DISPOSAL, REPROCESSING AND REUSE OPTIONS FOR ACIDIC DRAINAGE TREATMENT SLUDGE[1]

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Abstract: Sludge management is an escalating concern as the inventory of sludge continues to grow through perpetual "pump and treat" of acidic waters at mine sites. Current sludge management practices, in general, are ad hoc and frequently do not address long-term storage, and in some cases, long-term stability. While a variety of sludge disposal practices have been applied, many have not been fully investigated and monitoring data on the performance of these technologies is limited and not readily available. This paper discusses options for treatment sludge management including conventional disposal technologies, reprocessing options for metal recovery, novel sludge reuse technologies and options for reclamation of sludge areas.

Additional Key Words: lime treatment, high density sludge process, co-disposal, sludge stability, pond disposal, backfill, leaching, mine reclamation

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Introduction

Sludge management is an escalating concern as the inventory of sludge continues to increase and the stability of the sludge under various disposal conditions is poorly understood. As such, the management and disposal of these mining wastes requires careful consideration and planning.

Sludge management considerations

To design the most appropriate sludge management strategy for a site, several factors need to be considered. The principle considerations are 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.

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, it also makes it more attractive for reuse options. 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 (Vachon et al., 1987). These characteristics are linked directly to the water treatment process that generates the sludge and to the raw water chemistry (see Zinck, 2005, for further discussion).

Sludge Disposal

Storage and disposal of wastewater treatment sludge is not problem unique to acidic drainage or lime treatment. Pulp and paper, tannery, municipal, and acidic drainage sludges all face similar issues. Economics and land availability usually determine what sludge disposal strategy is adopted (Vachon et al., 1987). Sludge disposal constitutes a significant proportion of the overall treatment costs. Various options available for sludge disposal are reviewed below.

Pond disposal

Sludge management involves three principle steps, namely solid-liquid separation, sludge dewatering and disposal. Many sites utilize settling ponds as an efficient sludge management option. 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 land areas, this approach is simple and requires only minimal design and construction considerations (Lovell, 1973). Pond disposal refers to long-term disposal of the sludge in an impoundment. Examples of pond disposal are presented in Fig. 1.

Issues associated with pond disposal are minimal. Wind resuspension and dusting present problems at some sites, particularly in arid or northern regions. Due to the large requirement for space, land use can be a challenge for some sites. Disposal space 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).

Figure 1: Examples of pond disposal for sludge.

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. The desiccated surface may be reclaimed. Sludge pond reclamation is discussed later in the paper.

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 Creek Metallurgical Site (Timmins, Ontario) spends upwards of \$1 million per year on dredging costs (Scott, 2004). Ackman (1982) evaluates 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).

In general, sludge disposal in ponds exhibits minimal metal leaching. Where sludge leaching is a concern, the application of a water cover (subaqueous) proves to be effective in reducing metal mobility. In a laboratory study (CANMET, 2004), sludge was found to be more chemically stable when a water cover was applied to a 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. Zn) by as much as 10%. Zn and Cd are frequently the metals that mobilize readily and as such are problematic. Liners may also be required if sludge leaching is problematic. The cost for liners can range from \$4-\$12/m^2 for a synthetic liner and more than double that amount for a clay liner.

Codisposal with Tailings

Many mine sites dispose of treatment sludge with mill tailings to reduce the waste management resources required to dispose tailings and sludge separately. While there is some perception that the addition of lime treatment sludge to a tailings impoundment area may provide buffering capacity, this has yet to be validated. Moreover, the long-term stability of acidic drainage treatment sludge disposed with tailings is generally unknown and requires considerable further investigation.

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.

When fresh tailings were mixed with treatment sludge and leached over time in the laboratory with synthetic rainwater, the long-term stability of the sludge was compromised (CANMET, 2004). Results showed that the net alkalinity only offset acid generation and metal mobility in the short term. Once oxidation was established, the available alkalinity in the sludge was quickly depleted. 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 discouraged.

Sludge as a Cover Over Tailings

The application of wet and dry covers to prevent acidic drainage is widely adopted. Wet covers provide a barrier that minimizes oxygen contact with potentially acid generating material and, except for minor oxygen dissolved in the water, precludes oxygen contact completely. Laboratory results (CANMET, 2004) suggest that sludge as a cover material was not effective to impede oxidation of tailings. Contrary to what was expected, the sludge layer did not act as a barrier to oxygen and did not significantly reduce the rate of sulphide oxidation. However, these results were obtained from laboratory trials and several limitations were encountered. Some of the issues related to the application of a sludge cover on tailings are cracking and preferential channeling. Sludge needs to be disposed in a manner in which the particles will not segregate and consequently remain saturated. Maintaining water in the sludge pore space will prevent sludge cracking and minimize exposure of tailings to oxygen. The application of a water or vegetative cover could be beneficial in keeping the sludge saturated by limiting cracking and channeling. Figure 2 presents some examples of sludge disposed of over tailings.

Figure 2: Field example of sludge layered over tailings. Inset shows a core of a sludge over tailings disposal scenario.

Mian and Yanful (2004) investigated the effect of wind-driven resuspension of sludge placed over tailings in a pond at the Heath Steele site in New Brunswick. They concluded that wind resuspension of fine sludge particles caused the total suspended solids (TSS) in the discharge to exceed the Canadian effluent limits during periods of high winds. Peacey et al. (2002) studied the same site and found that, in the long-term, sludge formation and resuspension should not be an environmental problem with this disposal option.

Sludge Disposal with Waste Rock

Disposing sludge with waste rock 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 appears to be no adverse identifiable chemical effects (Coleman and Butler, 2004).

Disposal in Mine Workings

Disposal of treatment sludge into underground mine workings has several benefits that make it an attractive sludge management option. 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 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)

Meiers et al. (1995) looked at the technical feasibility of placing fixated scrubber sludge into underground coal mines. The sludge was injected through boreholes at a rate of 215 to 500 m^3/day. Short-term results indicated no discernable chemical effects on the mine water or groundwater quality. Gray et al. (1997) identified several sites in the United States using the practice of underground mine disposal for other wastes such as coal ash and kiln dust.

Since 1987, 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 OH^- ions or Fe^{+3} 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

Disposal in an abandoned open pit is typically one of the most economical solutions for sludge storage, if a pit is within a reasonable pumping distance from the treatment plant. Many companies frequently take advantage of open pits available on site as an appropriate short or long-term sludge disposal option. 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). Longer-term studies are required on sludge disposal in pit lakes. However, studies to date suggest that sludge disposal does not seem to negatively impact dissolved metal and TSS concentrations in the discharge waters.

Sludge in Backfill

The use of paste backfill is a common practice in the mining industry. Paste 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 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 Abitib-Témiscamingue) and CANMET (Benzaazoua et al., 2005) are investigating the option of incorporating sludge in paste backfill (Fiset, et al. 2005). The objective of their study is to develop and to evaluate the performance of a novel cemented paste backfill technique consisting of incorporating various treatment sludges within the conventional paste mixture. They found that while the performance of the Portland cement based binders appeared to be negatively impacted by sludge addition, slag based cement seemed to benefit from sludge addition.

Landfill

Landfills are a common option used for disposal of hazardous waste. A landfill is defined as a disposal facility or part of a facility where hazardous waste in bulk or containerized form is placed in or on land, typically in excavated trenches, cells, or engineered depressions in the ground. The aim is to avoid any hydraulic connection between the wastes and the surrounding environment, particularly groundwater. Disposal by landfilling involves placement of wastes in a secure containment system that consists of double liners, a leak-detection system, a leachate-collection system, and a final cover (US Army Corps. of Engineers, 1994).

The EPA defines two types of landfills; sanitary, and secure or hazardous. Sanitary landfills are disposal sites for non-hazardous solid wastes spread in layers, compacted to the smallest practical volume, and covered by material applied at the end of each operating day. Secure chemical landfills are disposal sites for hazardous waste, selected and designed to minimize the chance of release of hazardous substances into the environment. Sludge is disposed in both secure and sanitary landfills.

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.

Reprocessing of Sludges

Many sludges have potential economic value as they contain high concentrations of recoverable metals such as Zn and Cu. For instance, Cu ore normally contains less than 1% Cu, where Cu precipitate sludges from the printed wire board industry average 10% to 15% Cu (IPC, 2000). Acidic drainage treatment sludge can contain upwards of 22% Zn (Aubé and Zinck, 1999). Wastewater treatment sludges from electroplating operations, predominantly from the metal finishing and printed wire board industries, represent one of the largest sources in the United States of untapped metal-bearing secondary material amenable to metals recovery (Abrams, 2000).

Metal recovery from sludges has been discussed for decades. The cost of sludge reprocessing is often considered to be prohibitive and the process problematic. As a result, technologies for metal recovery from sludges are rarely adopted. However, with increasing environmental pressures and mining costs the option for metal recovery from treatments sludges becomes more attractive especially when coupled with the revenue from the recovered metals. With this in mind, we may see a move towards technologies that recover metals from mine wastes such as sludge.

There are two principal approaches used for metal recovery: hydrometallurgical and pyrometallurgical. 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.

Hydrometallurgical recycling methods use wet chemistry to extract usable metals from sludges. While these methods have been in use for many years, they are currently receiving more attention due to their ability to extract and reuse metals from sludges. Zinck (2005) discusses options for metal recovery using hydrometallurgical processes in more detail.

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 (via rotary dryer 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. Examples of sites utilizing smelting practices to recover metals from sludge are given in Zinck (2005).

In the majority of these metal recovery processes, the heavy metals are recovered for revenue and environmental reasons. Typically, a sludge still remains but it is free of many of the metals of concern and is thus easier to effectively dispose of or reuse.

Stabilization/Solidification

Solidification/stabilization technology as applied to wastes uses physical and chemical processes to produce chemically stable solids with improved contaminant containment and handling characteristics. There are six main types of stabilization methods: sorption, lime-based, cement-based, thermoplastic techniques, polymeric and encapsulation.

Several studies have been conducted to investigate stabilization/solidification (S/S) techniques for metal hydroxide sludges (Tseng, 1998; Chang et al., 1999; Conner and Hoeffner, 1998). Treatment sludge typically consists of metal hydroxides, gypsum, unreacted lime and calcite. The solubility of metal hydroxides is pH dependent; each metal has its own metal precipitation domain. The majority of metals are soluble at pH below 6, and some anionic complexes (As, Cr) exist in the range of 10-12. The S/S process is an interesting technology for sludge treatment because it can convert the waste into an inert material independent of the metal solubility of each metal. Also, it is possible to control some physical and chemical parameters such as permeability, compressive strength and metal mobility by proper selection of chemical additive types and ratios. The strength development could be improved by increasing the curing temperatures, lowering the water to cement ratio, or using early strength Portland cement or $CaCl_2$ additives. Various waste solidification methods have been developed using Portland cement (Cohen and Petry, 1997; Fisher et al., 1990; Taub 1986; Bowlin and Seyman, 1989), fly ash (Gabr et al., 1995), fluidized-bed-combustion ash (Knoll and Behr-Andres, 1998), silicate (Bowlin and Seyman, 1989; Reimers et al., 1989) and phosphate (Rao et al., 2000).

Sludge characteristics have a great influence on the compressive strength of a solidified sample (Tseng, 1998). Concentrations of Zn, Cu, Pb and Cd may cause a large variation in setting time and significant reduction in physical strength (Tseng, 1998). Also, organic materials tend to interfere in the hydration of cement.

Limitations of the Portland cement-sludge mixture are related to the effect of the sludge on the setting and stability of the silicates and aluminates that form when Portland cement hydrates (Culliane and Jones, 1989). Also, transportation, operational and cement costs are important limiting factors. The availability of cements and of the pozzolanic material near the mining site is very important for economic reasons. Mixture designs must be optimized for each site because of sludge characteristic variation from site to site.

A recent CANMET study (Fiset et al., 2003) revealed that Portland cement could be used as a binder to chemically and physically stabilize treatment sludge. Other binding systems such as combinations of Portland cement and fly ash, Portland cement and slag, lime and fly ash and a phosphate binder were also evaluated. For two different stabilized sludges, compressive strength values typically ranging between 0.3 MPa and 3.0 MPa were obtained using 5 to 20% of binder. Fiset et al. (2003) estimated the cost to stabilize acidic drainage sludge with Portland cement and fly ash to be in the range of $5/tonne.

Vitrification is another method used to stabilize wastes. Vitrification, or molten glass processes, is solidification methods that employ heat up to 1,200°C to melt and convert waste materials into glass or other glass and crystalline products. Material, such as heavy metals and radionuclides, are incorporated into the glass structure, which is generally a relatively strong, durable material that is resistant to leaching. In addition to solids, waste materials can be liquids, or wet or dry sludges. Borosilicate and soda lime are the principal glass formers and provide the basic matrix of the vitrified product. Vitrification produces a very durable material but because of its very high cost (~$300/t) it is only recommended for extremely hazardous sludges.

Additional high temperature stabilization/recycling technologies are discussed by Zinck (2005) including thermal bonding and sludge slagging.

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 construction materials or other products. It is often the heavy metal components that discourage the reuse of acidic drainage sludge. Further work in the area of sludge reuse is needed. Some studies have looked at the utilization of sludge in construction materials and water treatment; however the adoption of these technologies is limited.

Building Materials

The inorganic components in sludge can be used for the production of building materials (Levlin, 1998). In this option, the environmentally hazardous contaminants are bound as mineral to the material and utilization of sludge reduces mining of raw material for production of building material. The high Al content of sludge produced from treatment of acidic drainage at some coal and gold mines may be useful for production of aluminous cement (Lubarski et al., 1996).

Pulverized sludge ash and dewatered sludge/clay slurries have been used successfully in lightweight concrete applications without influencing the product's bulk properties (Tay and Show, 1991). Sludge based concrete has been deemed suitable for load-bearing walls, pavements, and sewers (Lisk, 1989). The sludge proportion and firing temperature are key items to the compressive strength of the material.

Many of the constituents in sludge are the same as that used in cement manufacturing. Calcite, gypsum, silica, Al, Fe and Mn 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) have suggested that sludge can 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. The practice of utilizing treatment sludge in cement manufacturing has been adopted in some specific sites in the United States (EPA, 2000).

Agricultural Land Applications

For low metal content sludges, such as sludges from coal mining operations, it was found that the excess alkalinity present in the sludge can be utilized to raise soil pH. In an attempt to limit the use of landfills, the Minnesota Pollution Control Agency (MPCA) (1999) examined the land application of coal ash as a fertilizer. The blend of agricultural lime and coal ash were found to contain useful nutrients such as S and B. In order to prevent build up of constituents of concern the MPCA place limits for As, Cd, Cu, Pb, Hg, Ni, Se, and Zn on the permit. While this option has very limited application due to public health and other social concerns, it demonstrates that the non-toxic sludge components can be beneficial to other industries.

Metal Adsorbent in Industrial Wastewater Treatment

The iron (ferrihydrite) component of sludge is highly adsorbent. Several researchers (Edwards and Benjamin, 1989) have conducted studies on ferrihydrite ($Fe(OH)_3$) 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 increases 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 Cd (Edwards and Benjamin, 1989) and Mn.

Similarly, treatment sludge has also 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.

Carbon Dioxide Sequestration

The same mechanism that generates CO_2 in the production of lime can be utilized to sequester carbon dioxide. CO_2 gas can react with treatment sludges and Fe-rich metallurgical residues to produce solid Ca, Mg and Fe carbonates while stabilizing the sludge/residue and its impurities. There is evidence that these reactions occur naturally in sludge/residue ponds, but the method requires development and optimization. An estimated 60,000 t CO_2 annually could be sequestered in Canada (not including steel mill sludges) enhancing the stability and compactness of sludges and residues.

Other Uses

Spray-dried sludge can be utilized as a rock dust substitute for explosion control (Simonyi et al., 1977). In addition, sludge ‘gravel’ can be produced by drying, pulverizing, pelletizing, and sintering to produce a lightweight, high strength aggregate (Hwa et al., 2004).

Reclamation

Once sufficiently dewatered, natural colonization of vegetation on alkaline ARD treatment sludge is very slow making it prone to erosion and dusting. These sludges pose many of the same reclamation constraints encountered with fine-grained tailings, such as small particle size, compaction, lack of nutrients, high metal content and, in some cases, salinity. However, the two biggest reclamation challenges are alkaline pH and lack of nutrient availability (Tisch et al., 2004). While acidic tailings can be limed to improve or optimize pH and metal availability, purposely decreasing the pH of treatment sludge is not an option due to the high risk of metal leaching. In addition, metal toxicity can occur, as both Al and Zn are toxic to roots at relatively low concentrations (Hogan and Rauser, 1979; Rauser and Winterhalder, 1985).

While the high pH is effective for limiting the availability of metals for uptake by plants, it can also severely limit the availability of plant nutrients, especially P. As discussed earlier, lime treatment sludges are composed primarily of calcite, gypsum and a large amorphous ferrihydrite-like phase. While this ferrihydrite phase is an effective scavenger of metal species such as Al, Cu, Fe, Mg, Na, Ni and Zn (Zinck and Dutrizac, 1998; Zinck et al., 1997), it is also an important sorbent in soil (Guzman et al., 1994). Inorganic fertilizers applied to the sludge will quickly be rendered unavailable to plants both through precipitation with Ca and adsorption to ferrihydrite. As a result, fertilization of alkaline sludges with inorganic fertilizers tends to be very ineffective and expensive. The use of acid generating fertilizers such as those containing NH_4^+ may assist in releasing P, but any associated decrease in pH is likely to also result in increased metal release (Tisch et al., 2004). The introduction of organic matter or the use of organic fertilizers (including biosolids, papermill sludge etc.) may be a more efficient method of limiting rapid phosphorus fixation.

The use of alkaline tolerant and P efficient species in reclaiming these areas will certainly assist in overcoming some or all of the hurdles associated with treatment sludge. However, the more common reclamation species, at least those that develop extensive root systems that are more efficient in terms of erosion control, tend to be only mildly alkaline tolerant. Species such as Alkali Grass (*Pucinellia distans*) have shown promise as being a key component at some sites (Tisch et al., 2004).

Conclusions

Sludge management is an ever-increasing issue as the inventory of sludge continues to grow through perpetual pump and treat. Current sludge management practices are ad hoc and frequently do not address long-term storage, and in some cases, long-term stability issues. While there is a plethora of disposal strategies available for sludges, many have not been fully investigated and monitoring data on the performance of these technologies is limited and not readily available. Further research is required into disposal options that can recover metal, densify existing sludge or safely dispose of the material in a way that it can either be easily reclaimed or disposed in mine workings. Promising options must be both technologically feasible and cost effective. In addition, sludge management options must be able to meet increasing environmental standards and pressures. With such limited data available on sludge characteristics, standardized methods, long-term laboratory and field performance, it is important to focus efforts now to address some of these gaps in the knowledge base.

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