Selection of active treatment systems for acid mine drainage

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Abstract

Treatment of acid mine drainage (AMD) can be accomplished by either active or passive treatment systems. In general, active treatment systems are more commonly used at active mine sites whereas passive treatment systems are typically used at closed and abandoned mines. Active mine sites often have limited space for remediation systems and have drainage chemistry and flow rates that can change as mining proceeds, factors that are addressed more easily with active treatment than with passive treatment. Although active treatment systems are less economic than passive systems over the long term, they have a small footprint compared to passive systems, are easily adaptable to changing chemistry and flow rate, and are extremely reliable. There are a variety of methods that are considered active, but the most predominate one is ODAS (oxidation, dosing with alkali, and sedimentation), which is common to that of traditional wastewater treatment plants. For treatment of AMD the most common order is DAOS. Dosing with alkali is typically the first step followed by oxidation and sedimentation. Oxidation rates for dissolved metals in reduced form such as Fe^{2+} are strongly influenced by pH, therefore it is beneficial to raise the pH prior to the oxidation step in treatment of AMD. A flow chart has been prepared to help design site-specific active treatment systems. Parameters necessary to use the flow chart are suspended solids content, iron and manganese concentrations, flow rate, and available land area. Prior to full scale construction, is it recommended to conduct bench scale tests on various chemicals, to complete a sequential titration acidity analysis, and to review cost, effectiveness, limitations, and risk of failure for various options.

keywords: AMD treatment, active treatment, active AMD treatment, acid mine drainage, New Zealand

Introduction

Contaminated surface runoff from disturbed areas of mines in potentially acid-forming regions is a major source of acid mine drainage (AMD) which can adversely affect the receiving environment around these mines (Eary, 1999; Nordstrom and Alpers, 1999; Skousen et al., 2000; Ezpana et al., 2005). For opencast mines, the disturbed areas are usually large and include such items as the mine pits, exposed coal seams, mine facilities, (mine dumps) disturbed overburden material, coal stockpiles, access roads and ditches. For underground mines, the disturbed areas largely corresponds to the coal measures exposed in the mine walls, ceiling and floor. Oxidation of sulphide minerals in these disturbed areas produces drainage with low pH and elevated concentrations of Fe, Al, Mn, Ni, Zn and sulphate (Rose and Cravotta, 1998).

These impacts can be managed either through mine waste management techniques or remediation. Mine waste management involves preventing and/or minimising AMD, whereas remediation involves treatment of AMD using water treatment systems. With remediation, treatment can be accomplished by either active or passive treatment systems. Active systems typically require continuous dosing with neutralising chemicals, consume power and require regular operation and maintenance, but they

are very reliable. Passive systems rely on natural physical, geochemical and biological processes to neutralise AMD, precipitate metals out of solution but can fail if not carefully selected, designed and monitored (Trumm, 2007).

The main advantages of active treatment systems over passive treatment systems are that they are very effective at removal of acid and metals from AMD, have precise process control such that they can be engineered and operated to produce a specific water chemistry and adapt to changing AMD chemistry and flow rates, and they can be accommodated at small sites. The main disadvantages of active treatment is the high capital cost and high ongoing operation and maintenance costs. The work presented here provides a method to select site-specific active treatment systems based on site characteristics such as chemistry, flow rate, and available land area.

Active Treatment of AMD

Active treatment for AMD is largely based on industrial wastewater treatment technologies (Younger et al., 2002). There are a variety of methods that are considered active, but by far the most predominate one is ODAS (oxidation, dosing with alkali, and sedimentation), which is common to that of traditional wastewater treatment plants (USEPA, 2000; USEPA, 2004). Other active treatment technologies that are occasionally used for AMD, but which are not covered here, include sulfidization, biosedimentation, sorption and ion exchange, and membrane processes like filtration and reverse osmosis (Younger et al., 2002).

Although the most common order of treatment in industrial wastewater treatment systems is ODAS, for treatment of AMD the most common order is DAOS (Younger et al., 2002). Dosing with alkali is typically the first step followed by oxidation and sedimentation. Oxidation rates for dissolved metals in reduced form such as Fe^{2+} are strongly influenced by pH (Stumm and Morgan, 1996), therefore it is beneficial to raise the pH prior to the oxidation step in treatment of AMD. Sometimes a pretreatment step precedes DAOS such as sedimentation to reduce the concentration of total suspended solids (TSS) which can affect treatment system performance.

A range of factors will influence the selection of appropriate active treatment systems including TSS content, Mn concentration (mg/L), flow rate (L/s), Fe concentration (mg/L), and available land area (Fig. 1). Details on each of these factors as well as a review of chemicals used in active treatment are provided below. Once an active treatment system has been selected, a computer program such as AMDTreat (Means et al., 2003) can be used to design specific components of the system and to determine potential costs.
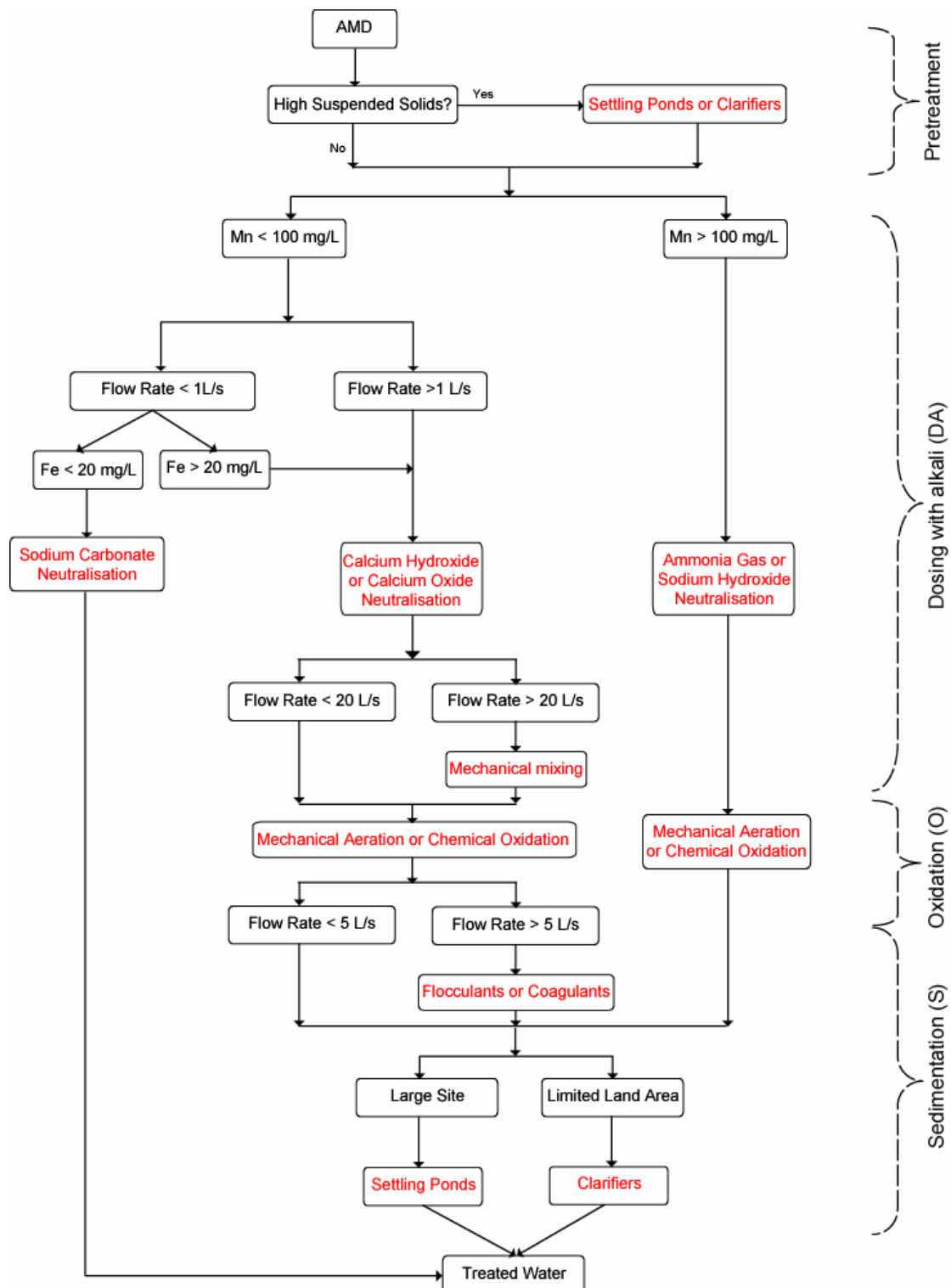
Figure 1: Flow chart to design a site-specific active treatment system for AMD (modified from Rajaram et al., 2001).

Pretreatment

Where high suspended solids loads are present, pretreatment of the AMD may be required. High concentrations of TSS can affect treatment system performance through clogging piping and flumes and damaging pumps. TSS concentrations are typically reduced through sedimentation techniques, such as gravity assisted

separation, with the solids recovered as a slurry or sludge. Depending on available land area, gravity assisted separation is accomplished either with clarification or by using settling ponds or sedimentation ponds (Rajaram et al., 2001). In clarification, water flows into the centre of a clarifier tank and then flows slowly and uniformly outward toward the tank walls (USEPA, 2000). The water leaves the clarifier over a weir at the top allowing solids to settle to the bottom of the clarifier. The solids are periodically removed, dewatered and disposed. With settling ponds, sufficient residence time is required for suspended solids to settle out of solution and accumulate at the base of the pond. Depending on the rate of accumulation of solids, sludge is removed periodically from the pond to maintain the necessary residence time.

Dosing with alkali (DA)

The main goal of this step is to add enough neutralising agent to raise the pH and to lower the concentrations of dissolved metals by forming metal hydroxides and oxyhydroxides. The most commonly used chemicals include soda ash or sodium carbonate (Na_2CO_3), hydrated lime or calcium hydroxide ($Ca(OH)_2$), quicklime or calcium oxide (CaO), caustic soda or sodium hydroxide (NaOH), and ammonia (NH_3). Magnesium oxide or hydroxide (MgO or $Mg(OH)_2$) and limestone ($CaCO_3$) are occasionally used. Selection of an appropriate chemical is primarily dependent on the concentrations of dissolved Mn and Fe and the flow rate of the AMD, although other factors will also influence chemical selection. These include: chemical cost, neutralising efficiency, maximum pH attainable and therefore ability to remove metals such as Mn, dispensing mechanism required, mixing mechanism required, health and safety issues, sludge settling rates and therefore requirement for flocculants or coagulants, and resulting sludge volume and density (Table 1; Figs 2 and 3; Skousen et al., 2000; Waters et al., 2003; Means, 2006).

Table 1: Table of characteristic of chemicals used to neutralise AMD in active treatment systems (Skousen et al., 2000; Waters et al., 2003; Means, 2006).

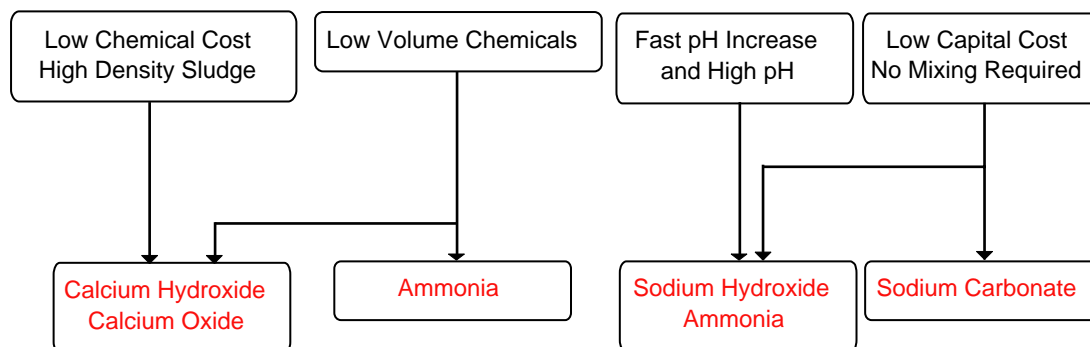| Chemical	Max pH attainable	Neutralisation efficiency (%)	Conversion Factor (mass needed compared to limestone)	Cost of Chemical (relative to NaOH)	Dispensing Mechanism	Key benefits	Key limitations	Risk of failure
Soda ash or sodium carbonate (Na_2CO_3)	11.6	95 - 100 (powder) 60 (briquettes)	1.06	0.56	Briquettes placed in wooden box or 55 gallon drum in AMD stream	High efficiency in powder form, most metals precipitate, low sludge volumes	Health and safety issues, poor sludge settling rates, potential sodium toxicity.	Potential for reduced treatment effectiveness when using briquettes if acidity loading rates increase significantly (best as an interim treatment or only for low flow/low acidity AMD)
Hydrated lime or calcium hydroxide $(Ca(OH)_2)$	12.4 - 12.5	90 - 95	0.74	0.17	Silo or hopper with mechanical feed screw to dispense powder. Batching tank to mix powder with water. Can use aqueous slurry. Mixing suggested.	High efficiency, most metals precipitate, low cost, widely available	Health and safety issues, reagent saturation can lower efficiency	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop. Poor maintenance can result in plugged dispensing mechanism and complete failure.
Quicklime or calcium oxide (CaO)	12.4 - 12.5	90	0.56	0.11	Silo or hopper with mechanical feed screw to dispense powder or water wheel feeder with 1 ton storage bin (no power). Batching tank to mix powder with water. Mixing suggested.	High efficiency, most metals precipitate, very low cost, widely available	Health and safety issues, reagent saturation can lower efficiency, possible armouring of pebbles	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop. Poor maintenance can result in plugged dispensing mechanism and complete failure. Must be watertight or will hydrate and form calcium hydroxide and plug dispensing mechanism.
Ammonia $(NH_3$ or $NH_4OH)$	9.2	100	0.34	0.60	Compressed and stored as liquid in tank, gas injected near bottom of pond or water inlet. No mixing required.	Very high efficiency, most metals precipitate, low sludge volumes	Health and safety issues, poor sludge settling rates, can be toxic to aquatic life, high cost	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop.
Caustic soda or sodium hydroxide (NaOH)	14	100	0.80 (solid)	1	Stored as a liquid in tank, dispense through metering pump or valve and feeder hose near top of pond or water inlet. No mixing required.	Very high efficiency, most metals precipitate, low sludge volumes	Health and safety issues, poor sludge settling rates, potential sodium toxicity, highest cost of all chemicals, low freezing point	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop. If insufficient antifreeze added, can freeze in winter resulting in complete failure.
Magnesium oxide or hydroxide $(MgO$ or $Mg(OH)_2)$	Theoretical: 10.2 Realistic: 9 - 9.5	90 - 95	0.40 or 0.58	0.22	Silo or hopper with mechanical feed screw to dispense powder. Batching tank to mix powder with water. Mixing suggested.	Very high efficiency, most metals precipitate, low sludge volumes, low cost	Some health and safety issues, not widely available, lower reaction rate than calcium hydroxide	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop.
Limestone $(CaCO_3)$	Theoretical: 9.4 Realistic: 6 - 7.5	30 - 90	1	0.04	Silo or hopper with mechanical feed screw to dispense powder. Batching tank to mix powder with water. Mixing suggested.	Safe to use, lowest cost of all chemicals, readily available, cannot overtreat	Low efficiency, not all metals removed (ineffective for Mn), armouring	If acidity loading rates increase beyond system capacity to neutralise and settle hydroxides, treatment effectiveness will drop.

Figure 2: Beneficial characteristics of five main chemicals used in active treatment of AMD.
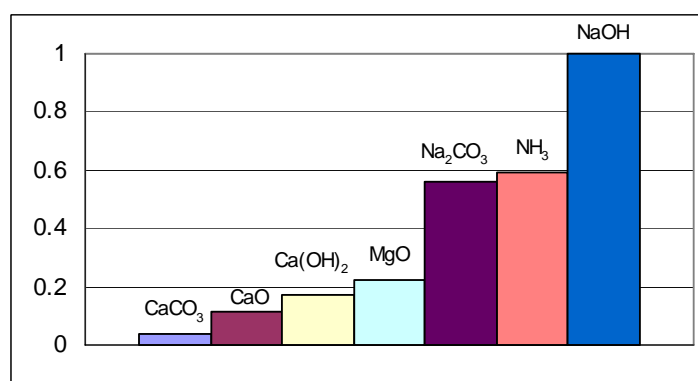

Figure 3. Costs of neutralising chemicals relative to the most expensive chemical, NaOH (Waters et al., 2003). Costs reflect purchase, purity and dispensing efficiency for eastern Australia.

Chemical cost in particular can be significant, as over the long term the largest single cost component in most systems is the neutralising chemical (Waters et al., 2003). It is recommended to conduct bench scale tests on various chemicals before final selection (Younger et al., 2002) and to conduct a sequential titration acidity analysis as described in Means and Hilton (2004). The rationale for using Mn and Fe concentrations and flow rate is described below along with a review of each of the main chemicals used in active treatment.

Manganese is a difficult metal to remove from solution as it exhibits high solubility over a broad pH range (4.5-8) and the chemical oxidation of Mn is kinetically slow (Bamforth et al., 2006). The most effective way to remove Mn from water is to raise the pH above 9 and allow Mn^{2+} to oxidize to Mn^{3+} or Mn^{4+} and form insoluble manganese oxides (Evangelou, 1998). Where high concentrations of Mn are present (>100 mg/L), the most effective neutralising chemicals for Mn removal are sodium hydroxide (NaOH) and ammonia (NH_3; Skousen et al., 1990, 2000). If ammonia is used, it is recommended to use a pH-driven monitoring system, because over application can lead to toxicity of the treated water. In addition, sodium hydroxide shows a nearly linear relationship with pH (to 12) while ammonia shows a logarithmic curve, with only small changes in pH occurring above 9.2 with the addition of more chemical (Skousen et al., 1990). It is not economical to use other chemicals for Mn removal due to the very long residence times needed to attain a high pH and the large amounts of unreacted lime that is produced when raising the pH above 7 with calcium-based compounds (Skousen et al., 2000).

Iron concentration is only a factor in treatment selection when considering treatment of very low flow AMD (<1 L/s) where active treatment may be considered as an interim solution or a solution to an intermittent problem. Where Fe is present in low concentrations (< 20 mg/L),

sodium carbonate (Na_2CO_3) dispensed via simple dispensing mechanisms (e.g. wooden box, barrel, or drums with water flowing in and out) is a suitable solution (Skousen et al., 1990, 2000; Means, 2006). If Fe concentration is above 20 mg/L, sodium carbonate may still be used although a mixing system should be employed, otherwise, another neutralising chemical and different dispensing mechanism may be more appropriate.

In situations where Mn is not a major concern and flow rates are generally above 1 L/s and/or Fe concentration is above 20 mg/L, calcium oxide, or the hydrated form calcium hydroxide, is the most commonly used chemical for neutralisation (Skousen et al., 1990, 2000). Over the long term, especially for high acidity and high flow rates, these are generally the least expensive chemicals for treatment (Fig. 4), however, in New Zealand powdered calcium carbonate (limestone) has been shown to be a cost effective solution for high flow and high acidity AMD (Weber et. al., 2007, 2008). The dissolution rate of calcium-based compounds such as calcium oxide or calcium hydroxide is slower than that of other chemicals, therefore effectiveness and efficiency of treatment are greatly improved by mechanical mixing (Skousen et al., 1990; Rajaram et al., 2001). Rajaram et al. (2001) recommend mechanical mixing above a flow rate of 20 L/s.
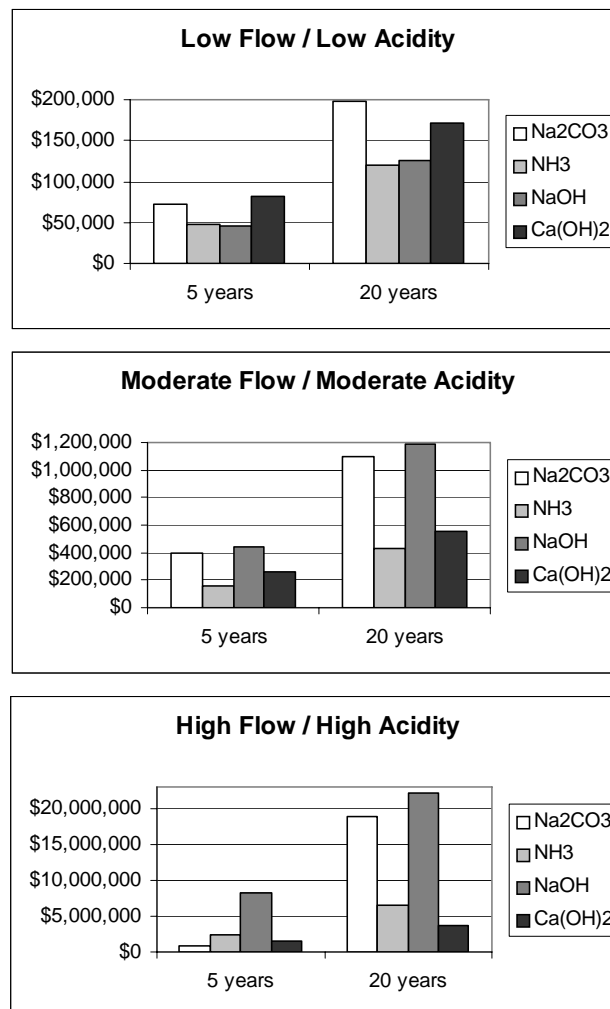

Figure 4: Comparison of potential costs for active treatment of AMD using five different chemicals (Fletcher et al., 1992). These costs are based on hypothetical 1992 costs in West Virginia, USA for equipment installation, annual labour, and annual chemical reagent costs over various AMD flow and acid concentration cases. Low flow/low acidity = 3.2 L/s at 100 mg/L, moderate flow/moderate acidity = 15.8 L/s at 500 mg/L; high flow/high acidity = 63.1 L/s at 2500 mg/L.

Soda ash or sodium carbonate (Na$_2$CO$_3$)

Soda ash is generally only used in small flow cases with low amounts of Fe and where Mn is not a problem (Skousen et al., 1990). It can also be used as a good interim solution until a more permanent system is constructed (Means, 2006). Selection of this chemical is sometimes based more on convenience rather than cost effectiveness. The chemical is delivered in briquette form and placed in a box, barrel or drum. Water flows through this dispensing mechanism dissolving a small amount of the chemical. Gravity keeps the briquettes feeding into the water for constant treatment.

Hydrated lime or calcium hydroxide (Ca(OH)$_2$)

Hydrated lime is the most common chemical used for neutralising AMD. Although the capital cost for a system using hydrate lime is high, low chemical cost makes this a very economical treatment method over the long term. It is generally delivered in powdery form, which is hydrophobic, so extensive mixing is recommended for high flow rates to make it soluble in water (Skousen et al., 1990). It is usually contained in large hoppers and dispensed into the AMD using a mechanical screw feeder (Means, 2006).

Quicklime or calcium oxide (CaO)

Quicklime is the non-hydrated form of hydrated lime. After limestone, quicklime is the least expensive chemical used in treatment of AMD, however, it must be stored in a water-tight container to avoid premature hydration and formation of hydrated lime (Means, 2006). If it does form hydrated lime, it can bridge and eventually plug the dispensing mechanism. It is commonly dispensed from a hopper through a waterwheel-powered auger into the AMD, requiring less operation and maintenance than a conventional system, and useful for areas without power (Skousen and Jenkins, 1993). At high flow rates, it is recommended to use a water driven mixer (Means, 2006).

Caustic soda or sodium hydroxide (NaOH)

Caustic soda is the most expensive chemical used in AMD treatment, is hazardous to handle, and freezes more readily than lime, however, it is 100% efficient, can raise the pH very high and therefore is able to remove Mn, and a treatment system using caustic soda has low capital costs (Means, 2006). It can be delivered to the site in pellet form or more commonly as an aqueous solution (20-50%). It is often stored in large tanks and dispensed either through a valve and feeder hose or with a metering pump into the top of the AMD (it is denser than water). Along with ammonia, no mixing is required, however, the resulting sludge is loose and gelatinous (Skousen et al., 2000).

Ammonia (NH$_3$)

After caustic soda, ammonia is the next most expensive chemical used in AMD treatment and is very hazardous to handle, however, like caustic soda it is 100% efficient, can raise the pH to 9.2 and therefore is able to remove Mn, and a treatment system using ammonia has low capital costs (Waters et al., 2003). It is delivered as a compressed gas (anhydrous ammonia), stored as a liquid in large tanks and bubbled into the water near the bottom of the water column where it returns to the gaseous state (Faulkner and Skousen, 1991). As it is a compressed gas, it does not have to be pumped or gravity fed. No mixing is required but the

resulting sludge is loose and gelatinous (Skousen et al., 2000). If ammonia is used, it is recommended to use a pH-driven monitoring system, because over application can lead to toxicity of the treated water. Ammonia reacts with sulphuric acid to form ammonium sulphate, consuming hydrogen ions (raising the pH), and forming hydroxyl ions which react with Fe and Al to form hydroxides (Faulkner and Skousen, 1991). It is one of the fastest ways to raise the pH.

Magnesium oxide or hydroxide (MgO or Mg(OH)$_2$)

Although magnesium oxide has a relatively low cost (but slightly more expensive than calcium hydroxide) and has a high efficiency, it needs mixing, has a low reaction rate, and most importantly, is not generally widely available (Waters et al., 2003). It is dispensed in a similar manner to and behaves like calcium hydroxide (Skousen et al., 1996).

Limestone (CaCO$_3$)

Limestone has the lowest material cost and is the safest and easiest to handle of the chemicals commonly used for AMD treatment. Unfortunately, its successful application is limited due to its low solubility and tendency to develop an external coating, or armour, of ferric hydroxide when added to AMD (Phipps, et al., 1996). In addition, limestone has the lowest treatment efficiency of the common chemicals used for AMD treatment. Limestone is generally only applicable when Fe concentrations are below 5 mg/L and total acidity is less than 50 mg/L (Skousen et al., 1990).

If limestone is ground to a powder it can be dispensed into an AMD stream by a waterwheel-powered doser and be effective in raising the pH and lowering the concentrations of dissolved metals (Mills, 1996; Zurbuch, 1996). In Mills (1996) waterwheel-powered dry powder limestone dosers raised the pH to neutral and treated water with Fe concentrations of about 7 mg/L and Al concentrations of about 8 mg/L. Zurbuch (1996) describes water powered rotary drums which autogenously grind limestone aggregate inside them into a slurry which is released into a river. The limestone drops into a small hopper where it enters the drum via an inverted screw feed which is part of the drum axle. Small holes in each drum vane permit water to enter the drum and CaCO$_3$ slurry to exit. A backup limestone powder doser was constructed adjacent to the drum station. In New Zealand powdered limestone (< 0.1 mm in size) is currently being used to treat AMD at the Stockton Mine (Weber et al., 2007, 2008). Powdered limestone is released from a hopper via an electrically-driven screw feed into the Mangatini Stream. The rate of the screw feed is regulated by a pH probe placed downstream of the hopper. The main disadvantage of simply dispensing a neutralising chemical into an AMD stream is that metals precipitate and settle out of solution along the water course resulting in an increase in TSS in the stream and large amounts of Fe and Al floc. At the Stockton Mine it is planned to construct a large reservoir downstream of the dosing plant to capture Fe and Al flocs.

Oxidation (O)

The goal of the oxidation step is to ensure reduced metals such as Fe^{2+} and Mn^{2+} are oxidised to Fe^{3+} and Mn^{4+} so that they can form hydroxide and oxide precipitates and be removed from AMD (Skousen et al., 2000; Younger et al., 2002). This step may not be necessary if the metals are already highly oxidised through the previous treatment step. Bench scale tests at the time of system design would be required to confirm this.

Oxidation is typically undertaken using mechanical means, although sometimes chemical oxidation is used. Cost and effectiveness can be used to decide between mechanical and chemical oxidation. Mechanical aeration techniques include stirring with rotating blades (most common), inline venturi aeration, trickle filter aeration (water trickling through a tank filled with high-surface area media and with air bubbled into the water), and cascade aeration (if sufficient land area is available).

Chemical oxidants commonly used include hydrogen peroxide (H_2O_2), sodium hypochlorite (NaClO), calcium hypochlorite ($Ca(ClO)_2$), and potassium permanganate ($KMnO_4$; Skousen et al., 1993; Skousen et al., 2000). Another potential oxidant is calcium peroxide (CaO_2) which not only can oxygenate AMD but can also neutralise acidity (Skousen et al., 2000). Cost, availability and effectiveness are typically used to decide among the various chemical oxidants.

Sedimentation (S)

The final step in the process is sedimentation to remove the metal precipitates formed during the early stages of treatment. The methods used include gravity assisted separation with or without coagulants/flocculants followed by sludge dewatering and disposal. Depending on available land area, gravity assisted separation is accomplished either with clarification or by using settling ponds or sedimentation ponds as described above in Pretreatment.

The use of coagulants/flocculants is reserved for higher flow rates (>5 L/s) when residence times in clarifiers or settling ponds can be insufficient for complete metal precipitation. Coagulation and flocculation are two separate processes involving addition of chemicals to promote settling of suspended particulates (Bratby, 1980; Skousen et al., 1993; Skousen et al., 2000). Both processes enhance sedimentation performance by increasing particle size resulting in increased settling rates.

Coagulation refers to the addition of chemicals to reduce the net electrical repulsive forces at particle surfaces, promoting consolidation of particles. The most commonly used coagulants include aluminium sulphate ($Al_2(SO_4)_3$), ferric sulphate ($Fe_2(SO_4)_3$), and ferrous sulphate ($FeSO_4$). Flocculation refers to the addition of chemicals to join particles by bridging the spaces between suspended particles. Flocculants consist of polymer chemicals which adsorb suspended particles onto polymer segments. The most commonly used flocculants include synthetic anionic (negatively-charged surfaces) and cationic (positively-charged surfaces) chemicals and polyampholytes (both positive and negative charges on surface based on pH).

Coagulants and/or flocculants are usually added in a rapid mix tank or with an in-line mixer and then the wastewater flows to a flocculation basin or tank where slow mixing allows the particles to agglomerate in a more settleable solid. The treated water then flows either into a clarifier or a settling pond for removal of TSS. Bench-scale laboratory experiments are recommended to determine appropriate type and dosage of coagulant/flocculant.

Sludge dewatering and disposal can be a significant cost of AMD treatment, frequently exceeding chemical costs by several times (Skousen et al., 2000). The sludge typically contains between one and five percent solids. The chemical composition is generally composed of hydrated Fe^{2+} or Fe^{3+} oxyhydroxides, $CaSO_4$, $Al(OH)_3 \cdot 6H_2O$, $CaCO_3$, and $Ca(HCO_3)_2$ with trace amounts of Si, PO_4, Mn, Cu, and Zn (Ackman, 1982). They are

dewatered using pressure, gravity, vacuum, or centrifugal force. Alternatively, sludge can be pumped from settling ponds directly into deep coal mines on a periodic basis or, if possible, ponds can be constructed with enough capacity to hold sludge for a number of years (case studies in Brown et al., 1994a). The most common dewatering methods are plate and frame pressure filtration, belt pressure filtration and vacuum filtration. A plate and frame filter press can produce the driest filter cake, followed by the belt press, and lastly, the vacuum filter (USEPA, 2000).

Disposal of filter cake (dewatered sludge) is usually to an off-site landfill, incineration facility or appropriate area for land application. If the sludge is non toxic, filter cake from the active treatment process can sometimes be disposed of on site, or as mentioned above, pumped directly into deep mines with little to no dewatering. See Brown et al. (1994a, 1994b, 1994c) for information on volume, stability, and composition of sludge generated from active treatment of AMD.

Conclusions

Although more costly than passive treatment systems in the long term, active treatment systems for AMD are often appropriate at active mine sites due to their small footprint compared to passive treatment systems and their ability to address drainage chemistry and flow rates that can change as mining proceeds. Traditional wastewater treatment ODAS technology (oxidation, dosing with alkali, and sedimentation) has been adapted to treat AMD by changing the order to DAOS. Oxidation rates are strongly influenced by pH, therefore it is beneficial to raise the pH through the dosing with alkali step prior to oxidation. A flow chart has been prepared that incorporates the parameters of suspended solids content, iron and manganese concentrations, flow rate, and available land area to help design site-specific active treatment systems. Prior to full scale construction, is it recommended to conduct bench scale tests on various chemicals, to complete a sequential titration acidity analysis, and to review cost, effectiveness, limitations, and risk of failure for various options.

Acknowledgements

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