A BRIEF OVERVIEW OF CONTROL AND TREATMENT TECHNOLOGIES FOR ACID MINE DRAINGE[1]

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Abstract. Acid mine drainage (AMD) occurs when metal sulfides are exposed to oxidizing conditions. Leaching of reaction products into surface waters pollute over 20,000 km of streams in the USA alone. Mining companies must predict the potential of creating AMD by using overburden analyses. Where a potential exists, special handling of overburden materials and quick coverage of acid-producing materials in the backfill should be practiced. The addition of acid-neutralizing materials can reduce or eliminate AMD problems. Placing acid-producing materials under dry barriers can isolate these materials from air and water. Other AMD control technologies being researched include injection of alkaline materials (ashes and limestone) into abandoned underground mines and into buried acid material in mine backfills, remining of abandoned areas, and installation of alkaline recharge trenches. Chemicals used for treating AMD are $Ca(OH)_2$, CaO, $NaOH$, Na_2CO_3, and NH_3, with each having advantages under certain conditions. Under low-flow situations, all of the chemicals except $Ca(OH)_2$ are cost effective, while at high flow $Ca(OH)_2$ and CaO are clearly the most cost effective. Floc, the metal hydroxide material collected after treatment, is disposed of in abandoned deep mines, refuse piles, or left in collection ponds. Wetlands remove metals from AMD through formation of oxyhydroxides and sulfides, exchange and organic complexation reactions, and direct plant uptake. Aerobic wetlands are used when water contains enough alkalinity to promote metal precipitation and anaerobic wetlands are used when alkalinity must be generated by microbial sulfate reduction and limestone dissolution. Anoxic limestone drains are buried trenches of limestone that intercept AMD underground to generate alkalinity. Under anoxia, limestone should not be coated with Fe^{+3} hydroxides in the drain, decreasing the likelihood of clogging. Successive alkalinity-producing systems pre-treat oxygenated AMD with organic matter to remove oxygen and Fe^{+3}, and then the water is introduced into limestone underneath the organic matter. Open limestone channels use limestone in aerobic environments to treat AMD. Coating of limestone occurs and the reduced limestone dissolution is designed into the treatment system. Alkaline leach beds, containing either limestone or slag, are used to add alkalinity to acid water. At present, most passive systems offer short-term treatment, and are more practical for installation on abandoned sites or watershed restoration projects where effluent limits do not apply and where some removal of acid and metals will benefit a stream.

Additional Key Words: Acid-Base Accounting, acid-producing material, alkalinity-producing systems, anoxic limestone drains, chemical treatment, open limestone channels, passive treatment, wetlands

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Introduction

The purpose of this paper is to provide a brief overview of current acid mine drainage (AMD) control and treatment technologies for individuals not familiar with the AMD literature. The overview is primarily based on knowledge and experience with coal mining in the eastern U.S. Not all technologies are mentioned in this paper, nor are all the different situations where an AMD technology has been applied. Nevertheless, a few of the most promising technologies are reviewed. Some of the technologies are well known and have shown favorable control and treatment under almost all conditions, while others may be new and still being applied in various scenarios.

Acid Mine Drainage Formation

Acid mine drainage (AMD) forms when sulfide minerals are oxidized in coal and metal mining, highway construction, and other large-scale excavations. Upon exposure to water and oxygen, sulfide minerals oxidize to form acidic products, which then can be dissolved in water. The water containing these dissolved products often has a low pH, high amounts of dissolved metals such as iron (Fe) and aluminum (Al), and sulfate. The metal concentrations in AMD depend on the type and quantity of sulfide minerals present, and the overall water quality from disturbed areas depends on the acid-producing (sulfide) and acid-neutralizing (carbonate) minerals contained in the disturbed rock. Therefore, sulfide-rich and carbonate-poor materials produce acidic drainage, while carbonate-rich materials produce alkaline conditions in drainage.

Approximately 20,000 km of streams and rivers in the United States are degraded by AMD. About 90% of the AMD reaching streams originates in abandoned surface and deep mines. Since no company or individual claims responsibility for reclaiming abandoned mine lands (AML), no treatment of the AMD occurs and continual contamination of surface and groundwater resources results.

The carbonate (and to a lesser degree, silicate) content of overburden determines whether there is enough neutralization potential (NP) to counteract the acid produced from pyrite oxidation. Of the many types of acid-neutralizing compounds present in rocks, only carbonates and clays occur in sufficient quantity to effectively neutralize acid-producing rocks. A balance between the acid-producing potential and neutralizing capacity of the disturbed overburden will

indicate the ultimate acidity or alkalinity that might be expected in the material upon complete weathering. Control of AMD before surface mining requires an understanding of three important factors: 1) overburden geochemistry, 2) method and precision of overburden handling and placement in the backfill during reclamation, and 3) the post-mining hydrology of the site.

Overburden Analyses, Handling and Placement

Pre-mining analyses of soils, overburden, and the coal pavement are required by law (Sobek et al., 2000). Identifying the chemical production potential of overburden aids in developing overburden handling and placement plans by knowing which layers are potentially acid-producing, neutral, or acid-neutralizing. Acid-Base Accounting (ABA) provides a simple, relatively inexpensive, and consistent procedure to evaluate overburdens. It balances potential acidity (based on total or pyritic sulfur content) against total neutralizers. Samples containing more acid-producing than acid-neutralizing materials are deficient in neutralizing materials ("maximum needed"), and those samples with the reverse situation have "excess" neutralizing materials. Rock layers with equal proportions of each type of material should be subjected to leaching or weathering analyses (Skousen et al., 1987). Kinetic tests such as humidity cells and leach columns are important because they examine the rate of acid-producing and neutralization reactions. This information from kinetic tests can supplement information given by ABA and help regulators in permitting decisions (Geidel et al., 2000).

The prevailing approach to control AMD in the eastern USA is to keep water away from pyritic material. Once overburden materials have been classified, an overburden handling and placement plan for the site can be designed. Segregating and placing acid-producing materials above the water table is generally recommended (Skousen et al., 1998; Skousen et al., 1987). Where alkaline materials overwhelm acid-producing materials, no special handling is necessary. Where acid-producing materials cannot be neutralized by on site alkaline materials, it is necessary to import a sufficient amount to neutralize the potential acidity or the mining activity may not be allowed. Often, an excess of neutralizing materials (sometimes up to two to three times the potential acidity) is required to offset the acid formation.

Post-mining Hydrology

The hydrology of a backfill and its effect on AMD are very complex. Generally, the porosity and hydraulic conductivity of the materials in a backfill are greater than those of the consolidated rock overburden that existed before mining, and changes in flow patterns and rates should be expected after mining (Caruccio and Geidel, 1989). Water does not move uniformly through the backfill by a consistent wetting front. As water moves into coarse materials in the backfill, it follows the path of least resistance, e.g., through more permeable sandstones and around shales. The water continues downward until it encounters a barrier, the coal pavement, or other compacted layer. Therefore, the chemistry of the water from a backfill will reflect only the rock types encountered in the water flow path, and not the entire geochemistry of the total overburden (Ziemkiewicz and Skousen, 1992).

Diverting surface water above the site to decrease the amount of water entering the mined area is highly recommended. Pyritic material can be placed where it will be rapidly and permanently inundated, thereby preventing oxidation. Inundation is only suggested where a water table may be re-established such as below drainage deep mines. Above mined areas, incoming water can be treated with limestone to improve water quality.

Control of AMD

Acid mine drainage control can be undertaken where AMD exists or is anticipated. At-source control methods treat the acid-producing rock directly and stop or retard the production of acidity, whereas treatment methods add chemicals directly to acidic water exiting the rock mass. Coal companies mining in acid-producing areas of the eastern USA must often treat AMD, and they face the prospect of long-term water treatment and its attendant liabilities. Cost-effective methods, which prevent the formation of AMD at its source, are preferable. Some control methods are most suited for abandoned mines and others are only practical on active operations. Other methods can be used in either setting.

Some techniques described below have demonstrated less than 100% control of acidity produced on-site, and are considered failures by some people. Removing a significant portion of the acid or metal load in a watershed by a control strategy may improve the health of a stream to a point of re-introducing some fish species or re-establishing some designated uses of the stream.

Alternatively, the method may be combined with another partial control schemes to achieve effluent limits. Since partial control methods are often the least costly, their use in combination with other techniques is financially attractive.

Land Reclamation

Backfilling and revegetation together are effective methods of reducing acid loads from current mining operations or abandoned mine lands. Backfilling alone can reduce the acid load substantially or improve water quality to the point of meeting effluent limits (Faulkner and Skousen, 1995). Water flow from seeps can be reduced by diversion and reclamation, and on some sites where flow may not be reduced, water quality can change from acid to alkaline. Diverting surface water or channeling surface waters to control volume, direction and contact time can be used to minimize the effects of AMD on receiving streams. Surface diversion involves construction of drainage ditches to move surface water quickly off the site before infiltration or by providing impervious channels for existing streams to convey water across the disturbed area.

Alkaline Amendment to Active Mines

Certain alkaline amendments can control AMD from spoil and refuse (Brady et al., 1990; Perry and Brady, 1995; Rich and Hutchison, 1990; Rose et al., 1995). All alkaline amendment schemes rely on ABA or kinetic tests to identify the required alkalinity for neutralization of pyritic materials. Special handling of overburden seeks to blend acid-producing and acid-neutralizing rocks in the mining process to develop a neutral rock mass. In the eastern USA, the pit floor is often rich in pyrite, so isolating it from groundwater may be necessary by building highwall drains (which move incoming groundwater away from the pit floor) or placing impermeable barriers on the pit floor. Acid-forming material can be compacted or capped within the spoil (Meek, 1994).

If insufficient alkalinity is available in the spoil, then external sources of alkalinity must be imported (Skousen and Larew, 1994; Wiram and Naumann, 1995). Limestone is often the least expensive and most readily available source of alkalinity. It has a neutralization potential (NP) of between 75 and 100%, and is safe and easy to handle. On the other hand, it has no cementing properties and cannot be used as a barrier. Fluidized Bed Combustion (FBC) ashes generally

have NPs of between 20 and 40%, and they tend to harden into a cement after wetting (Skousen et al., 1997). Other power-generation ashes, like flue gas desulfurization products and scrubber sludges, may also have significant NP, which make them suitable alkaline amendment materials (Stehouwer et al., 1995). Kiln dust, produced by lime and cement kilns, contains similar levels of CaO (15 to 30%) as FBC ash, but also contains 50 to 70% unreacted limestone. Kiln dust absorbs moisture and also hardens upon wetting (Rich and Hutchison, 1994) and it is widely used as a stabilization and barrier material. Lime mud, grit, and dregs from pulp and paper industries are also neutralizing products available in some areas. Steel slags, when fresh, have NPs from 45 to 90% and can be used as an alkaline amendment as well as a medium for alkaline recharge trenches. Slags are produced by a number of processes, so care is needed to ensure that candidate slags are not prone to leaching metal ions like Cr, Mn, and Ni. Phosphate rock has been used in some studies to control AMD. It may react with Fe released during pyrite oxidation to form insoluble coatings (Evangelou, 1995), but phosphate usually costs much more than other calcium-based amendments and is needed in about the same amounts (Ziemkiewicz and Meek, 1994).

Alkaline Recharge Trenches

Alkaline recharge trenches (Caruccio et al., 1984) are surface ditches or cells filled with alkaline materials, which can minimize or eliminate acid seeps through an alkaline-loading process with infiltrating water. Alkaline recharge trenches were constructed on top of an 8-ha, acid-producing coal refuse disposal site, and after three years the drainage water showed 25 to 90% acidity reductions with 70 to 95% reductions in Fe and sulfate (Nawrot et al., 1994). Pumping water into alkaline trenches greatly accelerates the movement of alkalinity into the backfill and can cause acid seeps to turn alkaline (Ziemkiewicz et al., 2000).

Dry Barriers

Dry barriers retard the movement of water and oxygen into areas containing acid-producing rock. These "water control" technologies (Skousen et al., 1998) include impervious membranes, dry seals, hydraulic mine seals, and grout curtains/walls. Surface barriers can achieve substantial reductions in water flow through piles, but generally do not control AMD completely. Grouts can be used to separate acid-producing rock and groundwater. Injection of grout barriers or

curtains may significantly reduce the volume of groundwater moving through spoil. Gabr et al. (1994) found that a 1.5-m-thick grout wall (installed by pumping a mixture of class F fly ash and Portland cement grout into vertical boreholes near the highwall) reduced groundwater inflow from the highwall to the spoil by 80%, resulting in some seeps drying up and others being substantially reduced in flow. At the Heath Steele Metal Mine in New Brunswick, a soil cover was designed to exclude oxygen and water from a tailings pile (Bell et al., 1994). It consisted of a 10-cm gravel layer for erosion control, 30-cm gravel/sand layer as a evaporation barrier, 60-cm compacted till (conductivity of 10^{-6} cm/sec), 30-cm sand, and pyritic waste rock. This barrier excluded 98% of precipitation, and oxygen concentrations in the waste rock dropped from 20% initially to around 1%. At the Upshur Mining Complex in West Virginia, Meek (1994) reported covering a 20-ha spoil pile with a 39-mil PVC liner, and this treatment reduced acid loads by 70%.

Wet Covers

Disposal of sulfide tailings under a water cover, such as a lake or fjord, is another way to prevent acid generation by excluding oxygen from sulfides. Wet covers also include flooding of aboveground tailings in ponds. Fraser and Robertson (1994) studied four freshwater lakes used for subaqueous tailings disposal and found that the reactivity of tailings under water was low and that there were low concentrations of dissolved metals, thereby allowing biological communities to exist.

Alkaline Amendment to Abandoned Mines

Abandoned surface mines comprise huge volumes of spoil of unknown composition and hydrology. Abandoned mines in the eastern USA generate more than 90% of the AMD in streams and rivers, most of which comes from underground mines. Abandoned underground mines are problematic because they are often partially caved and flooded, cannot be accessed, and have unreliable or nonexistent mine maps. Rehandling and mixing alkalinity into an already reclaimed backfill is generally prohibitively expensive.

Filling abandoned underground mine voids with non-permeable materials is one of the best methods to prevent AMD. Underground mine voids are extensive (a 60-ha mine with a coal bed height of 1.5 m and a recovery rate of 65% would contain about 600,000 m^3 of voids), so fill

material and the placement method must be cheap. Mixtures of class F fly ash and 3-5% Portland cement are used to control subsidence in residential areas and these slurries are generally injected through vertical boreholes at between 8- and 16-m centers. Pneumatic (air pressure) and slurry injection for placing FBC ash in abandoned underground mines are being tested (Burnett et al., 1995) and results indicate that pneumatic methods can extend the borehole spacing to about 30 m. On reclaimed surface mines still producing AMD, researchers in Pennsylvania saw small improvements in water quality after injecting coal combustion residues into buried pods of pyritic materials.

Remining and Reclamation

"Remining" means returning to abandoned surface or underground mines for further coal removal. Where AMD occurs, remining reduces acid loads by 1) decreasing infiltration rates, 2) covering acid-producing materials, and 3) removing the remaining coal which is the source of most of the pyrite. Hawkins (1994) studied 57 discharges from 24 remined sites in Pennsylvania, and found contaminant loads were either reduced or unchanged after remining and reclamation. Short-term loads were sometimes increased during the first six months after remining and reclamation, but reduction in loads after six months resulted from decreased flow rather than large changes in concentrations. Ten remining sites in Pennsylvania and West Virginia were reclaimed to current standards (which included eliminating highwalls, covering refuse, and revegetating the entire area), and all sites had improved water quality (Skousen et al., 1997).

Chemical Treatment of AMD

If AMD problems develop during mining or after reclamation, a plan to treat the discharge must be developed. NPDES permits on surface mines usually require monitoring of pH, total suspended solids (TSS), and Fe and Mn concentrations. An operator choosing an AMD treatment system must also determine flow rate, sulfate concentration, and Fe^{+2} concentration in the AMD. The receiving stream's designated use and seasonal fluctuations in flow rate are also important. After evaluating these variables over a period of time, the operator can consider the economics of different chemicals. Most chemical systems consist of an inflow pipe or ditch, a

storage tank or bin holding the treatment chemical, a means of controlling its application rate, a settling pond to capture precipitated metal oxyhydroxides, and a discharge point, where NPDES compliance is monitored.

Six chemicals are used to treat AMD (Table 1). Each is more or less appropriate for a specific condition. The best choice depends on both technical (acidity levels, flow, and the types and concentrations of metals) and economic factors (chemical prices, labor, machinery and equipment, treatment duration, and interest rates). Enough alkalinity must be added to raise pH to between 6 and 9 so insoluble metal hydroxides will form and settle out. Treatment of AMD with high Fe (ferric) concentrations often affords co-precipitation of other metals with the Fe hydroxide, thereby removing them from AMD at a lower pH. Limestone has been used for decades to raise pH and precipitate metals in AMD. It has the lowest material cost and is the safest and easiest to handle of the AMD chemicals. Unfortunately, it is limited due to its low solubility and tendency to develop an external coating, or armor, of $Fe(OH)_3$ when added to AMD. Fine-ground limestone may be dumped in streams directly or the limestone may be pulverized by water-powered rotating drums and metered into the stream. Limestone has also been used to treat AMD in anaerobic (anoxic limestone drains) and aerobic environments (open limestone channels).

Lime

Hydrated lime is commonly used for treating AMD. As a powder, it tends to be hydrophobic, and extensive mechanical mixing is required for dissolution. Hydrated lime is particularly useful and cost effective in large-flow, high-acidity situations where a lime treatment plant with a mixer/aerator is constructed to help dispense and mix the chemical with the water (Skousen and Ziemkiewicz, 1996). Hydrated lime has limited effectiveness if a very high pH (>9) is required to remove ions such as Mn. Unfortunately, increasing the lime rate increases the volume of unreacted lime that enters the floc-settling pond.

Pebble quicklime (CaO) is used with the Aquafix Water Treatment System utilizing a water wheel concept (Jenkins and Skousen, 2001). The amount of chemical added is dictated by the movement of the water wheel, which causes a screw feeder to dispense the chemical. This system was initially used for small and/or periodic flows of high acidity because CaO is very reactive, but water wheels have been attached to large silos for high-flow/high-acidity situations.

Tests show an average of 75% cost savings over NaOH systems and about 20 to 40% savings over NH_3 systems.

Soda Ash

Soda ash (Na_2CO_3) is generally used to treat AMD in remote areas with low flow and low amounts of acidity and metals.   This choice is usually based on convenience rather than chemical cost. Soda ash comes as solid briquettes, and is gravity fed into water through bins. The number of briquettes used per day is determined by the rate of flow and quality of the water. One problem is that the briquettes absorb moisture, expand, and stick to the corners of the bin, and won't drop into the stream. For short-term treatment, some operators use a much simpler system employing a wooden box or barrel with holes that allows water inflow and outflow. The operator simply fills the barrel with briquettes on a regular basis and places the barrel in the flowing water. This system offers less control of the amount of chemical used.

Caustic Soda

Caustic soda (i.e., lye, NaOH) is often used in remote low-flow, high-acidity situations, or if Mn concentrations in the AMD are high. The system can be gravity fed by dripping liquid NaOH directly into the AMD. Caustic is very soluble, disperses rapidly, and raises the pH quickly. Caustic should be applied at the surface of ponds because the chemical is denser than water. The major drawbacks of using liquid NaOH for AMD treatment are high cost and dangers in handling.

Ammonia

Ammonia compounds (NH_3 or NH_4OH) are extremely hazardous. NH_3 is compressed and stored as a liquid but returns to the gaseous state when released. Ammonia is extremely soluble, reacts rapidly, and can raise the pH of receiving water to 9.2. At pH 9.2, it buffers the solution to further pH increases, and therefore very high amounts of NH_3 must be added to go beyond 9.2. Injection of NH_3 into AMD is one of the quickest ways to raise water pH and it should be injected near the bottom of the pond or water inlet because NH_3 is less dense than water. NH_3 is cheap and a cost reduction of 50% to 70% is usually realized when NH_3 is substituted for NaOH (Skousen et al., 1990). Major disadvantages of using NH_3 include 1) the hazards, 2) uncertainty

concerning nitrification, denitrification, and acidification downstream, and 3) consequences of excessive application rates, which cause toxic conditions to aquatic life.

Costs of Treating AMD

Costs were estimated for five treatment chemicals under four sets of flow and acid concentration conditions (Table 1 from Skousen et al., 2000). Na_2CO_3 had the highest labor requirements (10 hrs per wk) because the dispensers must be filled by hand and inspected frequently. Caustic had the highest reagent cost per mole of acid-neutralizing capacity and Na_2CO_3 had the second highest. Hydrated lime treatment systems had the highest installation costs of the five chemicals because of the need to construct a lime treatment plant and install a pond aerator. However, the cost of $Ca(OH)_2$ was very low, and the combination of high installation costs and low reagent cost made $Ca(OH)_2$ systems particularly appropriate for long-term treatment of high-flow/high-acidity conditions.

For a five-year treatment, NH_3 had the lowest annual cost for the low-flow/low-acid situation. Pebble quicklime had about the same cost as the NH_3 system, but slightly higher installation costs. Caustic was third because of its high labor and reagent costs, and Na_2CO_3 was fourth due to high labor costs. Hydrated lime was the most expensive because of its high installation costs. At high-flow/high-acidity, the $Ca(OH)_2$ and CaO systems were clearly the cheapest treatment systems (annual costs of about $250,000 less than NH_3, the next best alternative).

After chemical treatment, the treated water flows into sedimentation ponds so metals in the water can precipitate. All AMD treatment chemicals cause the formation of metal hydroxide sludge or floc. Sufficient residence time of the water (dictated by pond size and depth) is important for adequate metal precipitation. The amount of metal floc generated depends on water quality and quantity, which in turn determines how often the ponds must be cleaned. Knowing the chemical and AMD being treated will provide an estimate of the stability of metal compounds in the floc. Floc disposal options include: 1) leaving it submerged indefinitely, 2) pumping or hauling it to abandoned deep mines or to pits dug on surface mines, and 3) dumping it into refuse piles. Pumping flocs onto land and letting them age and dry is a good strategy for disposal, because they become crystalline and behave like soil material.

Each AMD is unique, requiring site specific treatment. Each AMD source should be tested with various chemicals by titration tests to evaluate the most effective chemical for precipitation of the metals. The costs of each AMD treatment system based on neutralization (in terms of the reagent cost, capital investment and maintenance of the dispensing system) and floc disposal should be evaluated to determine the most cost- effective system.

Passive Treatment of AMD

Active chemical treatment of AMD is often an expensive, long-term proposition. Passive treatment systems have been developed that do not require continuous chemical inputs and that take advantage of natural chemical and biological processes to cleanse contaminated mine waters. Passive technologies include constructed wetlands, anoxic limestone drains (ALD), successive alkalinity-producing systems (SAPS), and open limestone channels (OLC). In low-flow and low-acidity situations, passive systems can be reliably implemented as a single permanent solution for many AMD problems.

Constructed Wetlands

Aerobic wetlands consist of wetland vegetation in shallow (<30cm), relatively impermeable sediments comprised of soil, clay or mine spoil. Anaerobic wetlands consisting of wetland vegetation in deep (>30cm), permeable sediments comprised of soil, peat moss, spent mushroom compost, sawdust, straw/manure, hay bales, or other organic mixtures, often underlain or admixed with limestone. Metals are retained within wetlands by 1) formation of metal oxides and oxyhydroxides, 2) formation of metal sulfides, 3) organic complexation reactions, 4) exchange with other cations on negatively-charged sites, and 5) direct uptake by living plants. Metals can also be retained by filtration and adsorption/exchange metals onto algal mats. Other beneficial reactions in wetlands include generation of alkalinity due to microbial mineralization of dead organic matter, microbial dissimilatory reduction of Fe oxyhydroxides and SO_4, and dissolution of carbonates.

Aerobic wetlands promote metal oxidation and hydrolysis, thereby causing precipitation and physical retention of Fe, Al, and Mn oxyhydroxides. Successful metal removal depends on dissolved metal concentrations, dissolved oxygen content, pH and net acidity of the mine water,

the presence of active microbial biomass, and detention time of the water in the wetland. The pH and net acidity/alkalinity of the water are particularly important because pH influences both the solubility of metal hydroxide precipitates and the kinetics of metal oxidation and hydrolysis. Therefore, aerobic wetlands are best used in conjunction with water that contains net alkalinity to neutralize metal acidity.

Anaerobic wetlands are most successful when used to treat small flows of acidic water. Anaerobic wetlands use chemical and microbial reduction reactions to precipitate metals and neutralize acidity. The water infiltrates through a thick permeable organic subsurface that becomes anaerobic due to high biological oxygen demand. Other chemical mechanisms that occur in-situ include metal exchanges, formation and precipitation of metal sulfides, microbial-generated alkalinity, and formation of carbonate alkalinity (due to limestone dissolution). Since anaerobic wetlands produce alkalinity, they can be used in net acidic and high dissolved oxygen (>2 mg/L) AMD. Microbial mechanisms of alkalinity production are critical to long-term AMD treatment. Under high acid loads (>300 mg/L), pH sensitive microbial activities are eventually overwhelmed. At present, the sizing value for Fe removal in these wetlands is 10 grams per day per meter squared (Hedin and Nairn, 1992).

Sorption onto organic materials (such as peat and sawdust) can initially remove 50 to 80% of the metals in AMD (Brodie et al., 1988), but the exchange capacity declines with time. Over the long term, metal hydroxide precipitation is the predominant form of metal retention in a wetland. Wieder (1993) reported up to 70% of the Fe in a wetland to be composed of Fe^{+3} oxyhydroxides, while the other 30% is reduced and combined with sulfides (Wieder, 1992).

Sulfate reducing bacteria (SRB) reactors have been used to generate alkalinity by optimizing anaerobic conditions. Good success has been noted for several systems receiving high and low flows (Canty, 2000; Gusek et al., 2000)

Anoxic Limestone Drains

Anoxic limestone drains (ALDs) are buried cells or trenches of limestone into which anoxic water is introduced. The limestone raises pH and adds alkalinity. Under anoxic conditions, the limestone does not coat or armor with Fe hydroxides because Fe^{+2} does not precipitate as $Fe(OH)_2$ at pH 6.0. Faulkner and Skousen (1994) reported both successes and failures among 11 ALDs with water pH being raised in all cases. However, three of the sites had pH values <5.0,

indicating that the ALD was not fully functioning (pH in ALDs rise to 6.0). Water acidity decreased 50 to 80%, but ferric iron and Al will precipitate as hydroxides at this pH. With observed Fe and Al decreases in outflow water, some coating of limestone is probably occurring inside the ALD.

Longevity of treatment is a major concern for ALDs, especially in terms of water flow through the limestone. Selection of the appropriate water and environmental conditions is critical for long-term alkalinity generation in an ALD. Eventual clogging of the limestone pore spaces with precipitated Al and Fe hydroxides, and gypsum is predicted (Nairn et al., 1991). For optimum performance, no Fe^{+3}, dissolved oxygen (DO), or Al should be present in the AMD. Like wetlands, ALDs may be a solution for AMD treatment for specific water conditions or for a finite period after which the system must be replenished or replaced.

Successive Alkalinity-Producing Systems

In successive alkalinity producing systems (SAPS, Kepler and McCleary, 1994), 1- to 3-m of acid water is ponded over an organic compost of 0.2 to 0.3 m, underlain by 0.5 to 1 m of limestone. Below the limestone are drainage pipes that convey the water into an aerobic pond where metals are precipitated. The hydraulic head drives ponded water through the anaerobic organic compost, where oxygen stripping as well as Fe and sulfate reduction can occur prior to water entry into the limestone. Water with high metal loads can be successively cycled through additional SAPS. Iron and Al clogging of limestone and pipes can be removed by flushing the system (Kepler and McCleary, 1997).

Open Limestone Channels

Open limestone channels (OLCs) are another means of introducing alkalinity to acid water (Ziemkiewicz et al., 1994). We usually assume that armored limestone ceases to dissolve, but Ziemkiewicz et al. (1997) found armored limestone to be 50 to 90% effective in neutralizing acid compared to unarmored limestone. Seven OLCs in the field reduced acidity in AMD by 4 to 62% compared to a 2% acid reduction in a sandstone channel. Open limestone channels show promise for neutralizing AMD in watershed restoration projects and AML reclamation projects where there can be only a one-time installation cost, little to no maintenance is required, and water exiting the system does not have to meet water quality standards. Long channels of

limestone can be used to convey acid water to a stream or other discharge point. Cross sections of channels can be designed with calculated amounts of limestone (which will become armored) to treat the water. Open limestone channels work best on steep slopes (>20%) where flow velocities keep metal hydroxides in suspension, thereby limiting plugging. If constructed correctly, OLCs should be maintenance free and provide AMD treatment for decades.

Alkaline Leach Beds

   Limestone, when placed in an open pond or leach bed, will dissolve slowly over time and continually add alkalinity to water unless the limestone gets coated with metal hydroxides, thereby reducing its dissolution rate (Ziemkiewicz et al. 1997). Therefore, limestone treatment in aerobic systems works best in low pH, metal-free water, and can add alkalinity to streams before encountering acid water downstream (Ziemkiewicz et al., 2001). Since limestone generally reacts relatively slowly under field conditions, steel slag, a byproduct of steel making and composed of hydrated amorphous silica and calcium compounds, can be used as an alkaline material to add alkalinity to water. Steel slags have high neutralization potentials (from about 50-70%), can generate exceptionally high levels of alkalinity in water, and do not armor (Ziemkiewicz and Skousen, 1998). Steel slag fines can be used in leach beds. Effluents from slag leach beds have pHs above 10 and have alkalinity concentrations in the thousands of mg/L. Slag leach beds may receive AMD directly or effluent from "fresh water" beds may be combined with an AMD source downstream to treat acid indirectly.

Summary

   Acid mine drainage occurs when metal sulfides are oxidized. Leaching of reaction products into surface waters pollute over 20,000 km of streams in the USA alone. Companies must predict AMD before mining by using overburden analyses. On sites where a potential exists, special handling of overburden materials and quick coverage of acid-producing materials in the backfill should be practiced. Alkaline addition with materials such as kiln dust and FBC ash can reducing or completely eliminating AMD problems. Other control techniques include dry barriers, wet barriers, injection of alkaline materials into underground mines, remining of abandoned areas, and alkaline recharge trenches. Five chemicals are typically used to treat AMD

and each has characteristics that make it suitable for specific applications. Companies must select a chemical that treats the water adequately and cost-effectively. Passive systems are low maintenance systems that are implemented on abandoned mine land and stream restoration projects. Certain systems are more suited to specific water quality and show good success where the acid levels do not overwhelm the system.

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Table 1. Chemical compounds used in AMD treatment.

Common Name	Chemical Name	Formula	Conversion Factor[1]	Neutralization Efficiency[2]	1999 Cost[3] $ per Mg or L Bulk	<Bulk
Limestone	Calcium carbonate	$CaCO_3$	1.00	30%	$ 11	$ 16
Hydrated Lime	Calcium hydroxide	$Ca(OH)_2$	0.74	90%	$ 66	$110
Pebble Quicklime	Calcium oxide	CaO	0.56	90%	$ 88	$264
Soda Ash	Sodium carbonate	Na_2CO_3	1.06	60%	$ 220	$350
Caustic Soda (solid)	Sodium hydroxide	$NaOH$	0.80	100%	$750	$970
20% Liquid Caustic	Sodium hydroxide	$NaOH$	784	100%	$0.06	$0.16
50% Liquid Caustic	Sodium hydroxide	$NaOH$	256	100%	$0.29	$0.33
Ammonia	Anhydrous ammonia	NH_3	0.34	100%	$330	$750

[1] The conversion factor may be multiplied by the estimated Mg acid/yr to get Mg of chemical needed for neutralization per year. For liquid caustic, the conversion factor gives L needed for neutralization.

[2] Neutralization Efficiency estimates the relative effectiveness of the chemical in neutralizing AMD acidity. For example, if 100 Mg of acid/yr was the amount of acid to be neutralized, then it can be estimated that 82 Mg of hydrated lime would be needed to neutralize the acidity in the water (100(0.74)/0.90).

[3] Price of chemical depends on the quantity being delivered. Bulk means delivery of chemical in a large truck, whereas <Bulk means purchased in small quantities. Liquid caustic prices are for L. Others in Mg.