Literature Review on Potential Geochemical and Geotechnical Effects of Adopting Paste Technology under Cold Climate Conditions

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Summary

The purpose of this literature review is to summarize the recent research regarding geochemical and geotechnical stability of paste tailings, identify knowledge gaps and future research needs. The present study has been conducted by the Division of Geosciences and Environmental Engineering together with the Division of Mining and Geotechnical Engineering at Luleå University of Technology on behalf of Boliden Mineral, LKAB and Outotec.

A survey conducted by MEND (Mine Environment Neutral Drainage) in 2006 on the environmental effects related to the use of paste tailings summarizes that only a few studies had been performed about long-term effects on the surface and groundwater quality. Instead, the focus had been on the additives and the strength of the paste. It is still uncertain how the paste technology affects the long-term environmental stability from a geochemical point of view. Concerns regarding the stability of paste with high sulphide content are still relevant. Studies performed indicate that sulphide oxidation occurs within cemented paste as well as on the surface of non-cemented paste and cracks formed on the surfaces could induce oxidation. For cemented paste, metals released by sulphide oxidation might be sequestered due to high pH induced by the alkaline additives, but anion such as Se has been shown to be mobilized. The leachate has been shown to be near-neutral initially, but the neutrality decreases with time and probably metals sequestered in the matrix will also be released. Again, it should be noted that no long term study was performed on leaching of paste, cemented or uncemented. The longest leaching study was performed for one year. Arsenic has been proven to be retained in Ca-arsenates in cemented paste, but the long term stability of these precipitates is relatively unknown. Expanded secondary phases e.g. gypsum and ettringite have been observed to form when there is sulphate in the process or drainage of water. These phases could crack the paste, but, on the other hand, can also fill former cracks when deposited in layers. The effects of the formation of these phases are relatively uncertain in a long-term perspective. Presence of different elements such as ammonium, sulphates and metals in the water has been shown to negatively affect the curing process and therefore water is suggested to be treated before use. The presence of carbon dioxide during the paste formation could also affect the curing process, but could sequester metals in carbonate phases.

Geotechnical and rheological properties of paste is well defined and documented. Several case studies have been found in literature providing valuable information about the details of the works being carried out. However, a difficulty has been noted during the investigation of the effects of cold climate conditions when current practice is applied in the colder parts of the world. It is not certain how some specific and vital parameters are going to be affected by cold temperatures. Parameters such as deposition slopes and deposition scheme, strength development of the paste are expected to be responsive to cold climate conditions. There are predictions about which properties are going to be affected in what way, but there is also a need to establish a scientific base for discussion. These have been highlighted as research needs and information gaps at the end of the report.
Introduction

Tailings are by-products from processing plants after extraction of valuable minerals. The process efficiency is never 100% and therefore unrecovered minerals, chemical additives and process water are disposed as slurry into surface facilities or underground. More than ca. 670 million tons of mine waste are generated annually in the European Union (27 countries) (European Commission, 2013) and of that, 89 million tons in Sweden. Over the last century, the volumes of tailings being generated have grown dramatically as a result of lower grade ores being mined since the demand for minerals and metals has increased and as a result of the advances in extraction and processing technology.

Paste is a rather new disposal technique and defined as dewatered tailings with non-segregating nature with minimal production of bleed water and differs from the High-Density Thickened tailings (HDTT) by higher degree of thickening. Paste tailings are considered to increase water reuse, reduce dust formation, land impact, pollution of watercourses and inundation risks associated with tailings disposal facilities. Backfilling of paste tailings is a widely used technique which aims at reducing surface disposal. Disposal of paste tailings on the surface in stacks is also an option, but is still relatively uncommon and untested compared to other methods of surface disposal on a global scale.

Co-mixing of reactive waste rock with paste tailings is also an option under consideration, with the aim to stabilize the pits, reducing surface disposal and reduce unwanted geochemical processes in reactive waste rock. Some waste rock is inert and can be used in construction, but often waste from non-ferrous metal mines contains significant quantities of sulphides. Tailings from non-ferrous metal mines often contain sulphides, especially Fe-sulphides such as pyrite, which might generate acid rock drainage (ARD) due to oxidation when exposed to moisture and air. ARD is characterized as an acid drainage with high content of metals and metalloids. The presence of bacteria and ferric iron enhance the oxidation rate with several orders of magnitude. In presence of carbonate, mine drainage could be neutral, but might still have elevated concentrations of elements such as As, Cd, Cu, Fe, Mn, Mo, Ni, Pb, Zn and sulphates (Heikkinen and Räisänen 2008; Lindsay et al. 2009). Some tailings contain only 1-2% of sulphides, but still have the potential to form ARD due to low neutralizing potential. The extent of the ARD formation in deposited tailings is dependent also on ambient factors such as oxygen transport, moisture content, water flow, and the exposure and kinetic reaction rates of neutralizing minerals and sulphides. Elements released from the sulphide oxidation could form secondary minerals, which could be soluble or less soluble sulphates, metal oxides and hydroxides, carbonates and sulphides depending on the physical-chemical conditions. Some secondary minerals may release acid during formation or during dissolution, which might affect the water quality. The stability of secondary minerals in the long term is highly dependent on the water flow, changes in the redox potential or pH.

The purpose of this study is to summarize recent research regarding geochemical and geotechnical stability of paste tailings, and identify knowledge gaps and future research needs.
Background
First suggested by the Canadian engineer E. I. Robinsky, the idea is to get rid of excess water and obtain tailings that exhibit a non-segregating (homogeneous) behavior and deposit at relatively high slope rates which in turn reduces the rate of embankment raises needed. The tailings slurry with such properties is generally obtained with the help of thickeners and as a result, the method is termed as the thickened tailings disposal. The reduced amount of excess water in the tailings mix also reduces seepage and stability problems. The claimed advantages and disadvantages will be covered in their respective sections.

It is suggested that the paste disposal is a subset in the domain of the high-density thickened tailings disposal scheme. Seddon (2010) states that the slurry behavior is a continuum over the full range of possible solids concentrations; the design principles apply to both thickened tailings and paste disposal methods, and concludes that there is not a “magic” step that makes paste technology different in principle. Similarly, Boger (2012) states that the attempts to make a distinction between thickened tailings and paste disposal methods are redundant. In fact, the term “paste” and thickened tailings are often presented in an interchangeable context in literature; loosely referring to the same kind of material.

Tailings
The ideal behavior of the deposited material with paste disposal to have the most beneficial results can be stated as the placement which gives conceptually even deposition slopes with no segregation of particles and virtually no drainage of water occurring. The properties of the solids in the tailings as well as the characteristics of the slurry as a whole have significant effects in achieving the above mentioned goal. These are covered in the coming sections.

Physical Properties
The majority of the physical properties of tailings materials are given in soil mechanics terminology with some additional terms originating from fluid mechanics and mineral processing (Fell, et al., 2005) disciplines. The properties of key interest are presented in two categories. The first group consists of the properties which are related to the solid particles present in the tailings mix, and the latter will be the properties of slurry (solid-water mixture) as a whole.

Specific Gravity ($G_s$)
Specific gravity is defined as the ratio of density of solids over the density of water. This is probably the most important feature of the solids in the mix as it directly affects other properties like the solids concentration, bulk and dry densities of the slurry.

Specific gravity of the solids in the paste depends on the ore type. Based on the type of mineral being mined, specific gravity will differ. Additionally, for ore bodies which are not homogeneous, specific gravity is likely to change during extraction of minerals in the mill (Spiers, 2010).
Particle Size Distribution

Besides helping to determine the fractions of different size ranges, particle size distribution is another important property which has a significant effect on the slurry behavior (segregating or non-segregating slurry), flow properties and rheology of the slurry. The particle size distribution curve will be affected by the ore type being processed along with the mineral processing method and will most likely influence the degree of thickening required as well. Average particle size (termed as $D_{50}$) and the size that 90% of the particles are finer than ($D_{90}$) are two important parameters which are involved in predicting the beach slopes of the deposited tailings.

By making use of the empirical equations based on the particle size distribution, it is also possible to get a rough estimation of the hydraulic conductivity of the deposit.

In addition, if the tailings are suitable enough, the particle size distribution curve can be utilized for filter or drainage design in cases where an embankment is required to contain the tailings.

Strength and deformation parameters

One of the advantages of the paste technology is the early strength development of the deposit due to the reduced amount of excess water and the non-segregating (homogeneous) nature of paste. The deposited material will have a denser configuration as well as the ability to support the loads quicker compared to the conventional disposal methods.

Determination of the strength and deformation properties of the mass is of importance when assessing the stability and load carrying capacity of the dried tailings after deposition. It is also of concern if it is incorporated in the construction of a dam embankment. If simple material models are used then the strength parameters of interest are: i) the cohesion and ii) the friction angle. For deformation analysis different types of deformation modulus are of concern as well as information of whether the material is deformation hardening or softening. This information can be obtained from in-situ tests and appropriate laboratory tests by using soil mechanic methodology.

Solid-Water Mixture Properties

Solid Content

Amount of solids ($C$) present in the mix is described either as percent by weight or by volume. The solid content is often given by weight, defined as the mass of solids ($M_s$) over the total mass of slurry, thus giving a number between 0 and 100%. The difference how the same thing is expressed in soil mechanics should be highlighted in order to reduce possible misunderstandings.

Removal of the excess water from the slurry will naturally result in an increase in the solid content, contributing to the paste-like behavior. However, it should also be noted that the
concentration value itself alone does not define paste (Boger, 2012). This can be better explained with the following graph:

![Graph showing Yield stress vs Solids Mass Fraction](image_url)

Figure 1 Yield stress – solid concentration relationship for different types of tailings (Boger, 2012)

Different tailings obtained from processing of different ore types are given in Figure 1. They have all been reported to exhibit non-segregating, homogeneous behavior with a little to negligible drainage of water. Figure 1 shows that this paste-like behavior can be observed over a wide range of concentration values, from 20 to 75% by mass, demonstrating the fact that paste cannot be defined solely by solids concentration. The type of particles involved (clay minerals etc.) as well as the mean particle size is of major importance in addition to the mass concentration. Paste holding more clay like minerals and particles can have a higher solid concentration than coarser materials. Additives used in the process and for densification will also be of importance here.

**Rheology**

As a result of the reduced amount of water (thus, a higher solid concentration percentage) as well as the relatively high fraction of fine particles, the flow behavior of paste can no longer be represented with the rheology of a Newtonian fluid. One of the key characteristics of paste is that it has a yield stress that needs to be exceeded to initiate motion/flow. Thus, Non-Newtonian rheology is more appropriate to represent such a flow characteristic.

Rheology plays a vital role when designing for the pipeline pumping of the tailings to the disposal area along with the placement stage where tailings settle and the beach profiles start to form. A common method and the simplest way of representing the non-Newtonian behavior of the tailings is to use the Bingham Plastic (two-parameter) model. It should be noted that within the context of some works to predict beach slopes, a three-parameter (Herschel-Bulkley) rheological model has also been utilized. The two-parameter Bingham
Plastic model represents the slurry rheology by defining a yield stress ($\tau_y$) and a viscosity ($\mu_B$, sometimes denoted as the Bingham plasticity as well). Non-Newtonian fluid models used to represent the flow behavior of paste are given in Figure 2.

Figure 2 Non-Newtonian fluid models (Fitton, 2007)

**Consistency Limits & Density**

Bulk and dry densities along with the associated water contents are important parameters; especially when surface disposal is considered. The reduction in the water content upon drying naturally results in a change of the bulk and dry densities. Dry density normally increases. As the deposition progresses and more layers are placed on top of each other, the dry density of the deeper layers may further increase due to consolidation. However, the magnitude of this process is very much related to the deformation behavior of the paste. If it has a deformation hardening behavior, which is most likely, then the magnitude of consolidation is fairly limited. On the other hand, it might be a softening material and then the consolidation process can result in considerable densification.

Furthermore, determination of consistency limits (i.e. liquid, plastic and shrinkage limits) and their relationship with dry density can be used to develop a deposition scheme (Spiers, 2010)

**Hydraulic Conductivity**

Hydraulic conductivity of the deposited material will vary based on the ore type and the processing method. In addition to these, the conductivity values will be further affected by depth within the deposit. With increasing depth, the permeability of the tailings will also decrease due to the reduced amount of pore volume as a result of overburden and possible consolidation.

Due to the layered nature of deposition, a difference between the vertical and horizontal conductivity values might also be encountered.
Above facts make the task of determination and/or coming up with a generalized value of hydraulic conductivity very difficult. The reported values of hydraulic conductivity for cemented paste are within the range of $10^{-7}$ to $10^{-8}$ m/s (Newman, et al., 2001). Accurate determination of the permeability values is vital to perform seepage analyses within the foundation (and embankments, if any). For conventionally deposited tailings the hydraulic conductivity is in the range of $10^{-4}$ to $10^{-7}$ m/s with a hydraulic conductivity in the horizontal direction being approximately 10 times higher than that in the vertical direction, due to layering.

**Literature Review**

**Disposal Methods**

The very first applications of the paste technology involved the paste to be used as a backfill to be deposited in underground openings. When mixed with cement, the strength of the tailings can be increased considerably, allowing for secondary stope and pillar mining (Henderson, et al., 2005).

With the recent developments in understanding the flow and the depositional behavior of the paste coupled with the availability of more advanced thickening equipment, the technology is evolving from being an underground disposal method to a more viable surface disposal method (Newman, et al., 2001). The growing number of the thickened/paste tailings storage facilities around the world and reports of relatively successful results are the supporting evidence for the reliability of paste as a surface disposal method.

In addition to underground and surface disposal methods there are also other proposed disposal schemes, feasibility of which is likely to differ from one project to another. These include disposal in mined out open pits, co-disposal and dry stacking (which involves thickening further beyond paste consistency, thus it cannot be pumped any longer).

**Surface Disposal**

The first practitioners of the paste as surface disposal are the alumina industry and at that time, the main focus of the mining community was on back-fill materials; having a very little interest in adapting paste as a surface disposal alternative (Boger, 2012). As a result of relatively recent, small and large-scale accidents in tailings storage facilities (generally due to instabilities created by the presence of excess water of conventional disposal schemes) all around the world; paste technology has become the focus of attention once again. Continuous flows of information presented at yearly conferences on paste/thickened tailings disposal is a major contribution for further development of the technology.

The surface disposal of paste can be carried out in a similar way compared to that of conventional disposal. After thickening, paste can be pumped to the storage area by pipelines and can be deposited to the storage facility by means of (a) discharge point(s). The choice of discharging tailings from several discharge points (spigots) gives more flexibility and allows
for more control over the storage area. Main differences between the surface disposal of paste and conventional tailings are in beach slope angles, amount of excess water and footprint of the tailings deposit.

Alternatively, thickened tailings can be discharged from a single elevated point as suggested by Robinsky (1975) resulting in a conical shaped deposit.

The first “true” paste surface disposal facility is the Bulyanhulu gold mine, located in Tanzania. The facility operates since 2001. The disposal scheme consists of 25% of the tailings produced to be used as an underground backfill (in the form of a paste and crushed rock mixture) and 75% of the tailings produced to be deposited on the surface in the form of a paste (Theriault et al, 2003). Main reasons to choose paste over other alternative disposal methods in this particular project were reported as the scarcity of water and the unavailability of the topographical conditions for conventional containment of tailings.

The discharge technique used for deposition is a slightly different version of the elevated single point discharge technique. There are five 12m high towers located in the storage area and deposition is cycled between these towers on a regular basis to facilitate an evenly spread deposition. Details of the deposition scheme are provided in Figure 3.

![Figure 3 Plan view of the tailings storage area at the Bulyanhulu gold mine (Theriault et al, 2003)](image)

Reported values of slope angles of the deposited material are 13.5:1 (4.2 degrees or 7.4%) on average. This is one of the highest deposition slopes reported in literature.
Cycling the deposition allows fresh paste to dry and harden, and the next disposed layer will fill in the cracks. Evaporation is desirable to induce strength and density, but only to a critical point before desaturation increase the oxygen entry (Simms et al. 2007). A salt crust was developed on the paste surfaces, which decreased both dust formation and erosion, even during intense rainfall (Theriault et al. 2003). Sulphate salts precipitated on the surface are of concern, since high amounts of dissolved sulphates are transported with run-off water.

Surface paste disposal has been undertaken at several other mines, for example at Neves Corvo, a Cu-Zn underground mine in Southern Portugal owned by Somincor, subsidiary of Lundin Mining. It has been mined since 1988. Expected mine life is to 2029. Neither surface disposal of the sulphide-rich (29 wt.%) and low carbonate containing tailings in an impoundment nor the sub-aqueous disposal was an option at Neves Corvo due to the ARD formation and the arid climate conditions, where the annual evaporation exceed the precipitation three times. Therefore, in 2000, thickened tailings technology was studied as an alternative to sub-aerial disposal. Since the mine was assumed to last until 2029, rising of the dams wanted to be avoided. Wet paste (250-mm slump), stiff paste (150-mm slump) and filter cake with and without additives were tested in laboratory in 2000, and expanded to field cells in 2002, and monitored for 3 years. In 2005, a pilot paste trial on 500000 m³ was implemented with an aim to investigate the deposition technique, co-disposal with sulphidic waste rock as well as to evaluate different composite cover applications (Verburg 2003, 2006 and 2009). Leaching of the paste samples for 200 days showed that paste pH decreased from 10 to around 4, and specific conductance increased for all different mixtures. The driest (cake) had lowest pH and specific conductance content in the leachate. Results indicate that sulphide oxidation occurs within the paste, but at lower grade if the sample is wet (Junqueira et al. 2009).

Simulation by draindown modeling of the paste tailings at Neves Corvo showed an initial water saturation of around 60% which decreased to 16% at the surface, and at 20m depth from 100% to c. 56% after 100 years. The first year paste tailings were partly saturated from the surface to a depth of 5m (60%-100), and below that 100%. Simulation of degree of saturation in paste with a composite cover above showed that the paste tailings could maintain high degree of saturation (>85%) to a depth of 30m. Low hydraulic conductivity cover, such as a barrier, decreased the water infiltration and caused a higher desaturation of the paste. An infiltration rate of 10 to 15% of the annual precipitation through the cover is expected to give the best performance. The construction of a cover system on sulphide-rich paste tailings have to be taken into consideration after mine closure. Low oxygen flux and relatively high hydraulic conductivity could reduce the sulphide oxidation. A cover with low hydraulic conductivity will decrease the infiltrating water, and might therefore increase the dewatering of the paste tailings depending on the drainage capacity. However, a cover still decreases the desaturation and sulphide oxidation compared to uncovered paste tailings (Junqueira et al. 2009, Verburg et al. 2009).
Monitoring of the water quality from the pilot cells during two years showed that a cover system decreased the sulphide oxidation compared to uncovered paste tailings. The pH decreased to 2 in uncovered tailings, and in the covered tailings pH was retained above 6.5. The only indicator of sulphide oxidation measured was pH.

Furthermore, personal communications with Rens Verburg at Golder Associates regarding the surface disposal of paste at Neves Corvo (which has been underway for about a year now) reveal that very little oxidation in the tailings profile (this is monitored through periodic coring of the paste and taking paste pH measurements) has taken place. However, the overlying water is acidic due to some oxidation occurring on the paste surface. The pH is being adjusted by adding lime. This was expected and not a surprise since the dikes and berms are made of acid generating waste rock as well. The key observation is that the bulk of the paste mass was unoxidized. Once a final paste layer has been placed in each cell, a low-flux cover will be constructed, thereby generating clean runoff while maintaining a high degree of saturation and preventing seepage.

Evaluation of disposal of thickened paste as backfill at Kidd Creek, Ontario shows that the drainage have been improved, but this has not been sufficient to prevent ARD formation (MEND, 2006 and references therein). As long as tailings are covered with a fresh layer within 12-18 months then acid generation does not become a problem.

**Paste Backfill**

The environmental risks associated with the “conventional” surface disposal of tailings have led to the quest of finding alternative safe ways of tailings disposal. One way of reducing such risks is to incorporate tailings in a backfill mixture and deposit it in the underground openings. In addition to the environmental benefits, the method might also provide economic advantages by allowing secondary stope and pillar mining if the strength of the backfill material can be enhanced by addition of cement and/or other additives. Dorricott and Grice (2002) lists the potential advantages of underground disposal as: i) higher extraction rates/better resource recovery, ii) improved stability (if cement is added to improve the strength of backfill) and iii) reduced land requirement for surface disposal as a result of which the costs for environmental management and mine closure are expected to reduce. It should be noted that backfilling cannot replace surface disposal completely and it is often used in combination with other disposal options.

Different types of backfill materials exist and the classification, to a large extent, is based on the amount of fines present in the mix. Paste backfill has a larger content of fines compared to that of hydraulic fill (a minimum of fines content 15% which are finer than 20µm according to the definition given by Potvin et. al., 2005) and will not drain. As a result of the non-Newtonian flow behavior of the paste, paste backfill has to be mixed with some kind of a binder to prevent liquefaction and remobilization when disturbed. Alternatively, paste fill can also be mixed with crushed (waste) rock or aggregates and be disposed in underground. The application is termed as blended fill (sometimes “paste rock”) in literature. The main
advantage in mixing paste with waste rock is that it will increase the bulk density, strength and stiffness (Dorricott and Grice, 2002).

A report titled “Paste Backfill Geochemistry - Environmental Effects of Leaching and Weathering” prepared for MEND (Mine Environment Neutral Drainage, Canada) was published in 2006. The aim was to summarize the current practice in geochemical characterization of un cemented and cemented paste backfill based on a literature review and also on a survey of mines that were known to use paste backfill. It was concluded that there was a lack of detailed information at the mine sites as well as a lack of monitoring for evaluation of former performance predictions. In general, it was stated that more information on specific case studies, large scale operations and the effects of key parameters such as the influence of thickener and the binder addition were needed. It was also concluded that few studies have been performed about the long-term effect on surface and groundwater quality related to the use of paste backfill. Instead, the focus has been on the additives and the strength of the paste. The survey was conducted in 2006, and the situation regarding the lack of information has not changed much up to this date despite the fact that backfill from non-ferrous mines have the potential to generate contaminated drainage in long term. In spite of the lack of information on surface and groundwater monitoring from paste backfill, the impact of paste technology on the environment is being advocated as an advantage (MEND, 2006).

The difference between conditions in an underground mine and laboratory experiments complicate the interpretation of laboratory results in relation to field conditions. In the underground, the quality of infiltrating water is different than that of water in laboratory. The water contained within rock walls have different temperature and air quality from the water used while paste production. These factors have been shown to interact. Conditions may also change from the time of backfilling when the underground voids are dry until they become flooded upon closure. The change in the geochemical properties of the paste caused by these effects is not well known.

**Sulphide Tailings in Cemented Backfill**

Paste based on sulphide-rich tailings can reduce the potential of the tailings to produce ARD, as oxygen diffusion into the sulphides decrease due to the high water content and reduced porosity. Uncemented backfill of pyrrhotite-rich slimes at Brunswick Mine in New Brunswick resulted in self-combustion in the upper surface, which resulted in ARD production for two decades that could not be controlled. It was therefore suggested that the amount of pyrrhotite should be less than 14% to avoid self-heating (MEND 2006).

The addition of alkaline binders can reduce the mobility of released metals and metalloids due to precipitation of secondary minerals or adsorption to particle surfaces. Cemented paste backfill (CPB) usually consists of 3-7% binders and 75-85% tailings and the remainder is water (Benzaazoua 2008). Several tests have been performed to mix sulphide tailings with binders such as Portland cement, and Portland cement mixed with alkaline by-products such as slag and fly ash (Benzaazoua et al. 2008). The amount of sulphides in the paste affects the
density of the paste and thereby the amount of binders that have to be added. This will also affect the precipitation of secondary sulphate minerals. Paste with low sulphide content (<12%) showed positive effects on the strength, while higher levels will enable sulphur attack which may result in precipitation of expansive minerals.

Hydraulic binders such as Portland cement which contain Ca(OH)$_2$, gypsum and siliceous materials react with water and produce a residue of calcium-silicate-hydrates (C-S-H) (Reaction 1). Sulphur could be released from sulphide oxidation in the waste or from mine walls or residual process water (Reaction 2), from cyanide destruction or from binders (contain gypsum). The sulphate reacts with Ca and forms more solid sulphates such as gypsum (Reaction 3) and ettringite (3CaSO$_4$.Al$_2$O$_3$.32H$_2$O) (Reaction 4). These are expansive phases that swell (Benzaazoua et al., 2004). Na, K and Mg present in the process water could also be included in the formation of expansive mineral phases by dissolution of binder minerals. This is called a sulphate attack and could reduce the backfill strength and potentially make the backfill collapse (Ercikdi et al. 2009; Benzaazoua et al., 2004). It has also been found that secondary minerals such as gypsum could fill in the pores in the CPB thereby reducing the porosity (Ercikdi 2010, Benzaazoua et al. 2004).

\[
\begin{align*}
3\text{Ca}^{2+} + 2\text{H}_2\text{SiO}_4^{2-} + 2\text{OH}^- + 2\text{H}_2\text{O} &\rightarrow \text{Ca}_3\text{H}_2\text{Si}_2\text{O}_7(\text{OH})_2·32\text{H}_2\text{O} & (1) \\
4\text{FeS}_2 + 15\text{O}_2 + 8\text{H}_2\text{O} &\rightarrow 2\text{Fe}_2\text{O}_3 + 8\text{SO}_4^{2-} + 16\text{H}^+ & (2) \\
\text{Ca(OH)}_2 + \text{SO}_4^{2-} + 2\text{H}_2\text{O} &\rightarrow \text{CaSO}_4·2\text{H}_2\text{O} + 2\text{OH}^- & \text{(gypsum)} & (3) \\
3\text{CaO}·\text{Al}_2\text{O}_3 + 3\text{CaSO}_4·2\text{H}_2\text{O} + 30\text{H}_2\text{O} &\rightarrow 3\text{CaO}·\text{Al}_2\text{O}_3·3\text{CaSO}_4·32\text{H}_2\text{O} & (4)
\end{align*}
\]

Metals released from sulphide oxidation have shown signs of reducing the cement hydration and total porosity. Also, presence of colloidal Fe, Mn and Si oxide could affect the curing process (Colin et al. 2012; Kumar and Rao 1994). The basic additives increase the neutralization potential, and might reduce the mobility of elements such as Cu and Pb, but mobilize anions such as As, Sb and Se (MEND, 2006). Increased mobility has been noticed at the Eskay Creek mine, where the ARD generation was reduced but Sb was elevated in the mine water. The additives will increase the neutralization potential early in the mine life, but may not be sufficient to maintain alkaline conditions in a long term perspective, since their reactivity is much higher than for carbonates. In excess of CO$_2$, transformation of Ca(OH)$_2$ to carbonates could occur, which decreases the alkalinity and destabilizes the curing process. The formation of carbonates has been shown to lead to stabilization of metals in the matrix (Dudgeon and Waite 2012).

Sulphide oxidation on exposed surfaces of the paste increases the permeability and thereby increases the weathering ability. When comparing concrete and paste tailings, concrete has lower porosity than cemented paste, which results in a higher availability of dissolution within the paste. Formation of concrete in presence of ammonium and nitrate rich solutions have been shown to dissolve Ca(OH)$_2$ and other phases, thereby affecting the curing process. The chemical composition of the inflowing water or residual process water should be taken under
consideration, since it could affect the curing and strength (MEND 2006, reference therein; Bertrand et al. 1998).

Some laboratory experiments have been conducted since the MEND report was published in 2006. Net acid generating tailings (30.3 wt.% sulphides) homogenously mixed with different amounts of Portland cement or without cement were column leached for 30 weeks. Results showed that the pH in the leachate decreased from approximately 8 to 4 in all samples except for the one with highest cement addition (2 wt.%). The relatively high release of sulphur observed was suggested to be related to weathering of sulphides induced by the addition of Portland cement, which increase the porosity and thereby the oxygen entry. Consideration was taken to the presence of gypsum in cement that could contribute to increased sulphur release (Deschamps et al. 2008). The effect on the porosity seemed to be more pronounced initially than after 91 days of curing (Deschamps et al. 2008). However, the overall result showed that it is suitable to stabilize sulphide-rich tailings and reduce the generation of ARD, with paste technology if low amount of Portland cement are used.

Tailings from a polymetallic mine in Quebec, Canada, contained 9.5% pyrite (NNP=126) were used in a paste formation and leached for 56 weeks. The paste was deposited in nine layers. Each layer was deposited in an interval of 2-3 days, and irrigated with tap water every 4th week, totally 14 times. Desiccation cracks were observed on the surface, and seemed to be reopening during dry periods at the same location, but seemed to have low importance on the percolating rate. The drainage water volume increased after seven cycles, which was suggested to be due to cracks in the underlying cemented layer, which also have been observed in other experiments (Deschamps et al. 2008). The upper tailings were oxidized and friable, but the drainage pH was near neutral throughout the experiment (Deschamps et al. 2011), indicating that sulphide oxidation occur but metals are retained within the matrix, and the acid solution neutralized.

At Doyon mine-gold mine, Quebec, Canada desulphurized tailings were used in CPB for laboratory testing. The binder (5% w/w) was Portland cement (30%) and BF slag (70%), which resulted in good strength. In the test with desulphurized tailings, no sulphates attack on the strength was observed (Benzaazoua et al. 2008). The results from leaching tests of sulphide tailings indicate that low sulphide tailings is suitable for paste formation, with addition of small quantities of alkaline additives.

For paste backfill, it has been observed that oxidation occurs at the edges and on the surface. Laboratory tests of oxygen consumption rate in sulphide (4-74 wt. %) paste tailings with binders of Portland cement was determined by Oulett et al. (2003). The binders were 50:50% Portland types 10 and 50 and also Portland 10 with ground granulated blast furnace slag. The results showed that an oxidized layer of c. 1mm was formed after 60 days and at high water saturation, oxygen consumption rate was 1 mol/day·m² and was considered as low. Similar oxygen consumption tests were performed in-situ at the Laronde Mine, Quebec, Canada. The paste backfill was highly reactive (sulphide content 53% pyrite) and Portland cement 10 and 50 was used which is resistant to sulphate attack (Portland 50). This is the only study of
oxygen consumption in-situ in a mine stope at 2150 depth. The oxygen diffusion was 0.2 mol/day·m² as lowest, a decrease from the initial diffusion of 2.4 mol/day·m² and much lower than laboratory tests and for tailings without binders (Outlett et al. 2006). The low consumption rate was explained by the high degree of saturation and coating on the pyrite grains. Pore-water was extracted from the cemented paste, and showed a decrease of pH from c. 13 to 10 after 80 days. The long-term stability, against for example crack formation by expansive phase that could increase the sulphide oxidation and decrease pH, was not known. Decrease of pH could also occur when the binders are consumed.

Metal rich tailings can be stabilized and solidified with the CPB method. Microprobe analysis of the CPB matrix formed due to the mixing of As, Cd, Cr and Pb-rich synthetic solutions with Portland cement showed that these trace elements were retained by different mechanisms as own precipitates or together with Ca or silicate compounds in the C–S–H matrix. Leaching of these elements was highest for Cr and lowest for As at pH 7-8 (Halim, 2004). Arsenic has also been found to substitute in ettringite (Coussy et al. 2011) or form stable Ca-arsenate.

Arsenic is a common element in various types of ores in conjunction with precious metals. In general, As is associated to arsenopyrite or occurs as a trace element within the crystalline lattice of pyrite. Arsenic is highly soluble in a wide range of pH and can form various oxyanions in solution depending on the pH and on the redox potential. In the presence of Ca-rich binders, the anionic species of As could react with Ca²⁺ in alkaline environments as follows:

\[
\begin{align*}
\text{H}_3\text{AsO}_3 + \text{Ca}^{2+} + \text{nH}_2\text{O} & \Rightarrow \text{CaHAsO}_4 \cdot \text{nH}_2\text{O} \quad (5) \\
2\text{AsO}_4^{3-} + 3\text{Ca}^{2+} + \text{nH}_2\text{O} & \Rightarrow \text{Ca}_3(\text{AsO}_4)_2 \cdot \text{nH}_2\text{O} \quad (6)
\end{align*}
\]

The composition and stability of the resulting Ca-arsenic compound depends on Ca and As concentration (Ahn et al. 2003), but this Ca-arsenic compound can reduce the As concentration in the solution significantly (Coussy 2011). Leaching of a matrix with binders such as fly ash-based CPB and slag-based Portland cement showed that As was most stabilized with Portland cement, but at low pH fly ash-based cement was better. Oxyanions of As, Se and Cr have been shown to decrease mobility in paste, in spite of the reduced adsorption capacity at high pH levels. This is probably due to retardation in undefined mineral phases (Glasser 1997).

Fly ash and slag in combination with Portland cement could lower the cost and increase the water retention capacity (Sun et al. 1998) and reduce the permeability (Glasser et al. 1997), but decrease the amount of available Ca(OH)₂, which lowers the alkalinity. A study where Portland cement was replaced with fly ash, blast furnace slag and silica fume, showed that these additives could replace Portland with respect to the strength of the CPB (Ercikdi et al. 2009). The dosage was, however, higher (15-20 w%) for slag and silica fume than for Portland cement (3-7w%).
Other Disposal Methods

In addition to what has been described above, there are a few additional disposal options that can be encountered in literature. Adoption of such methods is usually project specific and the advantages are situational.

An alternative method of disposal is discharging tailings into mined-out open pits. Decision making process to utilize this disposal option is not straightforward. Palkovits (2007) states that a mining company first needs to make sure that all the economically feasible ore is extracted with an emphasize on how relative the definition of “economic” can be in terms of market prices. He further points out that sometimes the end of an open pit mining phase can just be the beginning of an underground operation. Nevertheless, disposal of paste into open pits have been practiced at a number of tailings disposal facilities such as EKAPA and Kimberley diamond mines in South Africa, Pajingo gold mine in Australia and Vaudreuil (Jonquiere) bauxite mine in Canada (Fitton, 2007).

Another relatively new option for tailings handling is co-disposal. With co-disposal the aim is to combine waste rock and tailings streams in an attempt to exploit the advantages of both in one mixture. The method was developed to address the two biggest problems of tailings disposal, namely, ARD from mine waste rock and stability problems associated with the tailings disposal facilities (Wickland and Wilson, 2005). The idea is to make use of the high shear strength of the sulphidic waste rock and eliminate its susceptibility against ARD by combining it with the tailings stream which usually have lower hydraulic conductivity; keeping the mixture water saturated, enhancing its capacity to contain the water within and hindering the oxidation of the waste rock. The resulting mixture is potentially safer in terms of both geotechnical and geochemical stability (Martin and Davies, 2002).

Several alternatives for co-disposal of tailings and waste rock have been considered. For example, tailings and waste rock are disposed in opposite ends of the open pit at Kidston gold mine in Australia. Waste rock and tailings could be pumped together or waste rock and tailings could be homogeneously mixed before disposal. Few studies have been performed so far on the homogenous mixing, but it is of great interest. Mixing of acid generating waste rock with tailings paste (encapsulation) could significantly reduce the sulphide oxidation and reduce the need of waste facilities after closure. To form an effective encapsulating material of the paste, wastes from other industries could be used. Co-mixing is a relatively new technology, and the research focus has been on the mechanical strength. Tailings in paste form often are not utilized for co-mixing, but paste could perhaps be suitable. Layered co-mingling is a term that is used for waste rock layers interspersed with layers of compacted tailings (Fortin et al 2000). The compacted layers of tailings will act as a low hydraulic and oxygen intrusion barrier. Layered co-mingling with net acid generating tailings (not as paste) on waste rock have been shown to be effective in reducing the sulphide oxidation by its high degree of water saturation and due to the addition of alkaline by-products from other industries (Fortin et al. 2000). At Porgera gold mine, Papua New Guinea, waste rock was homogenously mixed with slurry tailings and the mixture was evaluated for its geotechnical
properties. The result showed similar degree of consolidation as for waste rock alone, similar hydraulic conductivity and water retention capacity as for tailings alone (Wickland et al. 2010). Most research of the geotechnical properties have the aim to decrease the hydraulic conductivity and limit the oxygen entry and thereby the sulphide oxidation, and transport of contaminants. However, no researches of the water quality of the drainage, surface water or groundwater that supports the decrease of sulphide oxidation and improve the water quality have been found.

Co-mixing is of interest worldwide, but there are a lot of issues such as the problem of different waste are being managed at different places on site, it is often to small void space to fill the tailings in, the process is energy consuming and it is difficult to mix. It could be beneficial to use co-mixed material as a cover in constructions to reduce the footprint on the surface and decrease water losses.

**Practical Impacts and the Parameters of Interest**

Depending on the nature of paste applications, it is vital to carry out numerous tests in an attempt to determine the parameters affecting a design process.

Of major concern is the suitability of the slurry in terms of being able to exhibit paste-like behavior when de-watered. The ideal behavior with paste is to have tailings which are non-segregating (homogeneous) with a little to none drainage of water upon deposition. Such behavior is generally controlled by solid concentration and the particle size distribution. It is usually expressed in terms of rheological parameters in combination with sedimentation and erosion parameters. Soil mechanics are also of importance in this context. Flow behavior (being a function of degree of thickening) of paste can be characterized by a yield stress and a viscosity value. The design sequence of whole thickened tailings disposal scheme is heavily influenced by tailings rheology. Degree of thickening, pipeline design and depositional (segregating or non-segregating behavior) characteristics along with beach slope profiles can all be related to rheology.

Based on the method of disposal, it is important to identify the desired rheological characteristic of tailings. For surface disposal, this usually begins with determining the minimum amount of solid concentration at which the tailings behave in a homogeneous (non-segregating) manner (Boger et al, 2006). This minimum value is sometimes referred as the “segregation threshold”. In rheological terms, yield stress can be regarded as the force holding particles together in suspension. This is considered to be responsible for achieving non-segregating behavior. Knowing the fact that rheology of the tailings depends on solid concentration, yield stress can be related to the segregation threshold. Vane technique is regarded as one of the most accurate ways of determining the rheological parameters (Boger et al, 2006). In addition to the vane-shear test, ordinary slump test of the cement industry have also been modified in order to have a preliminary idea about the yield stress of tailings on site.
Details of the pipeline pumping are governed mainly by fluid mechanics and the rheology of the paste is of major importance. The desired state of flow for tailings transport is when the solid particles are kept in suspension and thus preventing them from settling in the pipe and eventually clog it. With the practice of thickening the tailings to even higher solid concentrations the flow might shift to a state resulting in an increase of the yield stress (Boger et al, 2006), which might be problematic. Considering the fact that increasing yield stress means steeper slopes and lesser area required for deposition; coupled with the possibility to transport tailings at a higher concentration with a pumping energy requirement similar to that of the turbulent flow, there is room for optimization. Additionally, Boger (2006) states that the rheological properties might also change in the pipeline which reflects the interdependent nature of the thickening, pipeline transportation and the deposition processes all together.

Once preliminary operating parameters (segregation threshold and the associated yield stress) are determined, attempts to predict beach slopes can be made. There are various approaches for predicting the deposition slopes. However, it is worth noting that none of them is universally accepted to be accurate enough. It should also be emphasized that most (if not all) experience is related to high temperature and arid climate regions. Very limited information related to cold climate environment is available for this purpose.

Early attempts were based on small scale laboratory (flume) testing but, it is now commonly accepted that the information obtained from small scale tests are not good indicators of the true behavior on site due to scaling effects. Prediction methods based on theoretical approaches (open channel hydraulics and/or geotechnical approaches) also exist. For example, a semi-empirical beach slope prediction method by Fitton (2007) combines tailings rheology with other parameters such as the particle size distribution, tailings density and open channel flow theory. Here there is a big room for improvements of the methods being used today. Large scale pilot deposition tests, performed as field tests, are often being used by consultant companies, an example can be found in Figure 4.

![Figure 4. Pilot scale testing of Esperanza tailings project (Spiers, 2010)](image-url)
Beach slopes will heavily influence the design process of the disposal area. Tailings footprint (the area that will be covered by tailings), requirement of an embankment to contain tailings (if required, the rate of raise), deposition scheme, method of discharge (single point or spigotting) are some examples of properties which will be affected by the deposition slope.

Strength development of the deposited tailings will be achieved by means of desiccation (mainly evaporation). In such cases, determination of the consistency (Atterberg) limits might provide useful information especially for the design of the deposition scheme. Observations show that the water content of the thickener underflow and the freshly deposited tailings on the surface are often above the liquid limit (Seddon, 2010; Spiers, 2010). As the tailings dry and the evaporation takes place, the water content gradually decreases down to liquid, plastic and shrinkage limits respectively. This decrease in water content is accompanied by a reduction in volume until the shrinkage limit has been reached. Further reductions in volume might be possible by consolidation. Consistency limit of the tailings can therefore be used as rough guidelines when designing the deposition cycle. One way for deposition is based upon the idea of letting the deposited tailings dry down to the shrinkage limit before placing a new layer on top of the existing one (SRK Consulting, 2010). If the shrinkage limit is regarded as the end of the drying cycle, there is a need to have enough time for evaporation to reach this water content.

All these processes are only possible as long as the temperature of the material is above the freezing point. If freezing takes place this will interfere the processes and water reduction possibility will be strongly affected. Freezing might cause an increase of water during the frozen time but may also help to de-water the tailings (freeze-drying). While this is not an issue for all weather conditions, it certainly is a point to consider when operating under cold climate conditions.

Consolidation response of the deposit is also of interest for surface disposal and the type of deformational behavior is of major importance.

With the use of the paste technology, a reduction in the amount of seepage is expected as a natural outcome of the thickening process. Though it might be reduced, a complete elimination of seepage is not possible and therefore seepage analysis will be required to quantify the amount of seepage through the foundation (and the embankment, if any). For this purpose, determination of the hydraulic conductivity is needed so that seepage analyses can be carried out with relevant software(s). In addition to the seepage of the water contained within the paste, the effects of precipitation will also be of interest from an environmental point of view.

If embankments are going to be utilized to contain the paste then the stability of these needs to be assessed. If the construction of a starter embankment is not planned, the stability of the deposit becomes more significant as any instability would mean the mobilization of tailings. Relevant parameters in such cases are the cohesion and the friction angle of dried tailings. In addition, liquefaction might also become a problem as the deposit will have a loose
configuration with a considerable amount of water upon deposition and there are documented examples of liquefaction in literature (Theriault et al, 2003, Robinsky et al, 1991). For seismically active areas (mining induced seismicity and/or geologically active regions) additional considerations will be necessary. It should also be noted, however, in any case of mobilization of the deposit (slope stability or liquefaction) tailings are not expected to travel long distances downstream due to the relatively low amount of water in the paste. The maximum distance is a function of the rheological properties, but it is anticipated that the paste will stop by itself as a result of its yield stress.

**Geochemical Tests**

To perform a reliable risk assessment of the potential effects on ground and surface water and to understand more about the stability of the paste, a detailed mineralogical and chemical characterization, determination of the stability of different secondary phases and ageing and acid generation capacity is required. Static and kinetic tests for extracted wastes for Sweden and Europe could be found in standards and technical reports listed below, which should be used for risk assessment of sulphide paste tailings:

- Directive 2006/21/EC on the Management of Waste from the Extractive Industries and complement to the directive
- The technical requirements for the characterization of the waste (2009/360/EC)
- Criteria for the classification of waste facilities (2009/337/EC)
- Technical guidelines for the establishment of the financial guarantee (2009/335/EG)
- EN 15875 Characterization of waste - Static test for determination of acid potential of sulphidic waste (Swedish standard SS-EN 15875:2011)
Case Studies
In a MEND (2006) report, several mines around the world, which utilize the paste technology, were investigated. The aim was to investigate the extents of monitoring and characterization of the mine water quality and to find out about how the use of paste tailings has been influencing the mine water quality, for short and long term situations. 37 underground mines in Canada, US, Australia, Africa and Russia were studied. The questions asked by the investigators to mining companies were focused on whether there was any information about the geochemistry of paste backfill and predictions of how geochemistry will affect the short or long-term mine water quality. It was further asked if any of this information was used in the evaluation of long term strength of the paste.

In addition, questions about the source and the quality of the drainage water (such as whether it is collected from the stopes or from the mine site, which could be useful for evaluating the long term effects of paste tailings) were also included. The compilation of results of this survey is given as an appendix at the end of the report. The survey shows that 16 mines were using or has proposed to use paste backfill. 7 mines were storing cemented paste on surface, only 5 mines (which were using backfilling) were conducting predictions for underground water and only 2 mines were monitoring the mine water flowing from the paste backfilled stopes (MEND, 2006). For surface disposal, most mines did or were in the process of conducting predictions of the mine water quality. Mines that utilize surface disposal also had a good knowledge about the geochemistry of the paste.

Paste in Cold Climate Conditions
In addition to what has been presented in the previous sections, there are also climate related considerations when paste technology is utilized in cold regions. Paste disposal is practiced in different cold parts of the world (mainly in Canada) in the form of surface, sub-aqueous (underwater) and underground storage. Some examples are Polaris Mine (sub-aqueous discharge- Nunavut, Canada), Snap Lake Mine (surface and paste backfill – NWT, Canada), Nunavik Nickel Mine and NICO Project (Canada, both are in planning stage – co-disposal with thickened tailings is considered) (Journeaux Assoc., 2012).

Risks associated with the use of paste technology under normal climate conditions have been identified by several authors. When the technology is applied in the colder parts of the world, the effect of cold climate conditions on each risk factor also need to be considered. One anticipated outcome of operating under cold climate is the freezing problem and the presence of snow. Reduction in the water content (as a result of thickening) in combination with freezing temperatures will result in faster freezing. Under certain conditions this might create placement problems which might require more frequent continuous shifting of the line of discharge along the perimeter of the tailings storage facility. To reduce the amount of tailings stored on the surface, it is often suggested that paste back-fill should be utilized as much as possible in cold regions (Journeaux Assoc., 2012).
On the other hand, some features of cold climate operations can be exploited. Freezing, in general, can reduce the hydraulic conductivity of the deposit by containing the water in solid form and by reducing pore spaces of the deposit. However for this to be efficient, the deposit obviously needs to remain frozen (permafrost) for very long time periods. In such cases, the integrity of the permafrost is of major concern and its relation to the ongoing climate change should be considered.

Furthermore, strength development of the stack will be another point of interest. For climate conditions without considerable winter, the main agent for strength development is identified as evaporation with corresponding water reduction (Seddon, 2010). However, the contribution of evaporation on strength development under cold climate conditions is not anticipated. During freezing conditions water can be built into the frozen material and forming more or less continuous ice layers resulting in what is normally known as “frost heave”. This process will increase the amount of water (ice) in the paste. It increases strength as long as the material is frozen, but might cause major problems upon thawing. This is related to the thawing of the ice thus increasing the amount of water with the corresponding highly reduced strength in the paste.

Moreover, there is a process of freeze-drying; causing a consolidation process as long as the material is frozen. This can dry out materials with high water contents to very dry conditions with corresponding high strength and low deformation possibilities. Which of the processes being of highest importance is a matter of the materials in the paste, hydraulic conductivity, presence of water, temperature situation etc.

In addition, the presence of snow during deposition has to be considered. Deposition is likely to take place year round. During winter, deposition surface might be covered with snow. If deposition takes place above the snow a significant amount of water will be released upon thawing, thus reducing strength in the past and in the stack.

To sum up, behavior of paste tailings (from pipe and open channel flow to depositional behavior) in cold climate might be significantly different than what is observed at higher temperatures. Considering the fact the feasibility of paste technology heavily depends on its performance, investigation of these properties is crucial for a project.

Discussion

The choice of paste technology over conventional disposal is related to the advantages it provides on the basis of each project. Generally, the main reasons to adopt the paste technology can be identified as the savings in the construction costs for the raising of the embankment(s), improved stability of the tailings storage facility (relatively lower risks of failure compared to conventional disposal) and the reductions in water use.

In addition to these three proven and universally accepted advantages, there exists several more; reliability of which varies from one project to another. Fourie (2012), in his review of
the paste technology, draws attention to overstating the benefits of the paste technology and provides more information on how these claimed advantages are situational.

The advantages of the paste technology are summarized by Tacey and Ruse (2006) as follows:

Table 1: Claimed advantages of paste/thickened tailings (after Tacey and Ruse, 2006)

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Similar capital and reduced operating cost to wet disposal</td>
<td>Reduces costs associated with embankment construction</td>
</tr>
<tr>
<td>2. Costs accrued during operations</td>
<td>In contrast to wet disposal, where costs are incurred during operations</td>
</tr>
<tr>
<td>3. Increased deposit strength</td>
<td>Provides higher strength to the deposit, facilitating easier embankment construction</td>
</tr>
<tr>
<td>4. Decreased land footprint by at least doubling practical stacking</td>
<td>Reduces land footprint, allowing more volume to be stored per unit area</td>
</tr>
<tr>
<td>5. Decreased demand for borrow materials for construction</td>
<td>Minimizes reliance on external materials, reducing costs and environmental impact</td>
</tr>
<tr>
<td>6. Reduced risk of leachate seepage</td>
<td>Decreases the risk of leachate seepage, improving environmental sustainability</td>
</tr>
<tr>
<td>7. Reduces or eliminates ponding and low strength mud deposits</td>
<td>Prevents pooling of tailings, reducing environmental impact and operational difficulties</td>
</tr>
<tr>
<td>8. Prompt creation of firm, convex draining shape at completion</td>
<td>Enables efficient drainage, promoting faster and more effective use of the site</td>
</tr>
<tr>
<td>9. Earlier, better surface leaching and drainage</td>
<td>Improves drainage and leaching, enhancing the efficiency of the paste technology</td>
</tr>
<tr>
<td>10. Potentially large reductions in water use</td>
<td>Facilitates reduced water usage, improving environmental sustainability</td>
</tr>
<tr>
<td>11. Reduced potential for liquefaction</td>
<td>Reduces the likelihood of liquefaction, improving the stability of the deposit</td>
</tr>
<tr>
<td>12. Potentially reduced heating, lower water demand</td>
<td>Reduces the need for heating, reducing costs and energy consumption</td>
</tr>
<tr>
<td>13. Reduced reagent requirements</td>
<td>Minimizes the use of reagents, reducing costs and environmental impact</td>
</tr>
</tbody>
</table>

Reduced construction costs for the embankment raises are often associated with relatively high beach slopes (around 2-4%) of paste and thickened tailings disposal compared to those obtained by means of conventional methods (0.5-1%). The feasibility of the paste technology relies on beach slopes. For relatively higher values of beach slopes, it will be possible to fill more volume per unit surface storage area. As a result, embankment raises will be needed less often and considerable savings in the construction costs will be obtained.

One other advantage of the paste technology in terms of surface disposal is the reduced footprint (i.e. the area occupied by the deposited tailings) of the deposit. Due to reduced amount of water, elimination of segregation and increased beach angles, tailings are not expected to travel long distances down the beach in general; resulting in a reduced area occupied on the surface. Depending on the depositional behavior, sometimes it might even be possible to eliminate the construction of a large starter dam, further contributing to reduced capital costs (Newman, et al., 2001). However, it should be noted that some contradicting experiences have also been reported. Fourie (2012) stresses the fact that retaining embankments might be needed in order to achieve the goal of obtaining reduced footprints.

Upon deposition, desiccation and consolidation are the two agents responsible for the strength development of the deposit. For freshly deposited tailings, a major portion of the strength is gained by means of desiccation. Reduced amount of water and the non-segregating nature of the paste tailings will promote the strength development of the deposit. As the material dries
(by means of evaporation), gradually approaching its shrinkage limit from liquid limit, reductions in the volume and the water content will take place which naturally results in increased density and deposit strength. In later stages of the deposition cycle, where the placement of the tailings takes place on the existing layers (preferably after reaching the shrinkage limit), consolidation is responsible for further strength development of the deeper layers.

Another point to consider in terms of overall stability is the reduction of seepage as a result of the removal of excess water in paste technology. Compared to the conventional disposal methods, the deposit disposed with paste technology does not have any water pond (termed also as supernatant water) on the surface. The elimination of this excess water from the tailings storage facility along with the relatively low hydraulic conductivity of the deposit reduces the amount of seepage through the embankment and/or foundation, contributing to the overall stability. In addition, the technology allows the recovery of this excess water at the plant (or on site depending on the location of the thickener) rather than from the storage facility for recycling purposes to be used again in the mineral processing operations directly. This will prevent the loss of considerable amount of potentially recoverable process water due to evaporation in areas where the water is scarce and supplies are limited.

The combined effects of early strength development of the deposit and the elimination of the water pond also allow potential advantages for mine closure. Upon closure, Seddon (2010) claims that the disposal area almost immediately becomes available for rehabilitation while Palkovits (2007) discusses the possibility of vegetation of certain parts within the storage areas as the deposition continues elsewhere. Reduced land use, improved stability and the possibility to start rehabilitation almost immediately upon closure might also help to reduce permitting times for mining operations.

Additional geochemical benefits associated with the use of paste technology for sulphide tailings can be listed as:

- Reduction of drainage from the disposal facility due to reduction of free water since water is bound during the curing process

- Preferential flow around paste due to the lower hydraulic conductivity within the paste, thereby reducing transport of contaminants.

- Lower hydraulic conductivity and the high degree of saturation limit the oxygen intrusion.

- Increased potential for flooding after mine closure, which decrease the reactivity of sulphides in the long term.

- Increase of the neutralization potential and thereby increased retardation of released element in secondary phases at alkaline conditions.
- Decrease of porosity due to addition of alkaline materials and their cementing character thereby reducing oxygen intrusion.

- Addition of alkaline materials also increase the pH of eventual acid drainage formed by sulphide oxidation within the paste, mine walls or from other active areas at the mine site.

Since the curing process of cemented paste is sensitive to the chemical composition of the water, it is beneficial if the paste has the possibility to cure before it is exposed to neutral or acidic solutions. It is also suggested to clean the water from ammonium and sulphates during paste formation.

Finally, the following table from Jones (2000) compares the properties of the tailings generated with three different (conventional, thickened tailings and paste) disposal methods.

**Table 2 Comparison between different methods of disposal, Jones (2000)**

<table>
<thead>
<tr>
<th></th>
<th>Slurry</th>
<th>Thickened (CTD)</th>
<th>Paste</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Density</td>
<td>Low</td>
<td>Medium/High</td>
<td>High</td>
</tr>
<tr>
<td>Segregation</td>
<td>High</td>
<td>Slight</td>
<td>None</td>
</tr>
<tr>
<td>Supernatant water</td>
<td>High</td>
<td>Some</td>
<td>None</td>
</tr>
<tr>
<td>Post placement shrinkage</td>
<td>High</td>
<td>Some</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Seepage</td>
<td>High</td>
<td>Some</td>
<td>Insignificant</td>
</tr>
<tr>
<td>Rehabilitation</td>
<td>Delayed</td>
<td>Immediate</td>
<td>Immediate</td>
</tr>
<tr>
<td>Permeability</td>
<td>Medium/low</td>
<td>Low</td>
<td>Very low</td>
</tr>
<tr>
<td>Application</td>
<td>Above ground</td>
<td>Above ground</td>
<td>Above and under ground</td>
</tr>
<tr>
<td>Footprint</td>
<td>Medium</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Water consumption</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td>Reagent recovery</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
</tr>
</tbody>
</table>

The disadvantages of the paste disposal system are generally cost related. In addition to the economic concerns, the uncertainties in various stages of the deposition process also raise concerns for the adoption of the technology.

There are different opinions and evaluations regarding the costs of a paste disposal operation. Some claim that the initial and the operating costs of paste disposal are considerably higher than those of conventional disposal and that is the main reason why the majority of the decision makers in mining companies have been staying away from it. Others claim that the capital and operating costs of a paste operation is on par (even lower for some cases) or might be only slightly higher than the costs to operate a conventional storage facility. The initial cost of a paste disposal facility expected to be higher considering the additional investments in the equipment to produce and transport (the combined costs of the thickener and the design of a placement system) the paste. On the other hand, the savings for construction and/or raising of the embankments might off-set these initial costs.

The overall costs of each alternative can be predicted with certain accuracy on the basis of each project by means of feasibility studies and there are a number of case studies available comparing the costs of operating paste and conventional storage facilities. An equally important aspect, however, might be the consideration of uncertainties. Despite the recent
advances, beach slopes still remain hard to predict. Considering the fact that the feasibility of paste disposal is related to beach slopes and its ability to store more tailings per storage area, such an uncertainty might introduce a big risk; coupled with the difficulty to use the data of small scale tests to predict the results on site. In spite of relatively high (up to 10%) beach slopes obtained in small scale experiments, Fourie (2012) draws attention to the fact that the highest beach slope obtained on site to date is an average of 4%.

It should also be noted that the database regarding the paste technology is somewhat limited due to the relatively low number of paste disposal facilities operating all over the world. The method is mainly utilized in Australia and the current practice is based on the experience originating from that part of the world.

Modifications of the current practice and additional considerations of the associated uncertainties will be required when operating in cold climate conditions. From these regions, the experience is very limited regarding the use of thickened tailings and paste. There are a number of key issues which have to be addressed before the technology can be used in these regions in a safe and reliable way. The questions are all related to freezing temperatures and the presence of snow. If not dealt with properly, they can jeopardize all possible positive advantages and possibilities for environmental and cost savings.

Research Needs

Regardless of the type of approach (geotechnical or geochemical), a full assessment of the material needs to be conducted as the literature survey reveals that tailings cannot be generalized (i.e. properties vary from one project to another – might even vary at different occasions during the same project).

Generally speaking, one of the major problems this literature study identifies is the fact that there is too little information regarding the use of paste technology in colder parts of the world. Although application of paste technology for normal temperatures is relatively well documented, discussions, case studies and assessments from a geotechnical point of view based on a scientific ground were noted to be lacking for cold climate conditions.

To this end, a complete geotechnical characterization of the paste in question is essential. Such characterization not only provides valuable information regarding the post deposition stage but also forms a base that allows extending the study where the effects of cold climate conditions on these properties can be further studied.

The main logic of utilizing paste technology is to be able to modify and engineer the properties of tailings on the basis of each project. Such modifications are possible by making use of thickening, which directly affects the rheological properties of the mix. Decision regarding the desired rheological properties should be made based on the project requirements such as the method of disposal, transportation (pipe flow) and placement requirements. It should be noted that geotechnical assessments of the paste can only begin after a consistent
mix design has been finalized. This is mainly due to the fact that the geotechnical properties are affected by the changes in rheology, which has been mentioned earlier.

From a geotechnical point of view, the following research needs are identified in order to be able to use the technology in a safe way. They are all possible to address from a research perspective:

- A full geotechnical characterization including e.g. particle size distribution, determination of consistency limits, density and specific gravity as well as strength parameters and deformation characteristics
- Determination of hydraulic conductivity for different paste materials in relation to e.g. solid contents and deposition methods
- Thermal properties of paste materials, for assessing frost and thawing conditions and its relation to solid content
- Frost heaving properties of paste and how they are related to; i) grain size distribution, ii) chemical additives from the process being used, iii) climatic conditions and iv) geotechnical and hydrogeological conditions
- Modeling of how of ice layers in the frost heaving material are created during winter conditions, in order to assess their importance during thawing and the corresponding stability of the deposit
- Deposition methods during winter. Deposited material might be frozen layer by layer and thus build up a thick structure which will not be possible to thaw during summer.
- Possibility for permafrost formation due to deposition of paste during winter
- Integrity of the formed permafrost in a changing climate context
- Deposition on areas covered with snow. What are the conditions for having the snow to melt? If snow is not fully melted, how will the snow interact with the deposited paste?
- Stability of the paste (strength) during spring and when the frozen paste thaws. Interaction with water from melting ice layers in the frozen material and with snow built in during deposition (comparison with reduced bearing capacity for roads during thawing period)
- Slope angles at surface during melting of paste and corresponding slope stability. The need for dam structure to keep the footprint area constant.
- Surface erosion and rheology of the semi-liquid material during thawing period.
- Under what conditions and for what type of material freeze drying effect and corresponding dewatering due to freezing/thawing is obtained?
- Interaction with chemical additives during freezing and thawing
- Degradation of particles due to freezing/thawing processes. Smaller and smaller particles causing changes in the mechanical properties over time
- Characterization of strength and deformation properties in unfrozen, frozen and thawed condition by means of laboratory testing.
• Large scale experiments on depositional behavior with a special emphasis on taking cold climate conditions into account

Additionally, studies of sulphide oxidation and mineral alteration in ageing non-cemented and cemented paste, as well as the effects on ground or surface water quality are few or lacking. Several factors influence the stability on a long term perspective such as the disposal option, mineralogy and chemical composition of the waste, particle size distribution, degree of saturation, permeability, chemistry and amount of the binders or additives, quality and amount of inflowing water and climate.

There are also uncertainties regarding the effects of specific chemical/physical conditions occurring underground and in open pits, and how the paste is affected after mine closure. Differences between conditions during deposition and conditions in laboratory environment complicate the interpretation of laboratory results in relation to field data.

At the time of backfilling the chemical condition in the underground voids are often dry, but these will be flooded by time. The effect of the geochemical properties of the paste caused by this change is not well known.

Since the air have less oxygen underground, it is important to perform laboratory curing experiment in natural field conditions as the effect of available oxygen is critical for the sulphide oxidation. There are few studies of the oxygen diffusion in backfilled paste environments, but none performed in surface deposits.

In the underground mine, infiltrating water and drainage from the rock walls have a specific water quality; the temperature and the air quality are also different. These factors have been observed to interact. If the amount of water that is in contact with the paste is reduced by cementation, the transport of contaminants will also be reduced. If sulphide oxidation occurs and metals are retarded, metals may be remobilized in a long-term perspective but the mass load could be decreased due to the reduced water transport. Since it is well known that it might be a problem to reduce the reactivity in backfilled open pits due to the difficulty to retain high water table, cemented paste may enable raised water table level, which could decrease sulphide oxidation. The alkaline buffering in cemented paste will be exhausted with time, and an ARD formation might develop. The stability of secondary minerals formed as a consequence of cementation is uncertain. Therefore, it is necessary to perform long term leaching of cementing paste and to perform a detailed characterization of secondary minerals formed and the stability of these in a long-term perspective.

It is rather uncertain how different elements in the process water affect the paste formation and the stability of the paste. Therefore the quality of the water should be considered. If the paste tailings are considered to remain as a paste (high saturation), the final cover system have to consist of a material with high hydraulic conductivity and high water retention capacity. The evaluation of the effectiveness of such cover and the paste sustainability at different
climate is few, especially in cold climate. Below some research needs, from a geochemical point of view, are listed:

- The effect of process-water on the paste formation (especially cemented paste tailings) and the stability of the paste in a long-term perspective should be evaluated for different water qualities.

- Evaluation of the impact on the paste stability of inflowing water with a specific chemical composition that is relevant in the specific area.

- Effects on the process-water quality due to higher water recycling.

- Should paste tailings be covered after mine closure? Evaluation of new cover system and material with high or low hydraulic conductivity.

- Evaluation of the lasting of sulphide oxidation in non-cemented, cemented and at different applications such as backfilling and surface disposal. Investigation of stability of elements that are retained in secondary phases and which chemical-physical changes could remobilize these elements.

- Define if paste tailings are suitable for waste containing high levels of As and Sb. Identify additives and proportions for paste formation with tailings with a specific chemical composition (for example As-rich). This should also result in secondary precipitates which are long-term stable in the actual field conditions.

- Chemically and physically stable paste obtained in a laboratory environment has to be evaluated for the actual field conditions.

- Evaluate methods how co-mixing could be performed from an economic, logistic and environmental perspective.

- Evaluation of benefits to mix sulphide-rich tailings with non-acidic waste rock or vice versa to reduce the AMD formation. Evaluation of the mixture in a long-term perspective, what happens with co-mixture when flooded?
References


## Appendix

### Table A.1 Paste backfill survey results (taken from MEND, 2006)

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35
Table A. 2 Paste backfill survey results – continued (taken from MEND, 2006)

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<td>2%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Mike Tansey, Kinross, Jim Creese, BGC</td>
<td></td>
</tr>
<tr>
<td>Golden Giant</td>
<td>Newmont</td>
<td>Horseshoe, ON</td>
<td>Rock Fill</td>
<td>60-90 fly ash cement</td>
<td>4%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Wally Senza, Newmont</td>
<td></td>
</tr>
<tr>
<td>Holloway</td>
<td>Newmont</td>
<td>Matheson, ON</td>
<td>Rock Fill</td>
<td>60-40 fly ash cement</td>
<td>3%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Wally Senza, Newmont</td>
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</tr>
<tr>
<td>Blindthorn</td>
<td>Inco</td>
<td>Thompson, MB</td>
<td>Rock Fill</td>
<td>55-30 fly ash cement</td>
<td>3.5%</td>
<td>n</td>
<td>n</td>
<td>n</td>
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<td>n</td>
<td>n</td>
<td>Ike Iasgen, Inco</td>
<td></td>
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<tr>
<td>Coleman/ McCreedy East Mine</td>
<td>Inco</td>
<td>Copper Cliff, ON</td>
<td>Mix</td>
<td>100% cement</td>
<td>10% max</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Ike Iasgen, Inco</td>
<td></td>
</tr>
<tr>
<td>T-1</td>
<td>Inco</td>
<td>Thompson, MB</td>
<td>Mill Tail</td>
<td>100% cement</td>
<td>4%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Ike Iasgen, Inco</td>
<td></td>
</tr>
<tr>
<td>T-3 &amp; T-4D</td>
<td>Inco</td>
<td>Thompson, MB</td>
<td>Mill Tail</td>
<td>100% cement</td>
<td>4%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Ike Iasgen, Inco</td>
<td></td>
</tr>
<tr>
<td>T-3 &amp; T-4D</td>
<td>Inco</td>
<td>Thompson, MB</td>
<td>Waste Rock</td>
<td>100% cement</td>
<td>4%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Ike Iasgen, Inco</td>
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<tr>
<td>Polarita</td>
<td>Teck-Cornwall</td>
<td>Polaris, NU</td>
<td>Rock Fill</td>
<td>100% cement</td>
<td>4%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Janet Pirie, Teck-Cornwall</td>
<td></td>
</tr>
<tr>
<td>Williams/David Bell</td>
<td></td>
<td>Hermos, ON</td>
<td>Rock Fill</td>
<td>50-40 fly ash cement</td>
<td>2%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
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<td>n</td>
<td>n</td>
<td>Janet Pirie, Adie Faubert,Teck-Cornwall</td>
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</tr>
<tr>
<td>Myra Falls</td>
<td>Buxton</td>
<td>Campbell River, BC</td>
<td>operating</td>
<td>Rock Fill</td>
<td>100% cement</td>
<td>5%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Lyndon Clark, Mexico-Studio</td>
<td></td>
</tr>
<tr>
<td>USA</td>
<td></td>
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<td></td>
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<td></td>
<td></td>
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<tr>
<td>Rodoc-Missel</td>
<td>Barrick</td>
<td>Carlin, Nevada</td>
<td>operating</td>
<td>Rock Fill</td>
<td>100% cement</td>
<td>5%</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>n</td>
<td>Lyndon Clark, Mexico-Studio</td>
<td>Dry mines but with acidic seeps</td>
</tr>
</tbody>
</table>