closure need to be emphasized and explored. A concerted effort to standardize terminology and definitions is a necessary first step because it will make communication on the topic easier both within the industry and between the industry and public stakeholders.

One barrier to scaling up dewatering technology is the lack of an incentive to think beyond the calculated risk a given TSF presents for catastrophic failure. Ore processing innovation is driven by potential profits, and managing mine waste adds no value to the company as a corporate organism. Waste management only represents cascading liabilities that must be mitigated against or incur regulatory setbacks. Research and development of dewatering technologies will remain stagnant unless the individual pieces of the process can find use elsewhere (i.e., civil engineering in reclaimed wetlands or disturbed soils) or if the costs of operating a mine are significantly affected by tailings storage.

It is evident from this review that a combination of technologies for tailings dewatering and deposition needs to be developed (Table 8) to achieve the desired results, for example, flocculation followed by filtration or centrifugation followed by coagulation. Despite new technology and process development, implementation at the field level depends on the delicate balance between efficiency and economics. Laboratory-based technologies tend to be difficult to scale up because they are developed in a controlled environment with few independent variables, unlike the situation in the field. Current filter presses are limited by their need for constant preventive maintenance, use of consumables such as filter cloth, and high energy needs. Addressing any of these will represent important steps in improving tailings dewatering technology.

**4.2. Research Needs.** Published research studies, especially case studies, directly related to ST are relatively scarce. Among published studies that include ST, they are often considered a subcategory of thickened and paste tailings. The mechanics of unsaturated soils may adequately describe ST behavior, but aspects of tailings materials differ from regular soils and should be taken in account. The lack of research directed at ST opens the door for similar models to be used as proxies, which should be approached cautiously. For example, heap leach construction has many superficial similarities with ST: both are concerned about percolation of fluids through unsaturated, homogeneous bulk material built up in lifts. However, heap leaches generally use coarser material and are designed to encourage uniform flow of solution through as much of the heap as possible. By comparison, ST are generally finer, and the goal is to encourage preferential flow of liquid that avoids interaction with the bulk material.


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Fundamental research into failure modes for ST would greatly improve our knowledge of how, when, and where to implement these facilities. Failure modes of conventional tailings dams have been thoroughly explored and a similar understanding is urgently needed for ST facilities. As ST technology adoption moves toward more humid and/or seismically active areas, increased research on geotechnical failure modes is necessary. Understanding the liquefaction conditions would help improve initial designs and ensure safety parameters are sufficient to accommodate off-spec material and usual precipitation. Additionally, the behavior and stability of fine PSD ST facilities needs further research. As ST technology adoption moves toward a broader range of ore types, increased research on geochemical failure modes is needed. Significant innovation would be necessary to stack any sulfide containing tailings; this goes against industry best practices used for the past 50+ years to limit ARD by excluding oxygen. Additionally, the effect of flotation and dewatering agents on the geotechnical and geochemical stability should be researched. For example, could excessive flocculation agents cause gelling within the stack and lead to uneven consolidation? Or could the use of flotation reagents decompose into hazardous chemicals within the stack?

Ideally, the geotechnical stability would prevent all but the surface layers from interacting with the environment, but guaranteeing this is impossible. Deeper layers can easily be exposed by, for example, small scale circular failures in a lift or by excessive dusting and erosion. Dust generation, an existing challenge for tailings facilities, opens two broad research area needs for stacked tailings: one in relation to the amount and impact of dust generated by a stack on the surrounding environment and one in the ongoing development of dusting mitigation strategies. Stacked tailings may open entirely new avenues for failure or uncover ones which conventional tailings design once addressed.

**4.3. Lack of Consistency.** Concerns about nomenclature were raised in Section 2.1. It is worth noting that the term “dry-stack” describes a structure and “filtered” describes a process. The “tailings dewatering continuum”[22] accurately captures the idea that tailings dewatering must be designed to suit the mineralogy and ore processing steps that precede it at every operation. However, it leaves a lot of room for interpretation as to what “dry-stack” and “filtered” tailings are. In a climate where disastrous tailings dam failures are visible stains on the industry, this leaves an uncomfortably large arena in which unscrupulous actors who are eager to look socially and environmentally responsible can label their waste management systems as “filtered tailings” using a definition of unsaturated mine waste that suits them.

Even if failures of ST facilities are predicted to be extremely localized—resembling a circular slope failure—TSFs that contain off-spec material combined with loose definitions are, at best, confusing to those unfamiliar with the aims of the technology and, at worst, could further erode public and shareholder trust if the labels become attached to a large-scale failure. The mining industry tends to be comfortable operating out of the public eye and quick to point out that outraged laypeople are disingenuous about the source of the materials that contribute to their quality of life. Inconsistency in messaging around filtered tailings is bound to contribute to those feelings of derision and mistrust.

Consistency and more precise definitions will also have material benefits for an industry that continuously strives to improve its practices. They can improve communication between equipment designers, suppliers, researchers, corporate boards, and engineers trying to encourage their adoption. Being able to accurately describe what is meant by “filtered tailings” and having clear terminology around the construction and operation of these facilities will make the roles of researchers, engineers, and vendors easier in developing and promoting safer operations and in justifying higher capital and operating costs.

## 5. SUMMARY

A reliable supply of metals plays a critical role in ensuring the transition to cleaner sources of energy. While the demand for metals is increasing, the resource is limited, and the grade of ores is declining. This will translate into more ore being processed and finer grinding to liberate valuable minerals from the now-economical low-grade ores. The enormous volumes of tailings that will be generated need to be stored in a strategic manner while keeping the impacts of climate change in mind and avoiding tailings dam disasters. Disasters during the past five decades highlight the need for the mining industry to re-evaluate tailings storage techniques, preferably where most of the water is removed. At present, techniques like filtered “dry stacked” tailings are prohibitively expensive, but the reduction in tailings volume would make the TSF easier to remediate and more geotechnically stable for more sustainable storage.

Since thickened and paste tailings have lower solid weight percentages than ST, their transportation can be achieved using centrifugal or positive displacement pumps. ST need to be transported by conveyor belts or trucks. Construction of embankments in filtered TSFs cannot be eliminated, but their design can be greatly simplified as they are not principally water-retaining structures.

ST have no supernatant water and pose low risk of environmental catastrophe. The essence of successfully implementing these storage solutions lies in removal of water from the tailings. The fine-solid composition of tailings in addition to the surface chemistry, crystalline structure, surface charge, and swelling characteristics of clays makes dewatering a challenge. Many dewatering techniques have been investigated, and many more are being developed; however, the focus should shift to translating technology from the laboratory to the field scale. The use of flocculants is widespread, but research focus needs to shift to developing biobased flocculants that are inexpensive, biodegradable, and environmentally friendly (e.g., SAPs and electrokinetic dewatering). Technologies like the volute screw process and geotextile tubes have been shown to work at field trials, and their performance in large scale mining operations of nickel and copper should be the next focus of mining companies.

Moving to improve tailings dewatering technologies and storage techniques offers unparalleled research opportunities for environmental harm reduction, as the tailings produced in global metals production are a massive and predictable threat to sensitive ecosystems worldwide. Tailings disasters displace or kill populations near them, and a concerted effort to eliminate the major risks involved in tailings storage is an important step toward mending relationships and societal good-will.


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## ■ ASSOCIATED CONTENT

### Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsestengg.1c00480.

Additional details regarding transportation of dry-cake tailings (PDF)

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### Notes

The authors declare no competing financial interest.

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