ACID MINE DRAINAGE AND ITS TREATMENT

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ABSTRACT

This paper made an attempt to highlight what Acid Mine Drainage is as well as the possible management and control methods employed in the mining sector where AMD is a problem. Acid Mine Drainage is an environmental pollutant of major concern throughout the world. The mining sector is responsible for the contamination of the environment through its release. It is generated through the mining of sulphur-bearing ore deposits. This exposes sulphidic rocks to surface water and oxygen which accelerates oxidation, leaching and release of metals and generation of the Acid Mine Drainage. It is characterized by a pH of 2 or less, total dissolved solids (TDS) in the order of 4000-5000mg/l, high Fe content, high Al and Mn concentrations and a high sulphate content. In terms of management and control of AMD, the objective is to satisfy environmental requirements using the most cost-effective techniques. There are three key strategies in acid mine drainage management, namely: the control of acid generation process, control of acid migration and the collection and treatment of AMD. The paper also added a fourth one which has been shown to be effective in the management and control of AMD. This involves AMD treatment through co-disposal with Coal ash. Using this co-disposal method, most metals were removed by approximately 100 % when the pH of minimum solubility of hydroxides was achieved. Sulphate removal was found to be approximately 80 % due to gypsum precipitation.

Keywords: *Acid Mine Drainage, Co-disposal, Sulphidic Rocks, Coal Ash, Neutralisation, Water Chemistry, Acid Migration.*

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INTRODUCTION

Mining sector plays a crucial role in the economies of many countries, especially through both backward and forward linkages(Jerie & Sibanda, 2010). Significant contributions can be noted in the form of employment creation and foreign currency earnings that are essential for socio-economic development(Jerie & Sibanda, 2010). Focus in the mining sector should, however, not be only on the economic aspects, but also on sustainable environmental management, which is part of the integrated global efforts for environmentally friendly production processes (Ajusa, 2003). According to a South African Water Research Commission, a greater part of water related pollution originates from mining activities (Du Plessis, 1997). This further influences negatively the already dwindling water resources, especially in Southern Africa where most of the countries are said to be water scarce. Water is described as a finite, vulnerable and an essential resource(ICWE, 1992). This resource is one of the key natural resources available to human kind whose scarcity can be seen as the most limiting factor to economic growth and social development(ICWE, 1992). Its vulnerability makes it very easy to pollute, yet it’s essential for the survival of human beings. Thus, the polluting of this very important resource should ideally be a thing never to be done by whosoever and by whatever. This paper made a review of an environmentally unfriendly by- product in areas where sulphur bearing ore deposits are mined- Acid Mine Drainage (AMD). In particular, this paper has tried to highlight what AMD is as well as the possible management and control methods employed in the mining sector where AMD is a problem.

Acid Mine Drainage (AMD)

Mining of sulphur-bearing ore deposits exposes sulphidic rocks to surface water and oxygen which accelerates oxidation, leaching and release of metals and generation of acid-a process called Acid Mine Drainage (AMD)(Rukezo, 2003). Acid Mine Drainage is an environmental pollutant of major concern throughout the world in mining areas. Formation of AMD is primarily a function of the geology, hydrology and mining technology employed at the mine site to (Kepler & McCleary, 1994). The resulting water is usually high in acidity and dissolved heavy metals. The metals stay dissolved in solution until the pH raises to a level where precipitation occurs. For instance, upon infiltration by rainwater, spoil heaps leach highly acidic AMD to ground waters as a result of pyrite oxidation that forms sulphuric acid, which in turn mobilizes toxic metal species by dissolution. AMD is characterized by a pH of 2 or less, total dissolved solids (TDS) in the order of 4000-5000mg/l, high Fe content, high Al and Mn concentrations and a high sulphate content (Bell & Bullock, 1997). It is a product formed by the atmospheric (by the water, oxygen and carbon dioxide) oxidation of the relatively common iron-sulphur minerals pyrite (FeS_2) and pyrrhotite (FeS) in the presence of catalyzing bacteria *Thiobacillus ferrooxidans* (Bell & Bullock, 1997). AMD is produced when the neutralizing potential is no longer capable of maintaining neutral pH conditions in a measurable volume of drainage. According to Webster et al.,(1998), AMD management strategies rely heavily on the ability to measure the AMD potential of waste materials to ensure strategies are appropriate to the AMD risks. A good case study is Iron Duke mine in Zimbabwe where AMD is formed as a result of mining activities and its release into the environment affects the water chemistry. Generally, AMD is a combination of human activities (mining, quarrying, civil engineering works and logging) and natural events.

Sources of AMD

According to Bell (1998), AMD can be associated with underground workings, open pit workings, spoil heaps, tailings ponds or mineral stockpiles.

Underground mining

Generally, AMD from underground mines occur as point discharges. A major source of AMD may result from the closure of a mine. When a mine is abandoned and dewatering by pumping ceases, the water levels rebound. Consequently, a residual dewatered zone remains that is subject to continuing oxidation. Groundwater may drain to the surface from old drainage pits, river bank mine mouths, faults, springs and shafts which intercept rock in which water is under artesian pressure (Hedin & Nairn, 1993). The mine water quality is determined by the hydrological system and the geochemistry of the upper mine levels. Hence, in terms of a working mine, it is important that ground water levels are monitored to estimate the rebound potential.

Open cast mining

The large areas of fractured rock exposed in opencast mines or open pits can give rise to large volumes of AMD. Even when abandoned, slope deterioration and failure can lead to fresh rock being exposed, allowing the process of acid generation to continue. Where the workings extend beneath the surrounding topography, the pit drainage system leads to the water table being lowered. Increased oxidation can occur in the dewatered zone.

Spoil heaps

Spoil heaps represent waste generated by the mining operation. As such, they vary from waste produced by subsurface mining to waste produced by any associated smelting or beneficiation. Acid generation tends to occur in the surface layers of spoil heaps, where air and water have access to sulphide minerals.

Tailings deposits

Tailings deposits with a high content of sulphide represent another potential source of acid generation. However, the low permeability of many tailings deposits together with the fact that they commonly are flooded means that the rate of acid generation and release is limited. Consequently, the generation of AMD can continue to take place long after a tailings deposit has been abandoned.

Mineral stockpiles

Mineral stockpiles may represent a concentrated source of AMD. Major acid flushes commonly occur during periods of heavy rainfall after long periods of dry weather. Heap-leach operation at metalliferous mines includes; e.g. cyanide leach for gold recovery and acid leach for base metal recovery. Spent leach heaps can represent sources of AMD, especially those associated with low-pH leachates (Forstner & Salomons, 1988).

Basic Chemistry of AMD Generation

According to Zipper (2001), the process for AMD generation is commonly represented by the following chemical reactions:

$$2FeS_{2(s)} + 7O_{2\,(g)} + 2H_2O_{\,(l)} \rightarrow 2Fe^{2+}{}_{(aq)} + 4SO_4{}^{2-}{}_{(aq)} + 4H^+{}_{(aq)} \ldots\ldots\ldots\ldots (1)$$

$$4Fe^{2+}{}_{(aq)} + O_{2\,(g)} + 4H^+{}_{(aq)} \xrightarrow{\textit{Thiobacillus Ferroxidans}} 4Fe^{3+}{}_{(aq)} + 2H_2O_{\,(l)} \ldots\ldots (2)$$

$$Fe^{3+}{}_{(aq)} + 2H_2O_{\,(l)} \longrightarrow FeOOH_{(s)} + 3H^+{}_{(aq)} \ldots\ldots\ldots\ldots (3)$$

The process is initiated with the oxidation of pyrite and the release of ferrous Iron (Fe^{2+}), sulphate and acidity reaction (1). The sulphide-oxidation process is accelerated by the presence of *Thiobacillus* bacteria reaction (2). Ferrous Iron (Fe^{2+}) then undergoes oxidation forming ferric Iron (Fe^{3+}). Finally Fe^{3+} is hydrolyzed, forming insoluble hydroxide (FeOOH), an orange-coloured precipitate, and releasing additional acidity reaction (3).

Lastly, pyrite can also be oxidized by Fe^{3+} as shown below:

$$FeS_{2(s)} + 14Fe^{3+}{}_{(aq)} + 8H_2O_{\,(l)} \longrightarrow 15Fe^{2+}{}_{(aq)} + 2SO_4{}^{2-}{}_{(aq)} + 16H^+{}_{(aq)} \ldots\ldots (4)$$

The Fe^{3+} is generated from reaction (2). This is the cyclic and self-propagating part of the overall reaction and takes place very rapidly and continues until either ferric Iron or pyrite is depleted. In the reaction, Iron is the oxidizing agent (Hadley & Snow, 1974). Hassett (1998) also described the oxidation of pyrite (FeS_2) to the products that constitute the contaminants generically termed Acid Rock Drainage (ARD) by the chemical reactions below (Extract from(Hassett, 1998)) although similar reactions may be written for the oxidation of pyrrhotite (FeS) as shown by reactions 1 to 4 above.

$$FeS_2 + 7Fe_2(SO_4)_3 + 8H_2O \longrightarrow 15FeSO_4 + 8H_2SO_4$$

$$FeS_2 + Fe_2(SO_4)_3 \longrightarrow 3FeSO_4 + 2S$$

$$4FeSO_4 + O_2 + 2H_2SO_4 \xrightarrow{T.ferrooxidans} 2Fe_2(SO_4)_3 + 2H_2O$$

$$2S + 3O_2 + 2H_2O \xrightarrow{T.ferrooxidans} 2H_2SO_4$$

$$4FeS_2 + 15O_2 + 2H_2O \longrightarrow 2Fe_2(SO_4)_3 + 2H_2SO_4$$

$$S + 3Fe_2(SO_4)_3 + 4H_2O \longrightarrow 6FeSO_4 + 4H_2SO_4$$

Where

FeS_2 - pyrite; H_2O - water; O_2 - oxygen; S - sulphur; H_2SO_4 - sulphuric acid; $FeSO_4$ - ferrous sulphate; $Fe_2(SO_4)_3$ - ferric sulphate.

Chemical reactions 2 and 6 are accelerated by bacteria. The bacteria, which are usually site-specific strains of *Thiobacillus ferrooxidans*, utilise the sulphur present as their source of energy. They are autotrophic, obtaining their nutritional needs from the atmosphere (nitrogen, oxygen, carbon dioxide and water) and from minerals (sulphur and phosphorus). While these bacteria are not catalysts by true definition, they do act as accelerating agents if their habitat conditions are at or close to optimal and they are a most important factor in the generation of ARD. They are adaptative through mutation if their habitat is markedly changed. It is thought that in the absence of bacteria (*T. ferrooxidans)* reactions 4, 5 and 7 predominate, while in the presence of bacteria reactions are best described by reaction 7, which can be regarded as a combination of reactions 2 and 4, or reactions 5, 2 and 6, or reactions 4, 5, 2 and 6.

It may be seen that in addition to pyrite, the presence of both *oxygen* and *water* is required for process progression. This has important ramifications in that removal of the oxygen source (e.g. by total submersion under water) or the water source (e.g. conditions of aridity) will halt AMD production (Pflughoeft-Hassett et al.,1993). AMD production would also be considerably slowed or halted by the termination of *T. ferrooxidans* reproduction by a bactericidal agent. The end products are sulphuric acid and ferric sulphate. Also, sulphuric acid is an important intermediate product. From the onset of pyrite oxidation, pH falls (acidity increases) quickly and then stabilizes, typically at values around pH 2.5 to 3.0. The pH of stabilization is normally determined by the optimal habitat requirement of the site-specific strain of bacteria (Evangelou & Zhang, 1995).

If pyrite and/or pyrrhotite are the only sulphide minerals open to atmospheric oxidation then the products of the oxidation process are those described above. Depending upon the availability of water and oxygen, reactions may not always approach completion as indicated by reactions 4 to 8, and in such cases intermediate phases of chemical compounds or minerals may remain at the oxidation site. If metallic sulphide minerals such as; galena (PbS), chalcopyrite (FeS.CuS), sphalerite (ZnS), in addition to pyrite and pyrrhotite are present (as is usually the case in the natural oxidation of a mineral deposit and the oxidation of products from the mining of a mineral deposit) then there may be a secondary effect of the oxidation of the iron-sulphur minerals to sulphuric acid and ferric iron

In a study by Seth and Elliot (2000) ,a stable pH was developed (2.5 to 3.0) and the products of sulphuric acid and ferric sulphate created conditions where the ferric iron itself acted as an oxidant (above about pH 3 the ferric iron is itself hydrolysed to ferric hydroxide, which precipitates as the familiar rust-coloured stain associated with ARD). In the absence of ferric iron at pH 2.5-3.0, sulphuric acid dissolved some heavy metal carbonate and oxide minerals, but had little reactive effect on heavy metal sulphides. However, ferric iron ion was capable of dissolving many heavy metal sulphide minerals, including those of lead, copper, zinc, and cadmium, by the general reaction (Seth & Elliot, 2000):

$$MS + nFe^{3+} \longrightarrow M^{n+} + S + nFe^{2+} \ldots\ldots\ldots\ldots (9)$$

Where: MS = solid heavy metal sulphide; M^{n+} = aqueous heavy metal ion; S = sulphur.

It is by this process that significant amounts of heavy metals may be solubilised by AMD. It has been customary to call ARD with the dissolution of metals by reaction (9) Acid Mine Drainage even though this term implies that the process occurs only in association with mining activity. In addition, many metallic elements are often present in trace levels within the minerals pyrite and pyrrhotite. Oxidation of these minerals can therefore release and mobilise these trace elements.

Untreated AMD creates two distinct environmental problems - the acidity from sulphuric acid (which is invariably a product by definition) and the heavy metal solubilization caused by ferric iron (which may occur under the conditions described above). It is important that these two effects be recognized as separate, since their consequences to ecosystems are distinct, and because ARD generation and heavy metal transport are separate processes.

Chemistry of AMD Neutralisation

Neutralization of AMD by adding an alkaline reagent produces sludges generally dominated by amorphous ferrihydrite, often with high levels of adsorbed heavy metals (Burgers, 2002).

Modifications to the AMD treatment procedure, in particular control of oxidation state and aluminium levels, can substantially increase the crystallinity and improve the chemical stability of the sludge precipitated, and have a much greater influence on sludge leachability than the neutralization reagent used.

In a research by William and Griffin (1984), the pH of ARD is increased, as would happen with contact with basic minerals such as calcite ($CaCO_3$) or dolomite ($CaMg(CO_3)_2$) or entry into a water system of higher pH, then metallic ions such as Fe^{3+} and Cu^{2+}, Zn^{2+}, Pb^{2+} and As^{3+} will react to eventually form hydroxides as precipitates by the general reaction:

$$\longrightarrow$$

Where: OH^- = hydroxyl ion; $M(OH)_n$ = metal hydroxide.

This over-simplification represents chemical neutralization as it occurs by human intervention, rather than an accurate portrayal of natural occurrence, where the precipitation products are usually carbonates and sulphates and their hydrated and/or hydroxyl-complexes. In nature, acid generating minerals such as pyrite often occur in close association with acid neutralizing minerals such as calcite and dolomite, and acid produced from pyrite is neutralized, *in situ*, by these minerals. According to Webster et al.,(1998), the sulphate most commonly formed is gypsum, which is sparingly soluble in water, and which therefore contributes to elevated sulphate levels in ground and surface waters. Other minerals, including some silicates such as plagioclase feldspar, may also neutralize acid produced by sulphide mineral oxidation. However, this process is relatively slow compared with neutralization by carbonates.

The science and understanding of AMD generation is still developing and there are some mining operations that were developed and operated without the benefit of current knowledge. As a consequence, these mines do generate AMD that has to be treated by neutralization. In commercial practice AMD is neutralized with lime (CaO) to reduce acidity and to precipitate metals - an expensive and long-term necessity.

In nature, the neutralization of AMD, either *in-situ* or at some distance from the source of generation, results in a difference in rock appearance (oxidized, and different in texture and colour from the host rock) and/or additions to bottom sediments or sediment particle surfaces (including rocks and boulders in watercourse beds). Economic mineral deposits such as bauxite (ore of aluminium), laterite (ore of iron) and super gene oxide zones (that may contain economic deposits of copper, gold and silver) are products of natural acid rock generation developed over geologic time. They are derived from the breakdown of minerals at surface levels. Minerals are also formed as a result of AMD processes, some of which are rare and highly prized by mineral collectors (e.g. boleite), some of which are used for jewellery (e.g. malachite), and some of which form mineral deposits (e.g. chalcocite).

It must be understood that the above is a highly simplified description of the basic chemistry of ARD. For example, the precipitation of hydroxides or related chemicals is dependent upon the aqueous concentration of a metal, the pH and the redox potential of the solution as well as the concentrations of other ions. The chemistry of real ARD systems is extremely complex.

AMD Kinetics

While chemical equations and their related thermodynamic data are a useful concept in the understanding of ARD generation, they refer to equilibrium conditions at infinite time and give no indication of the kinetics, or speed, with which a reaction will take place. An accurate prediction of AMD is necessary to know how to bring it under control. The length of time over which the control measures are required to be effective is a factor which needs to be determined prior to the design of a system to control AMD. The kinetics of chemical reactions is considered to be either chemically or transport controlled. A chemically controlled reaction is one controlled only by the concentrations of the chemicals reacting with one another, while a transport controlled reaction is dependent upon the rate of transfer of reagents or products to or from the reaction site. It is also reasonable to consider reaction rates controlled by biological activity to be a separate case.

ARD generation is a complex group of reactions which involve all three of these possibilities vying for dominance. Thus in conditions of atmospheric oxidation it is probable that ARD generation is predominantly transport controlled during periods of high rainfall and runoff, biologically controlled during low rainfall and optimal temperature for bacterial growth, and chemically controlled at other times. At any given time, control may involve all three mechanisms(Cambell, 1998). In addition temperature affects the rate of these three processes differently, and temperature effects are controlled not just by atmospheric variations but also by the heat generated by the (exothermic) chemical reactions and the rate of dissipation of this heat. Thus seasonal variations of precipitation may affect the transport characteristics of the process by water flow, and temperature control through heat transfer. It follows that prediction of ARD generation rates is a complex, difficult process involving the interaction of a large number of system variables. The prediction of metal hydroxide precipitation from ARD is equally difficult because of the complexity of the reaction kinetics.

Chemically controlled reaction

At pH values greater than four, pyrite is oxidized by oxygen dissolved in water as:

$$2FeS_{2(s)} + 7O_2 + 2H_2O \longrightarrow 2Fe^{2+} + 4SO_4^{2-} + 4H^+ \ldots\ldots\ldots\ldots (1)$$

Ferrous iron is released to the water solution where it is oxidized to ferric iron: (Markhol, 1985).

$$4Fe^{2+} + O_2 + 4H^+ \longrightarrow 4Fe^{3+} + 2H_2O \ldots\ldots\ldots (2)$$

At pH values less than four the ferric iron reacts with pyrite according to reaction (4)

$$FeS_{2(s)} + 14Fe^{3+} + 8H_2O \longrightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \ldots\ldots\ldots (4)$$

At high pH values the ferric iron reacts further with oxygen and water, and forms ferric hydroxide which precipitates:

$$Fe^{3+} + 3H_2O \longrightarrow Fe\ (OH)_3(s) + 3H^+ \ldots\ldots\ldots (3)$$

Reactions (1), (4) and (3) produce acid, which, if not neutralized, mobilizes metal ions, contained in the waste rock. High pH values can be maintained by neutralizing minerals which often are present in the waste rock or by minerals (like calcite) added to the waste rock. The process of neutralization by calcite is described by reactions (11) and (12).

$$CaCO_3 + 2\,H^+ + SO_4^{2-} + 2H_2O \longrightarrow CaSO_4 \cdot 2H_2O + H_2CO_3 \ldots\ldots\ldots (11)$$

$$CaCO_3 + H^+ + SO_4^{2-} + H_2O \longrightarrow CaSO_4 \cdot 2H_2O + HCO_3^- \ldots\ldots\ldots\ldots (12)$$

The relative rates of the reaction (11) and (12) depend on pH values and are responsible for the efficiency of the neutralization process. The rate of oxidation of ferrous iron increases with increasing pH values and the neutralizing potential of the reactions (11) and (12) decreases when pH increases. This leads to a stoichiometric incompatibility between acid-generating and acid-neutralizing reactions. Minimizing the stoichiometric incompatibility during the neutralization process should reduce the amount of sludge generated and lower the cost of neutralization. Since the analysis of the neutralization process is limited to equilibrium conditions for the neutralizing species (pH is a control parameter), further analysis is required.

At pH less than four, ferric hydroxide is soluble and the reaction of pyrite oxidation by ferric iron contributes to acidic drainage. The source of ferric iron may be reaction (R_2) (oxidation of ferrous iron) or the ferric hydroxide formed higher in the pile and washed down to a region of low pH. The oxidation of pyrite by ferrous iron may also be initiated if an insufficient amount of neutralizing minerals is used.

Biologically controlled reaction

According to (Markhol, 1985), at low pH values and at temperatures of about 303 K (3^{0}Ċ), *Thiobacillus ferrooxidans*, can accelerate the process of pyrite dissolution by about a thousand times. Bacterial processes accelerate each of the reactions (1), (2) and (3) in a different way. The reaction (1) is accelerated about three hundred times. The reaction (2) becomes about a million times faster. Bacteria accelerate the reaction (3) about three times.

The reactions of the bacterial oxidation of ferrous iron to ferric iron and the pyrite oxidation by ferric iron provide a nonlinear negative feedback mechanism which is responsible for a smaller than desired effect of slowing-down pyrite oxidation by reducing oxygen concentration. This negative feedback mechanism is also responsible for a chemistatic bacterial action and prolonged bacterial activity in an acidic environment.

AMD Management and Control

The objective of AMD management is to satisfy environmental requirements using the most cost-effective techniques. There are three key strategies in acid mine drainage management, namely: the control of acid generation process, control of acid migration and the collection and treatment of AMD (Judi & Kelli, 1997). The paper also added a fourth one which has been studied by several authors (Mpofu et al., (2013); Bell and Bullock, (1997); Burgers (2002); (Gitari et al., (2006); Hullet and Weinbeger, (1980)) and has been shown to be effective in the management and control of AMD. This involves AMD treatment through co-disposal with Coal ash.

Control of acid generation.

The best solution is to control acid generation if possible. Source control of AMD involves measures to prevent or inhibit oxidation, acid generation or contaminant leaching. If acid generation is prevented, there is no risk of the contaminants entering the environment. Such control methods involve the removal or isolation of sulphide material, or the exclusion of water or air. The latter is much more practical and can be achieved by the placement of a cover over acid-generating material such as waste or air sealing of adits in mines (O'Brien, 2000).

Migration control

It is considered when acid generation is occurring and can not be inhibited. Because water is the transporting medium, control relies on the prevention of water entry to the source of AMD. Water entry may be controlled by the diversion of surface water flowing towards the source by drainage ditches, the prevention of ground water flow into the source by interception and isolation and the prevention of infiltration of precipitation into the source by the placement of cover materials.

Release control

It is based on the measures to collect and treat AMD. It is the only practical option available. The collection requires the collection of both ground water and surface polluted by AMD, and involves the installation of drainage ditches, collection trenches and wells. Treatment processes have concentrated on neutralization to raise pH and precipitate metals. More sophisticated processes (Active treatment methods) involve osmosis (water removal through membranes), ion exchange (ion removal using resins), electro dialysis (selective ion removal through membranes), electrolysis (metal recovery by electrodes) and solvent extraction (removal of specific ions with solvents) (Hadley & Snow, 1974). Passive treatment methods can be used which involve engineering a combination of low-maintenance biochemical systems (e.g anoxic limestone drains, aerobic and anaerobic wetlands and rock filters). Such treatment system tries to minimize the input of energy, materials and manpower, and so reduce operational costs.

AMD Treatment using Coal Ash

Treatment of AMD is currently done by natural means or by active treatment and passive treatment. The most commonly used chemicals for treating AMD are; CaO, $Ca\ (OH)_2$, $CaCO_3$, NaOH, NH_3 and Na_2CO_3 (Hedin & Nairn, 1993). These systems require the installation of a plant with agitated reactors, precipitators, clarifiers and thickeners (Gazea et al., 1996). Another chemical investigated for use in abating AMD is coal ash. Coal ash is the mineral matter in coal that remains after coal has been thermally altered through a combustion process(Madzivire, 2009). Coal Ash application to treat AMD was found to be able to neutralize the acidity(Madzivire, 2009). This is because of the lime present in coal ash (Gitari et al., 2006; Klink, 2003). Its chemical compositions reveal that all natural elements can be found in the coal ash. The major elements in coal ash are Fe, Al and Si together with significant amounts of Ca, K, Na and Ti. The most common minerals that constitute coal ash include: quartz (SiO_2), mullite ($Al_6Si_2O_{13}$), hematite (Fe_2O_3), magnetite (Fe_3O_4) and small portion of unburnt carbon. In addition to these minerals anhydrite ($CaSO_4$), lime (CaO) and periclase (MgO) are also included. The free alkalinity imparted by CaO (approx.7wt %) and the fact that coal ash has a very high surface area due to small particle size makes it a good neutralization agent (O'Brien, 2000). An analysis of coal ash material has shown that many toxic elements are present (Adriano et al.,1980). Minerals such as; sulphates, carbonates, phosphates, silicates and clay minerals enrich the inorganic component of coal with elements such as Si, Fe, S and P.

These toxic elements remaining in coal ash arise from rock weathering into coal basins or from trace element enrichment of humus formed from the original vegetable matter. Toxic metals, anions and cations can be leached out from an ash heap during rainfall. This caustic (pH>12) leachate contains high concentrations of hydroxides, carbonates and sulphates and precipitates minerals such as Iron oxides and sulphate (Adriano et al.,1980).

Pilot studies indicated that co-disposal of AMD with aqueous extracts of coal ash neutralizes the corrosive waste. Precipitation of alumino-silicates and iron compounds occurred at a pH of 10. Direct mixing of various ratios of simulated AMD and coal ash to a predetermined pH in the co-disposal process enhanced the formation of gypsum and soil components. These secondary aluminosilicate and/or aluminocalcium sulphate (ettringitic) or ferrihydrite ($Fe_2 (SO_4)_3$) precipitates have the capacity for mutual beneficiation of water quality in co-disposed AMD and coal ash (Burgers, 2002). Using this co-disposal method, most metals were removed by approximately 100 % when the pH of minimum solubility of hydroxides was achieved. Sulphate removal was found to be approximately 80 % due to gypsum precipitation.

CONCLUSION

The paper has shown that the overall pyrite reaction series is among the most acid-producing of all weathering processes in nature. In nature, acid generating minerals such as pyrite often occur in close association with acid neutralizing minerals such as calcite and dolomite, and acid produced from pyrite is neutralized, *in situ*, by these minerals. The sulphate most commonly formed is gypsum, which is sparingly soluble in water, and which therefore contributes to elevated sulphate levels in ground and surface waters. It was also stated that AMD is produced if acid producing minerals are far more abundant than acid neutralizing minerals.

Overall, the science and understanding of AMD generation is still developing and there are some mining operations around the world that were developed and operated without the benefit of current knowledge. Thus, this paper has tried to highlight what AMD is, the threats it pauses to the environment as well as the possible management and control methods employed in the mining sector where AMD is a problem. Of particular note was the co-disposal of AMD with Coal Ash. Using this co-disposal method, most metals were removed by approximately 100 % when the pH of minimum solubility of hydroxides was achieved. Sulphate removal was found to be approximately 80 % due to gypsum precipitation. Co-disposal is, therefore a very effective yet cheaper way of managing and controlling AMD and its use must be promoted if ever the environment will be spared or will have at least some breathing space. AMD elimination cannot be achieved as the process is the cyclic and self-propagating due to reaction (2), but management and control only have been shown to be possible from literature.

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