Surface-Placed Cemented-Paste Tailings

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Introduction

Surface placement of cemented-paste tailings is an innovative and logical application of two proven technologies: cemented-paste tailings backfill and surface placement of paste tailings. This approach reduces the long-term risks associated with tailings dams (subaqueous tailings impoundments), and lessens potentially unfavorable environmental conditions observed in traditional tailings facilities, such as dust and water quality impacts. Although this technology has not yet been implemented at the facility scale, studies of surface placement of cemented-paste tailings began in the early 2000s. Critics within the mining industry claim that adding cement to paste tailings in a surface facility creates unnecessary expense, yet the benefits of this tailings management strategy are increasingly clear. The United Nations recently published a rapid response assessment to mine tailings storage and recommends that tailings facility design objectives be raised to the level of “zero-failure” (“Mine Tailings Storage: Safety is No Accident.” Roche et al., 2017).

The utilization of cemented-paste tailings in a surface facility, while acknowledged as a very expensive approach, is the highest level of tailings safety management and goes well beyond the recommendations of the 2017 United Nations report. This adaptation of proven best management practices culminates in an industry-led approach to responsible resource development.

Effective tailings management requires consideration of operational design constraints, environmental protection, regulatory requirements, short- and long-term economics, and social expectations, as well as closure and remediation options. Public perception has recently been influenced by catastrophic failures of subaqueous tailings facilities, which have received much more attention than their far more abundant, properly-functioning counterparts. As a result, there is an increasing demand for proactive and innovative design to prevent such incidents (Bowker and Chambers, 2017; Commonwealth of Australia, 2016; Franks et al., 2011; Roche et al., 2017; Schoenberger, 2016), which are commonly associated with mismanagement of operational water balance (Adiansyah et al., 2015; ICOLD, 2001).

¹ This report was written as a part of ongoing work for the Black Butte Copper Project.
Although most surface tailings storage facilities are safely designed and operated, maintaining social license to operate into the future requires that the mining industry consider improved strategies for surface tailings placement. Innovative techniques for tailings management have been proposed (Barrera et al., 2015; Böhm et al., 2005; Commonwealth of Australia, 2016; Davies et al., 2010; Edraki et al., 2014), including placement of paste tailings in surface facilities, which has been implemented at a select number of mines. More recently, cemented-paste tailings have also been proposed for surface placement, to reduce potential flow, reactive surface area, and dust generation.

**Background**

*Acid rock drainage*

Acid rock drainage (ARD) is a common problem for mining of sulfide-bearing rock, where extraction and crushing of rocks exposes new mineral surfaces to oxidative weathering and dissolution. The oxidation of sulfide minerals (e.g. pyrite) by oxygen in the presence of water releases acid, rust-forming iron and sulfate salts. Once water is acidic, accelerated weathering of minerals can lead to metal release and accelerated oxidation. Some metals and metalloids can persist at neutral pH, also impacting downgradient water quality.

Tailings is the material remaining after ore has been processed to remove the targeted mineral, e.g. copper. Tailings are finely-ground to maximize recovery of the desired mineral, and therefore have a high surface area available for weathering via reaction with water and oxygen. The water management of tailings facilities is a significant aspect of mine operations that extends through the life-of-mine, well into closure. Minimizing reactive surface area reduces reaction rates and the potential for ARD and other water quality impacts.

**Tailings Management**

Mining technology evolves continuously through incorporation of advances in engineering and environmental management. Not unlike technological advances observed in vehicles or personal computers, the 21st century mine is barely recognizable next to its counterpart from the previous century. Although these advances have led to global innovation in operational design and management strategies, selection of tailings technology varies greatly with site-specific variables. Current tailings management practices can be generally categorized by tailings properties and methods for containment of tailings.

Tailings are produced as a slurry. They can be thickened to reduce water content prior to placement in three types of tailings: thickened, paste, and filtered, which vary in solids content. Other variables, such as particle size, also influence classification (Ercikdi et al., 2017). Slurry has the highest potential to flow
with gravity, but “thickened” tailings can as well. Conversely, filtered tailings are too dry to flow, even under pumping pressure, and must be transported mechanically with trucks or belts.

Paste tailings, defined by flowability based on a solids content which is unique for each particle size distribution, can flow with the application of pressure, much like cake-frosting which only flows out of a tube onto a cake under pressure. For paste tailings, this means that positive pressure pumps and appropriate pipeline designs are required to transport the material for placement. Paste tailings also do not segregate (by particle size) when placed, and admixtures and binders can be added to increase flowability or strength prior to placement underground as backfill or in surface facilities.

Binders are materials added to paste tailings which have cementitious properties that make the cured cemented-paste tailings stronger. Portland cement has been most frequently used, because it has very good binding capabilities. However, economic considerations, benefits of circular economy, and the unique chemistry of tailings often leads to use of a combination of binders. Other materials used in binder mixes include fly ash from coal-fired power plants, slag from smelting, clay, as well as newer, less-tested materials discussed below. Admixtures are another class of materials added to cemented-paste tailings that increase the utility of the mixture. For cemented-paste tailings, admixtures are used to improve flowability for transport.

**Current State of Knowledge**

The merit of adding binders to tailings in order to increase strength of the cured paste in backfill is well-established (Tariq and Yanful, 2013; Ercikdi et al., 2017). Placement of non-cemented paste tailings in surface impoundments is a well-studied and increasingly common technology. Each of these styles of tailings management offers distinct benefits that have been generally accepted, yet placement of cemented-paste tailings in surface impoundments has been limited, largely due to cost.
A review of the current-state-of-knowledge for each of these technologies demonstrates that the application of cemented paste tailings in a surface impoundment is an innovative and effective use of proven technologies. The following discussion reviews the benefits and limits of the established technologies as applied in active mining operations and summarizes recent research.

**Cemented-paste tailings backfill**

*Benefits and limitations of cemented-paste tailings backfill*

Cemented-paste tailings backfill technology was used as early as 1957 (Tariq and Yanful, 2013) and revolutionized mining. Today, it is a common method for underground tailings placement: as of 2010, at least 100 facilities were reported to employ paste or cemented-paste backfill techniques (Yumlu, 2010), and that number has undoubtedly risen. A range of materials can be placed as fill, including waste rock, paste tailings, and cemented-paste tailings, using a variety of binders. Widespread placement of cemented-paste tailings as underground backfill has well documented benefits, but also some limitations.

As a result of the broad acceptance of cemented-paste tailings backfill technology, the current understanding of this tailings management strategy is well documented for active facilities and has been thoroughly explored in recent research. Case studies of the use of cemented-paste tailings backfill are available (e.g. MEND, 2006) and not repeated here. This review describes current goals for improved application of this technology and does not attempt to provide an exhaustive summary of cemented-paste tailings backfill research and applications.
### ADVANTAGES

**Operational**  
- No need to separate coarse and fine tailings fractions  
- Fewer tailings placed at surface  
- Smaller surface impoundment  
- Simplified operational management of surface facility  
- Risk of catastrophic failure lower due to smaller size  
- Allows “drift and fill” mining method (creates structurally stable floors, walls, and roofs to mine around, increasing access to mineral reserves)  

**Safety**  
- Prevents collapse of native rock underground or subsidence to surface

**Water Usage**  
- Allows for greater reuse of process water  
- Less free water/leachate from underground backfill and smaller surface facilities requiring water treatment

**Geochemical Considerations**  
- Fills voids and cracks and bonds to natural rock reducing oxidative weathering of rock surfaces  
- High moisture retention in pores of backfill reduces oxygen diffusion  
- Consistently low hydraulic conductivity of backfill means water flows around, rather than through backfilled cemented-paste tailings  
- Flooded underground at closure leads to lower oxidative weathering of tailings  
- Neutralizing binders may decrease acidic conditions in low-sulfide tailings

### DISADVANTAGES

**Operational**  
- Cost of implementation  
- Plant and pumping costs  
- Binder cost  

**Safety**  
- Site-specific binder selection and amount requires custom design and testing to optimize strength and reduce sulfate attack.  

**Water Usage**  
- Potential for backfill collapse when using underhand cut-and-fill (can be mitigated with higher cement addition).

### LIMITATIONS

- Requires underground stopes for placement  
- Must be combined with surface disposal methods

- Cemented backfill is less reactive, but not inert.  
- Neutralizing binders have little impact on acid generation potential in high-sulfide tailings  
- Long term geochemical stability in high-sulfide tailings uncertain due to oxidative weathering within the backfill.

*After Ercik et al., 2017, MENO, 2006*
**Research on cemented-paste tailings backfill**

Current research on cemented-paste tailings backfill is focused on optimizing operational use of this technology, investigating influences on backfill strength, and evaluating geochemical characteristics and methods. The technical program for the 12th International Symposium on Mining with Backfill (SME, 2017) presents an overview of these current topics in backfill research. Specific topics covered in recent peer-reviewed literature include evaluations of binder types and content; influence of particle and pore sizes on strength; the influence of temperature on strength and reactivity; and geochemical studies.

Tariq and Yanful (2013) conducted an extensive peer-review of research on various binders used with paste tailings and concluded that the use of Portland cement as a sole binder is both unsuitable for sulfidic tailings and not cost effective. Rather, the inclusion of pozzolanic material, such as fly ash or slag, with the cement improves strength and reduces negative risks of internal disaggregation due to recrystallization of sulfate minerals (also known as “sulfate attack”). The benefits of this binary approach to binder mixing were confirmed by Yilmaz et al. (2015), who reported that cemented-paste containing slag binders performed better, with respect to consolidation, than paste with Portland cement alone or Portland cement with fly ash.

In their 2013 review, Tariq and Yanful suggest that laboratory-based research into the use of innovative materials and more complicated binder mixes (e.g. with more than two components) is likely to increase, which will lead to greater flexibility in tailings design and may reduce the cost associated with cemented-paste tailings. Indeed, more recent publications demonstrate successful use of innovative binders including phosphogypsum and phosphate tailings, calcined hard kaolin, and superplasticizers (Chen et al., 2017; Zheng et al., 2017; and Mangane et al., 2018, respectively).

Chen et al. (2017) found that phosphogypsum and phosphate tailings, which are waste streams from industrial processes and phosphate mining, were not suitable binders on their own, but worked well in concert with Portland cement and lime addition. Zheng et al. (2017) investigated characteristics of cemented-paste mixtures made with varying proportions of calcined hard kaolin and Portland cement. Their research showed that use of 30% calcined hard kaolin and 70% Portland cement led to increased strength over time and less expansive formation of gypsum than with Portland cement alone.

Superplasticizers are chemicals that are added to cement mixes to improve workability (e.g., flowability) under lower water content, which is important for placement of cemented-paste tailings. Mangane et al. (2018) evaluated five different superplasticizers as admixtures to cemented-paste tailings with mixed binders of Portland cement and slag. All five superplasticizers allowed lower water content and higher workability without compromising general strength. However, they varied in workability timeframe (how quickly the material must be placed) and long term strength. This study clearly showed that polycarboxylate performed the best in terms of low water content and strength, and allowed use of lower overall binder content, which indicates possible economic benefits.

Particle size plays an important role in the properties of pasted-tailings and their interaction with binders. Yang et al. examined feasibility of super-fine tailings for placement as cemented-paste backfill and demonstrated techniques for optimizing solid content of superfine cemented paste tailings to enhance
flow characteristics and strength at contacts with non-cemented paste backfill. They demonstrated successful use of super-fine tailings in subsidence control with numerical modeling and showed that their placement in cemented-paste backfill is feasible.

Pore size and structure within cemented-paste tailings is intrinsically linked to the strength of the material and under certain conditions, influences the long term stability of the cured material. Sun et al. (2017) uniquely applied an X-ray CT scanning technology to evaluate the evolution of pore structures during compression testing. They demonstrated the application of CT Scanning technology for this purpose while defining the microstructural mechanisms that can lead to macroscopic failure of cemented-paste tailings in backfill. The authors propose to account for diversity in chemical composition and particle size in tailings from different sources, in future studies.

Mine location and hydration of cemented-paste tailings during curing influence the temperatures and therefore the strength of these materials. Current research includes detailed investigations of curing temperatures and climate influences on cemented-paste tailings backfill. Aldhafeeri et al. (2016) found that atmospheric and curing temperatures have different effects on the reactivity of three types of cemented-paste tailings with multiple controlled pyrite proportions (5, 15, and 45%). These tests showed lower reactivity in samples cured at higher temperatures, with some additional influence by pyrite. However, in samples cured at room temperature, higher ambient temperatures during oxygen consumption testing led to higher reactivity of the samples, particularly in early stages of curing. In a complimentary study, Cui and Fall (2016) reported that higher initial temperatures of cemented-paste tailings influenced various factors of curing and thereby increased the strength of the backfill.

Another study investigated the effects of freezing on cemented-paste backfill (Jiang et al., 2017). These authors conducted a column experiment with artificial tailings, and concluded that cemented-paste tailings backfill cured under freezing conditions exhibited high strength, due to ice formation within the matrix of the cemented-paste. However, this study did not address the strength of this material if thawed. All of these studies investigating temperature were conducted using Portland cement as the sole binder. Additional work is therefore needed to study these temperature effects with increasingly common, complex binder mixes.

Many of the environmental benefits of cemented-paste tailings backfill result from alteration of tailings geochemistry following thickening and binder addition. A great deal of research has been conducted on this topic. Multiple overview publications discuss the influence of sulfide minerals on the reactivity of the cemented-paste backfill (MEND, 2006; Alakangas et al., 2013). However, due to the high variability in mineralogy and particle size distribution, more recent publications regarding geochemistry of cemented-paste tailings backfill tend to be more site-specific. For example, Hamberg et al. (2015 and 2017) investigated the influence of reduced binder content and reduced water content on arsenic release from cemented-pastes of tailings at a Finnish gold mine. The results demonstrated that, for these particular tailings, placement as cemented-paste backfill increased arsenic mobility compared to that observed in non-cemented tailings. This was true regardless of binder content and water saturation level, and may reflect the enhanced mobility of arsenic at neutral to alkaline pH.
Yilmaz et al. (2014a) investigated the effects of curing cemented-paste tailings under pressure on a variety of characteristics, including geochemistry, using three binder proportions and three curing times. The results of this study indicated that longer curing time was effective at reducing sulfate release by the materials used in this study.

With respect to advances in cemented-paste tailings backfill geochemistry, recent research includes development of improved testing methods that can be more broadly applied to a variety of sites. For example, Moran et al. (2013) published findings from a comparative study and concluded that application of ASTM 1308 diffusion test method was an effective tool for predicting the diffusion of constituents from saturated cemented-paste tailings backfill (i.e. post-closure). In 2016, Schafer presented findings from an evaluation of Leaching Environmental Assessment Framework (LEAF) method for use in predicting environmental impacts of cemented-paste tailings backfill at the International Mine Water Association conference (Shafer, 2016). Conclusions from this study included assessment that the LEAF methods were suitable for providing necessary information for geochemical predictions, and in particular, the diffusion test method (comparable to those recommended by Moran et al., 2013) was most-representative of intact cemented-paste tailings.

Research focused on geotechnical optimization includes investigation of strength at the interface of cemented-paste backfill and natural rock surfaces. (Koupouli et al., 2017) concluded that roughness of the rock surface had a greater influence on strength than curing time. Also, rheology (or flowability) studies of solid content optimization have evolved (Yin et al., 2012), allowing development and testing of a model for predicting rheology of cemented paste backfill (Lang et al., 2015). With respect to safety, Lu and Fall (2017) tested a model using lab and field blasting experiments to predict liquefaction of freshly-placed cemented-paste backfill during operations. Liquefaction occurs when an otherwise solid material, usually partially saturated with water, loses strength and flows like a liquid. Their results showed that only the upper portions of freshly placed backfill exhibit potential for liquefaction. Been et al. (2002) conducted a study of the minimum proportion of cement required to prevent liquefaction of cemented-paste tailings backfill at the Neves Corvo Mine in Portugal, and concluded that the minimum content must be greater than 1% to prevent liquefaction.

Extensive laboratory studies and anecdotal case studies exist documenting the implementation of cemented paste tailings as backfill. However, in situ tests of existing cemented-paste tailings backfill, which confirm and extend lab-scale testing, is more limited due to the relatively recent use of this method. Following the 2014 collapse of a cemented-paste tailings backfill at the Lucky Friday Mine in Idaho (resulting from underhand cut-and fill mining methods), Johnson et al. (2015) published an evaluation of strength and elastic testing methods. This work was followed-up with placement of in situ instrumentation to provide timely information about the stability of the backfill as operations continue.

Two stopes in the Cayeli mine in Turkey were outfitted with in situ instrumentation for monitoring of stress loads and temperature in the backfilled materials and the barricades (Karaoglu and Yilmaz, 2017). This in situ monitoring was conducted using two tailings materials (clastic and spec) and varying binder contents. Results demonstrated that the temperature and strength of the cemented paste backfill were influenced by stope size and by the character of the original tailings material.
Another study by Le Roux et al. (2005) documented comparisons between lab-scale and in situ data from the Golden Giant Mine in Ontario Canada. This study identified challenges in obtaining suitable field samples from backfilled material. They identified greater variability in the properties of field samples compared to lab samples and determined that lab-scale strength tests were conservative.

**Surface-placed paste tailings**

_Benefits and limitations of surface-placed paste tailings_

Paste tailings are increasingly placed in surface facilities. This placement is distinct from conventional subaqueous tailings placement, because the paste tailings are not submerged in water, but are allowed to weather subaerially. Despite the exposure to air, the low permeability of paste tailings limits oxidative weathering. Surface placement of paste tailings was patented in 1996 (Brackebusch, 1996), but the first operational use did not occur until 2003. Subsequent application of this technology has shown that it can be tailored to fit site-specific geotechnical and environmental requirements, and may offer an innovative way to enhance economic efficiency and mine sustainability (Alakangas et al., 2013; Simms, 2017, Williams et al., 2008; Wu et al., 2011).

These limitations and benefits are distinct from those reported for cemented-paste backfill. For instance, this technology can be implemented for open pit or underground mines. Williams et al. (2008) point out that while seepage from surface-placed paste tailings is extremely unlikely, because they have very low hydraulic conductivity by design, any potential seepage to groundwater could be mitigated with the use of clay or synthetic liners.

Furthermore, surface-placed paste tailings do not require binder, thereby reducing associated costs. Despite the benefits of placing paste tailings in surface facilities, a few problems with engineering of surface paste placement facilities persist. These include over-topping, erosion of paste within the facility (which increases pressure on dams), and potential for static liquefaction accompanied by static or seismic slope instability.
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<td>Capital costs</td>
<td>Facilities not designed to store significant water, so requires separate system for storm water collection and treatment</td>
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<td>No need to separate coarse and fine tailings fractions</td>
<td>- Plant and pumping costs</td>
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<td>Can be implemented at open pit or underground mines</td>
<td>Requires consistent placement to prevent increased weathering of surface</td>
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<td>Requires different slope/dam design considerations</td>
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<td>Simplified management of operational water balance</td>
<td>Site-specific characteristics do not always allow for adequate paste generation and may require continuous optimization</td>
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<td>Lined facility possible as additional environmental safeguard</td>
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<td>Lower risk of dust generation</td>
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<td>Increased durability of paste compared to conventional tailings</td>
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<td>Reduces risk of catastrophic failure</td>
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<td>Earlier closure construction activities</td>
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<td><strong>Water Usage</strong></td>
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<td>Allows for greater reuse of process water</td>
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<td>Less free water/leachate from facility requiring water treatment</td>
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<td><strong>Geochemical Considerations</strong></td>
<td>Consolidated paste is less reactive but not inert.</td>
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<td>High moisture retention in pores of paste slows oxidative weathering under subaerial placement</td>
<td>Erosion of paste surface in facility can cause increased reactivity, sediment deposition against dam, and dust generation</td>
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<td>Little-to-no free water draining from paste</td>
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<td>Consistently low hydraulic conductivity means less reaction with precipitation</td>
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After Basotel et al., 2017; Dirk et al., 2016; Fourie 2012 MEND, 2017
Active Facility Descriptions

Placement of thickened tailings in surface facilities is relatively common, and as a result of developing terminology, such facilities are often (erroneously) listed as surface paste facilities. Placement of true paste tailings in surface facilities has been documented at the following locations:

- Bulyanhulu, Tanzania
- Neves Corvo, Portugal
- Myra Falls, B.C., Canada
- New Jersey Mining, Idaho, USA
- Cobriza, Peru

The Bulyanhulu Mine is an active gold mine in Tanzania, which was the first to implement surface-placement of paste tailings. An initial report of surface paste facility design and implementation for this well-studied facility was published in 2003 (Theriault et al., 2003). The findings demonstrate that addition of the paste in thin lifts, with a maximum thickness of 30 cm, allowed for sufficient desiccation (drying) to provide required geotechnical stability. Furthermore, continuous application of these lifts on a 5-day deposition cycle prevented oxidative weathering of exposed surfaces. The authors noted erosion within desiccation cracks, and observed that when the paste materials were physically disturbed, they became unstable and lost geotechnical and environmental benefits. This facility has also been the subject of numerous studies, and is generally considered a successful facility (Shuttleworth et al., 2005; Simms et al., 2005 and 2007; Theron et al., 2005).

In 2010, Neves Corvo, a copper-zinc mine in southern Portugal owned by Somnicor (a subsidiary of Lundin Mining), converted their tailings facility from a sub-aqueous to a sub-aerial, surface paste tailings operation. Significant research was invested in development and design for a successful facility, including a feasibility study, laboratory- and field-scale testing followed by implementation of a pilot-scale paste plant and continuous monitoring of the active facility (Newman et al., 2004; Verburg and Oliviera, 2016). Despite the high-sulfide content of these tailings, which indicates potential for high environmental risk, results of these studies demonstrate the reliability of lab- and field-scale methods for predicting the minimized acid generation potential of low-permeability sulfidic paste. The success of this facility is described by Lundin Mining, in plans for life-of-mine expansions which involve increasing the surface tailings facility by 25 hectares (Lundin, 2016 and 2017).

In North America, two operations using surface paste placement are known to exist: the Myra Falls Mine in British Columbia, Canada operated by Nyrstar and the New Jersey Mill in Kellogg Idaho, USA operated by New Jersey Mining Company. The Myra Falls Mine is located in the Strathcona-Westmin Provincial Park on Vancouver Island, British Columbia, an environmentally sensitive location. Two tailings disposal facilities (TDFs) exist at this site, both of which incorporate unique application of paste technology (Nyrstar, 2014; MEND, 2017). The “Old TDF” was originally a conventional subaqueous surface facility with tailings separated by particle size and placed behind a constructed berm. However, beginning in 2003, a new cell was constructed within the Old TDF for placement of paste tailings. This paste placement increased storage capacity in the Old TDF, by allowing use of steeper slopes, but ceased in 2011 when the capacity of the new cell was reached. Reclamation plans for this facility are currently under review.
Freed et al. (2012) summarized monitoring and modeling efforts in support of closure planning. This study included sampling of monitoring locations around the Old TDF and modeling of flow paths using historic monitoring data. Finally, they present an overview of the closure plan, involving various types of cover to prevent infiltration in strategic locations.

The second surface facility at the Myra Falls Mine, called the Lynx TDF, is a former open pit. Placement of paste tailings in this facility began in 2008. Paste placement was chosen for this facility to reduce the risk of tailings inflow into connected underground workings. To further safeguard nearby active workings, the initial lifts were placed as a cemented paste tailings plug. Subsequent lifts of non-cemented paste tailings were placed in the Lynx TDF. All future tailings are proposed to be placed as backfill, which will allow concurrent closure of surface facilities while mining continues (Nyrstar, 2017).

A third party review of possible tailings dam breach scenarios for this site indicated that the most likely mechanism for failure would be liquefaction of the pasted tailings as a result of seismic activity (BGC Engineering, 2014). Erosion of the paste tailings surface within the Old TDF was noted, creating a need to improve stability of the embankment during closure. A rock layer was used to remedy erosion prior to closure. Some surface erosion was also noted in the Lynx TDF.

The New Jersey Mill is located in Kellogg, Idaho and is operated by New Jersey Mining Company. Grant Brackebusch described the two ore processing streams for the paste tailings production in a 2014 publication (Brackebusch 2014). The Idaho Department of Environmental Quality issued the New Jersey Mill an award for their surface paste facility. The award highlighted the reduction of risk to nearby surface water due to the lack of water retention in facilities onsite (IDEQ, 2014). Furthermore, water is mostly recycled into the processing stream rather than being placed with tailings in the surface facility.

Another documented facility is the Cobriza Mine, an underground copper mine in Peru that began placement of paste in a surface facility in 2004. Publically available information for this zero-discharge tailings facility documents improved the operational safety and success in tailings storage (Gonzales, 2005).

Numerous publications document placement of paste tailings in surface facilities with varying degrees of uncertainty about the actual implementation. Hohne et al. (2004) documented placement of paste tailings in an open pit at the former De Beers Mine in Kimberley South Africa, which is currently owned by Petra Diamonds and Ekapa Mining. This report indicates successful placement of paste in the former pit, following reprocessing. However, a later publication, refers to these materials as “highly thickened” leaves uncertainty about whether materials placed in the pit were true paste tailings. The Pajingo Gold Mine in Queensland Australia was noted as having a paste operation for placing paste in a former open pit (Williams et al., 2008), though more recent discussion of this facility has not been identified. Barrera et al. (2015) also noted implementation of surface-placed thickened and/or paste tailings in Chile, but details were not provided for these facilities.
Research on surface-placed paste tailings

In addition to application of pasted tailings in the aforementioned facilities, the placement of paste tailings in surface facilities has been extensively investigated for more than 20 years. The most recent publications on surface-placed paste tailings generally focused on flow characteristics and geochemical performance.

Bryan et al. (2010) investigated the influence of surface crack formation on sulfide oxidation in paste tailings and the influence that multilayer deposition has on the drying of freshly-added layers of paste tailings. They concluded that, despite the increased surface area available for oxidative weathering along cracks, no significant difference in sulfide oxidation was measured. Furthermore, they predicted that dry, underlying layers of paste tailings in a surface impoundment would lessen the drying of freshly-applied layers, and that this effect could be prevented by application of sand layers as capillary breaks. More recently, Bascetin et al. (2018) evaluated the influence of crack formation in a lab-scale test of surface paste of geochemical parameters within a broader ongoing research program. This study was the most recent of many conducted by this research group (Bascetin et al., 2013 and 2014).

Ozdemir et al. (2016) presented the results of their rheological study of paste tailings specific to surface placement at the 2016 SME meeting. Their study confirms that yield stress can be adequately predicted from slump tests, which are easily implemented and important in predicting consistency of a paste for pumpability.

In 2017, Bascetin et al. (2017) published a comprehensive review of characteristics important to paste tailings placed at the surface, in which they detail methods for testing and predictions. This review includes details of investigations using surface placement of paste tailings. They conclude that although surface placement of paste tailings provides economic and environmental advantages over other tailings management strategies, more information on geochemical and geotechnical performance at field-scale is required to better-define appropriate application of this technology.

Surface-placed cemented-paste tailings

Benefits and limitations of surface-placed cemented-paste tailings

While no single technology can address environmental concerns for tailings management at all facilities, addition of binders to paste placed in surface facilities could reduce or eliminate the dominant concerns of surface placement of paste tailings. Interest in placement of cemented paste tailings in surface facilities has been documented as early as the late 1990s (Cincilla et al., 1997), and the technology has been the topic of research for more than 15 years. However, it has only been partially implemented at the facility scale at a single known facility.

Economics are the primary argument against merging the two technologies of cemented-paste tailings backfill and surface placed paste tailings. Critics consider the added benefits from binder addition to paste placed in surface facilities to be too small in comparison to the additional cost incurred.
**Active Facility Descriptions**

The only documented application of surface placement of cemented-paste tailings is in the initial lifts of the Lynx TDF at the Myra Falls Mine. Anecdotal evidence of another application of this technology has been identified in Spain, but cannot be confirmed.

This technology was implemented at the Myra Falls Mine to form a foundation for subsequent placement of paste tailings in the Lynx TDF. Details are provided above in “Surface-Placed Paste Tailings: Active Facility Descriptions.” Initial deposition in the pit consisted of cemented paste tailings to eliminate an element of risk that could not be addressed by paste alone.

**Research on surface-placed cemented-paste tailings**

Researchers at University of Quebec-Abitibi have conducted a number of well-designed studies into the various aspects of placing cemented paste tailings in surface facilities, some of which are described here. These include development of a lab-scale method for testing surface deposition, evaluation of geochemical properties in response to binder proportions, and desiccation crack formation (Benzaazoua et al., 2004; Deschamps et al., 2008; Deschamps et al., 2011; Icharak et al., 2016). Other research groups have investigated binder types, climate effects, or compared the geochemistry of cemented and non-cemented paste tailings (Dinis et al., 2016; Liu et al., 2016; Seipel et al., 2017; Verburg, 2001).

In 2001, Verburg published a summary of the proposed benefits of paste technology which specifically address the use of binders for geotechnical reasons that also provide environmental benefits. This report also summarizes lab- and pilot-scale test methods for predicting geochemistry of surface paste placement are also relevant to characterization of cemented paste placed at the surface.

Benzaazou et al. (2004) described a lab-scale method that simulated *in situ* surface placement of cemented-paste tailings. Their study included evaluation of deposition, as well as basic geochemical parameters. The outcome of this study yields a well-documented lab-scale design for testing cemented-paste placement in facilities, as well as the general conclusion that addition of Portland cement reduced reactivity, despite the formation of cracks.

In 2008, Deschamps et al. conducted a series of 30-week layered column leaching tests using varying proportions of Portland cement as a binder in sulfidic paste tailings. Their study included micro-scale investigation of porosity and surface area, as well as some geochemical characteristics. Overall, they determined that addition of modest amounts of Portland cement was an effective way to stabilize sulfide minerals in a surface placement scenario. Interestingly, this study support intermittent addition of binder at modest proportions over continuous addition of low proportions of binder. Although this is promising research, it remains to be seen whether use of more complicated binder mixes yields different results.

Following the 2008 column study, Deschamps et al. (2011) published initial results of a long term study of lab-scale surface-placed cemented-paste tailings, which were placed in strategic layers within layers of paste tailings using the test apparatus described in Benzaazou et al., 2004. The authors observed that the pH did not drop despite the development of preferential oxidation paths and persistent desiccation cracking.
<table>
<thead>
<tr>
<th>ADVANTAGES</th>
<th>DISADVANTAGES</th>
<th>LIMITATIONS</th>
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<tbody>
<tr>
<td><strong>Operational</strong></td>
<td><strong>Cost of implementation</strong></td>
<td>Facilities not designed to store significant water, so requires separate system for storm water collection and treatment</td>
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<td>No need to separate coarse and fine tailings fractions</td>
<td>- Plant and pumping costs</td>
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<td>Can be implemented at open pit or underground mines</td>
<td>- Binder cost</td>
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<td>Requires less strength than backfill placement</td>
<td>Requires consistent placement to prevent increased weathering of surface</td>
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<td>Binder proportion can be varied throughout operations to meet project needs</td>
<td>Requires different slope/dam design considerations</td>
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<tr>
<td>Simplified management of operational water balance</td>
<td>Site-specific characteristics do not always allow for adequate paste generation and may require continuous optimization</td>
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<tr>
<td>Lined facility possible as additional environmental safeguard</td>
<td>Binder selection and amount are site-specific</td>
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<tr>
<td>Extremely low risk of dust generation</td>
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<tr>
<td>Increased durability of paste compared to conventional tailings steeper placement slopes, and smaller facility footprint</td>
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<td>Extremely low-to-no risk of catastrophic failure</td>
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<td>Earlier closure construction activities</td>
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<tr>
<td><strong>Water Usage</strong></td>
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<td>Allows for greater reuse of process water</td>
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<tr>
<td>Less free water/leachate from facility requiring water treatment</td>
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<tr>
<td><strong>Geochemical Considerations</strong></td>
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<tr>
<td>High moisture retention in pores of cemented-paste minimizes oxidative weathering under subaerial placement</td>
<td>Consolidated cemented-paste is less reactive but not inert</td>
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<tr>
<td>Little-to-no free water draining from cemented-paste</td>
<td>Neutralizing binders have little impact on acid production in high-sulfide tailings</td>
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<tr>
<td>Extremely low hydraulic conductivity means less reaction with precipitation</td>
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<tr>
<td>Neutralizing binders may decrease acidic conditions in low-sulfide tailings</td>
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After Barcelo et al., 2017; Ercokol et al., 2017; Foust 2014 MENO, 2017
Ichrak et al. (2016) continued this study with addition of a final cemented-paste layer and application of seven wetting and drying cycles. Furthermore, they conducted post-test examinations of the microstructure within the layers using destructive sampling techniques. These results indicate that drying of deeper layers of paste tailings appears to have been inhibited by addition of a final cemented-paste layer. The authors note that desiccation cracks appeared on the final cemented-paste layer 6 hours after placement. However, they note that this layer was only 4 cm thick, which may influence the observed desiccation and crack formation.

Dinis et al. (2016) conducted a study of the short-term leachate and mechanical properties of surface paste with coal ash (a pozzolanic binder material). There results indicate a decrease in compressive strength as a result of coal ash addition. However curing time, which has a strong influence on strength, was not documented, so no conclusions can be drawn from this aspect of the study. The inclusion of short term leachate chemistries does indicate that coal ash reduced weathering, and therefore prevented increases in electrical conductivity that were observed in the tailings-only control. Finally, fly ash was found to be a superior additive to bottom ash, which has a lower pH and also yielded poorer compression test results.

Liu et al. (2016) showed that cemented-paste tailings in a surface facility is feasible in a tropical climate. This study reviewed optimum binders and erosion in response to heavy rainfall. The results of this research show that the right proportion of clay, which absorb excess moisture, and Portland cement had sufficient flowability and strength for surface placement, and erosion was minimized after only 6 hours of curing. The authors plan to continue research and include geochemical analyses in future work. This study is particularly interesting, because it addressed erosion with the application of binders, which could be implemented in any climate to mitigate erosion from other surface disturbance, such as wind, thereby reducing risk of dust generation or re-deposition of particles against a dam.

Seipel et al. (2017) conducted a series of geochemical tests of high-sulfide tailings, showing that addition of binders (Portland cement and fly ash) decreased the reactivity of the tailings. The results of this study demonstrated the influence of reactive surface area on the leachate chemistry and agree with other research indicating that consolidated cemented-paste tailings are less reactive than non-cemented paste tailings.

At the pilot-scale, Yilmaz et al. (2014b) investigated the effects of a cemented layer in the lower portion of an otherwise-not-cemented paste surface deposition facility. Because this study was meant to address transition of an active, traditional tailings impoundment to a surface paste disposal facility, the underlying material in both cells was tailings slurry. Subsequent layers consisted of paste tailings. They use two field cells- one using cemented-paste for an initial paste layer followed by nine non-cemented, or plain, paste; and the other cell consisted of ten plain paste layers. Specifically, they investigated matrix suction and volumetric water content, and cracking. This study was largely an investigation of paste (not cemented-paste), yet the results show that addition of cement to at least some layers led to decreased matrix suction and more, yet smaller cracks. These authors recognize that they did not address the geochemical outcomes of their study in this publication and they propose to do so along with other various mineralogical evaluations of these field cells.
Conclusions

Based on the current state-of-knowledge about existing facilities and results of targeted research, integration of the two technologies: (1) cemented-paste tailings backfill, and (2) surface-placed paste tailings provides a promising avenue to reduce environmental liability and improve social license to operate. Adoption of further strategies with added cost requires adequate evidence of benefit, which can only be obtained as this technology is demonstrated. Thorough analysis of the life cycle cost-benefit of cement addition to paste tailings is warranted. Available research combined with extensive in situ demonstration of cemented-paste tailings backfill and surface-placed paste tailings strongly supports the merging of these technologies. Certain limitations of these two well-documented technologies can be addressed by their integration.

Widespread implementation of cemented-paste tailings placement in surface facilities is limited by insufficient long-term evidence of predicted benefits, as well as a lack of defined testing framework for generating reliable predictions of performance in support of cost/benefit analyses. There is a growing body of knowledge that can be legitimately applied to implementation of this technology, as is demonstrated by this review. Research into application of established test methods shows that these
methods are useful in predicting geochemistry of paste and cemented-paste tailings in various settings. Scale-up for such tests remains a key issue (MEND, 2006; Moran et al., 2013; Schafer, 2016; Seipel et al., 2017). The extensive work conducted at Neves Corvo demonstrates that a multi-scale approach to testing provides reliable predictions for facility design and permitting. Lab-scale facility simulations by researchers, correlated with in situ success at cemented-paste tailings surface facilities, will greatly reduce this barrier to entry.

Other limitations of optimization and operational nature are similar to those reported for cemented-paste tailings backfill. As such, these limitations are already being addressed (e.g., use of optimized binder mixes) or are becoming less-restrictive to due technological advances (economics of advanced processing technology). Use of alternative binders which are by-products of other processes offers significant efficiency within a circular economy context.

Operational costs associated with cemented-paste tailings technologies, particularly in surface applications, are often cited as a constraint for this technology. The costs of generating paste tailings, as well as the cost of binders, are quantifiable costs of implementation. In the case of backfilling of cemented-paste tailings, increased ore recovery is a calculable economic benefit that has generally outweighed the hurdles to implementation, leading to widespread acceptance of this technology. It is more difficult to appraise components of mine plans which influence cost indirectly, such as smaller mine footprint, reduced duration of closure, or reduction in water quality impacts or long term water treatment (Boger, 2012; Fourie, 2012). Nevertheless, there is increasing demand for incorporation of these cost-saving benefits in tailings facility selection, making surface application of cemented-paste tailings a more viable alternative.

A persistent challenge for mining, even in the 21st century, involves assurance of environmental protection. Although evidence indicates that binder addition is an effective way to limit reactivity, it cannot be eliminated entirely, particularly in strongly sulfidic materials. In this case, incorporation of additional, technologically-advanced methods for ensuring environmental protection could be utilized in the facility design. For example, a benefit of surface paste application over backfilling is the possible use of liner to isolate the tailings from the surrounding environment. To this end, placement of cemented-paste tailings within a lined surface facility appears to offer the best-available environmental controls.

Surface placement of cemented-paste tailings improves the physical and chemical stability of mined materials, reduces their reactivity by minimizing exposure to mine water and minimizing footprint, improves water-reuse, and reduces post closure risk. As such, this technology addresses calls from multiple stakeholders for improved sustainable practices in waste management (Franks et al., 2011; Boswell and Sobkowicz, 2011; Taguchi, 2014; Adiansyah et al., 2015). Likewise, this technology offers improved potential to meet the United Nations call for zero-failure standards in tailings facility design (Roche et al., 2017). The preceding discussion demonstrates that the integration of two well-studied technologies, in combination with other safeguards such as facility liners, is a best-management practice that offers the greatest potential for a “zero-failure” facility.
Surface Place Cemented Paste Tailings

References

Social Demand


Tailings Management Strategies


Cemented Paste Tailings Backfill


Surface Placed Cemented Paste Tailings


Surface-Placed Paste Tailings


Surface Placed Cemented Paste Tailings


Surface Placed Cemented-Paste Tailings


