2.0 Alkaline Addition and Overburden/Refuse Reclamation

During mining or other rock disturbing activities, strata of varying chemical compositions are disturbed and the ultimate quality of the drainage is a blend of all drainage chemistries produced by each disturbed rock type. Various techniques are available to evaluate the acid and alkaline potentials of overburden material and these techniques are fully discussed by the Prediction Committee report of ADTI (In preparation, 1998; see also Skousen et al. 1987, Sobek et al. 1978). This section of the handbook discusses the *in situ* or at-source control technologies and reclamation techniques which have been developed and evaluated for disturbances predicted to have a mine drainage quality concerns. These technologies, while used to either 1) prevent or retard the oxidation of pyrite and production of acid or 2) neutralize the acid produced within the backfill, are often used in conjunction with each other. Attempts have been made to provide case studies which have utilized only one technology, however, in Section 2.9 the synergistic effects of various reclamation techniques are discussed.

Once overburden materials have been identified and classified based on overburden analyses, the overburden (including toxic material) handling and placement plan for the particular site must be carefully followed. The plan often has a number of elements which may include, depending on the nature of the overburden: selective handling of the acid-producing materials (section 2.6); the addition of alkaline materials which serve to either neutralize the acid generated or retard the oxidation of pyrite (section 2.2); encapsulation of the acid-producing material, a technique which has been used both during and post reclamation (section 2.4); removal of toxic material by remining, reprocessing or daylighting deep mines (sections 2.5 and 2.8); and inhibition of pyrite oxidation by bactericides (section 2.1), through the incorporation of sewage sludge (section 2.3) or by inundation of the acid-producing materials (section 3.1).

In the Appalachian Coal Region of the U.S., recommended reclamation procedures have included segregating and placing acid-producing materials above the water table on top of a 1- to 2-m layer of nontoxic material on the pavement, and then treating, compacting and covering the materials with a clay cap or other type of sealant material to

reduce surface water infiltration into this material (Skousen et al.1987). Except when alkaline infiltration techniques (such as surface applications, trenches or alkaline funnels) are part of the plan, diverting surface water above the site to decrease the amount of water entering the mine has also been highly recommended.

An alternative approach to controlling the release of acid products from pyritic material is to rapidly and permanently inundate the acid-producing material, thereby preventing pyrite oxidation. Inundation is only suggested where a water table may be permanently reestablished to cover acid-producing materials (such as below drainage deep or surface mines), or where the materials such as tailings, can be placed in a lake (section 3.1). Inundation has not been commonly used as an alternative for surface-mined lands or above-drainage underground mines in the mountainous Appalachian region.

Limestone or other alkaline materials may occur in the overburden or, if calcareous material is deficient in the section, limestone may be imported and incorporated into the overburden handling and placement plan. This plan may include blending alkaline overburden or imported limestone to neutralize acid-producing materials in the overburden or to neutralize any residual acid in topsoil materials to aid vegetation establishment. Alkaline materials may also be used to create zones of alkaline rich waters to infiltrate through controlled seepage areas and increase the alkalinity of the backfill. Upgradient of mined areas, surface and ground water with low mineral acidity can be treated with limestone (section 4.2.1) or other alkaline material in either the water course or watershed to improve water quality.

Acid mine drainage control technologies are measures that can be undertaken where AMD formation has already taken place or is anticipated. At-source control methods treat the acid-producing rock directly and stop or retard the production of acid, whereas treatment methods add chemicals directly to acidified water leaving the rock mass (section 4.0) or direct the acid water through various passive systems for treatment (section 5.0). Coal companies mining in acid prone areas of the eastern U.S. must treat AMD and face the prospect of long term to indefinite water treatment and its attendant liabilities. It is

obvious that cost-effective methods which prevent the formation of AMD at its source would be preferable. Some control methods are most suitable for abandoned mines and others are only practical on active operations. Other methods can be used in either setting.

Some of the techniques described below have been very successful. Others have been only partially successful and have demonstrated less than 100% control of acid produced on-site. This may be due to several site specific factors including: mining technique, rock type and chemistry, ground water flow rates, etc. While a technique that controls 80% of a site's acid production and reduces long-term operation and maintenance costs may not relieve a mine operator of liability, the method may be suitable for active sites which meet certain criteria, abandoned mine reclamation programs, or watershed restoration projects. Removing a significant portion of the acid or metal load in a watershed by partially-effective control strategies 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 scheme to achieve effluent limits. Since partial control methods are often the least costly, their use in combination with other techniques is often financially attractive. For example, a partial control method such as regrading/topsoiling can be combined with alkaline amendment to reduce the amount of alkalinity required to offset potential acid production.

2.1 Bactericides

Anionic surfactants are used to control bacteria that catalyze the conversion of Fe^{2+} to Fe^{3+}, which thereby control pyritic oxidation (Equation 1.2, section 1.1) (Kleinmann et al. 1981). They are used primarily in situations where immediate control of AMD formation is important and work best on fresh, unoxidized sulfides. Bactericides are often liquid amendments, which can be applied to refuse conveyor belts or sprayed by trucks on cells of acid-producing materials in the backfill. Bactericides have also been used successfully at metal mines (Parisi et al. 1994).

Surfactants, by themselves, are not seen as a permanent solution to AMD. Eventually the compounds either leach out of the rock mass or are decomposed. However, slow-release formulations are commercially available and have been successfully used at regraded sites (Splittorf and Rastogi 1995). Bactericides appear to

work best when used in combination with other control methods and can be useful in preventing acid conditions in pyritic rock piles which remain open for several years until the site is reclaimed.

Case Studies:

One example of surfactant application was done in 1988 on a 4.5 ha refuse site in Pennsylvania. Surfactant was applied via a hydroseeder at rates of 225 kg/ha initially, then successive amounts were added as fresh refuse was deposited. Effluent from the pile showed a 79% decrease in acidity and an 82% decrease in Fe. Cost savings at the AMD plant were $300,000 per year (Rastogi 1994).

In another example, a 14 ha (35 acre) coal refuse pile in West Virginia was regraded, then controlled release surfactant pellets (Promac) were applied to the surface, followed by topsoiling, liming, and revegetation between 1986 and 1988 at a cost of $124,180. Compared with the 0.5 ha untreated control portion of the project, the discharge from the 14 treated ha improved from pH 2.9 to 6.2, acidities decreased from 1680 to 1 mg/L as $CaCO_3$, and Fe and Mn concentrations were reduced to 2 and 0.8 mg/L from 300 and 25 mg/L, respectively.

Bactericides were not as effective when applied to the overburden surface of a pre-1970 mined site in Ohio. No topsoil was applied at the site, but reclamation efforts had established some surface vegetation. Controlled release surfactant pellets were applied by hydroseeder in 1982 to a predominantly sandstone overburden containing pyrite nodules. Seeps discharging from the site initially had acidities between 1000 to 3000 mg/L as $CaCO_3$; however, there was only minor improvement (Geidel, personal communication).

2.2 Alkaline Addition

Recent studies have indicated that certain types of alkaline amendments can successfully control AMD from pyritic spoil and refuse (Brady et al. 1990, Burnett et al. 1995, Perry and Brady 1995, Rich and Hutchinson 1990, Rose et al. 1995 , Wiram and Naumann 1995). The use of alkaline additions can be divided into several categories, including: 1) blended with potentially acid-producing material to either neutralize the acid or to retard and, in some cases, prevent the oxidation of pyrite; 2) incorporated as

stratified layers at specific intervals within the backfill or spoil; 3) applied as trenches or funnels to create alkaline groundwater conduits through the reclaimed mine; 4) applied on or near the surface to enhance plant growth and create an alkaline wetting front that will migrate downward through the overburden, and 5) applied as a chemical cap to create a hardpan (either on the surface or the floor of the mine).. Because a number of alkaline materials can be used or applied by various methods, the discussions which follow will identify the material used (e.g. limestone) and then provide case studies evaluating the use and effectiveness of the material under different application methodologies.

When alkaline material is blended or incorporated in stratified layers, especially in coal mines, the schemes usually rely on Acid Base Accounting (ABA) to estimate the required amount of alkalinity for neutralization of pyritic materials. The rationale behind this reliance is based on a total neutralizing capacity of the section compared with the total acid production capacity. While this does not take kinetics of release into account, it recognizes that if all of the pyrite were to oxidize, then there would be sufficient alkaline material to neutralize the acid. Therefore, accurate, representative overburden analyses before mining are crucial in developing mining plans and alkaline addition programs in acid-producing areas. When acid problems are identified, it is best to generate cost-effective control strategies during premining planning. Errors in predicting postmining water quality from premining overburden analyses include unrepresentative sampling of overburdens and inaccurate analyses (Rymer et al. 1991, Wiram and Naumann 1995) and non-homogeneous placement of spoils. For example, Schueck (1990) reported AMD generation from a surface mine in Pennsylvania resulted largely from buried refuse and pit cleanings within an otherwise neutral to alkaline spoil matrix as identified by ABA. If insufficient alkalinity is available in the spoil, then external sources of alkalinity may be imported (Skousen and Larew 1994, Wiram and Naumann 1995).

2.2.1 Limestone

Limestone is often the least expensive and most readily available source of alkalinity. It has an 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. Field and laboratory studies have indicated that there are threshold levels of Neutralization Potential

(NP), above which acid conditions in coal mines do not develop when the mines are properly reclaimed. Bradham and Caruccio (1997) found that within the northeastern U.S. coal fields, at 3.7% NP no acid would be produced at a 95% confidence level. diPretoro and Rauch (1988) found sites with >3% NP as $CaCO_3$ equivalent in overburden produced alkaline drainages, while acid drainage resulted at $\leq$1% NP. Brady and Hornberger (1989) suggest threshold values of NP $\geq$3% and S <0.5% as guidelines for delineating alkaline-producing strata. Brady et al. (1994) showed that 3% net NP in an overburden caused alkaline drainage while <1% net NP produced acid drainage from 38 mines in Pennsylvania. They concluded that mining practices (such as selective handling and concurrent reclamation) enhanced that effect of alkaline addition on reducing acid production. Further refinements (Perry and Brady 1995) gave a value of 21 Mg/1000 Mg net NP (2.1%) to produce alkaline drainage at 40 sites in Pennsylvania.

Brady and Hornberger (1990) conclude that NP from ABA shows the strongest relationship with actual postmining water quality. This relationship is only qualitative (e.g. acid vs. non-acid) and NP must significantly exceed maximum potential acidity (MPA) in order to produce alkaline water. If NP and MPA are similar, AMD will most likely result (see ADTI Prediction Committee report on Prediction of Mine Drainage 1998).

2.2.1.1 Blending and Stratified Layers

Spoils are composed of a mixture of acid-forming, alkaline-generating and inert rocks, while materials like refuse are dominated by acid-producing rocks with no NP. In spite of significant alkalinity in overburdens, AMD may originate from localized sites within the backfill. Due to the pseudo-karst hydrology of many surface mines (Caruccio et al. 1984, Hawkins and Aljoe 1992), infiltrating water is influenced only by acid and alkaline rocks directly in its path. If water flows primarily through permeable acid rocks, AMD can result and the water may discharge to the nearest stream while the alkaline material in the pile remains unreacted. Unless contacted directly by acid water, most of the spoil limestone will remain in solid form. Thus the presence of alkaline material in the backfill does not ensure that it will neutralize acidity. For efficient neutralization, the acid-forming and alkaline material must be thoroughly mixed. Where insufficient alkalinity is present, it is necessary to add alkaline material to the rock mass. If one relied on random spoil

dumping, an overwhelming supply of alkaline material would be needed. If there were a consensus on the subject, it would appear that material mixtures with an NP/MPA ratio above 2 and a net NP above 30 Mg/1000 Mg (3.0% net NP) generate alkaline water. Even at high NP/MPA ratios, acidity may be produced if the acid-producing materials are incorrectly placed so that they intercept the groundwater, or insufficient alkaline material is added only to the surface (Lusari and Erickson 1985). Thorough mixing during materials handling can reduce the required NP/MPA ratio.

Addition of alkaline material to refuse is a relatively simple process. Since the refuse leaves the preparation plant on a belt conveyor or in a slurry line, the alkalinity can be metered directly into the refuse stream and thoroughly mixed.

Adding alkalinity to spoil requires more care during mining and reclamation. The high volume of spoil necessitates applying alkalinity only to those rock masses that are identified as potentially acid-producing. Surface coal mining operations can remove the identified rock (often the coal roof rock, partings and pavement) and place the acid-producing materials in cells in the backfill for treatment with alkaline amendments (Skousen and Larew 1994). Since acid-producing rock types are often a small percentage of the total spoil, such a procedure results in efficient use of the alkaline material. Additional compaction is desirable during placement of cells. Often the final pit floor contains considerable pyrite, much of it within 30 cm of the coal. Two approaches can be taken: 1) remove the pyritic material and place it in cells for alkaline amendment or 2) seal the pit floor with self-cementing material such as FBC ash.

Case Studies:

In Tennessee, a surface coal mine, using both cast blasting and dragline equipment for overburden handling, incorporated limestone on the pit floor, in spoil during cast blasting, on the dragline bench, and at the topsoil/backfill interface (Wiram and Naumann 1995). The amount of limestone added was calculated based on net NP and also taking into account the presence of siderite. While the handling plan also included surface alkaline recharge structures, the ground water in the vicinity of the blended limestone showed high alkalinities (400 to 500 mg/L as $CaCO_3$), a 10 fold decrease in Fe concentrations, and a 2 to 3 times decrease in Mn concentrations.

A surface coal mine in Pennsylvania improved the water quality from an old deep mine by partially remining the deep mine and by adding 1350 Mg/ha (600 tons/ac) limestone. Of the 1350 Mg, 225 Mg (100 tons) were added to the pit floor, 225 Mg/ha were applied at the top of the regraded backfill prior to the replacement of topsoil, and 900 Mg/ha were dispersed throughout the mine spoil. The 900 Mg/ha were mixed by a simple yet innovative and practical technique. Drill holes, charged with explosive for overburden blasting, were "stemmed" with imported waste limestone rather than drill cuttings. Because the waste limestone is a mixture of sizes (from 200 mesh to 0.8 cm), it provided a dense explosive cover. The alkaline material was mixed effectively by the blasting and was further mixed by the dragline's random spoiling process. The mine water discharge improved from an acidity of 120 mg/L as $CaCO_3$ to 19 mg/L net alkalinity and Fe was significantly reduced (Smith and Dodge 1995).

2.2.1.2 Alkaline Recharge Structures

Alkaline recharge structures are surface structures designed to collect and divert infiltrating water through porous alkaline zones thereby inducing alkaline water into the reclaimed area. In many instances, recharge zones can be determined from surface depressions and the construction of structures, whether trenches, funnels or pits, will provide an avenue for alkalinity. Infiltrating alkaline waters provide an alkaline front that migrates through the backfill, neutralizing acidity and raising pH. This alkalinity can displace bacteria and cause the acid-producing reaction to be slowed or completely stopped.

Case Studies:

Fifteen alkaline recharge trenches, averaging 3 m wide, 1 m deep and varying in length from 23 to 220 m, were installed on a previously mined WV surface coal mine (Caruccio et al. 1984). Concurrent with the emergence of halogen tracers, the seep quality improved from 600 mg/L acidity as $CaCO_3$ to around 100 mg/L, and the metal and sulfate concentrations decreased. Acidities remained at about 100 mg/L as $CaCO_3$ for a number of years. In 1994, zones of ground water recharge were identified and eight alkaline funnels (recharge structures which were approximately 3 m deep and 1 m in diameter)

were installed. The spoil was excavated and the "funnel" filled with coarse limestone. The quality of the seeps improved by about 50% (Carrucio and Geidel 1995).

Alkaline structures have also been incorporated into active mine plans (Wiram and Naumann 1995). In a Tennessee surface coal mine, recharge structures, approximately 45 m long by 15 m wide by 4 m deep, were placed over chimney drains installed in the backfill and filled with 2.5 m of limestone. Monitoring of wells showed a significant increase in alkalinity levels and a decrease in Fe and Mn concentrations.

2.2.1.3 Surface Application

While limestone or lime is routinely added to the soil to enhance reclamation and vegetation growth, it has also been used as a surface amendment to improve ground water quality (Caruccio and Geidel 1996). The concept of surface application is that rainwater in contact with limestone will generate alkalinity and the alkalinity will create a wetting front which moves through the spoil. This technique has had limited success and, unless the seeps or discharges were initially low in acidity (<100 mg/L acidity as $CaCO_3$), the limestone only minimally improved seep quality.

Case Studies:

A 12 year old, partially reclaimed, pre-SMCRA surface mine in Ohio was amended with a surface application of limestone in five of seven areas (two areas were controls). Limestone was applied at rates varying from 90 to 160 Mg/ha (40 to 70 tons/ac) over the 60 ha site and 25 seeps were monitored for six years. Concurrent with tracer appearance, the low acidity (50 to 70 mg/L as $CaCO_3$) seeps became alkaline, however, the highly acid seeps (500 to 3000 mg/L as $CaCO_3$) showed only minimal response to the limestone. While the seep acidity decreased by about one third over the six years, the rate of decrease in the treated compared to the control seeps was only slightly improved (Geidel and Caruccio 1982).

2.2.2 Calcium and Magnesium Oxides

Because of limestone's limited solubility, it can only raise the pH of a system to approximately 8.3. Under certain situations, primarily when Mn levels must be decreased, higher pH levels are required. Examples of such materials that can increase water pH above 8.3 include: calcium-magnesium oxide (Magnalime), CaO and $Ca(OH)_2$.

Case Studies:

Since 1994, a surface coal mine in WV has been using Magnalime (a highly alkaline material containing approximately 30% CaO and 20% MgO, a waste by-product marketed by Ashland Chemical) to precipitate metals on the pit floor, thereby creating a seal. Applying approximately 112 Mg/ha (50 tons/ac) to the pit floor, the oxide forms a layer similar to cement thereby sealing the pit floor and providing alkalinity to the water accumulated there. While the primary objective was to reduce the level of available Mn, the acidity also decreased and the site was reclaimed with good vegetation (Faulkner, personal communication).

Alkaline recharge trenches have also been constructed with CaO and $Ca(OH)_2$ on top of an 8 ha coal refuse disposal site, which produced AMD seepage (Nawrot et al. 1994). After installing the alkaline recharge pools, acidity reductions of 25 to 90% were realized with concomitant 70 to 90% reductions in Fe and sulfate in seepage water. The following conclusions and recommendations were made: 1) use highly soluble alkaline materials (e.g.. CaO, $Ca(OH)_2$ waste products); 2) maximize water volumes through trenches by directing surface water flow into the pool; 3) use multiple alkaline recharge pools to increase chances of influencing groundwater flows; 4) construct infiltration paths into the backfill to improve alkaline diffusion and flushing; and 5) allow sufficient time (possibly 3 to 5 annual cycles) for the effect to become apparent.

2.2.3 Coal Combustion By-Products

Fluidized Bed Combustion (FBC) ash is produced at power generating plants that burn high sulfur coal or refuse in an FBC system. Sulfur dioxide emissions are controlled by injecting limestone into the combustion bed. At combustion temperatures, the limestone calcines leaving calcium oxide. About one-half of the CaO reacts with sulfur dioxide to form gypsum and the rest remains unreacted. Therefore, FBC ashes generally have NP's of between 20 to 40% and they tend to harden into a cement after wetting (Skousen et al. 1997a). Other power generation ashes, like flue gas desulfurization (FGD) products and scrubber sludges, may also have a significant NP which make them suitable alkaline amendment materials (Stehouwer et al. 1995).

Case Studies:

Hamric (1993) used FBC ash as material to seal the pit floor thus preventing groundwater from contacting acid-producing shales immediately below the coal in northern West Virginia. The ash was also placed on top of the regraded area to reduce infiltration and to lime the soil. Results of the application showed slight reductions in acidity of AMD coming from the mine site where ash was applied.

Researchers from American Electric Power and Ohio State University used FGD material to amend coal refuse in field and laboratory studies at the Rehobeth site. The FGD was determined to have a neutralizing potential of 15% $CaCO_3$ equivalency and a permeability of 1×10^{-6} cm/sec. The FGD material produced a larger yield of vegetation than refuse amended with agricultural lime at equivalent amounts. Water quality from the field experiments met drinking water standards, while untreated (control) runoff had high acidity and metal concentrations. Additionally, FGD material test plots had reduced infiltration rates, were highly stable, and resisted erosion (Mafi 1995).

2.2.4 Kiln Dust and Steel Slags

Kiln dust, produced by lime and cement kilns, contains 15 to 30% CaO with the remaining 70 to 85% of the material being hydrated lime and limestone. Kiln dust absorbs moisture and also hardens upon wetting. It is widely used as a stabilization and barrier material.

Steel making slags are locally available in large quantities at low cost and, when fresh, have NP's from 45 to 90%. Studies indicate that columns of steel slag maintain constant hydraulic conductivity over time and produce highly (>1,000 mg/L as $CaCO_3$) alkaline leachate (Ziemkiewicz and Skousen 1998). Steel slag 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 will not leach metal ions such as Cr, Mn, Ni, or Pb.

Other alkaline materials may have higher NPs than limestone, but the source of the material should be checked and a complete analysis done to evaluate NP and metal content before use. Quicklime, kiln dust and hydrated lime all react more rapidly than limestone, though it is not clear whether this is an advantage in AMD prevention. These

substances also have the potential to create pH values above 11, though such values are rarely reached in field applications.

Case Studies:

Rich and Hutchison (1990 and 1994) reported a successful operation where 2% lime kiln dust is added to refuse at a preparation plant in West Virginia. Not only did the kiln dust prevent acid formation, it improved the strength of the refuse pile by absorbing moisture from the filter cake, allowing easy access for large haulage trucks. Currently at least eight preparation plants in the eastern U.S. are using this technique.

Lime kiln dust has also been added to the overburden of a coal mine having alkaline deficiencies of up to 2450 Mg $CaCO_3$/ha (1090 tons $CaCO_3$/ac). The dust was applied to the pit floor at about 224 Mg/ha (100 tons/ac), also around special-handled cells, and also on fractured overburden after blasting. After grading, the dust was applied to the backfill surface, back-dragged by bulldozers to afford some mixing, and then topsoiled. Because the lime kiln dust could be back-hauled in coal trucks, about $0.81/Mg ($0.90/ton) of coal were estimated to be added to the normal mining costs. Compared to an acid discharge from an adjacent mine in the same coal bed, the water quality from this amended site is alkaline with low metal concentrations (Rose et al. 1995).

2.2.5 Phosphate Rock

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 required in about the same amounts (Ziemkiewicz and Meek 1994).

Case Studies:

Small field plots have been tested but no large scale case studies are available at this time.

2.2.6 AMD Sludge

Addition of alkaline sludges or flocs, generated from the neutralization of AMD, to the surfaces of backfills or to acid-producing materials during mining and backfilling may provide several benefits. First, flocs from all neutralization processes contain excess alkalinity and this alkalinity may be used to neutralize acid-producing materials or acidic

water in the backfill. Lime-treated flocs often contain up to 50% unreacted lime, which may be used to further neutralize acidity. Second, disposal of the metal flocs from AMD treatment ponds is an expensive and long term problem and disposal in nearby surface mine soils or within spoil materials during mining can provide a cost effective alternative to other disposal options.

Case Studies:

Coleman et al. (1997) studied the application of lime-treated AMD floc to the surface of spoils and to acid-producing materials. In a column test, the floc did not accelerate or reduce the generation of acidity by acid-producing materials. Further, metal hydroxides contained in the floc did not dissolve in the presence of acid-generating material under these conditions. The floc did not develop low permeability properties, thus it could not be used as a capping material over acid-producing materials.

This technology was applied in the field at a coal refuse disposal area in West Virginia where dry AMD treatment sludge was used as a substitute for soil cover. The sludge was concentrated by pumping it to steel dumpsters lined with filter fabric, thereby allowing the water to filter into a sediment pool. This concentrated sludge was hauled to drying cells and then moved to the refuse pile for spreading and seeding. The sludge generated by AMD neutralization with calcium oxide was well suited for establishing and supporting vegetation. Vegetation on this soil substitute surpassed growth on native soils. Water quality was positively influenced by the improved vegetation and metals were stabilized. Underground disposal of this material into abandoned deep mines on this property was initiated in 1997 and careful monitoring of all deep mine openings related to these underground works is being conducted (Faulkner, personal communication).

2.2.7 Organic Wastes

Organic wastes as alkaline additions are discussed in detail in Section 5.7 (Bioremediation). While most bioremediation of AMD has been noted to occur in passive treatments such as anaerobic wetlands, organic wastes (such as sawdust and sewage sludge) have been incorporated into spoils to aid in the *in-situ* treatment of water by the use of indigenous microorganisms (Rose et al. 1996).

2.2.8 Others

Over the years other types of alkaline amendments have been tried by various mine operators and researchers to control AMD. These have included, among others: sodium carbonate, as briquettes, in recharge areas of spoil and in the base of alkaline trenches (Caruccio et al. 1984), $Ca(OH)_2$ in alkaline trenches (Nawrot et al. 1994) and sodium hydroxide (NaOH) liquid poured into backfills via well bores. Most of these techniques have been used in conjunction with other amendments or reclamation efforts and no definitive information is available regarding their sole use.

2.3 Sewage Sludge

There is evidence from laboratory studies that the oxidation of pyrite can be inhibited by organic waste materials such as manures and sewage sludge (Backes et al. 1987). The inhibition process may be a combination of several mechanisms. First, Thiobacillus bacteria, which can catalyze iron oxidation in Equation 1.2 (section 1.1), may convert from a chemolithotrophic bacteria to a heterotroph in the presence of readily decomposable organic matter (Lundgren 1971). A second mechanism of inhibition may allow the sludge to complex Fe and eliminate it from oxidizing more pyrite, or adsorb/complex Al and other metal ions, thereby reducing hydrolysis and pH decreases. Sludge may also coat pyrite surfaces minimizing reaction surfaces. Decomposition of sludge consumes oxygen, thereby decreasing its availability for pyrite oxidation.

Case Study:

In 1977, digested and dewatered municipal biosolids were applied to an abandoned surface mine at the rate of 184 Mg/ha (85 tons/ac) on a 0.4 ha plot in Pennsylvania. Data were collected for a 5-year period and the site was re-evaluated after 12 years. The results showed that vegetation could be established and that the groundwater quality improved (Sopper and Seaker 1990). The State of Pennsylvania has used this technology to revegetate over 2,000 ha (5,000 ac) of mine land (Sopper 1993).

2.4 Encapsulation

This process encircles or covers acid-producing material with an impermeable material to limit its exposure to air and water. The material can be a synthetic liner or it may be a clayey material or other compacted material, which results in a layer with a low

hydraulic conductivity (Meek 1994, Geidel and Caruccio 1984). The material surrounding the acid-producing material may also be composed of alkaline material. Encapsulation can occur during the mining process where acid-producing materials are placed "high and dry" off the pit floor and away from the highwall (Skousen et al. 1987). After placement and compaction (and treatment with alkaline material if required), the acid-producing material is then covered with local clayey material or topsoil and this material is also compacted on top of the acid-producing material. Backfilling then continues over the layers of acid and cover material until the final grade is achieved.

Encapsulation has also been attempted after reclamation. If AMD is coming from a site, geophysical techniques are used to map the location of "hotspots" in a backfill by the use of conductivity or resistivity measurements. Wells are drilled into the hotspots in the backfill, encountering the acid material and cased. A grout mix is then pumped down the wells to encapsulate or permeate through the acid-producing material.

Case Studies:

At two West Virginia mines where synthetic materials (PVC liners) were used and one mine where compacted clay was used to encapsulate acid-producing material (Caruccio 1983, Geidel and Caruccio 1984, Meek 1994), both methods were only partially successful. This probably was due to incomplete coverage of the acid-producing material with the barrier material.

The plastic liner technology was applied at a surface coal mine in Alton, WV (Caruccio 1983). Approximately 18 ha (45 ac) of a combined refuse disposal and overburden site were covered with a 20 mil continuously-seamed PVC liner. The liner was placed over the surface of the backfill material and covered with 0.5 m (18 in) of soil. Due to the steep slopes on the periphery of the backfill, approximately 3 ha (or about 20% of the site) were not covered. The seeps and groundwater fluctuations from a larger, unlined portion of the mine were compared to seeps and groundwater levels from the PVC-lined area. The ground water wells in the lined area reflected a diminution in groundwater recharge. During the year following the installation, the seeps emanating from the PVC-lined area showed a 63% reduction in acid loads while there was no reduction in the seeps from the unlined portion .

In a series of studies and demonstrations, several organizations determined the location of acid-producing material in several backfills, drilled and cased wells, and pumped grout down the wells into the acid-producing material in the backfill (Ackman and Cohen 1994, Jones et al. 1997, Schueck et al. 1994). The use of coal combustion by-products, which may set up like concrete, have largely been used as the grouting and encapsulation material. Grouts of fly ash, lime and cement, when injected underground, decreased permeability and porosity, diverting water away from the pyritic material. Both mechanisms, alkaline additions and water diversion, are expected to reduce the amount of acid produced. Uninjected grout wells have been observed to discharge grout that was being injected 45 m away. The pH of water from ungrouted wells rose from 3 to 11. The amount of grout injected into the backfill was minimal (<4% of total volume) when considering the amount of void space in the subsurface of a reclaimed surface mine. Slight, but significant improvements in water quality have been observed. More notable changes may have occurred had the amount of grout injected been larger.

2.5 Removal of Toxic Material (Remining and Reprocessing)

Remining is 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. Remining has been combined successfully with alkaline addition and special handling to change water quality from acid to alkaline at specific sites.

Case Studies:

Hawkins (1994) studied 57 discharges from 24 remined sites in Pennsylvania, and found contaminant loadings (e.g. flows and metal concentrations) were either reduced or unchanged after remining and reclamation. Short term loads were sometimes increased during the first six months after remining and reclamation. Reduction in loads resulted from decreased flow rather than large changes in concentrations. An evaluation of ten remining sites in Pennsylvania and West Virginia showed eight of the sites to produce a net profit from coal sales (Skousen et al. 1997b). All the sites were reclaimed to current standards, thereby eliminating highwalls, covering refuse, and revegetating the entire areas. All sites also had improved water quality and some completely eliminated AMD

leaving the site. Faulkner and Skousen (1995) found significant reductions in acid loads after land reclamation, and the acid load reductions were due both to reductions in water flow from the site and reductions in acid concentration in the water.

Skousen and Larew (1994) described the surface remining of an underground mine in Preston County, West Virginia. Alkaline overburden from an adjacent mine was imported at a rate of 15,000 Mg/ha (6,700 tons/ac) to the remining job at a cost of $0.55/Mg ($0.50/ton) of coal removed. An average of about 18,000 Mg/ha (8,000 tons/ac) of coal was removed, making the cost of hauling the alkaline material to the site around $9,900/ha ($4,000/ac). Water quality from the deep mine prior to remining averaged pH 3.7 and 75 mg/L acidity as $CaCO_3$, while after remining and reclamation, pH was above 7.0 with no acidity. Based on average premining water flows and analyses of the deep mine discharge on the site, the chemical cost for treating AMD on this site would have been around $200,000 over a 20-year period. The alkaline addition had a one-time cost of $45,000.

2.6 Selective Handling

Selective handling or "special" handling is used in surface coal mining operations to dispose of potentially acid-producing materials in backfills. In the eastern U.S. coalfields, identification of potentially acid-producing materials in the overburden is necessary to selectively handle this material for placement in specific areas of the backfill. As toxic material is encountered, the primary strategy is to segregate and place this material as quickly as possible off the pit floor and away from the highwall to limit its exposure to air and water (Skousen et al. 1987). Compaction of the material upon placement is helpful and sometimes treating the acid material with alkaline amendments will help neutralize the acid-producing potential.

Selective handling may also create a postmining hydrologic regime that minimizes the contact between acid-forming rock and groundwater or it may isolate potential acid-producing rocks from the rest of the backfill by the use of barriers (Geidel and Caruccio 1984). The coal pit floor is often rich in pyrite, therefore, isolating it from groundwater may be necessary. Isolation methods can include building highwall drains to move incoming groundwater away from the pit floor or placing impermeable barriers on the pit floor.

Proper identification, handling, blending or treatment, and placement of the acid-producing materials in the backfill are key issues to controlling AMD (Skousen et al. 1987).

Case Studies:

Perry et al. (1997) found that special handling techniques did not always have an effect on reducing AMD from acid-producing materials. They found that speed and continuity of mining operations affected post mining water quality more than the specific mining techniques used. Sites where mining ceased, and then resumed, generally produced poorer quality drainage than sites where mining proceeded rapidly to completion. Extended exposure of unreclaimed spoil to infiltration and circulation of water and oxygen apparently encouraged substantially greater pyrite oxidation and AMD generation.

2.7 Reclamation (regrading and revegetation)

Backfilling and revegetation together are one method of reducing acid loads from current mining operations or abandoned mine sites. Covering pyritic refuse or other acid-producing materials on a site with good soil material and establishing vegetation has a major impact on reducing acid concentrations in water and often decreases the flow of water from these sites by encouraging infiltration into soil and evapotranspiration by plants. If the majority of the water from an abandoned site is coming from underground mines, then surface treatments may have limited effects on reducing acid loads.

Regrading and revegetation have the potential to reduce acid loads and improve water quality to the point of meeting effluent limits. Backfilling and revegetation remains the primary approach to reducing water quality problems at surface mines (Skousen et al. 1995). If the pavement is visible and toxic materials present, appropriate material handling to keep toxic material "high and dry" in the backfill is desirable. Liming the pit with alkaline materials or lime products will also reduce the acid produced on-site. Encouraging controlled, rapid runoff and discouraging recharge into zones of pyritic backfill materials will help reduce the total acid load from the site. Results demonstrate that backfilling generally reduces total acid load either by reducing the flow or by reducing acidity concentrations in the water, or both.

Case Studies:

Water flow was reduced on 12 out of the 16 sites in West Virginia where reclamation was accomplished on bond-forfeited and unreclaimed areas (Faulkner and Skousen 1995). On those sites where flow was not reduced, water quality changed from acid to alkaline. In only two out of 16 cases was the acidity increased in the water, but flows were reduced dramatically causing a 45% decrease in total acid load. Vegetation establishment greatly reduced the occurrence and amount of runoff compared to a barren tailings area in Montana (Spotts et al. 1997). Runoff water from the vegetated area had a higher pH (6.2 vs 4.0), and metal loadings of As, Cu, and Zn were also more than four orders of magnitude lower than the unvegetated area.

2.8 Daylighting Deep Mines

See section 2.5 Removal of Toxic Material (Remining and Reprocessing)

2.9 Synergistic Effects

Many of the techniques and methods described above are often used in combination and as a result produce synergistic effects. Mining operators recognize that if the materials have the potential to produce AMD, a number of techniques can be incorporated into their material handling plans to minimize or eliminate the production of AMD. These often include selective handling of the overburden, alkaline additions and reclamation/revegetation. While each of these technologies may be effective by itself, that is not always the case, as demonstrated in some of the preceding case studies. The combined use of several methods, however, has allowed the key aspects of each technique to interact with other techniques. For example, selective handling of acidic material and segregating it out of the water table, in conjunction with blending alkaline material and constructing alkaline recharge zones have been successful (Wiram and Naumann 1995).

2.10 New Techniques

While a number of new techniques may be attempted each year, this section will be devoted to those new techniques that have data which are of sufficient duration to adequately evaluate the technology, preferably three years of data, but shorter time spans may be sufficient depending on the technology and its application.

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