Evaluation of Sludge Management Options

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Abstract
With many sites opting to pump and treat in perpetuity the question remains what is the most effective way to manage the sludge? A recent survey of treatment options has documented that there are a variety of practices being used to manage the sludge produced from the treatment of acidic drainage and process effluent. The selection of the most appropriate option is clearly site specific and depends on an array of factors including composition, climate, topography, other waste streams, and economics. However, some options outperform others in terms of long term stability of the precipitated/ adsorbed metals, metal recovery potential, economics, etc. Using data collected from long-term sludge disposal studies, detailed sludge characterization and plant/management information this paper will discuss the performance of various sludge management strategies and their applicability under different conditions. Options to be discussed include pond disposal, codisposal with other waste, disposal in underground workings, re-processing opportunities and sludge as an oxygen barrier or metal sorbent.

Key Words: lime treatment, codisposal, reprocessing, metal recovery, acidic drainage, effluent

Introduction
Most if not all sites will be required to treat mine effluent or acidic drainage at some point during the mining life cycle. Regardless of the treatment option applied (chemical, biological or physical) the result is a metal-laden residue or sludge that requires further management. The options available to manage the residue are directly dependant on several factors which include the mass of sludge produced, whether the mine is operating or closed, dewatering ability of the sludge, sludge density (moisture content), sludge volume, chemical and physical stability, sludge composition, disposal location availability and economics (Zinck 2005). The ability of sludge to dewater may limit the options available. Sludge that can dewater without mechanical assistance will not only reduce the area required for disposal, but also can be more readily reprocessed. The ability of sludge to dewater depends on its particle size, morphology and surface charge. As a particle deviates from a spherical shape, the surface area per unit volume increases, resulting in reduced settleability and decreased dewatering rate. These characteristics are linked directly to the water treatment process that generates the sludge and to the raw water chemistry (Zinck 2005).

Several options are available for sludge management ranging from simple pond disposal, to placement in underground workings to recovery of sludge components by reprocessing (Figure 1). This paper describes several of these options and where possible provides performance data.

Resource Recovery
Sludges provide potential sources for recoverable metals and many sludges contain high concentrations of metals such as zinc and copper, which offer economic opportunity for recovery. For instance, copper ore normally contains less than 1% copper, where copper precipitate sludges from the printed wire board industry average 10% to 15% copper (IPC 2000), copper in treatment sludge is typically an order of magnitude lower (Zinck *et al.* 1997). Acidic drainage treatment sludge can contain upwards of 22% zinc (Aubé and Zinck 1999). Abrams (2000) states that one of the largest sources of untapped metal-bearing secondary material amenable to metals recovery in the US is treatment sludge from electroplating operations.

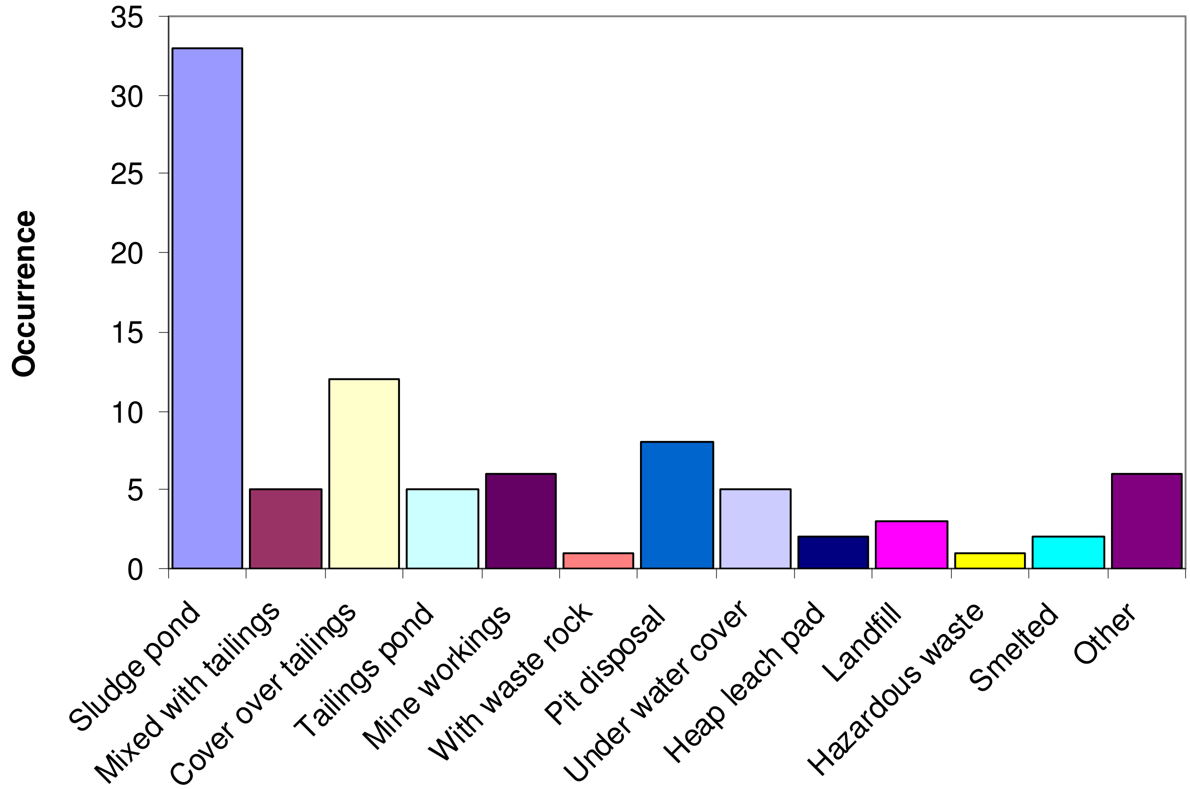

Figure 1: Sludge management options recorded (Zinck and Griffith 2012).

Two principal approaches are used for metal recovery: hydrometallurgical and pyrometallurgical processing. Many of the hydrometallurgical approaches involve leaching of the sludge followed by solvent extraction or ion exchange, while the pyrometallurgical processes tend to involve metal recovery using smelting.

The extraction of zinc from a zinc-bearing treatment sludge can be achieved with alkaline solutions. In a recent study, Fiset *et al*. 2009 proved that sodium hydroxide was a more effective lixiviant than ammonia to recover zinc from hydroxide sludge. The zinc was mobilized as the NaOH attacked the ferrihydrite phase, as evidenced by the dissolution of small amounts of iron. Despite its strong complexing affinity for zinc, ammonia gave relatively low zinc extractions when applied in dilute solutions. The efficiency of NaOH increased considerably with increasing concentration, with 2M NaOH found to be the optimum concentration. A preliminary batch counter-current circuit showed that up to 80% of Zn could be extracted in three stages with high selectivity. The precipitation of ZnS from the pregnant leach solution was found to be technically feasible and this approach would allow the recovery of Zn in a marketable form and regenerate the NaOH solution for recycling.

Recovering metals present in treatment sludge through smelting is an attractive sludge management option. Depending on distance to the nearest smelter, transportation costs, quantities generated, and contaminants present, the mining industry may be able to use some of these options as alternatives to current disposal methods. Unlike hydrometallurgical options, metal recovery using pyrometallurgy requires sludge drying (to less than 20% moisture). In addition, certain impurities in the sludge can have a negative impact on smelter performance. However, process upsets may be offset by advantages such as additional metal revenue and minimal costs (including liability) associated with surface sludge disposal.

Sludge Reuse Options

For the most part, the components that make up sludge, such as gypsum, calcite and ferrihydrite are minerals that are utilized as raw material in the manufacturing of other products. It is often the heavy metal components that discourage the reuse of acidic drainage sludge. There is significant potential to reuse all or part of the treatment sludge produced and while some studies have developed sludge reuse options, the adoption of these technologies is limited.

Building materials

Calcite, gypsum, silica, aluminum, iron and magnesium are common raw materials for cement. Simonyi *et al.* (1977) found that acidic drainage sludge could be added to cement in amounts less than 5% with little or no net effect on compressive strength. Other studies (Hwa *et al.* 2004) suggested that sludge could replace up to as much as 30% Portland cement in blended cement. As with most reuse options, the sludge requires drying before it can be utilized. Coloured concrete can be formed through the addition of iron-sludge (Silva *et al.* 2011) making for a potential attractive commercial product. The practice of utilizing treatment sludge in cement manufacturing has been adopted in some specific sites in the United States (EPA 2000). The sludge proportion and firing temperature are key to the compressive strength of the material.

Pigments

The major component of sludge is ferric (oxy) hydroxide. Depending on the type of iron precipitate, a range of distinctive ochre colours will be produced; yellow for goethite to orange-brown for ferrihydrite to red for hematite (Schwertmann and Cornell 2000). Through selective precipitation Silva *et al.* (2011) produced iron pigments for use in paints and concrete. Hedin Environmental's Iron Oxide Recovery, Inc. (IOR) specializes in the production of pigment-grade iron oxide from abandoned coal mine drainage. The IOR process removes iron from polluted mine water through precipitation as iron oxide. The patented technology (Hedin 1999) consists of interconnected ponds that are designed to promote the formation of iron oxide solids and facilitate their efficient recovery. Over time, the iron oxide is removed from the production ponds, cleaned, dewatered, and transported to the processing facility for drying, milling, and packaging. Methods are being developed that will decrease the processing costs so that iron oxide can be produced passively from mine drainage in a profitable manner (Hedin 2006).

Metal adsorbent

The iron (ferrihydrite) component of sludge is highly adsorbent. Several researchers (Edwards and Benjamin 1989) conducted studies on ferrihydrite and found it to be highly effective for metal removal. Both sludge dosage and pH affect metal removal using sludge from lime treatment plants. Shultz and Xie (2002) found that metal recovery was most effective at pH 7.8. Increasing the sludge dosage increased the metal removal. Copper was found to be the easiest metal to remove. Zinc was also readily removed at pH 7.8 Extreme pH conditions, greater than pH 11, are necessary to remove cadmium (Edwards and Benjamin 1989) and manganese.

Sibrell *et al.* (2010) determined that drainage sludge could be beneficially used to sequester phosphorus from the environment, while at the same time decreasing the expense of sludge disposal. Similarly, treatment sludge has been used to remove carcinogenic dyes/colors from wastewater. Netpradit *et al.* (2003) found that dye adsorption was greatest at pH 8-9, close to the zero point charge (pH_{zpc}) and the maximum adsorbent capacity of the sludge was determined to be 48-62 mg dye per gram sludge. The efficiency of the adsorption capacity of sludge is highest in the slightly basic to circa-neutral pH range.

Disposal Options

If sludge reprocessing or reuse is not feasible then the sludge must be disposed. Sludge disposal involves three principle steps, namely solid-liquid separation, sludge dewatering and disposal. Several options exist if the treatment sludge produced requires final disposal. The selection of each of these options depends on various factors such as composition, stability, moisture content, operating status, and site conditions.

Pond disposal

Many sites utilize ponds as an efficient sludge management option (Figure 1). The sludge is pumped to a settling pond where solid-liquid separation, dewatering and in many cases disposal occur simultaneously. While settling and disposal in the same pond requires large surface areas, this approach is simple and requires only minimal design and construction considerations (Lovell 1973). In this discussion pond disposal refers to long-term disposal of the sludge in an impoundment.

Issues associated with pond disposal tend to be minimal. Wind suspension and dusting present problems at some sites, particularly in arid or northern regions. Due to the surface area required, land use can be a challenge for some sites. Disposal area is not a present concern at most Canadian sites, but with perpetual chemical treatment it may become an issue. Due to the thixiotropic nature of sludges (viscosity decreases as shear strength increases), pond failure could present some concerns although not to the same extent as with tailings impoundments. However, in a pond environment, either with or without a water cover, the degree of metal leaching is expected to be minimal, as the excess alkalinity available in the sludge is enough to sustain a moderate pH for decades, even centuries (Zinck *et al.* 1997).

Sludge disposal in a pond environment can be either subaerial or subaqueous. In a subaerial environment, the sludge is exposed to weathering conditions. Sludge cracking due to moisture loss at the surface is prevalent, causing an increase in surface water infiltration. Under these conditions, sludge dewatering occurs at the surface while the majority of the sludge at depth is still very moist.

A multi-year column leaching study (Zinck *et al*. 2010) was undertaken to ascertain the degree to which metals are mobilized from sludge disposed in settling ponds. For the sludges studied, the results (Figure 2) showed that metal mobility was not significant for the given leaching period. As long as the buffering capacity was available, metal mobility was minimal. However, the sludge samples showed higher zinc mobility during the leaching study, but the pH remained neutral. In general, metal and sulphate concentrations decreased with time below regulated limits.

Where sludge leaching is a concern, the application of a water cover (subaqueous) proves to be effective in reducing metal mobility. In the column leaching laboratory investigation, sludge studied was found to be more chemically stable when a water cover was applied to the pond disposal scenario. In this case, the amount of Cd, Cu, Mg and Zn mobilized was significantly lower with a water cover compared to without. The presence of a water cover over the sludge provided better distribution of the alkalinity and buffering capacity resulting in better pH control and lower metal mobility. Water covers may reduce metal mobility (e.g. zinc) by as much as 10%. Detailed mineralogy and chemical analyses conducted on the samples before and after column leaching revealed significant gypsum depletion in the sludge and a reduction in calcium and sulphate concentration in the solid phase.

The cost of pond sludge disposal depends on the production rate and the stability of the sludge. However, this method of disposal is relatively inexpensive. Unfortunately, ponds are often under-designed to meet sludge management requirements and frequently fill up prematurely. Mechanical sludge removal can cost approximately $5 to as much $30 per tonne for removal with a truck and backhoe. For example, Kidd - Metallurgical Site (Timmins, Ontario) spends upwards of $1 million per year on dredging costs (Scott 2004). Ackman (1982) evaluated sludge removal techniques in terms of storage capacity, economics, maintenance and versatility. Due to the high long-term maintenance costs of dredging, it is best if the sludge can be disposed of long-term in the pond in order to avoid frequent and costly sludge removal from the pond. If long-term pond disposal is not an option, the sludge must be removed and disposed of in a more suitable, site-specific location (e.g. in underground workings).

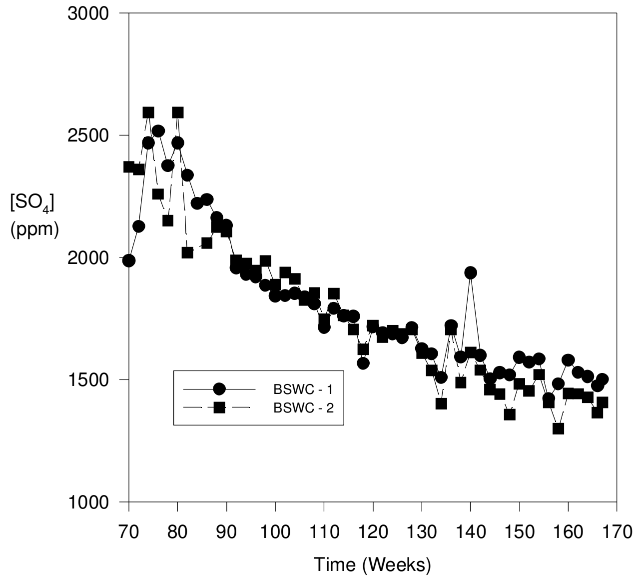

Figure 2: Brunswick fresh sludge with water cover, sulphate concentration versus time (Zinck *et al.* 2010).

Codisposal with tailings or other wastes

Disposal of sludge with other mining wastes is a common practice as it reduces the waste management resources required to dispose tailings/waste rock and sludge separately. Treatment sludge may serve as a source of alkalinity and offers the opportunity to neutralize the acidity generated by the sulphide-bearing waste. The practice of co-mixing tailings with treatment sludge for disposal involves injecting the treatment sludge into the tailings slurry prior to discharge to the impoundment. Typically, the sludge to tailings ratio is less than 1:20. Here the sludge serves to fill void spaces within the tailings, in theory reducing the potential for water or air infiltration and the hydraulic conductivity of the mixture. This method of disposal could be an effective option provided that the tailings are either non-acid generating or that tailings oxidation is prevented. However, if the tailings undergo oxidation and commence acid generation, the likelihood for sludge dissolution and metal mobilization is very high. In addition, an alternative sludge disposal strategy would be required post closure as sludge continues to be generated while tailings production ceases.

The performance of this disposal scenario seems to be very site specific particularly in relation to the waste composition. For example, in a recent study examining sludge-tailings codisposal results showed that the net alkalinity only offset acid generation and metal mobility in the short term (Zinck *et al.* 2010). Once sulphide oxidation in the tailings was established, the available alkalinity in the sludge was quickly depleted. Figure 3 shows how iron waste readily leached when fresh sludge was mixed with tailings and leached over a period of months. Under acidic conditions sludge dissolution occurs, opening void spaces and increasing infiltration and metal leaching. If under these same conditions a water cover was applied to the waste, then it is expected that limited metal leaching would occur, as oxidation would be suppressed.

Similar to mixing the sludge into the tailings, sludge can be codisposed with tailings as a cover. In this option the sludge can form a barrier to oxygen particularly if the sludge is significantly moist. Wet covers provide a barrier that minimizes oxygen ingress with potentially acid generating material and, except for minor oxygen dissolved in the water, precludes oxygen contact completely. The sludge also provides a source of alkalinity. Precipitation contacting the sludge can generate alkaline water that may percolate through the tailings. Laboratory results (Zinck *et al.* 2010) suggest that sludge as a cover material may not be effective to impede oxidation of tailings. As shown in Figure 4 the available alkalinity could only delay the onset of acid generation for a few months. The extent of oxidation and metal leaching was evidenced by high concentrations iron and zinc leached as well as the marked pH drop from 8 to 2.5.

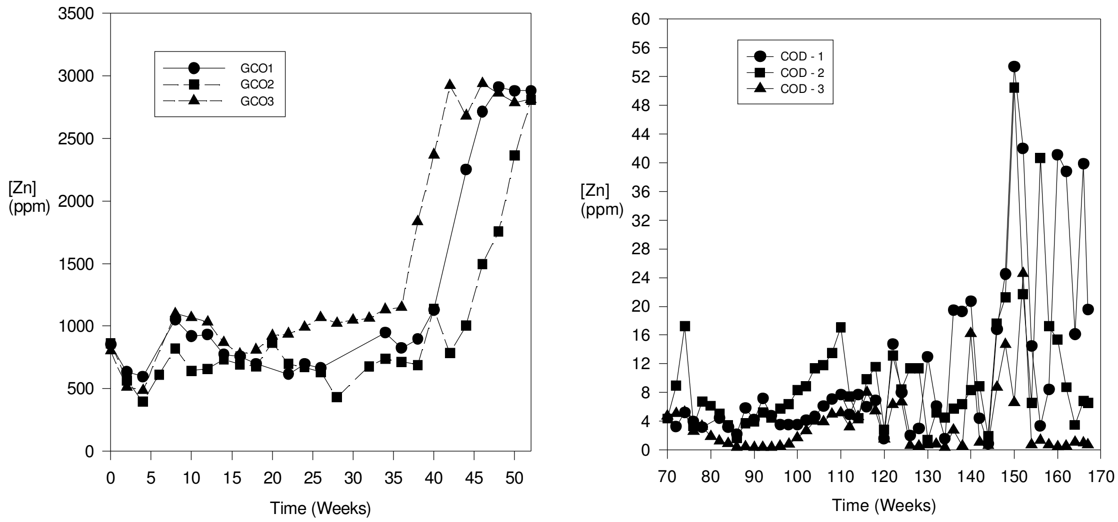

Figure 3: Zinc mobilization for two test codisposal test scenarios using different sludge and tailings samples (Zinck *et al.* 2010).

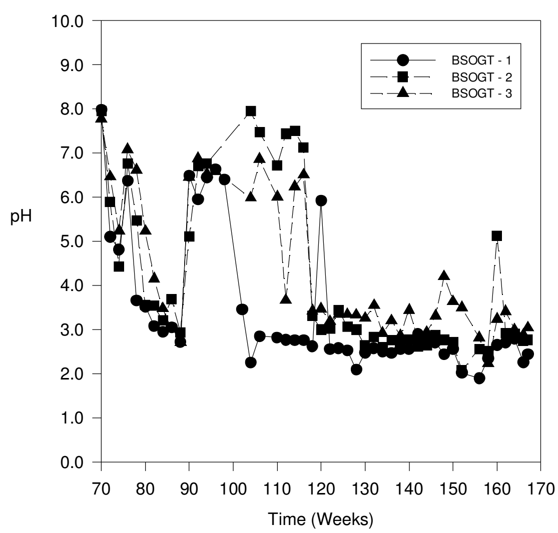

Figure 4: pH measured during the leaching period for the sludge cover over tailings disposal scenario (Zinck *et al.* 2010).

Sludge permeability plays a particularly important role in this type of disposal as the less permeable the material the less likely water and oxygen would contact the tailings, causing oxidation. The challenge is maintaining the integrity of the sludge barrier. Cracks that commonly occur in the sludge through desiccation provide for preferential channels for the leachant to travel through the sludge directly contacting the tailings.

Issues related to the application of a sludge cover on tailings such as cracking and preferential channelling can allow oxygen to reach the tailings. As well, wind suspension of fine sludge particles can cause total suspended solids (TSS) in the discharge to exceed the effluent limits during periods of high winds (Mian and Yanful 2004). Maintaining water in the sludge pore space could prevent sludge cracking and minimize exposure of tailings to oxygen. In addition, the application of a water or vegetative cover could be beneficial in keeping the sludge saturated by limiting cracking and channelling.

Another codisposal option involves disposing sludge with waste rock. This option has several of the same potential benefits as disposal with tailings, including utilization of excess alkalinity to offset acid generation and filling of void spaces. This practice of disposing treatment sludge in waste rock piles is being adopted at some sites. NB Coal's Fire Road mine (Minto, New Brunswick) started looking at the option of codisposal of sludge with waste rock in 1993 after it was determined that there was 160-770 years of sludge storage capacity within the waste rock. Coleman *et al*. (1997) conducted an investigation into the placement of sludge on acid generating waste rock. While their results showed that sludge was not effective as a capping material as originally hoped, this method was found to be a low-cost final disposal option as the sludge filled pore spaces and voids within the waste rock pile. The mine water chemistry has been monitored since 1993 and there appear to be no adverse identifiable chemical effects (Coleman and Butler 2004).

Disposal in mine workings

If site availability, mine capacity and configuration are appropriate sludge disposal in mine workings offers an excellent sludge management strategy. Benefits of this option include potential for the sludge to assist in mine water neutralization and minimization of surface reclamation. The deposition of sludge into underground mines reduces the footprint required for disposal sites (landfills and impoundments), eliminates the potential for surface water pollution, reduces the potential for subsidence, and improves the aesthetics of the local area. Also, in acidic mine workings, the disposal of sludge underground could have the additional benefit of reducing the acidity of the mine water (Gray *et al*. 1997). This practice involves pumping or trucking sludge to boreholes, which are drilled into underground inactive mines. Some of the factors that need to be considered in this disposal option include: site availability and access mine capacity, void space, configuration sludge properties (e.g. viscosity). A survey of sludge management practices found that roughly 6% of the sites reported disposing of sludge in underground mine workings. Some of the sites disposing in mine workings include Britannia Mine, Chisel Lake, Rambler Mine, Waite Amulet and Victoria Junction (Zinck and Griffith 2012).

The limited data available on the performance suggests positive results during the monitoring period. For example Mettiki Coal has been injecting alkaline metal hydroxide sludge from its mine drainage treatment facility along with thickener underflow from its coal preparation plant into inactive portions of its underground mine in Garrett County, Maryland under an Underground Injection Control (UIC) permit (Ashby 2001). Based on available data, it was felt that alkaline solids addition would assist Mettiki in maintaining an alkaline environment in its underground mine pool at closure and minimize acid generation. From 1996 to 2000 the pH of the mine water increased from 5.98 to 6.1.

Aubé *et al.* (2003) observed a similar trend. A laboratory study simulating the disposal of HDS and ferrous sludge into underground coal mine workings containing high strength acidic drainage was completed. The pH of the mine water increased from pH~3 to ~6.7 with increasing amounts of sludge added. In all cases where sludge was added, the concentrations of both Al and Fe decreased in the mine water. Results showed that some metal concentrations (Cd, Ni, and Zn) increased prior to decreasing at higher sludge addition rates. These metals are typically mobile at neutral or acid pH. The results also showed that there is a greater increase in dissolved metal concentration when the ferrous sludge was added to the acidic mine water.

When sludge is in equilibrium with the surrounding mine water, little or no dissolution of the iron sludge will occur. Any addition of either hydroxide ions or ferric ions would result in precipitation. These results suggest that sludge returned to the underground workings would actually reduce the lime required to treat the acidic mine water.

This method is very attractive from an economic and environmental standpoint. However, like most disposal options presented this is clearly site specific. Sludge with high iron content can most probably be disposed of this way economically. Disposal of sludge with high Cd, Zn, or Ni content in this manner may or may not be economic or environmentally acceptable depending on contact means (solids/AMD (S/L) ratio), alkalinity of sludge, and acidity of the acidic drainage (Aubé 2004; Aubé *et al*. 2005).

Disposal in pit lakes

Sludge disposal in open pits is an effective and commonly economical option for sludge storage and long term disposal. There are several advantages and disadvantages accompanying sludge disposal in pit lakes. In general, the stability of the sludge and at its interface with its aqueous environment is a main prerequisite for successful long term storage below a water cover. Risks such as long term change of conditions inside and around the pit lake, as groundwater contamination or as toxication of aquatic life have to be evaluated carefully (Schultze et al. 2011).

McNee *et al*. (2003) conducted a three-year research program studying two pit lakes at the Equity Silver Mine near Houston, British Columbia. Neutralization sludge was added to the Main Zone pit at a rate of ~5 L/s. The discharge of sludge into the Main Zone pit had a pronounced effect on its physical limnology. Their research found that the addition of sludge to the pit lake introduced oxygen into the lake through entrainment. Specifically, the input of dense oxygen-rich slurries and their rapid settling were found to cause lake mixing and produced oxygenated bottom waters. In addition, they found sludge disposal in the pit lake resulted in a plume of metal-rich particulate matter at depth (70-120 m). This did not, however, result in an increase in the dissolved metal content or total suspended solids levels at discharge. The pit lake experienced increased production as observed by the reduced light transmission and increase plankton biomass in the surface waters. It was postulated that the increased production was due to the delivery of phosphate into the lake with the sludge. Overall, the dynamics of the lake changed considerably and whole-lake mixing occurred with the introduction of the sludge (McNee 2004).

Schultze *et al.* (2011) provided several examples of sludge disposal in pit lakes. In these examples the addition of sludge increased the pH of the pit lake water. In addition, evaluations of potential sludge disposal in pit lakes or mine voids were completed at Gilt Edge Mine Superfund Site. In general early case studies suggest that sludge disposal does not seem to negatively impact dissolved metal and TSS concentrations in the discharge waters.

Sludge in backfill

Backfill integrates tailings, sludge and slag along with other wastes into backfill material to reduce the amount of waste to dispose on the mine surface. Paste backfill is defined as an engineered mixture of fine solid particles (with or without a binder) and water, containing between 72% and 85% solids by weight. Unlike a slurry, particles in a paste mixture will not settle out of the mixture if allowed to remain stationary. It can be placed in stopes, with or without binder addition depending on the strength requirements for the backfill. Improved pumping technology, environmental concerns, and the need for a low cost/high strength fill in mines are driving mine operators to consider paste backfill as a tailings management and mine backfill alternative. Incorporating sludge into paste serves to both stabilize the sludge and allow for codisposal of wastes underground. The URSTM (Université du Québec en Abitibi-Témiscamingue) and CANMET (Benzaazoua *et al.* 2006) investigated the option of incorporating sludge in paste backfill (Fiset *et al.* 2005). Results showed the addition of 0.15% wt and 0.3% wt of treatment sludge in cemented paste backfill does not significantly reduce the strength of the paste. Moreover, leaching tests performed on the samples indicated that contaminants were immobile.

Landfill

Landfill disposal is necessary for some sites that do not possess sufficient area for on-site disposal or require specialized disposal for sludge declared hazardous by regulatory leachate tests. Landfills are a common option used for disposal of hazardous waste. Landfilling is becoming less of a viable option, as environmental problems and restrictive legislation are making landfills a buried liability (Pickell and Wunderlich, 1995). One of the specific issues regarding the practice of landfilling treatment sludge is solid-liquid separation. Due to the low solids content of the treatment sludge it requires significant dewatering and drying before it can be transported. There may be additional public concern with the transportation of sludge off the mine site to a landfill facility. Depending on the sludge, stabilization may be an added requirement.

Conclusions

Many options exist to effectively manage acidic drainage treatment sludge. Prior to completing a sludge management plan it is imperative that data on the sludge chemical and physical characteristics be obtained. The sludge should be first considered a resource and reprocessing or metal recovery opportunities should be evaluated prior to disposal scenarios. A full column leaching evaluation should be completed if sludge is to be codisposed with potentially acid generating wastes.

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