

# Integrated Approach to Water Management

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## Abstract

*The increasing regulatory and social demand for the environmentally conscious disposal of mining waste products, the escalating demand of fresh water resources and the disposal of mine and process water back into the environment are some of the key issues affecting mining community and, ultimately, affecting the cost of mining operations.*

*The overwhelming desire to use less process water and to reduce the footprint caused by the disposal of waste materials ranks high on the lists of required actions for mining companies, regulatory agencies, communities and environmental groups.*

*One component of an overall solution which is becoming widely accepted is the use of dewatered tailings which, as part an integrated process approach, returns the surplus water to the mill for re-use. For many processes, this allows immediate recycle of process water hence reduces the amount of impacted water therefore the cost of treating it. It also means that there is less of a need for make-up water. As a result, cost savings can be created in a number of applications around water management including environmental permitting, energy consumption, cost of equipment and water transportation.*

*The integrated approach also considers the sludge by-products from water treatment. In most cases, the sludge is deposited separately from the tailings, waste rock and other waste materials. However, combining these materials may well reduce the geographic footprint of the mine's waste. A smaller footprint means less area for which a permit must be sought as well as less area that must be monitored during operation and post-closure. This creates flexibility regarding where the waste can be deposited, and reduces operating costs and post-closure liabilities.*

*The paper will discuss advantages of an integrated approach to managing mine wastes and mine water as well as water produced as part of the tailings management process using case studies.*

## 1 Introduction

### 1.1 Mining, milling and metallurgical processes and need for water

Mining including milling and metallurgical processes requires the use of significant amount of water. The amount of water required per processing of one tonne ore may range from about 0.4 m<sup>3</sup> to a few m<sup>3</sup> depending on the type of ore, mining/milling and metallurgical processes. A typical water management plan for a mining site typically requires handling of water from a number of processes or operations from the mine, metallurgical processes, and other miscellaneous flows. For instance, when counter-current decantation is used, about 2.5 m<sup>3</sup> water per tonne of ore would be required as washwater (Ripley et al., 1995). Inflows and outflows vary across operations, primarily including pit or underground mine dewatering, precipitation and runoff, waste sources (tailings, rock piles) ore stockpiles, concentrates, and process plants. A typical water sources and management practice for a mine site is illustrated in Figure 1.

As clean and potable water resources are becoming scarce in the world, especially in Europe, Africa and Australia, water is considered to be a commodity. Approaches and processes reducing water consumption and increasing recycle/reuse of water in mining processes have been gaining importance.

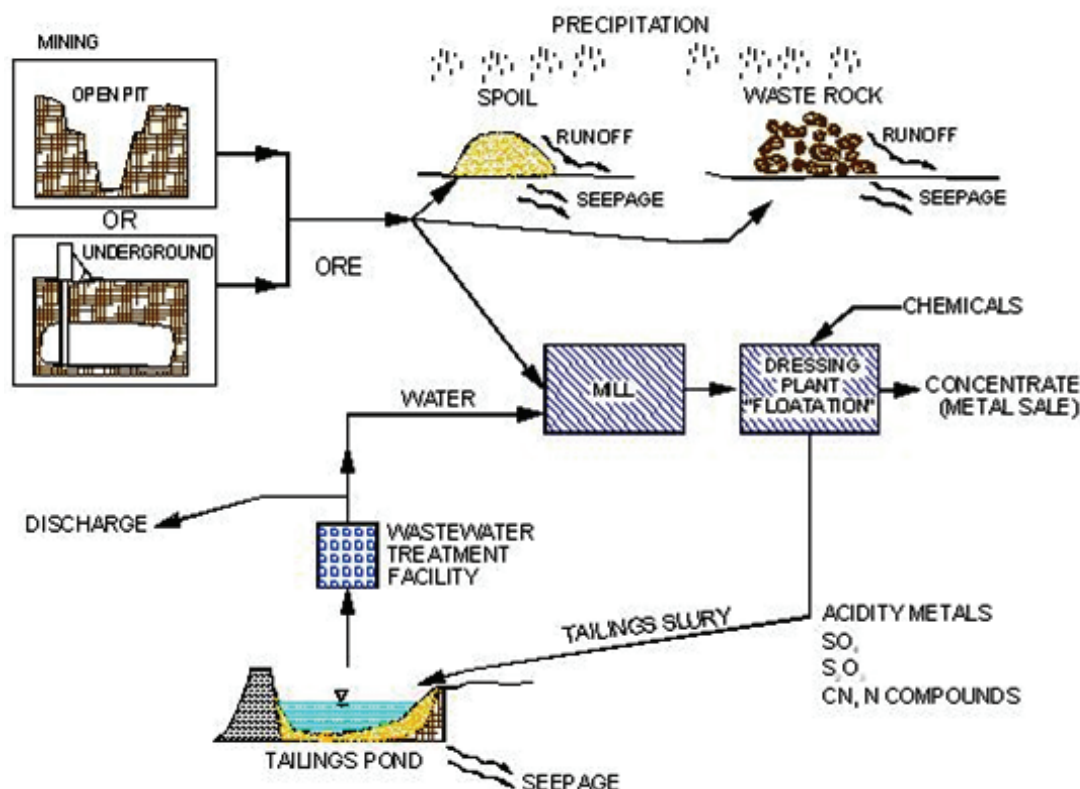


Figure 1 Typical water sources and water management at a mine site

## 1.2 Potential water quality coming from mining, milling and metallurgical processes

Mine water quality profiles vary according to the nature of the exposed minerals and ore bodies. A large spectrum of quality profiles that may be found in water resulting from mining/metallurgical processes could include: alkaline and saline waters; acid, saline and metals rich waters (Kuyucak, 2006). Salinity profiles may typically consist of anions (e.g. carbonate, sulphate, chloride) and cations (e.g. sodium (Na), calcium (Ca), magnesium (Mg), metal ions such as iron (Fe), aluminum (Al), manganese (Mn), zinc (Zn), nickel (Ni), Copper (Cu) etc.).

Due to the use of explosives water resulting from dewatering of open pits and/or underground mines may contain ammonia (NH<sub>3</sub>) and nitrate (NO<sub>3</sub>). Cyanide (CN) may also be found in waters coming from metallurgical processes through its use as a chemical reagent in base metal mines and in leaching reagent in gold/silver (precious metals) mines. Degradation of CN may also result in ammonia and nitrate compounds. Incomplete oxidation of sulphides during milling and flotation processes may generate thiosalts (S<sub>2</sub>O<sub>3</sub>, S<sub>2</sub>O<sub>4</sub>, S<sub>2</sub>O<sub>6</sub>, etc.) which continue to oxidise until the final oxidation product (SO<sub>4</sub>) is reached. This represents a delayed acidity for receiving water reservoirs, as oxidation of thiosalts generate H<sup>+</sup> ions (i.e. proton acidity).

## 2 Treatment of waters

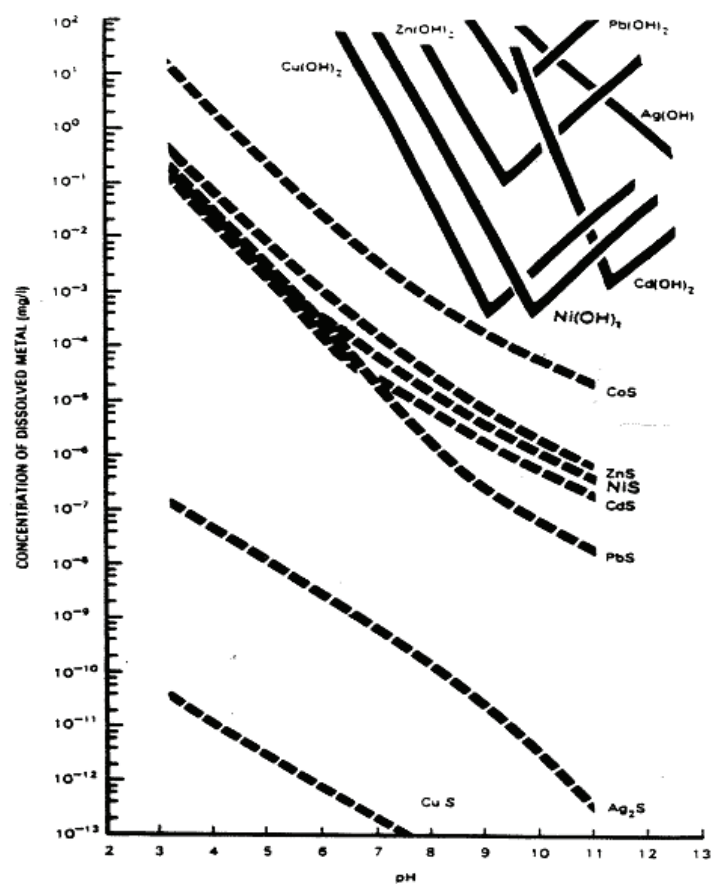
### 2.1 Best available technology economically achievable (BATEA)

Physical, chemical and/or biological methods could be used effluents depending on the type of contaminants found in the mining effluents. Common heavy metals such as Cu, Zn, Ni, Cd, Pb, and Fe<sup>(2+/3+)</sup> could be efficiently removed/reduced by lime neutralisation/precipitation process, which is accepted as a best available technology economically achievable (BATEA) and proven method. Acid is neutralised and metals and sulphate are precipitated in the form of metal hydroxides and gypsum (CaSO<sub>4</sub>), respectively, as shown in Equation (1). The mixture of precipitates is called sludge which requires management for its proper disposal and storage. Therefore, the amount and quality of sludge generated is important.



Air is frequently used to oxidise the ferrous to ferric iron during precipitation to obtain sludges that are more chemically stable. Due to the amphoteric nature of metal hydroxides where the solubility limit for each metal is achieved at an optimum point, above and below the optimum pH, metal hydroxides become more soluble as shown by solubility curves in Figure 2. For instance, at pH 9–10, Cu and Zn can be reduced to levels of <0.1 mg/l while Pb and Fe<sup>3+</sup> are reduced to µg/l. Levels of Cd and Ni below 1 mg/l can be achieved with pH adjustment above 10 unless the water contains high levels of iron. Cr can be lowered to levels of <0.5 µg/l at pH 7–8, following reduction of Cr<sup>6+</sup> to Cr<sup>3+</sup>. Mn removal requires strong oxidation followed by liming at a pH greater than 10. Other contaminants such as As, Sb, Mo and Se require additional chemicals (H<sub>2</sub>O<sub>2</sub>, FeCl<sub>3</sub> or Fe<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>, Na<sub>2</sub>S, CO<sub>2</sub>) as adjuncts to the lime process. A common method for removing Hg is by sulphide precipitation, resulting in an effluent of 10–20 µg/l. Coprecipitation with iron at a pH 3–4 may lower Mo to <0.5 mg/l (Kuyucak, 1998).

Lime neutralisation facilities may range from the simple addition of lime to the tailings pipelines to facilities consisting of reactors, clarifiers, and sludge dewatering equipment, as in Figure 3. The high density sludge (HDS) process as illustrated in Figure 3, Type III and VI, where a portion of the sludge generated is recycled from the clarifier underflow to the process and either is used alone to partially neutralise the mining effluents or along with lime as the alkaline reagent, is capable of producing more compacted sludges (e.g. 10–30% S) than traditional methods of liming. Flocculant can be added either in a (flocculant) reactor or in the pipeline or directly in the clarifier feed-well. HDS process usually removes SO<sub>4</sub> in high concentrations up to theoretical solubility limit of gypsum. Gypsum forms in crystalline particles with a defined shape which makes dewatering of sludge to low moisture contents (e.g. 60% solids) possible (Kuyucak and Sheremata, 1995).



**Figure 2** Relationship between pH and solubility of metal hydroxide and metal sulphide compounds

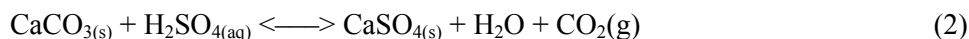
Although HDS capital and operating costs are higher than conventional methods, the recent tendency in mining is to use HDS or upgrade existing plants to HDS. Due to the improved sludge characteristics (e.g. less volume) and effluent quality (e.g. less SO<sub>4</sub>), HDS offers a number of cost advantages (Zinck and Griffith, 2000). It increases the quantity of the recovered water and, subsequently, the quantity of lime used per unit of water treated decreases. More water can be recycled back to the process, reducing the need for fresh water at operations (Kuyucak et al., 1999). Scaling in the process is significantly reduced due to removal of SO<sub>4</sub> in high concentrations. The process control is reasonably well automated requiring less maintenance and labour. Sludge disposal and site monitoring costs are lowered. Formation of gypsum in crystals improves the paste properties when acid tailings are neutralised or sludge is mixed with tailings for paste production.

## 2.2 Alternative treatment methods and neutralising reagents

Stringent final effluent limits for controlling dissolved metals and suspended solids, sodium sulphide (Na<sub>2</sub>S) and a more sophisticated solid/liquid separation equipment such as filters (sand or fabric) could be employed (Kuyucak and Payant, 1995). For instance, addition of a few mg/L of Na<sub>2</sub>S at neutral pH levels could lower Cd concentrations to low levels (e.g. <0.01 mg/L) without affecting the solubility of other metals (Figure 2). Oxidation of As<sup>3+</sup> to As<sup>5+</sup> is necessary to remove As from effluent prior to lime, sulphide and/or ferric iron precipitation. When pH adjustment is ineffective the use of combination of methods is considered to meet the required standards.

When the water contains metal and sulphate ions in low concentrations (e.g. Fe<sup>2+</sup> <200 mg/L and SO<sub>4</sub> <2000 mg/L), caustic reagent and air could be injected into a port of a jet pump (in-line treatment) which could result in a single step process and subsequently savings in capital, operating and maintenance costs.

Under controlled conditions, limestone can remove acidity and precipitate metals (e.g. Al, Cu, Fe<sup>3+</sup>) producing in higher density sludges as opposed to lime. CO<sub>2</sub> gas is released as CaCO<sub>3(s)</sub> dissociates in water (Equations (2) and (3)).



CO<sub>2</sub> forms carbonate ion, which acts as a buffer and sets an upper limit on pH (maximum pH 6.5) and also affects the rate and amount of lime consumption. The precipitates may settle very slowly because of their small particle size. Removal of a broad range of metals and ferrous iron cannot be achieved since they require higher pH levels than 6.5. A combined limestone-lime process could be considered for removal of a wide range of metal ions.

Magnesium Hydroxide (Mg(OH)<sub>2</sub>) can result in a lower volume of metal hydroxide sludge when it is properly applied due to higher solubility of MgSO<sub>4</sub> as opposed to CaSO<sub>4</sub>. Mg(OH)<sub>2</sub> can also remove metals through surface adsorption. However, the rate of neutralisation is slow and the buffering capability of Mg(OH)<sub>2</sub> prevents the pH from exceeding 9. Depending on the pH requirements, it can be used in conjunction with NaOH. Mg(OH)<sub>2</sub> is usually employed in treatment plants to reduce sludge disposal costs (e.g. transportation and landfill).

Sodium Hydroxide (NaOH) has high reactivity and results in less voluminous sludge. This is expensive and the resulting sludge does not settle well and in most cases requires filtering. Ammonia (NH<sub>3</sub>) due to its high solubility and resulting less sludge properties was a preferable reagent mainly by the coal industry. Because of some hazards are associated with the handling of ammonia and some uncertainty about potential biological reactions, the use of ammonia has become limited.

Some industrial waste or by-products such as fly ash from power plants, crude oil combustion and gasification processes have potential as a lime substitute for the treatment of mine effluents. However, metal contaminants present in fly ash may raise some concerns and its reaction rate may be slow compared to lime.

### 2.3 Removal/reduction of fine particles and total suspended solids (tss)

Fine particles (precipitates) in suspension, i.e. high suspended solids, need to be aggregated to improve solid/liquid separation or sedimentation in clarifiers and dewatering of the sludge for further compaction in basins. Coagulation is a specific type of aggregation, which leads to the formation of aggregates called flocs, which are compact. The addition of a coagulant, such as inorganic  $\text{Al}^{3+}$  or  $\text{Fe}^{3+}$  salts or organic ‘polymers’, helps to discharge or destabilise the electronegative colloids and bridge the neutral particles. The important parameters include the type of polymer, temperature of the system, viscosity and chemical characteristics of the pulp, and external stirring.

### 2.4 pH adjustment

When it is necessary to lower the pH to between 6.5 and 8.5 in the final effluent following neutralisation at a higher pH, the pH is adjusted to the desired level with either sulphuric acid or  $\text{CO}_2$ . If an increase in the water alkalinity is not required or an increase in  $\text{SO}_4$  levels is not a concern, sulphuric acid is preferred.

### 2.5 Cyanide destruction, removal of nitrogen compounds and thiosalts

The widely used method for cyanide destruction and removal of nitrogen compounds is natural degradation in holding ponds. Cyanides are biologically or chemically oxidised and are then converted to ammonia and carbon dioxide. The natural degradation of ammonia involves the transpiration of dissolved ammonia gas from the wastewater. Increased pond area and pH enhance the removal. A biological process unique to Homestake Mining in South Dakota decomposes metal-cyanide complexes and efficiently oxidises cyanides to ammonia, which is further oxidised by bacteria (‘nitrification’) to nitrate. Base metal cyanide complexes are selectively oxidised to cyanate by a mixture of  $\text{SO}_2$  and air (the ‘Inco Method’) in the presence of copper as a catalyst, in a controlled pH range. A number of operations use hydrogen peroxide to oxidise cyanides to cyanates. A premixed  $\text{CuSO}_4/\text{FeSO}_4$  reagent can also remove cyanide at a pH of 9.5. Other methods such as: air stripping, steam stripping, alkaline chlorination with hypochlorite at pH 10–11, engineered wetlands, acidification/volatilisation, adsorbents and ion exchange resins have limited use (Randol, 1998).

Nitrates/nitrites are reduced to nitrogen gas by the biological denitrification method for their removal. Ion exchange and reverse osmosis generates a concentrated solution of compounds that require disposal. Wetlands have limited use.

The natural degradation process, due to air and sunlight, in tailings ponds is the most common method for dealing with thiosalts. However, this process is quite slow and requires a long retention time (e.g. several weeks to months). Organic compounds such as frothers and collectors found in the tailings, along with thiosalts, can also be degraded by these conditions. In general, thiosalts are biologically or chemically (e.g. hydrogen peroxide, chlorine and ozone) oxidised and are then converted to sulphate (Kuyucak and Yaschyshyn, 2007). The use of membrane and electrochemical processes (e.g. reverse osmosis, electrodialysis and electro-oxidation) and air oxidation (e.g. alkaline oxidation, Cu-catalysed air oxidation and  $\text{SO}_2$ -air oxidation) have been also investigated. These methods, except biological oxidation and hydrogen peroxide, have been evaluated in laboratory scale tests and were found to be technically feasible, but expensive. Hydrogen peroxide is currently being used for treating tailings reclaim water at Boliden’s Apirsa operation in Spain, before an HDS lime neutralisation/precipitation process. The biological oxidation methods were examined with pilot-scale tests on site in Canada. Biological reduction of thiosalts to elemental sulphur ( $\text{S}^0$ ) is investigated with laboratory tests as an alternative method. For low concentrations of thiosalts (e.g.  $<100$  mg/l as  $\text{S}_2\text{O}_3$ ), the use of  $\text{NaHCO}_3$  or increased pH levels (e.g.  $>\text{pH } 10$  to remove metals and other ions) along with  $\text{CO}_2$  pH regulation is also practiced.

## 3 New emerging technologies

New emerging technologies are mainly based on either physico-chemical (e.g. ion exchange, solvent extraction, membrane processes – that is, reverse osmosis, ultrafiltration, microfiltration and nanofiltration, and silicate micro-encapsulation) or biological (e.g. wetlands, biological sulphate reduction ‘SRB’, nitrification/ denitrification) or passive (e.g. wetlands, SRB processes, anoxic limestone drains (ALD) and biosorbents) processes (Kuyucak, 2000). For treating mine effluents, emerging technologies have been considered as alternatives to conventional methods. However, their use is limited to site-specific

applications, because they are still not technically and economically feasible. In general, passive processes have been found to be suitable for the treatment of low flow and low-strength (that is, metal concentrations) wastewater situations. However, ALD have been used widely in the US to restore abandoned mines and for pretreating acid drainage before routing to a constructed wetland (e.g. 2 and 3).

### 3.1 Ion exchange and membrane processes

Ion exchange (IX) appears to be an alternative method to remove/reduce metal ions (e.g. Cu, Ni, Zn, Hg, Mo) from waters containing single ions and/or simple ion matrix and to achieve low Hg and Mo levels, 1–5 µg/l and 2 mg/l, respectively. Resin blinding due to presence of multiple ions in the water may cause inefficient use of IX.

### 3.2 Membrane processes

The use of membrane processes including microfiltration (MF), nanofiltration (NF) and reverse osmosis (RO) has been increasing as the technology advances to reduce the energy requirements and to improve the quality of membrane material. RO has been recently often used for removal of total dissolved salts (TDS) when recycle/reuse of water is required and fresh water resources are limited especially in Africa, Australia and Europe (Gunther et al., 2006; van Niekerk et al., 2006). MF and NF are able to remove fine particles and could be used in a pre-treatment step along with other conventional treatment methods (e.g. lime neutralisation by HDS) prior to RO. Management of resulting brine that contains contaminants in concentrated levels poses concerns. Evaporation is one of the methods used for managing brine.

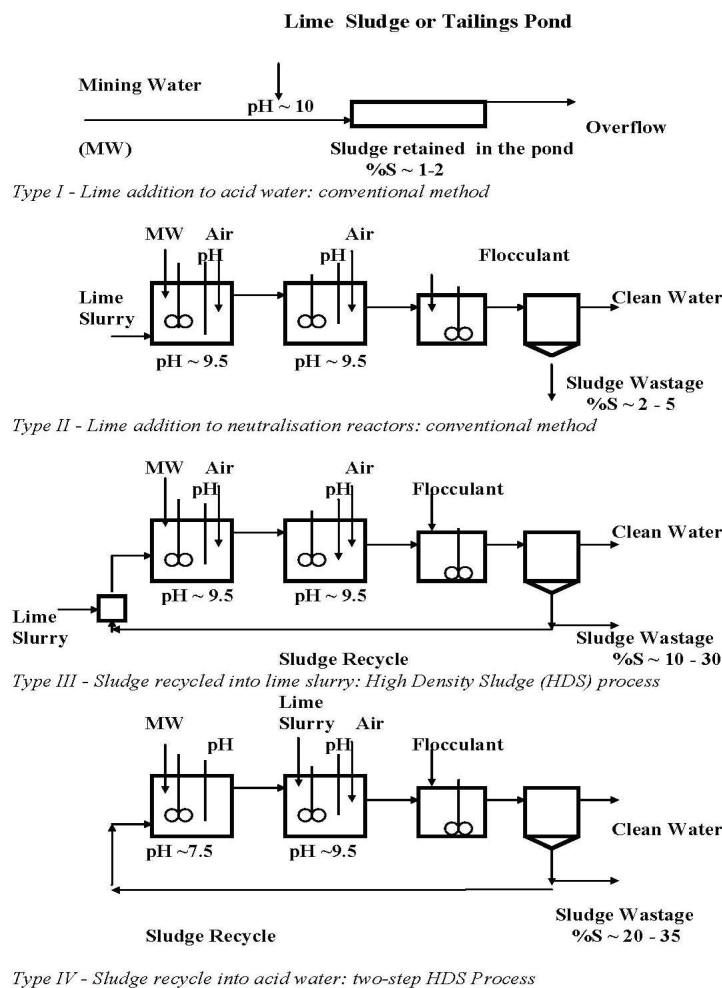


Figure 3 Types of lime neutralisation processes resulting sludge densities

## 4 Sludge management

The water strength and the sophistication of treatment process affect the sludge percent solids content (%S, 'sludge density'). As a result, sludge densities may vary from 1 to 30% solids (Figure 3). The process parameters are set to optimum to obtain denser, less voluminous sludge. Major process parameters affecting sludge characteristics include: the rate of neutralisation; rate of oxidation;  $\text{Fe}^{2+}$  to  $\text{Fe}^{3+}$  ratio; concentration of ions; aging, recycling of settled sludge; temperature; and crystal formation (Kuyucak, 1998, 2006; Zinck and Griffith, 2000; MEND, 1994).

The sludge produced is allowed to settle in ponds or clarifiers/thickeners. When the solid content is less than 1 mg/l, sand-bed filters (or membrane processes, e.g. MF, NF) are employed to remove solids and polishing effluents, to meet the required level of suspended solids in the final effluent. Polishing ponds or marshlands may also be used to further polish supernatant which is then discharged to a receiving stream. The settled sludge is disposed of in specifically designed ponds for its storage for perpetuity. During storage of the sludge, heavy metals may become solubilised and released into the water in the sludge pond and into ground and surface waters. The possibility of metal mobilisation is determined by a leaching test (e.g. US EPA's TCLP, Ontario 347, Quebec Menviq, etc.). Depending on sludge characteristics and site specific requirements, sludge is stabilised by mixing it with cement and/or lime prior to its disposal. Integrated processes along with paste technology could avoid separate disposal storage of sludge.

## 5 Paste process

New tailings disposal options used for preparation and transport of thickened tailings or paste provide a more sustainable water management system and a higher degree of environmental protection. Growing resistance towards mining and especially for subaqueous disposal worldwide creates greater limitations on the use of water and footprint. In addition, regulators are increasingly searching for improved methods of waste management relative to conventional systems. Improvements in dewatering and transportation systems, greater awareness of the cost-benefits and growing acceptance by the mining community has now pushed the technology over the tipping point. The use of paste technology has become widely accepted as a technically viable and economically attractive alternative for underground back fill and for so-called 'dry' surface disposal of tailings. Furthermore, paste disposal could reduce regulatory pressure on hydraulic structures (dams) and other aspects (e.g. the use of liners for leachate) of the more traditional subaerial tailings management methods.

The public perception of tailings impoundments as being generally structurally unsafe and source for leaching of contaminated seepage is another driving force behind the current revival of alternative tailings management concepts (Verburg et al., 2006; Simms and Bryan, 2007). The benefits of paste technology are many, and cover a wide range of issues, including design, operation, reclamation, environmental protection, and public perception for both operating and closed mine sites. The environmental benefits of paste are generally characterised as follows:

- A reduced potential for infiltration and subsequently leachate and seepage generation.
- A reduced potential for penetration of oxygen thereby oxidation of sulphide minerals resulting in generation of acid rock drainage (ARD).
- Paste properties are readily modified (such as by adding cement) to produce integrated physically stable material with mechanical strength and increasing alkalinity and encapsulating pyrite minerals to prevent/minimise generation of ARD.
- A reduced foot print for waste (e.g. tailings, waste rock) management area.
- Minimise/reduce need for costly raises of dam embankments and potential geotechnical risks related to dam stability (failure).
- Minimised/reduced dust emissions.
- The potential for co-disposal of other wastes using paste as a carrier medium.

Lastly, the use of paste in combination with a store-and-release cover would facilitate early progressive reclamation of the tailings impoundment to allow rapid re-establishment of the original vegetative cover.

Gypsum, a common control on sulfate concentrations in mine waters, is slightly under saturated in the 'best-case' and 'worst-case' solutions, and closer to saturation in the "average-case" solution, despite the very high sulfate levels. However, due to relatively low calcium concentrations and complexation of sulfate with various cations, the solubility product of gypsum is exceeded. In high  $\text{SO}_4$  concentration situations, the use of HDS process for neutralisation of water and removal of  $\text{SO}_4$  shows benefits.

## **6 Integration of water management: water treatment, sludge management and paste**

The testing program has also provided technical data supporting the use of tailings paste as a viable disposal alternative for sulphide ores where generation of ARD is inhibited (Verburg et al., 2006). The paste production process allows for development of an engineered material with lower permeability which can be designed such that many environmental impacts can be minimised. This provides increased flexibility in both facility siting and disposal strategy. In addition, the lower permeability and reduced leachate generation will lessen potential impacts on the environment and receptors. Furthermore, the reduced requirement for water to maintain a water cover over a large area of the impoundment can have significant economic implications, especially in arid areas.

Mixing sludge generated from the treatment of mine effluents and other products (e.g. jarosites) produced at a mine site with paste offers short-term and long-term cost effective alternatives for separate disposal options of each product where waste disposal area footprint is reduced and monitoring/maintaining requirements as well as liabilities are decreased. Production of paste with waste materials increases water recovery and possible reuse/recycle while reducing the need for fresh water sources. Incorporation of sludge resulting from a HDS process with about 30% solids content into a backfill material has been successfully practiced (Kuyucak et al., 2001). Production of sludge is relatively insignificant to mine production and so it is expected to have likely minimal impact on paste backfill quality. However, a proper test program is needed to ascertain the interactions. If the interaction is problematic, then separate cemented sludge for disposal into underground openings can be considered.

Sludge can also be intermixed within a tight paste matrix for surface disposal or combined with underground mine backfill in measured amounts, though assessment of the reactions with binders is critical for operations. Disposal of a chemically stable sludge, either with fully mixed, encapsulated or surrounded by paste backfill can reduce surface impoundment requirements. Sludge prepared as a cemented product that would attain strengths similar to a consolidated backfill may be beneficial for underground disposal – very limited production relative to mine production (<1 t/d versus '000s tpd).

## **7 Conclusions**

Mining companies often look for options to reduce the need for fresh water use and the footprint caused by the disposal of waste materials because of increasing regulatory, environmental and social demands. Incorporation of waste materials such as sludge resulting from the treatment of waste waters at a mining site into backfill material or a paste material for either underground or surface disposal can offer a viable option in comparison to separate disposal or conventional co-disposal with tailings method. Production of paste with waste materials increases water recovery and possible reuse/recycle while reducing the need for fresh water sources. Waste disposal area footprint is reduced and monitoring/maintaining requirements as well as liabilities are decreased.

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