ABSTRACT

Coming to Terms with Acid Drainage

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Acid drainage at mine sites usually develops when naturally occurring iron-sulphide minerals are exposed to air during the dewatering and mining process. In the presence of air and water, the sulphides decompose to release sulphuric acid and soluble metals. Apart from its corrosive impact on equipment and infrastructure, acid drainage can damage aquatic ecosystems and degrade water quality. Unless correctly addressed, acid drainage will often lead to long term and costly remediation.

Whilst there have been many advances in the early recognition and mitigation of acid drainage, many mine sites around the world still continue to underestimate its likelihood and severity. A recent report by the Australian Government (Harries, 1997) indicated that rehabilitation costs for acid drainage affected sites are likely to be in excess of A$100,000 per hectare, excluding the cost of treating water from mine workings.

Currently, best practice environmental management of sulphidic mine wastes involves integration of acid drainage prevention, minimisation and control into the mining process. It can be summarised as the early characterisation and classification of the acid generating potential of these materials, development of strategies to minimise the oxidation of sulphides, and where acid drainage formation is unavoidable, the implementation of suitable long term control and treatment technologies. In almost all circumstances, resources spent on prevention and minimisation of acid drainage are returned many fold through lower control and treatment costs.

Based on the experiences of mine sites throughout the world, control and management solutions for acid drainage are often site specific taking into account environmental risk, economics, regulatory regime, climate, terrain, local natural resources and site logistics.

Using case studies from the Asia-Pacific, this paper reviews and evaluates a range of established techniques, recent advances and new concepts developed for the control and management of acid drainage from mine sites. It identifies the strengths and weaknesses of different approaches and highlights where each can be most cost effectively and successfully used. It also reviews some areas of continuing research into cost-effective techniques for minimising or avoiding acid drainage formation, techniques that offer hope for expanding the future options of environmental managers.

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1.0 Background to Acid Generation and Metal Mobilisation

Acid drainage is a low pH, iron and sulphate-bearing water usually formed when rocks containing sulphide minerals (eg. pyrite, pyrrhotite etc) are exposed to the atmosphere or an oxidising environment, and subsequently leached by water. Acid drainage is a major issue affecting the metal mining and coal industry throughout the world. Many old mining sites have a legacy of acid drainage long after the completion of mining. The major sources of acid drainage at mine sites and the associated minimisation, control and treatment techniques are summarised in Figure 1.

The production of acid via iron sulphide (eg pyrite) oxidation can be represented by the following reaction:

$FeS_2 + 3.75\ O_2 + 3.5\ H_2O = Fe(OH)_3$ (orange precipitate) $+ 2\ SO_4^{2-} + 4\ H^+$ **(1)**

(Iron sulphide + Oxygen + Water = Ferric Hydroxide + Aqueous sulphuric acid)

The following more detailed reactions demonstrate the key steps in the acid forming process, and highlight the importance of ferric hydroxide ($Fe(OH)_3$) precipitation in the production of acidity:

$FeS_2 + 3.5\ O_2 + H_2O = Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+$ **(2)**

Pyrite is exposed to air and decomposes into water soluble components; acid is produced.

$Fe^{2+} + 0.25\ O_2 + H^+ = Fe^{3+} + 0.5\ H_2O$ **(3)**

The relatively reduced water soluble components are further oxidised; acid is consumed.

$Fe^{3+} + 3\ H_2O = Fe(OH)_3$ (orange precipitate) $+ 3\ H^+$ **(4)**

The formation of ferric iron in water results in the precipitation of ferric hydroxide precipitate; acid is produced.

Ferric hydroxide will only precipitate from water (above pH 3.3) after it has been sufficiently aerated / oxidised to facilitate the conversion of soluble ferrous iron to soluble ferric iron. As can be seen from reaction (4), this process is a key acid producing stage. Once sulphides have been oxidised, it is extremely difficult to avoid ferric hydroxide precipitation.

With the formation of soluble ferric iron (Fe^{3+}) in the presence of fresh iron sulphide, further sulphide oxidation is accelerated, as represented in the following reaction:

$FeS_2 + 14\ Fe^{3+} + 8\ H_2O = 15\ Fe^{2+} + 2\ SO_4^{2-} + 16\ H^+$ **(5)**

Iron sulphides in geologic materials that are located below the water table will remain essentially stable, since the potential for oxidation is limited[2]. However, where sulphidic materials are exposed to oxidising conditions (air) the iron sulphides will react and water can move the reaction products (eg. iron and sulphate) into surface water and groundwater. As the acid water migrates, it further reacts with other minerals and dissolves a broader range of metals.

Whilst pH is a measure of hydrogen ion concentration (H^+ in reactions (2) to (5)), "acidity" is a measure of both hydrogen ion concentration and mineral (or latent) acidity. Mineral or latent

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[2] The concentration of dissolved oxygen in natural waters is approximately 25,000 times lower than found in the atmosphere.

acidity includes the concentration of hydrogen ions that could potentially be generated by the precipitation of various metal hydroxides from any given solution when titrated to a specific pH (eg. such as for ferric hydroxide as shown in reaction (4) above). Commonly acid drainage solutions contain iron, aluminium, manganese, copper, lead, zinc, cadmium and other metals. Total Acidity (ie. existing + latent) is measured in a laboratory by thoroughly oxidising a water sample, and titrating it to a specific pH (eg. commonly 8.3). Provided in units of mg/l $CaCO_3$, this measurement quantifies the ideal neutralisation requirements of the water sample to the specified pH.

One thousand tonnes of material containing 0.5% sulphur as pyrite which completely oxidises will require approximately 16 tonnes of $CaCO_3$ (used efficiently) to neutralise the sulphuric acid generated.

1.1 What Problems are Created by Acid Drainage?

Acid drainage can have extreme impacts on the ecology of streams, affecting the beneficial use of waterways downstream of mining operations. Acid conditions can:

- mobilise (bring into solution) metals to levels injurious to aquatic ecosystems, riparian communities and possibly human health (eg. zinc, cadmium, aluminium, copper);
- limit the downstream beneficial uses of the receiving water (eg. stock, recreation, fishing, aquaculture, irrigation);
- alter important life supporting balances in water chemistry (eg. bicarbonate buffering system);
- lead to the development of chemical precipitates (eg. ferric hydroxide, aluminium hydroxide...etc) that can smother aquatic habitat and reduce light penetration;
- impact on groundwater quality;
- lead to the installation of expensive control, treatment and rehabilitation programs;
- create long term environmental liabilities; and
- limit the reuse of mine site water and exacerbate the corrosion of site infrastructure and equipment.

Acid drainage can also cause revegetation and rehabilitation difficulties. Acidity in soils can lead to significant excesses and deficiencies of key elements for plant growth and difficulties in stabilising mine wastes. Acid conditions in soils are at best a significant limitation on the vegetation types that can be used for rehabilitation and at worst the cause of a failed rehabilitation programme.

A recent study assessing acid mine drainage in Australia (Harries, 1997) conservatively estimated that over 15 years, the total cost of managing potentially acid generating mine wastes from current mines is A$ 900 million. The cost of rehabilitating the Rum Jungle mine site, a relatively small mine in the Northern Territory, from funds provided by the Australian Government was A$ 18.6 million (Harries, 1997). Detailed studies of the Mount Lyell mining area in Tasmania estimate expenditure exceeding A$ 10 million in capital costs and A$ 2 million in yearly operating costs to neutralise all acid drainage sources from the mine area (Koehnken, 1997).

Typical costs for rehabilitating potentially acid generating wastes at historic abandoned mine sites has been estimated as being in excess of $100,000 per ha (Harries, 1997). These costs do not include acid drainage treatment costs of mine workings. In contrast, the cost of managing acid drainage at existing mine sites is significantly less than this figure, indicating that site recognition and on-going management of acid drainage is an important long term cost saving.

Experience has shown that acid drainage, if not properly managed has the potential to be a long term liability for mine operators, regulators and the community.

1.2 Factors Influencing Acid Drainage from Sulphides

The following factors can enhance the production of acid drainage from iron sulphides:

- the ready availability of oxygen and water;
- physical characteristics of geologic materials which encourage rapid oxidation (ie. high surface area / small grainsize iron sulphides);
- water with a low pH;
- elevated water temperatures;
- high soluble Fe^{3+}/Fe^{2+} ratios;
- the presence of micro-organisms (bacteria, eg. *Thiobacillus thiooxidans and T. ferrooxidans)* which can act as a catalyst by utilising iron sulphide as an energy source, thereby oxidising the sulphide mineral;
- the absence of neutralising materials (eg. calcium carbonate); and
- warm, wet climates.

2.0 Best Practice Management and Control of Acid Drainage

Best practice management of acid drainage is routinely pre-emptive and can usually be summarised by the following:

- Understanding the site mechanisms for acid generation, predicting the acid generating potential and incorporating this information into mine design and management (eg. location of waste dumps, blending of wastes, dump design and management procedures, water management plans...etc).
- Development of suitable minimisation and control strategies.
- Monitoring to seek warning signs of the early development of acid drainage, and later to quantify the effectiveness of minimisation and control strategies.
- Treatment where minimisation and control strategies are not totally effective or where costs of treatment are less than the costs of minimisation and control (refer to Figures 1& 2).

More specific detail on measures to implement best practice management of acid drainage follow.

2.1 Identification and Prediction of Acid Drainage

Accurate prediction of acid drainage requires a knowledge of the mineralogy and chemistry of geologic materials, site hydrology and the distribution of key rock types. It is important to understand which lithologies are acid generating, non-acid generating or geochemically ambiguous, and how rapidly sulphidic minerals decompose in the presence of oxygen. To identify the potential implications of acid drainage for a site detailed assessment is required of the following issues:

- A baseline or the background receiving water quality conditions of the site / area?

- The presence of sulphide minerals or other acid forming components in the ore or waste rock material. If present, detailed materials characterisation (eg. acid-base accounting, kinetic tests).

- Acid budget for the site, possibly incorporating a site water balance.

- Requirements for site water discharge. How often, how much, when, and what are the water quality parameters to be achieved?

Various types of both static and kinetic tests have been developed to assist with the characterisation of acid generation potential.

2.1.1 Static Tests

Static tests are the first step in evaluation of acid drainage potential of various rock materials. Current best practice static tests involve acid-base accounting or the Net Acid Producing Potential or NAPP test, and the Net Acid Generation or NAG test. The objective of acid-base accounting is to determine the balance between acid forming and acid consuming components of geologic materials. The Maximum Potential Acidity (MPA) is determined by analysis for total sulphur, which is assumed to be in the form of pyrite (FeS_2). The NAPP is calculated by subtracting the Acid Neutralising Capacity (ANC; determined by titration with acid) from the MPA.

In order to avoid the need to determine the MPA and acid neutralising capacity separately, the net acid generation or NAG test was developed. This test involves the addition of hydrogen peroxide (normally unstabilised 30% H_2O_2 diluted 1:1 with deionised water) to a pulverised geologic sample (normally 2.5 grams). If sulphide minerals are present, the peroxide reacts to produce heat and acid, and this will react with available neutralising material. NAG tests are sometimes preferred to the more time consuming NAPP tests as a first pass indication of acid generating capacity due to their relative simplicity and lower cost.

2.1.2 Kinetic Tests

Kinetic tests simulate weathering and oxidation of rock material over time via exposure to moisture and air. The tests can be used to provide an indication of oxidation rate, the time period before the onset of acid generation, the rate of acid neutralisation and data on potential metal release into acidic leachate. A variety of laboratory and field based kinetic tests have been devised, and all require a longer time period and are more expensive than static tests.

2.2 Monitoring

Monitoring is a critical component of best practice management of acid mine drainage. Identifying acid drainage or the likelihood of acid drainage at an early stage may provide advance warning of more significant problems. This will enable pro-active control and possibly treatment strategies to be adopted.

Key features of a monitoring programme include:

- monitoring of surface water and groundwater upstream and downstream of the mine including the analysis of key acid drainage indicators such as pH, acidity, sulphate, iron, aluminium, manganese.

- monitoring of seeps, and water and waste storages on the mine site for key acid drainage indicators.

- routine testing of geological materials during mining to validate predicted acid generating capacity.

Other monitoring strategies that may be applicable at sites with potentially severe acid drainage include:

- temperature profiles through waste dumps to identify the presence or otherwise of exothermic oxidation (the appearance of steam from waste dumps or hot spots on the waste surface may be immediate indicators of exothermic acid producing reactions within a waste dump);

- water flux or ingress through a waste dump; and

- oxygen diffusion rates through engineered covers on waste dumps and tailings ponds.

2.3 Minimisation and Control of Acid Generation

Minimising acid drainage requires restricting the availability of oxygen and moisture to sulphides. Oxygen converts the sulphides to sulphates, and water facilitates the dissolution and transport of the resulting sulphuric acid.

Control strategies are defined as those measures which are required to either limit the formation of acidic products (ie. inhibiting sulphide oxidation), or minimise the dissolution and mobilisation of these products by water (ie. limiting interaction with water).

Techniques that are commonly used for control include the following:

- Diversion / dilution

- Containment and evaporative disposal

- Waste encapsulation / covers
- Waste blending / segregation (selective handling)
- Waste submergence

Ideally, acid mine drainage control measures should be implemented pro-actively. This can be assisted through prediction by characterising waste materials under conditions which simulate site conditions. When such tests identify potential acid drainage risks, control options need to be explored, and an Acid Drainage Management Plan (ADMP) established.

An environmental manager's choice of control (and treatment) is a function of:

- the nature and extent of current and potential acid drainage problems (sulphide content, type, distribution, reactivity, available neutralising material, water chemistry);
- the sensitivity of the receiving environment (environmental risk);
- existing natural amelioration factors (eg. high river flows, alkaline water, natural wetlands);
- the regulatory regime (discharge standards and compliance requirements, rehabilitation requirements);
- climate (eg. site water balance, local hydrology);
- site logistics (eg. terrain considerations, availability of space, water storage capability);
- local natural resources (suitable for control and treatment measures); and
- economic resources / budgetary requirements.

The choice of control techniques is site specific, and multiple techniques are often employed. Control techniques display varying success at different sites, and may be employed with or without treatment methods.

2.3.1 Diversion

The diversion of unpolluted runoff away from acidic products or ponded acid drainage, or the diversion of acid drainage from unpolluted water bodies is a fundamental control method. The concept behind diversion is simply to minimise the volume of acidic leachate.

There are very few sites where diversion is not appropriate. Water diversion can provide savings in both cost and space.

2.3.2 Dilution

In some instances, discharge of acid drainage into a local waterway with relatively high flow-rates is regarded as a suitable control measure. The viability of this option is dependent on the relative locations of discharge and compliance points, as well as local hydrological factors.

2.3.3 Selective Handling

Selective handling involves the location of waste rock material to minimise the generation of acid drainage. Usually this involves handling acid generating waste and placing it in a location which limits its exposure to air and water. It can also involve the blending or mixing of acid neutralising and acid generating wastes to minimise acid release.

The costs of selective handling are complex to estimate and vary enormously depending on the nature of the mining operation.

2.3.4 Barrier Formation

A common approach to controlling acid drainage is the formation of various types of barriers or covers. The prime function of a barrier is to exclude oxygen and/or water.

Water Covers

In the simplest terms, a cover may be a layer of water. Sulphidic mine wastes are largely unreactive when stored under water due to the reduced availability of oxygen. The concentration of oxygen in natural waters is approximately 25,000 times lower than that found in the atmosphere.

Flooding of underground or opencut workings is often an effective mechanism for submerging sulphides and dramatically reducing sulphide oxidation. Backfilling of underground and opencut workings with waste rock and/or tailings is often conducted in conjunction with flooding as a method of placing water covers over sulphidic material. The backfilled material is sometimes stabilised with the addition of quartz sand and binders such as fly-ash, various cements or lime (ref. Helms and Heinrich, 1997), or may be re-disposed without amendment (Lewis-Russ et al., 1997).

Mine flooding and engineered water covers should only be considered if the hydrogeology and water balance of a site are well known and appropriate.

At the Kelian Gold Mine in Indonesia (PT Kelian Equatorial Mining) a dam was constructed (Upper Nakan Dam) to store all potentially acid forming rock under water. The cost of construction of this dam was US$ 15 million (Firth and Van der Linden, 1997).

Dry and Wet Soil Covers

A broad variety of soil-based wet and dry site covers have been developed for the control of acid drainage from mine wastes. These range from simple clay barriers to complex, composite, multi-layer, organic-bearing covers. The design of a soil cover is dependent on the climate of a site (Swanson et al., 1997). Composite soil cover systems for wet sites typically consist of a compacted layer covered by erosion protection and vegetation support layers. Capillary break layers (ref. Swanson et al., 1997; Ricard et al., 1997) are sometimes installed beneath the compacted layer, but are also used above for reducing evaporation from the compacted material (ie. a moisture retention layer). The key aspects of a successful wet site cover are promotion of runoff and maintenance of a high degree of saturation in the compacted layer. These factors minimise oxygen diffusion and water infiltration into the waste material.

Dry site covers comprise a variety of geologic materials (eg. alluvium, topsoil, oxide rock) which are designed to store relatively large volumes of infiltrating water for long enough to enable evapotranspiration before it percolates into the mine waste (Swanson et al., 1997). With an emphasis on promoting evapotranspiration, dry-site covers commonly incorporate extensive vegetation support layers to enhance their store-and-release capacity.

To assist with the control of acid formation, alkaline amendments are added to the tops of some covers to further stabilise the chemistry of the underlying wastes. Alkaline amendments include fly-ash, cement kiln dust, cement stabilised fly-ash, lime neutralisation sludge, limestone, dolomite, alkaline tailings and alkaline paper mill waste, and largely depend on local, low-cost resources. They are often added to dry site covers where their presence may assist plant growth by treating near surface acid generation.

Vegetation support horizons incorporate a range of organic additives to encourage plant growth. Organic material may include forestry wastes (sawdust/wood-chips), sewage sludge, animal manures, paper mill wastes, and municipal waste composts. Once again, the choice of organic additives is generally a function of local resources, but care must be taken to understand their potential impact on leachate quality. Another key benefit of organic-rich layers is that they react with atmospheric oxygen (to produce CO_2) and can dramatically lower oxygen diffusion into mine wastes. Some organic materials provide additional benefits as capillary barriers, alkalinity producing systems, reducing environments and moisture retention layers. Shallow-rooted vegetation should be chosen for planting in wet site soil covers in order to maintain the water saturated oxygen barrier, and deep-rooted varieties are more suited in dry site covers to maximise evapotranspiration (Swanson et al., 1997).

Synthetic Barriers

Synthetic barriers comprising welded sheets of high density polyethylene (HDPE) are being used at some sites to control sulphide oxidation and water infiltration. This is commonly an expensive option with a limited life expectancy. Polymer-modified clay and grout barriers (eg. fly-ash Portland cement mixture) have been employed to isolate acid forming rock from groundwater. Such techniques can provide some success, but the costs need to be justified on a case by case basis.

At the Kelian Mine a low grade ore stockpile and waste rock dump have been covered by HDPE plastic costing US $1.5 million.

2.3.5 Chemical Control Methods

A variety of acid drainage control strategies, largely of a chemical nature include:

(i) Selective placement of acid generating and acid neutralising waste material;
(ii) Blending of neutralising material during disposal of waste rock or tailings;
(iii) Co-disposal of appropriate proportions of waste-rock and tailings;
(iv) In-situ alkaline amendment of sulphidic wastes (eg. Spotts et al., 1997);
(v) Addition of lime neutralisation sludge.

Many of these solutions need to be integrated with mining procedures, and are currently in broad use. They are effective in minimising acid drainage in many situations. Neutralising materials forming part of mine wastes generally offer the lowest cost solutions for controlling acid drainage, and should be thoroughly utilised wherever possible.

2.3.6 Biological Control Methods

Bactericides are a group of chemicals (surfactants) that are used to kill bacteria catalysing the conversion of ferrous to ferric iron, a process which accelerates the oxidation and dissolution of pyrite. They do not provide permanent solutions to acid drainage but in certain applications (eg temporary rock stockpiles) they may be used to delay the onset of acid drainage. In the US coal industry they have been used during rehabilitation to assist in the establishment of a vegetation cover prior to the onset of significant acid generation.

Bactericides are relatively expensive, and their use needs to be justified at each individual site.

3.0 Treatment of Acid Drainage

Treatment techniques are usually reactive rather than pro-active, and are generally designed to:

(i) raise pH,
(ii) lower toxic metal concentrations (eg. precipitation, adsorption)
(iii) lower aqueous sulphate concentrations,
(iv) lower the toxicity / bioavailability of metals in solution (eg. oxidation, reduction)
(v) oxidise the solution (eg. Fe(II)-Fe(III), Mn(II)-Mn(IV), As(III)-As(V)),
(vi) reduce the solution (eg. SO_4-H_2S)
(vii) collect / dispose / isolate the metallic sludge generated.

Acid drainage control and treatment techniques can be broadly classified into physical, chemical and biological, and those using combinations of these (refer Figure 2).

3.1 Dilution / Reaction

Due to a favourable location or climate, some sites have the option of treating their acid drainage simply by dilution and/or reaction with nearby water resources. Some operations can achieve their discharge standards by:

(i) releasing water only during periods of high rainfall or peak river flow,
(ii) releasing water into local waterways with significant natural buffering capacity (eg. a carbonate terrain),
(iii) releasing water into estuarine or marine settings where bicarbonate buffering, gypsum saturation and direct dilution have the effect of treating the acid drainage.

3.1.1 Concentration

In collaboration with chemical treatment methods, evaporative concentration of acidic drainage can be an effective method of reducing the volumes of water to treat, and generally permits lower cost treatment reagents (eg. limestone) to be used at least for partial treatment. This strategy is of course climate dependent and will usually not be appropriate in a tropical setting.

3.2 Chemical Treatment Methods

3.2.1 Active Treatment

The most common method for treating acid drainage is via reaction with alkaline reagents / amendments. A large variety of natural, by-product or manufactured alkaline reagents can be used at different mine sites, depending on local availability and cost. The most cost effective, and therefore the most commonly used reagents are the lime based reagents which include quicklime (CaO), hydrated lime ($CaOH$), and limestone ($CaCO_3$).

When treating acid drainage the choice of treatment reagent(s) and dispensing device needs to be carefully considered to ensure cost effectiveness, technical suitability to the acid drainage and desired treatment objectives (eg. post treatment metal concentrations, quantity of sludge generated...etc).

Hydrated lime is the most used of the three lime based reagents in the treatment of acid drainage. It is easily handled and suitable in high flow and acidity conditions. Extensive mechanical mixing of hydrated lime in water is required because it is hydrophobic.

Quicklime is an extremely effective neutralising reagent because it is very reactive, however, difficulties in handling and dispensing often limit its use.

Limestone or calcium carbonate can also be used in certain circumstances. It has the lowest material cost and is safe and easy to handle. However, its use is limited due to its low solubility and its tendency to develop an external coating. This is a key problem with treating acid drainage. A number of reagents (including the limestone based reagents) form “rinds” or “blankets” of precipitates which coat / blind reagent particles and inhibit complete reaction. Few conventional dosing systems take this effect into account, and thus suffer from low efficiencies of reagent use. Passive systems (below) are also prone to armouring reactions which have the capacity to rapidly diminish alkalinity production, and most designs adopt steps to avoid metal hydroxide precipitation. Any dispensing / mixing method which is able to address armouring effects will improve reagent efficiency and therefore lower treatment costs, often significantly.

Another problem increasingly evident during chemical water treatment is the formation of strong chemical gradients in bodies of treated water (ie. bodies deeper than 3-5 m). The development of these gradients is associated with significant over treatment of some water bodies, and this phenomenon appears to be infrequently recognised. Routine depth monitoring of water bodies undergoing treatment will often be warranted (eg. pit lakes, tailings ponds, acid drainage collection ponds).

A spectrum of small to large conventional, fixed neutralisation plants, high density sludge plants (additional circuits for increasing the density of treatment precipitates), portable chemical dispensing plants (ie. Neutra-Mills), portable or fixed, stream oxidation ± dosing systems (eg. In-Line Systems) and in-stream dosing systems (Aquafix plants) are used.

Treatment of acid drainage is often not trivial with a number of mine sites operating in tropical environments expending significant sums on treatment. One site, for example, uses approximately 250 tonne of hydrated lime per day (usual cost of lime is approximately US $100 / tonne, but may be as much as US $300 / tonne in remote locations when transport costs are included).

Efficiency of reagent use is a key criteria in deciding the choice of treatment plant as reagent costs are usually the most significant cost. Reagent efficiencies of less than 50% are not uncommon with some type of reagents and treatment apparatus. Improving reagent efficiency will often constitute a substantial saving in treatment costs.

Several other chemical methods not directly employing alkaline addition, but also important for treating acid drainage are:

(i) *Sulphide precipitation / reduction:* soluble sulphide compounds such as NaS are also used to facilitate the precipitation of toxic metal sulphides from acid drainage.

(ii) *Physical and/or chemical oxidation*, sometimes in conjunction with neutralisation: conversion of aqueous Fe(II) to insoluble ferric hydroxide, aqueous Mn(II) to insoluble Mn(III) hydroxides and oxides, and soluble As(III) to less toxic As(V) can be achieved by oxidation.

(iii) *Adsorption:* metals can be adsorbed onto organic and inorganic surfaces. Adsorption of Cd, Pb, Cu, Zn increases with increasing pH (Gerhardt, 1993). Coagulants and flocculants are useful for removing an array of metals from solution.

(iv) *Ion Exchange:* toxic metals can substitute for harmless ions using natural or synthetic zeolites, or a variety of synthetic polymeric resins.

(v) *Electrochemistry:* solvent extraction and electrowinning techniques can be applied to solutions that would be regarded as typical acid drainage. Such techniques are suited to those mine sites where cost recovery can justify implementation.

3.2.2 Passive Chemical Treatment

A growing number of passive treatment systems are available to environmental managers. Most are based on low-cost reagents such as limestone. A range of passive systems include:

(i) *Open Limestone Drains:* uncovered drainage channels filled with aggregate limestone. Their design recognises the effect of armouring reactions, and scales up the volume of reagent on the assumption that very low proportions of limestone will be available for dissolution (Ziemkiewicz et al., 1995).

(ii) *Anoxic Limestone Drains (ALD):* buried trenches of limestone aggregate designed to exclude oxygen in order to maintain iron in a reduced (ferrous) and thereby soluble state. Once pH has been adjusted and the drainage has exited from the channel, controlled aeration permits oxidation, hydrolysis and precipitation.

(iii) *Alkalinity Producing Systems (APS)* or *Successive Alkalinity Producing Systems (SAPS)*: these systems represent a combination of ALD’s and an anaerobic reactor (eg. constructed wetland or engineered reactor). In combination, these processes promote increases in alkalinity using limestone, and avoid clogging of the drains by reducing ferric iron to ferrous iron. While ALD’s attempt to exclude oxygen, APS’s promote reduction via organic material and microbiological processes.

(iv) *Limestone Ponds (LSP) and Reverse Alkalinity Producing Systems (RAPS):* these are concepts for treating acid drainage seeps or groundwater discharges by creating a pond around the zone, and introducing limestone ± organic matter into the pond.

(v) *Hydro-Active Limestone Treatment (HALT)*: Water powered limestone fed mills designed to increase the efficiency of using limestone for acid drainage treatment

The success of these passive systems generally depends on the absence or strict control of dissolved oxygen, ferric iron and aluminium, in order to control metal hydroxide precipitation.

While this is often possible, especially at coal mines, these requirements tend to limit the effective application of passive systems.

3.3 Biological Treatment Methods

Most biological / microbiological systems require the establishment and maintenance of anaerobic conditions to permit the appropriate bacteria to flourish. Remediation is essentially conducted by bacteria capable of reducing aqueous sulphate and generating bicarbonate alkalinity. Biological treatment methods may be divided into the following categories:

(i) *Wetlands*: systems are generally anaerobic, organic-rich, water saturated environments with a large water/air surface. They are commonly actively involved in filtering, cation exchange, redox reactions, neutralisation reactions and complex microbiological processes (eg. biosorption). They are generally regarded as being quite effective in ameliorating low-medium strength and medium to low flow acid drainage (eg. Skousen, 1995; Sobolewski, 1997), and are often usefully employed in combination with other treatment systems. Limitations to wetlands include the clogging of the substrate with precipitate sludges, difficulties in the treatment of large flows and of obtaining suitable land on a minesite of sufficient size.

(ii) *ARUM Cells* (Acid Reduction Using Microbiology): involves an iron reduction or (oxidation and) removal stage, followed by anaerobic microbial treatment (reduction) and the establishment of a self sustaining organic supply to the anaerobic cell (Kalin and Smith, 1997).

(iii) *Bioremediation in a pit lake*: trials are being conducted on the role of bacteria in reducing acid and sulphate levels in largely static bodies of water. Insufficient information is available to draw conclusions at present.

Although used widely in relation to surficial wetland systems, sulphate reducing processes associated with organic substrates are essentially never used in the context of waste rock piles and tailings dams. There appears to be significant scope for the application of passive low-cost methods in these settings.

Biological acid drainage treatment methods provide attractive close-out solutions for many mine sites, but often need to be coordinated with other control and sometimes treatment measures. The application of wetlands for remediating low strength acidic drainage (ie. final polishing) is well established, but the sustainability and value of wetland systems for long-term and moderate strength acid drainage treatment will be under review for years to come.

3.4 Chemical & Biological Treatment Methods

Bioprocess technologies are being developed and tested at present. These rely upon the production of H_2S from the biological reduction of sulphate to immobilise toxic metals in acid drainage. While using sulphate reducing bacteria, the processes often have discrete chemical and biological components permitting full control of treatment and isolation of metal concentrates, metal sludge and biomass. The proprietary Biosulphide process is discussed by Rowley et al., 1997, and a consecutive hydroxide-sulphide process is discussed by Diaz, 1997.

4.0 Rehabilitation

Where a site with acid drainage is being rehabilitated a combination of prevention, minimisation, control and treatment options are usually adopted. Where acid drainage has not as yet developed prevention and minimisation techniques are employed. Where acid drainage has developed, minimisation, control and treatment are employed.

In almost all circumstances the cost of removing acid generating waste as part of a rehabilitation strategy is cost prohibitive. Reactive remedial measures will again usually focus on reducing, preventing or at least minimising the oxidation of sulphides and the dissolution of the oxidation products.

Acidity or low pH in soils can also be of concern. Low soil pH (below about 5.5 when measured in water) can reduce the availability of some nutrients and cause aluminium and manganese toxicity. Limestone can be added to assist in the amelioration (neutralisation) of the soil, but this will not provide a lasting benefit to the soil unless the source of the acidity is no longer present.

Where acid drainage is a site issue, it needs to be incorporated into rehabilitation and mine decommissioning plans. However, sound prevention, minimisation and control strategies are critical for limiting the need for expensive rehabilitation techniques.

5.0 Summary & Conclusions

Acid drainage is accepted as one of the most difficult and important environmental issues confronting the mining industry, and therefore considerable resources have been marshalled within the industry to establish best practice procedures under different management scenarios.

Currently, best practice environmental management of sulphidic mine wastes involves integration of acid drainage prevention, minimisation and control into the mining process. It can be summarised as the early characterisation and classification of the acid generating potential of these materials, development of strategies to minimise the oxidation of sulphides, and where acid drainage formation is unavoidable, the implementation of suitable long term control and treatment technologies. In almost all circumstances, resources spent on prevention and minimisation of acid drainage are returned many fold through lower control and treatment costs.

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