Studies on Environmental Impact of Acid Mine Drainage Generation and its Treatment : An Appraisal

Sangita, G. Udayabhanu and Bably Prasad

Central Institute of Mining and Fuel Research, Environmental Management Group, Barwa Road, Dhanbad – 826 015

Acid mine drainage is the most significant environmental pollution problem associated with mining industry. The main cause of acid mine drainage is the occurrence of pyrite and sulphide minerals with the rock of coal seams. During mining these sulphide minerals get exposed to air and mine water, then oxidation and hydrolysis results in the generation of acid mine drainage. The low pH value of the discharge mine water results in the further dissolution of minerals and release of toxic metals, when it allowed getting discharge into other water bodies. This acidity and high toxic metals concentration are harmful to the vegetation, aquatic life and wild life. This review paper describes the general chemistry of acid mine drainage generation; its impact on environment; different treatment techniques as remedial and control measures and future trend in treatment technology.

KEYWORD

INTRODUCTION

Acid mine drainage (AMD) is an unavoidable byproduct of the mining and mineral industry which is generally characterized by high concentration of dissolved heavy metals, sulphate and low pH as low as 2 and continues to be an important water pollution problem in mining industry around the world (Gazea *et al.,* 1996; Steed *et al.,* 2000; Tsukamoto *et al.,* 2004; Somerest *et al.,* 2005). Although the generation of AMD occurs naturally, mining and processing of metal ores and coals can promote AMD generation through exposing sulphide minerals to both oxygen and water (Johnson and Hallberg, 2005; Akcil and Koldas, 2006). AMD pollutes the receiving streams and aquifers, when it is allowed to discharge without any treatment. Contaminants from mine drainage can persist for a long time after mining has stopped (Modis *et al.,* 1998; Demchark *et al.,* 2004).

AMD also results from outflow of acidic water from outflow of acidic water from thousands of abandoned an abundance of sulphide minerals and microbial activity. These results in high acidity and high dissolved metal concentration in mind drainage which has adverse effects on aquatic ecosystems of the receiving rivers, corrosion of mining machinery and other environmental degradation (Rawat and Singh, 1982; Berghorn and Hunzeke, 2001; Heme *et al.,* 2003; Gaikwad and Gupta, 2008). AMD is not only associated with surface ground water pollution, but also responsible for the degradation of soil quality, aquatic habitats and for leaching of heavy metals in ground water (Alder and Rascher, 2007).

The amount of AMD produced depends on the size of the exposed surface area of sulphide minerals. The concentration of dissolved metal ions in AMD also depends on the type and quantity of sulphide minerals present as well as the host rock composition (Hema *et al.,* 2003; Ziemkiewcz *et al.,* 2003). The AMD problem is severe in metal mining areas, such as Iberian Pyrite Belt in the south west of Spain, the largest sulphide deposits in the world (Olias *et al.,* 2004). In India, the coal mines that face a

Table 1. *Source of acid mine drainage*

Primary source	Secondary source
Mine rock dumps	Treatment sludg pounds
Tailings impoundment	Rock cuts
Underground and open pit mine working	Concentrated load out
Pumped/nature discharge ground water	Stockpiles
Diffuse seeps from replaced overburden in rehabilitated areas	Concentrate spills along roads
Construction rock used in roads, dams, etc.	Emergency ponds

**Table 2.** *Sulphides responsible for acid generation*

Sulphide	Formula
Pyrite	FeS_2
Pyrrhotite	Fe_xS_x
Chalcocite	Cu_2S
Covelite	CuS
Chalcopyrite	$CuFeS_2$
Arsenopyrite	$FeAsS_2$
Molibdenite	MoS_2
Galena	PbS
Millerite	NiS
Sphalerite	ZnS

serious pollution problem due to AMD are Baragolai (ECL); Churcha, West Chirimiri, Ambora and Rkhikol (WCL); Gorbi (NCL) and Margarita group of mines, Assam (NECL) (Rawat *et al.*, 1982; Jama *et al.*, 1991).

In Chandmata colliery of WCL, AMD has been found which has low pH, high sulphate and iron content. AMD problem is also found in Northern Coalfields with low pH, high sulphate, total dissolved solid and iron concentration of the mine water. Tertiary coal of NECL contains as high as 8% sulphur with different percentage of pyrite, sulphate, organic and free sulphur. Acid drainage due to overburden near this coalified is a serious environment problem due to low pH and high sulphate. TDS and iron of mine water (Tewary, 2001).

## CHEMISTRY OF ACID MINE DRAINAGE GENERATION

The weathering of sulphide minerals accounts for most of the surface water and groundwater contamination that result from mining activities. Pyrite, the most ubiquitous sulphide mineral, is principally responsible for acid discharges from underground coal and metal mines, surface mine spoils and tailing disposal areas (Hammack *et al.*, 1988). The oxidation of iron sulphide, pyrite is the primary mechanism by which the acid is released into mine drainage (Banks *et al.*, 1997; Gray, 1997; Akcil and Koldas, 2006; Neculita *et al.*, 2007; Gaikwad and Gupta, 2007; Abbasi *et al.*, 2009). The process in initiated by the breakdown of pyrite in the presence of oxygen and water to yield ferrous iron, sulphate and acidity (Singer and Stumm, 1970).

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe_2 + 2SO_4^{2-} + 2H^+ \quad \text{... (1)}$$
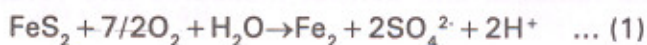
When sufficient oxygen is dissolved in water, the oxidation of ferrous (Fe^{2+}) to ferric (Fe^{3+}) iron occurs, in the next step. This step is referred to as rate determining step for the over all sequence (Singer and Stumm, 1970). This reaction is greatly accelerated by a species of bacteria, thiobacillus ferrooxidans.

$$Fe^{2+} + 1/4O_2 + H^+ + Fe^{3+} + 1/2H_2O \quad \text{... (2)}$$
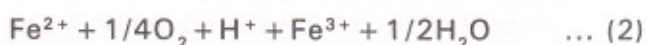
The third step involves hydrolysis of ferric iron to produce the solid ferric hydroxide and the release of additional acidity. This step is pH dependent. With pH less than 3.5, the solid mineral does not form and ferric iron remains in solution and when pH is above 3.5 a precipitate of $Fe(OH)_3$ forms which is commonly referred to as 'yellow boy' (Girard and Kaplan, 1967; Nicholson, 1994; Jambor and Blowes, 1998).

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \quad \text{... (3)}$$
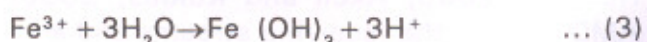
As the acidity increases, the reaction reinitiates because ferric iron remains in solution and is reduced by pyrite, results in the release of ferrous iron and acidity.

$$FeS_2 + 14Fe^{3+} + 8H_2O \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \quad \text{... (3)}$$
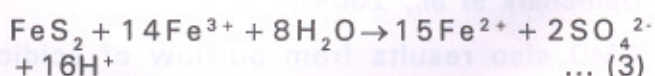
This cyclic propagation of acid generation by ferric iron takes place very rapidly and continues until the supply of ferric iron of pyrite is exhausted. The overall sequence of reactions is acid producing :
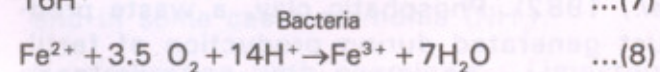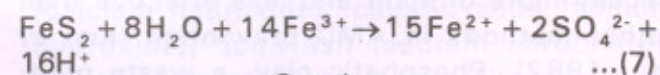
$$4FeS_2 + 15O_2 + 14H_2O \rightarrow 4Fe(OH)_3 + 8H_2SO_4 \dots (5)$$
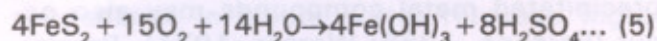
Pyrite + Oxygen + Water → 'Yellow boy' + Sulphuric acid
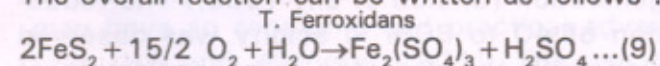
ROLE OF BACTERIA IN ACID MINE DRAINAGE GENERATION

Interaction of bacteria with sulphide minerals is a significant factor in the formation of AMD. Thiobacillus ferroxidas and thiobacillus thiooxidans ubiquitously present in sulphide mineral bearing ore deposits, mine tailings and abandoned mines, plays an important role in acid production due to its ability to rapidly oxidize reduced forms of iron and sulphur which can results in the generation of sulphuric acid (Bruynesteyn and Hackl, 1982; Nyavour et al., 1996; Natarajan, 2008). The bio-oxidation of sulphide minerals is explained by direct and indirect mechanism (Phillip, 1998; Zeballos, 2001; Zumaran Farfan, 2003). The direct mechanism occurs due to direct contact between bacteria and sulphide minerals by the following reaction:

$$\overset{Bacteria}{FeS_2 + H_2O + 7/2\ O_2 \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+} \dots (6)$$
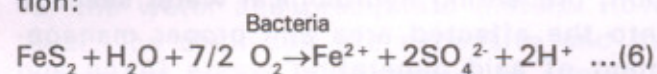
The indirect mechanism takes place by the action of ferric iron produced by bacterial oxidation by the following reaction :

$$FeS_2 + 8H_2O + 14Fe^{3+} \rightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \dots (7)$$

$$\overset{Bacteria}{Fe^{2+} + 3.5\ O_2 + 14H^+ \rightarrow Fe^{3+} + 7H_2O} \dots (8)$$

The overall reaction can be written as follows :

$$\overset{T.\ Ferroxidans}{2FeS_2 + 15/2\ O_2 + H_2O \rightarrow Fe_2(SO_4)_3 + H_2SO_4} \dots (9)$$

A study was done any Nyavor et al. (1996) to determine which of these two mechanisms plays a dominant role during AMD formation. The result shows that the direct mechanism of pyrite oxidation is insignificant and the predominant pathway involves the indirect bacterial oxidation of available Fe^{2+} to Fe^{3+}, which in turn oxidizes FeS_2 to

generate further Fe^{2+} and acidity in a cyclic process. At pH above 4.5, thiobacillus ferroxidans increases initial acidification; below pH 4.5, it allows acidification to continue by oxidizing Fe^{2+}. Below a pH of approximately 2.5, the activity of Fe^{3+} is significant and results in steady state cycling between oxidation of pyrite of Fe^{3+} and bacterial oxidation of Fe^{2+} (Kleinmann et al., 1981). These acidophilic bacteria derive energy for its metabolic processes from the oxidation of reduced sulphur and iron compounds and utilizes CO_2 as a carbon source (Banks et al., 1997). Thiobacillus ferroxidans and thiobacillus thiooxidans both tolerate very well the acidity of the medium and remain effective in the pH range from 0.5 to 4.5 (Clair et al., 1994; Could, 1996; Phillip et al., 1998; Bowel et al., 2000). Thiobacillus ferroxidans has been shown to increase the iron conversion reaction rate by a factor of hundreds to as much as one millions times (Singer and Stumm, 1970; Nordstrom, 1979; Brown et al., 2002).

SOURCES AND FACTORS FOR ACID MINE DRAINAGE GENERATION

The mineral and mining industries produces two sources of AMD generation, primary and secondary sources which is given in table 1 (Akcil and Koldas, 2006; Natarajan, 2008). Factors enhancing AMD can be many but the major once are moisture content in atmosphere, presence of oxidants, pH levels, temperature, chemical activity of ferric iron, surface area of exposed sulphide mineral, chemical activation energy required to initiate acid generation and biological activity. The sulphides which are responsible for AMD generation are associate with several valuable minerals in varied combinations (Skousen, 1995). Some sulphides involved in the formation of acidic drainage under oxidizing conditions are given in table 2 (Souza, 1995; Gray, 1997).

ENVIRONMENTAL EFFECTS OF ACID MINE DRAINAGE

AMD is a unique pollutant because acid generation and discharge continue to occur

even after the mining is ceased. As a result of this acidity it is unsuitable for the use of animals, plants, mankind and aquatic life (Riley et al., 1972). The problem of AMD is not restricted to the local area at the source, but may extend to distances if the acid water is allowed to get discharged into the main water stream (Jamal et al., 1997). AMD impacts more frequently on the quality of ground water than that of surface water. If acid producing mines located in permeable formation, water with low pH percolates into the aquifers and gets spread over a wide area through ground water movement which is ultimately consumed in different ways by human being through wells and bore wells (Lottermoser, 2003). The acidic and ferruginous water are not only responsible for the corrosion of mine plant and equipment and formation of scales in the delivery pipe range, but also pollution of the mine surface environment, thus affecting the surface ecology (Atkins and Singh, 1982).

AMD causes serious threat to human health and ecological systems because it contains heavy metal contaminant which is not biodegradable and thus tends to accumulate in living organisms causing various diseases and disorders (Moreno et al., 2001; Bailey et al., 1999; Carlson et al., 2002). Low pH of mine drainage results in solubility of heavy metals in water and its high concentration causes toxicological effects on aquatic ecosystems. Acute exposure of high concentration of metals can kill organisms directly, while long term exposure to lower can cause mortality or other effects, such as stunted growth, lower reproduction rates, deformities and lesions (Lewis and Clark, 1996).

AMD also has direct effects on fish by causing various physiological disturbances. High acidity may adversely affect fish growth rates and reproduction (Kimmel, 1983). The primary cause of fish death in acid water is loss of sodium ions from the blood. Less availability of oxygen to the cells and tissues leads to anoxia and death as acid water increases the permeability of fish gills to water, adversely affecting the gills func-

tion (Brown and Sadler, 1989). Besides chemical effects of mine drainage, physical effects, such as increased turbidity from soil erosion, accumulation of coal fines and smothering of the stream substrate from precipitated metal compounds may also occur (Parsons, 1968; Warner, 1971). Precipitation of ferric hydroxide may results in a complete layering of the stream bottom, filling in crevices in rocks and making the substrate unstable and unfit for habitation by benthic organisms (Hoehn and Sizemore, 1977). Trace metals, such as zinc, cadmium and copper which may also be present in mine drainage are toxic at extremely two concentrations.

CONTROL OF ACID MINE DRAINAGE GENERATION

AMD generation can be prevented by checking chemical reaction that generate acid and microbial reaction that catalyze the above process. As water is considered as basic transport medium for contaminants, therefore, AMD migration can be controlled by managing the flow of water, diverting the surface water flowing towards the site of pollution, preventing groundwater infiltration, preventing hydrological water seepage into the affected area and proper management of acid generating waste (Akcil and Koldas, 2006). Flooding can also prevent AMD as this method eliminates oxygen and severely curtail acid generation but is technically more difficult and less effective than other methods in AMD prevention (Kim et al., 1982). Phosphatic clay, a waste product generated during production of fertilizer was used to prevent or reduce AMD generation (Chaido et al., 1988). The reduction of 40 to 80% in acidity was observed alongwith the decrease in concentration of Fe, Mn, Mg, Al and sulphate. Anionic surfactant was used by Erickson et al. (1985, 1986), to control the activity of thiobacillus ferroxidants that accelerates pyrite oxidation. Organic compounds, like benzoic acid, sorbic acid and sodium lauryl sulphate was found to be an effective anionic surfactant to inhibit the bacterial oxidation (Dugan and

Apel, 1983; Olem *et al.,* 1983; Kleinmann, 1981, 1982, 1983; Onysko, 1985). In another study rock phosphate was used as a pyrite oxidation inhibitor (Renton *et al.,* 1988; Meek, 1991). Dissolution of rock phospahte in acidic water releases highly reactive phosphate ions which combine with iron to form insoluble iron phosphates that inhibit the cyclic reaction or iron and pyrite.

## DIFFERENT TREATMENT TECHNIQUES FOR ACID MINE DRAINAGE

Over the past 20 year a variety of treatment systems have been developed. To reduce the concentrations of dissolved metals and acidity, AMD is treated with alkaline chemicals by most mining operations and the precipitated metals are collected in settling ponds (Hedin *et al.,* 1997; Ziemkiewicz *et al.,* 1997). Chemicals treatment is expensive and may be necessary long after mining has ceased. The two extensively used methodologies to treat AMD are :

Active treatment

Active treatment involves addition of chemicals to the source of AMD and the stream contaminated by AMD, which raise the pH of the water and precipitate metals. However, the chemicals are expensive and the treatment facility is expensive to construct and operate (Skousen *et al.,* 1990). The chemicals used for active treatments are limestone (calcium carbonate); hydrated lime (calcium hydroxide); caustic soda (sodium hydroxide); soda ash (sodium carbonate); and in some cases ammonia (NH_3).

Neutralization with chemicals : Limestone is normally use for treatment of AMD and may have an economic and practical advantage (Hill and Wilmote, 1971). The use of limestone for treating AMD has been studied by a number of researches (Mihok and Duel, 1968; Hill and Wilmote, 1972; Ford, 1976; Geidel and Caruccio, 1984; Maree *et al.,* 1992; Webb and Sasowsky, 1994; Maree *et al.,* 1996). Limestone (calcium carbonate) increases the pH of water by consuming hydrogen ions and adding alkalinity through bicarbonate ions (Younger *et al.,* 2002). As the pH of the acidic water raised metals can precipitate to form hydroxides and oxyhydroxides.

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + H_2O + CO_2 \qquad ... (10)$$
$$CaCO_3 + H_2CO_3 \rightarrow Ca^{2+} + 2HCO_3^- \qquad ... (11)$$
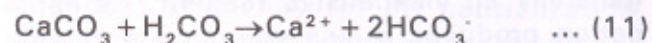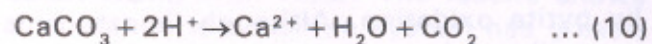
Neutralization occur both through dissolution of the limestone and exsolution of carbon dioxide from the water. Demonstration of these processes in a natural system is provided by the East Fork of the Obey river, where acidic mine water travel through conduits in lime stone bedrock for several kilometer (Webb and Sasowsky, 1994). Us Bureau of mines developed a method for neutralization of AMD. IN this process mine water is mixed with very fine limestone slurry followed by aeration of the resulting mixture to remove CO_2 and precipitate iron, separate solids from liquid by sedimentation (Mihok and Duel, 1968). Maree *et al.* (1996) has been developed a fluidized-bed limestone neutralization process to neutralize free acid and remove Fe (II) from underground acid mine water. McDonald *et al.* (1976) observed using limestone and lime, separately and in commination on AMD treatment that lime treatment in a series flow eliminated upto 85% of the metal cations in the plant influent. A major West Virgina river, affected by AMD, was treated by instream applications of limestone sand (Zurbuch *et al.,* 1997). Menedez *et al.* (2000) used sand sized limestone aggregate as a neutralizing agent for treatment of streams impacted by AMD which results in significant reduction of acidity of the stream. An integrated iron oxidation and limestone neutralization process can be used to simultaneously remove acidity, iron, aluminium (to less than 2 mg/L) and sulphate (to a level of 2,500 mg/L) (Maree *et al.,* 1994). For water containing 3 g/L Fe (II), a reaction time of 2 hr was required when the process was operated in a sequencing batch mode; 5 hr was required when it is operated on a continuous basis. A surface application of limestone for controlling acid mine discharges from abandoned strip mines, Sewellsville, Ohio was studied (Geidel, 1983). Both field

and laboratory experiments shows that the amount of alkalinity generated by surface application of limestone is not sufficient to reduce the ground water acidity generated by pyrite oxidation. Although limestone is generally an inexpensive reagent, its application produces a less voluminous sludge; it is not widely used because carbon dioxide buffers the reaction, therefore, making it difficult to raise the pH above 6 (Akcil and Koldas, 2006). Limestone is also inefficient for AMD with acidity levels greater than 50 mg/L as $CaCO_3$ or Fe concentrations above 5 mg/L because of armoring (Skousen et al., 1995).

Other active treatment methods : Along with chemical neutralization of AMD other treatment methods are also used, such as ion exchange, reverse osmosis, electrodialysis and electrolytic recovery but these are expensive and not commonly used (Prasad et al., 1999).

The reverse osmosis separation behaviour of Ca, Mg, Zn, Mn, Cu, Al and Fe as nitrate, chloride and sulphate salts from acid mine water was studies (Sastri, 1979). The results showed that 95 to 99% separation of metal ions along with the recovery of product water of suitable quality for use in recycle operations. A pilot plant treatment of AMD by reverse osmosis was studied (Blackshaw et al., 1974). This study was reviewed in 1975 by Blackshaw and Pappano showing the technical and economical feasibility of using reverse osmosis as a unit operation for treatment and purification of AMD. Ultra-low-pressure reverse osmosis (ULPRO) and nanofiltration (NF) membranes was used for treatment of AMD (Zhong et al., 2007). In this study, the rejections of heavy metal and total conductivity was found greater than 97 and 96% for the ULPROM tested, suggested the suitability of such membrane for AMD treatment.

Anon (1971) was used an ion exchange method for producing potable water from surface drainage contaminated by AMD. The removal of heavy metal ions from the AMD of South African gold mine by precipitation with lime followed by ion exchange was investigated by Feng et al. (2000).

Passive treatment

A variety of passive treatment systems have received much attention lately and the literature offers extensive studies related to these systems (Ziemkiewicz et al., 2003). This method use chemical and biological reactions occurred naturally to decrease metal concentrations and neutralize acidity. It generally requires more land areas, but less costly reagents and less operational attention and maintenance (Hedin et al., 1993). Primary passive treatment methods used for AMD mitigation are (Champagne et al., 2005; Ziemkiewicz et al., 2005) :

Aerobic wetlands : Aerobic wetlands promote mixed oxidation and hydrolysis reactions and are most effective when the raw mine water in net alkaline. A studies shows that constructed wetlands with cattails and other marsh plants can efficiently and inexpensively treat discharge of acid mine water. Wetland plants remove metals from acid water by adsorption (especially ion exchange); consumption (plant uptake) and simple filtration (Chirons, 1987). Constructed wetlands with a different organic substrate (Sphagnum peat with limestone and fertilizer, Sphagnum peat, sawdust, straw-manure or mushroom compost) were used by Wieder (1993) to controlled inputs of AMD. The results show that the Sphagnum peat wetland has least contaminant removal capacity than straw/manure and mushroom compost wetlands. Iron uptake by Sphagnum plants can play only a relatively minor role in iron retention in wetland constructed for AMD treatment (Spratt et al., 1988). Constructed wetlands with Typha cattail results in the removal of less than 1% of the total iron added to the wetlands by mine drainage (Sencindiver and Bhumbla, 1988). Adsorption of metals by organic material, such as peats decreased total suspended solids from 32 to 12 mg/L (63%), Fe from 32 to 5 mg/L (84%) and Mn from 15 to 14 mg/L (7%), but ultimately all adsorption sites on substrate materials are

exhausted by continual introduction of metals in acid water (Brodie *et al.*, 1988).

US Bureau of Mines has investigated the feasibility of a Sphagnum moss bog as a self-perpetuating treatment system. It removes iron by cation exchange, oxidation of Fe^{2+} and precipitation of iron hydroxides and sulphides. A potable bog/limestone system was constructed near an acid stream in the Zaleski State Forest in south-eastern Ohio. It reduces ferrous iron by as much as 99%, total iron by as much as 90%. The Sphagnum moss tolerated pH as low as 2.3 (Kleinmann, 1984).

Anaerobic wetlands : Organic compost wetlands promote anaerobic bacterial activity that results in the precipitation of metal sulphides and the generation of bicarbonate alkalinity (Hedin *et al.*, 1993). Tuttle *et al.* (1969) was the first to suggest the use of sulphate reducing bacteria (SRB) for treatment of AMD. SRB convert sulphate to sulphide using an organic carbon source as an electron donar, as a result of this process acetate and bicarbonate ion are also produced. The soluble sulphide reacts with the dissolved metals of AMD to form insoluble metal sulphides, (equation 13) and the bicarbonate ions increase the pH and alkalinity of the water, (equation 12) (Hammack *et al.*, 1994; Widdel, 1988; Zaluski *et al.*, 2000). The reaction is generally expressed as :

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \qquad \dots (12)$$

$$H_2S + M^{+2} \rightarrow MS + 2H \qquad \dots (13)$$
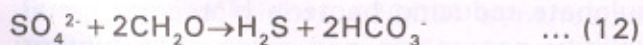
SRB use the easily degradable organic matter, such as low molecular weight compounds with simple structure, like lactose (Costa *et al.*, 2005), acetic acid (Steed *et al.*, 2000) and whey (Christensen *et al.*, 1996; Drury, 1999). A pilot-scale anaerobic bioreactor utilizing a mixture of horse manure and sand as substrate removed < 10% of the influent sulphate and iron by the end of the second year (Tsukamoto and Miller, 1999). Two anaerobic solid-substrate reactors were run parallel in an experiment. One reactor was filled with cow manure and saw

dust. The second reactor also filled with these solids and cheese whey continuously added along with AMD. The results shows that with whey addition system has greater treatment efficiency for pH neutralization, alkalinity production and sulphate, Fe, Zn and Mn removal then without whey addition (Drury, 1999). The ability to reduce dissolved metal concentration and neutralize AMD acidity makes SRB useful catalysts in treating AMD and other metal contaminated materials (Steed *et al.*, 2000).

In an experimental constructed wetland in the Idoha springs-central city mining district of Colorado, metal removal from AMD was studies. This study suggested that the adsorption of metals varies with the fluctuation of pH in the outflow water. It also indicated that the microbial reduction of sulphate with a corresponding increase in the sulphide concentration of the water (Machemer and Wildeman, 1992). A significant retention of ferric hydroxides in surface sediments of anaerobic wetlands was studied (Wieder, 1993).

Open limestone channel : Open limestone channel (OLC) consists of open channels or ditches lined with limestone. When the acid mine drainage flows over the limestone, dissolution of the limestone adds alkalinity to the water and raises pH (Ziemkiewicz *et al.*, 1994). Armoring of the limestone with Fe hydroxides decreases limestone dissolution by 20 to 50%, so longer channels and more limestone is required for acid water treatment. In a series of laboratory experiments it shows that armored limestone was 50 to 90% as effective as unarmored limestone in neutralizing acid (Ziemkiewicz *et al.*, 1997). Seven open limestone channels in the field reduced acidity in AMD by 4 to 205 mg/L as $CaCO_3$, at rates of 0.03 to 19 mg/L per meter of channel length. The highest removal rates were with channels on slope of 45 to 60% and for AMD with acidity of 500 to 2600 mg/L as $CaCO_3$. In another study three OLCs results in 60% removal of acidity and 66% decrease in Fe (Ziemkiewicz and Brant, 1996).

Anoxic limestone drains : ALDs are abiotic systems consisting of buried limestone bed that passively generate bicarbonate alkalinity and can be useful for the pretreatment of mine water before it flows into a wetland (Hedin *et al.*, 1993). ALDs were first described by Turner and McCoy (1990) and Brodie *et al.* (1990) found that ALDs helped pre-treat acid water for wetlands. Success and failure among 11 ALDs treating mine water in WV was reported by Faulkner and Skousen (1995). In all cases, pH was raised after ALD treatment, but three of the sites had pH values < 5.0, indicating that the ALDs were not fully functioning or that the acid concentrations and retention times were too low for effective treatment. Acidity of water in these drains, varying from 170-2200 mg/L, decreased 50-80%, but Fe and Al concentrations in the outflow also decreased, indicating that Fe^{3+} and Al^{3+} hydroxides were precipitating inside the drains. Mine drainage containing appreciable Al^{3+} contents are also not suitable for ALDs treatment. Watzlaf *et al.* (2000) studies showed that ALDs which received 21 mg/L Al failed within 8 month of operation. The aluminium will precipitate as hydroxide, causing clogging of limestone pores, plugging of the drain and armoring of the carbonates with aluminium precipitates (Demchak *et al.*, 2001). The effectiveness of an ALDs as a passive treatment method depends on influent water quality and works most efficiently when influent waters have moderate to low dissolved oxygen contents (< 2 mg/L), low ferric/ferrous irons ratios, less dissolved aluminium concentrations (< 25 mg/L) and sulphate concentrations less than 2,000 mg/L (Skousen, 1991; Brodie *et al.*, 1993; Hedin and Watzlaf, 1994; Ziemkiewicz *et al.*, 1994).

Rotting, *et al.* (2008) was used a dispersed alkaline substrate (DAS) composed of fine grained calcite grain mixed with a coarse inert matrix (wood chips). Chemical and hydraulic performance results in removal of 900 to 1600 mg/L acidity, 3 to 4.5 times more than conventional passive treatment system. Al, Fe III, Pb and Cu were almost completely eliminated. High acidity removal is possible because metals accumulate intentionally in DAS and their precipitation promotes further calcite dissolution. The large pores of the inert DAS matrix and the dispersion (separation) of the calcite grains reduce clogging problems.

Successive alkalinity producing systems : Successive alkalinity producing systems (SAPS) combine the use of an ALD and an organic substrate into one system (Kepler and McCleary, 1997). Oxygenated water is pre-treated by organic substrate removing O_2 and Fe^{+3}, and then the anoxic water flows through and ALD at the base of the system. Kepler and McCleary (1997) use SAPs method for AMD treatment in OH, PA and WV. In this process, Al in AMD precipitated allows to be flushed from the pipes thereby maintaining hydraulic conductivity through the limestone and pipes. It results in increased the pH from 2.8 to 6.5, changed the water from a net acid water (925 mg/L as $CaCO_3$) to a net alkaline water (150 mg/L as $CaCO_3$), Fe from 40 to 35 mg/L and Al from 140 to < 1 mg/L.

A vertical-low combined passive system, consisting of four components with specific treatment functions : An oxidation/precipitation basin for excess Fe removal; a peat biofilter for the bio-sorption of heavy metals and the establishment of anoxic conditions through aerobic biological activity; a sulphate reducing bacteria bioreacter for alkalinity generation and sulphate reduction; and an anoxic limestone drain for alkalinity addition was developed by Champagne, *et al.* (2005) for the mitigation of AMD. Its removal efficiency was above 98% for Fe, Al, Zn, Mn, Ni and Cu. Sulphate concentrations were also reduced to 948 mg/L.. The pH of the effluent was neutralized of 7.0 and a net alkalinity of 1340 mg/L (as $CaCO_3$).

RECENT AND FUTURE TREND IN ACID MINE DRAINAGE TREATMENT,

AMD treatment is presently done by active treatment (where chemicals are added to the AMD) and by passive treatment (where AMD

allows to passed through wetlands). Limestone is widely used for neutralization of acid mine water in the active treatment. The disadvantage of using limestone is :

(1) Limestone is ineffective with high ferrous iron water.

(2) Lower reactivity necessitates longer detention time. Large tanks are required.

(3) Reaction is not very sensitive, thus the neutralizations is extremely inefficient.

(4) It is difficult to get a pH higher than 5.5 with limestone due to buffering effect.'

(5) The use of large oxidation and reaction vessels and increased power requirements render the limestone treatment unfeasible for AMD water containing over 50 mg/L of ferrous iron.

(6) Loss in efficiency of the system because of coating of the limestone particles with iron precipitates.

To overcome the disadvantages of limestone in active treatment, the use of flyash zeolite as an adsorbent has gained interest because its adsorption properties provide a combination of iron exchange and molecular sieve properties. Natural zeolite, such as Clinoptilolite has been used by Li *et al.* (2008) and Motsi *et al.* (2009) for treatment of acidic water and results showed that it has great potential to effectively remove heavy metals from AMD. Moreno *et al.* (2001) and Fungaro and Izidoro (2006) synthesized zeolitic material from coal flyash and application of zeolitic product for decontamination of waters from AMD was evaluated. The results showed that flyash zeolite increases the pH of AMD and decrease metal concentration due to cation exchange or solid precipitation. Active treatment of AMD with application of flyash zeolite will have many advantages over limestone treatment. Flyash is produced in huge amount in thermal power plants and hardly about 20% of it is utilized in different utilization sector. Rest of the flyash is disposed off to low lying area with high environmental risk. Therefore, the problem of flyash can be re-duced by preparing zeolite from flyash and it has been found as an effective material for treatment of AMD.

CONCLUSION

Acid mine drainage is presently one of the most severe environmental pollution problem associated with mining activities. AMD is generated from active underground and open cast coal mines containing pyrite mineral. It is also generated from abandoned mines and heaps containing pyrite. The discharge of acid mine water causes direct severe impact on water environment and indirectly on human health. There are many treatment techniques as remedial measures for AMD. Active and passive treatments are mainly done to improve the water quality of AMD. Limestone is mainly used for active treatment of AMD, which has got many disadvantages. To do better active treatemnt of AMD, utilization of low cost material; like flyash zeolite which is prepared from waste flyash will be found to be an excellent material to treat AMD.

ACKNOWLEDGEMENT

REFERENCE

Abbassi, R., F. Khan and K. Hawboldt. 2009. Prediction of minerals producing acid mine drainage using a computer assisted thermodynamic chemical equilibrium model. *Mine Water Env.,* 28:74-78.

Akcil, A. and K. Koldas. 2006. Acid mine drainage (AMD) : Causes, treatment and case studies. *J. Cleaner Production.* 14:1139-1145.

Adler, R. and J. Rascher. 2007. A strategy for the management of acid mine drainage from gold mines in gauteng. Report no. CSIR/NRE/PW/ER/2007/0053/C.CSIR, Pretoria.

Anon. 1971. Acid mine drainage converted to potable water. *Coal Mining Process.* 8 (3):38-42.

Atkins, A.S. and R.N. Singh. 1982. A study of acid and ferruginous mine water in coal mining operations. *Int. J. Mine Water.* 2:37-57.

Banks, D., *et al.* 1997. Mine water chemistry : The good, the bad and the ugly. *Env. Geology.* 32:157-174.

Bailey, S.E., *et al.* 1999. A review of potentially low cost sorbents for heavy metals. *Water Res.,* 33 (11):2469-2479.

Berghorn, G.H. and G.R. Hunzeker. 2001. Passive treatment alternatives for remediation abandonedmine drainage. John Willy and Sons, New York. pp 111-127.

Bruynesteyn, A. and R.P. Hackl. 1982. Evaluation of acid production potential of mining waste materials. *Miner. Env.,* 4 (1):5-8.

Bowel, R.J. S.B. Rees and J.V. Parshely. 2000. Geochemical prediction of metal leaching and acid generation : Geologic controls and baseline assessment. Geology and Ore, Great Basin and Beyond Processing, 2. pp 799-822.

Brown, D.J.A. and K. Sadler. 1989. Fish survival in acid water. In Acid toxicity and aquatic animals. Society for Experimental Biology Seminar series : 34. Cambridge University Press. pp 31-44.

Brown, M., B. Barley and H. Wood. 2002. Mine water treatment. In The mine water problem. Ed M. Brwon, B. Barley and H. Wood. IWA Pub., Alliance House, London. pp 1-31.

Blackshow, L.G., A.W. Pappano and V.S. Arakali. 1974. Pilot plant treatment of AMD by reverse osmosis based techniques. Symp. on Coal mine drain res., 5th Coal and the Env. Tech. Conf., Louisville, Ky. Proceedings, pp 312-330.

Blackshow, L.G. and A.W. Pappano. 1975. Potable water from acid mine drainage by reverse osmosis. 5th Env. Eng. and Sci. Conf., Louisville, Ky. Proceedings, pp 559, 561-571.

Brodie, G.A., D.A. Hammer and D.A. Tomjanovich. 1988. An evaluation of substrate types in constructed wetlands acid drainage treatment systems. In Mine drainage and surface mine reclamation (vol 1). Info. Circular 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 389-398.

Brodie, G.A., *et al.* 1990. Passive anoxic limestone drains to increase effectiveness of wetlands acid drainage treatment systems. 12th Natl. AML Conf., Breckinridge, CO.

Brodie, G.A., *et al.* 1993. Anoxic limestone drains to enhance performance of aerobic acid drainage treatment wetlands : Experiecnces of the Tennessee Valley Authority. In Constructed wetlands for water quality improvement. Ed G.A. Moshiri. Lewis Publishers/CRC Press, Boca Raton, FL. pp 129-138.

Clair, N.S., *et al.* 1994. Chemical environmental engineering. Mc Graw-Hill, Incorreto.

Carlson, L., *et al.* 2002. Scavenging of As from acid mine drainage by schwertmannite and ferrihydrite: A comparison with synthetic analogues. *Env. Sci. Tech.,* 36:1712-1719.

Chironis, N.P. 1987. Mine-built ponds economically clear acid mine waters. *Coal Age.* 92 (1) : 58-61.

Chiado, E.D., J.J. Bowders and J.C. Sencindiver. 1988. Phosphatic clay slurries for reducing acid mine drainage from reclaimed mine sites. In Mine drainage and surface mine reclamation (vol 1). Info. Circular No. 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 44-51.

Christensen, B., M. Laake and T. Lien. 1996. Treatment of acid mine water by sulphate reducing bacteria; results from a bench scale experiment. *Water Res.,* 30:1617-1624.

Costa, M.C. and J.C. Durate. 2005. Bioremediation of acid mine drainage using acidic soil and organic wastes for promoting sulphate-reducing bacteria activity on a column reactor. *Water, Air, Soil Poll.,* 165:325-345.

Demchak, J., T. Morrow and J. Skousen. 2001. Treatment of acid mine drainage by four vertical flow wetlands in Pennsylvania. *Geochem. Explore. Env.,* Anal 1 : 71-80.

Demchak, J., J. Skousen and L.M. McDonald. 2004. Longevity of acid discharges from underground mines located above the

regional water table. *J. Env. Qual.*, 33:656-668.

Dugan, P.R. and W.A. Apel. 1983. Bacteria and acid drainage from coal refuse: Inhibition by sodium lauryl sulphate and sodium benzoate. *Appl. Env. Mircobiol.*, 46(1):279-282.

Drury, W.J. 1999. Treatment of acid mine drainage with anaerobic solid-substrate reactors. *Water Env. Res.*, 71 (6):1244-1250.

Erickson, P.M. and K.J. Ladwig. 1985. Chemical inhibition of acid mine drainage formation. Surface mining and water quality. West Verginia, USA. pp 11.

Erickson, P.M., *et al.* 1984. Reclamation and the control of acid mine drainage. Symposium on the reclamation, treatment and utilization of coal mining wastes. Durham, UK. Proceedings, pp 1-30.

Feng, D., C. Aldrich and H. Tan. 2000. Treatment of acid mine drainage by use of heavy metal precipitation and ion exchange. *Minerals Eng.*, 13 (6): 623-642.

Faulkner, B.B. and J.G. Skousen. 1995. Effects of land reclamation and passive treatment systems on improving water quality. *Green Lands.* 25(4):34-40.

Ford, C.T. 1974. Use of limestone in AMD treatment. Coal mine drain res., 5th Coal and the env. tech. Conf., Louisville, Ky. Proceedings, pp 205-228.

Fungaro, D.A. and J.D.C. Izidoro. 2006. Remediation of acid mine drainage using zeolites synthesized from coal flyash. *Quim. Nova.* 29(4):735-740.

Gazea, B., K. Adam and A. Kontopoulos. 1996. Review of passive systems for the treatment of acid mine drainage. *Minerals Eng.*, 9(1):23-42.

Gaikwad, R.W. and D.V. Gupta. 2007. Acid mine drainage (AMD) management. *J. Ind. Poll. Cont.*, 23(2):285-297.

Gaikwad, R.W. and D.V. Gupta. 2008. Review on removal of heavy metals from acid mine drainage. *Applied Ecology Env. Res.*, 6 (3):81-98.

Gray, F.N. 1997. Environmental impact and remediation of acid mine drainage : A management problem. *Env. Geology.* 30($^1/_2$):62-71.

Gray, F.N. 1998. Acid mine drainage composition and the implications for its impact on logic system. *Water Resour.*, 32(7):2122-2134.

Gould, W.D. 1996. The role of microbiology in the prevention and treatment of acid mine drainage. Workshop, CANMET/CETEM, Mining and environment. Proceedings, pp 68-77.

Geidel, G. and F.T. Caruccio. 1984. Evaluation of a surface application of limestone for controlling acid mine draingaes from abandoned strip mines. Sewellsville, Ohio. Final report. PB-84-148535 : 185.

Girard, L. and R. Kaplan. 1967. 'Operation yellow boy' treatment of acid mine drainge. *Coal Age.* 72(1):72-74.

Hammack, R.W., R.W. Lai and J.R. Diehl. 1988. Methods for determining fundamental chemical differences between iron disulphide from different geologic provenances. **In** Mine drainage and surface mine reclamation (vol 1). Info. Circular no. 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 136-146.

Hammack, R.W., H.M. Edenborn and D.H. Dvorak. 1994. Treatment of water from an open-pit copper mine using biogenic sulphide and limestone : A feasibility study. *Water Resour.,* 28:2321.

Hoehn, R.C. and D.R. Sizemore. 1977. Acid mine drainage (AMD) and its impact on a small Virgina stream *Water Resour. Bulletin.* 13:153-160.

Hedin, R.S., R.W. Nairn and R.L.P. Kleinmann. 1994. Passive treatment of coal mine drainage. US Bureau of Mines IC 9389, Washington, DC. pp 35.

Hill, R.D. and R.C. Wilmote. 1971. Limestone treatment of acid mine drainage. *Trans. Soc. Mining Eng., AIME.* 250 (2):162-166.

Hedin, R.S., R.W. Nairn and R.L.P. Kleinmann. 1993. Passive treatment of coal mine drainage. Information circular/1994. Report no. Pb-94-173341/XAB. Bureau of Mines, Pittsburgh, PA. 43.

Hedin, R.S. and G.R. Watzlaf. 1994. The effects of anoxic limestone drains on mine drainage Conference and the Third International Conference on the Abatement of acidic drainage. Pittsburgh, PA. U.S. Bureau of Mines special publications SP-06A-

94. pp 185-194.

Jamal, A., B.B. Dhar and S. Ratan. 1991. Acid mine drainage control in an open cast coal mine. *Mine Water Env.,* 10:1-16.

Jambor, J.L. and D.W. Blowes. 1998. Theory and applications of mineralogy in environmental studies of sulphide bearing mine wastes. Environmental Mineralogy, Mineral Association of Canada. Short course. Vol. 27. Ottawa, Ontario. pp 367-401.

Johnson, D.B. and K.B. Hallberg. 2005. Acid mine drainage remediation options : A review. *Sci. Total Env.,* 338 (1-2) : 3-14.

Kim, A., *et al.* 1982. Acid mine drainage : Control and abatement research. U.S. Bureau of Mines. Information circular 8905.

Kimmel, W.G. 1983. The impact of acid mine drainage on the stream ecosystem. **In** Pennsylvania coal, resources, technology and utilization. **Ed** S.K. Majunder and W.W. Miller. The Pa. Acad. Sci. Publ., pp 424-427.

Kepler, D.A. and E.C. McCleary. 1997. Passive aluminum treatment successes. Eighteenth West Virginia Surface mine drainage task force Symposium. Morgantown, WV.

Kleinmann, R.L.P., D.A. Crerar and R.R. Pacelli. 1981. Biogeochemistry of acid mine drainage and a method to control acid formation. *Min. Eng.,* 33(3):300-305.

Kleinmann, R.L.P. and P.M. Erickson. 1982. Control of acid mine drainage using anionic surfactants. First International Mine water Congress. Budapest, Hungary. Proceedings, pp 51-64.

Kleinmann, R.L.P. and P.M. Erickson. 1983. Control of acid mine driange from coal refuse using anionic surfactants. Report of investigations/1983. Bureau of Mines, Pittsburgh, PA (USA). PB-84-141076 BM-RI-8847. pp 22.

Kleinmann, R.L.P., *et al.* 1983. A low cost, low maintenance treatment system for acid mine drainage using sphagnum moss and limestone. Symp. on Surface mining, hydrology, sedimentology, reclamation. Lexington, Ky, USA. UKY-UB-133. Proceedings, pp 241-245.

Lewis, M.E. and M.L. Clark. 1996. How does stream flow affect metals in the upper Arkansas river ? US Geological Survey Fact Sheet. pp. 226-296.

Li, L.Y., *et al.* 2008. Treatment of acid rock drainage by clinoptilolite-Adsorptivity and structural stability for different pH environments. *Applied Clay Sci.,* 39(1-2):1-9.

Lottermoser, B.G. 2003. Mine wastes, characterization, treatment and environmental impacts. Springer, Verlag, Germany. pp 122-140.

Machemer, S.D. and T.R. Wildeman. 1992. Adsorption compared with sulphide precipitation as metal removal processes from acid mine drainage in a constructed wetland. *J. Contam. Hydrol.,* 9(1-2):115-131.

Menendez, R., *et al.* 2000. Sand-sized limestone treatment of streams impacted by acid mine drainage. *Water, Air Soil Poll.,* 124:411-428.

Modis, K., *et al.* 1998. Development and validation of a geostatical model for prediction of acid mine drainage in underground sulphide mines. *J. Trans. Instn. Min. Metall. (Sec A:Min Industry).* A102-A107.

Moreno, N., X. Querol and C. Ayora. 2001. Utilization of zeolites synthesized from coal flyash for the purification of acid mine waters. *Env. Sci. Tech.,* 35:3526-3534.

Maree, J.P. and P. du Plessis. 1994. Neutralization of acid mine water with calcium carbonate. *Water Sci. Tech.,* 29 (9):285-296.

Mihok, E.A. and M. Deul. 1968. Limestone neutralization. Low cost and effective treatment for acid mine waters. *Coal Age.* 73(12):65-70.

Maree, J.P., P. du Plesis and W.C. Vander. 1992. Treatment of acidic effluents with limestone instead of lime. *J. Water Sci. Tech.,* 26 (1-2): 345-355.

Maree, J.P., *et al.* 1996. Pilot scale neutralization of underground mine water. *Water Sci. Tech.,* 34 (10):141-149.

McDonald, D.G., H. Yocum and A.F. Grandt. 1974. Studies of lime-limestone treatment of acid mine drainage. Sypm. on Coal mine drain res., 5th Coal and the environ., Tech. Conf. Louisville, Ky. Proceedings, pp 229-245.

Meek, A. 1991. Assessment of acid preventative techniques at the Island Creek Mining Co., Tenmile Site. Twelfth Annual West

Virginia Surface mine drainage task force Symposium. Morgantown, West Virgina.

Motsi, T., N.A. Rowson and M.J.H. Simmons. 2009. Adsorption of heavy metals from acid mine drainage by natural zeolite. *Int. J. Mineral Processing.* 92 (1-2) : 42-48.

Natarajan, K.A. 2008. Microbial aspects of acid mine drainage and its bioremediation. *Trans. Nonferrous Met. Soc., China.* 18 : 1352-1360.

Neculita, C.M., G.J. Zagury and B. Bussiere. 2007. Passive treatment of acid mine drainage in bioreactors using sulphate reducing bacteria: Critical review and research needs. *J. Env. Qual.,* 36:1-16.

Nicholson, R.V. 1994. Iron sulphide oxidation mechanisms: Laboratory. Short course handbook on geochemistry of sulphide mine-wastes. 22. Mineralogical Association of Canada. pp 163-183.

Nordstrom, D.K. 1979. Aqueous pyrite oxidation and the consequent formation of secondary iron minerals. **In** Acid sulphate weathering. Soil Science Society of America. Special publication no. 10. pp 37-56.

Nyavor, K., N.O. Egiebor and P.M. Fedorak. 1996. Bacteria oxidation of sulphides during acid mine drainage formation : A mechanistic study. EPD Congress 1996. Minerals, Metals and Materials Society, Warrendale, PA, USA. Proceedings, pp 269-287.

Onysko, S.J. R.L.P. Kleinmann and P.M. Erickson. 1984. Ferrous iron oxidation by thiobacillus ferrooxidans : Inhibition with benzoic acid, sorbic acid and sodium lauryl sulphate. *Appl. Env. Microbiol.,* 48 (1):229-231.

Olem, H., T.L. Bell and J.J. Longaker. 1983. Prevention of acid mine drainage from stored coal. *J.Sol. Energy Eng.,* 109 (2) : 103-112.

Olias, M., *et al.* 2004. Seasonal water quality variations in river affected by acid mine drainage : The Odiel river (South West Spain). *Sci. Total Env.,* 333:267-281.

Prasad, D., *et al.* 1999. Evaluating substracts in the biological treatment of acid mine drainage. *Env. Tech.,* 20:449-458.

Parsons, J.D. 1968. The effects of acid strip mine effluents on the ecology of a stream. *Arch. Hydroboil.,* 65:25-50.

Phillip, E., R. Santo and C. David. 1998. Growth of sulphate-reducing bacteria under acidic conditions in an upflow anaerobic bioreactor as a treatment system for acid mine drainage. *Water Resour.,* 32 (12):3724-3730.

Rawat, N.S. and G. Singh. 1982. The role of micro-organisms in the formation of acid mine drainage in the North Eastern Coal Field of India. *Int. J. Mine Water.* 2:29-36.

Renton, J., A.H. Sitller and T.E. Rymer. 1988. The use of phosphate materials as ameliorants for acid mine drainage. **In** Mine drainage and surface mine reclamation (vol 1). Info. Circular no. 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 67-75.

Riley, R.U. and J.A. Rinier. 1972. Reclamation and mine tip damage in Europe. 4th Symposium on coal mine drainage research. Pittsburg, Pa. Proceedings, pp 43-48.

Rotting, T.S. *et al.* 2008. Passive treatment of acid mine drainage with high metal concentrations using dispersed alkaline substrate. *J. Env. Qual.,* 37:1741-1751.

Somerset, V.S., *et al.* 2005. Alkaline hydrothermal zeolites synthesized from high SiO_2 and Al_2O_3 co-disposal flyash filterates. *Fuel.* 84:2324-2329.

Steed, V.S., *et al.* 2000. Development of a sulphate reducing biological process to remove heavy metals from acid mine drainage. *Water Env. Res.,* 72:530-535.

Siriwardane, H.J., R.S.S. Kannan and P.F. Ziemkiewicz. 2003. Use of waste materials for control of acid mine drainage and subsidence. *J. Env. Eng.,* 129 (10): 910-915.

Skousen, J., *et al.* 1990. Acid mine drainage treatment systems : Chemicals and costs. *Green Lands.* 20 (4) : 31-37.

Skousen, J. 1991. Anoxic limestone drains for acid mine drainage treatment. *Green Lands.* 21 (4) : 30-35.

Singer, P.C. and W. Strumm. 1970. Acid mine drainage : The rate-determining step. *Sci. (New York).* 167 : 1121-1123.

Skousen, J. 1995. Prevention of acid mine drainage control and treatment. Compiled West Virginia University. pp 13-14.

Skousen, J., *et al.* 1995. Acid mine drainage treatment systems. Chemical and costs. In Acid mine drainage-Control and treatment (chapter 14). West Virginia University and the National Mine Land Reclamation Center, Morgantown, WV. pp 121-129.

Souza V.P. 1995. Drenagens Acidas do Esteril Piritoso da Mina de Uranio de Pocos de Caldas : Interpretacao e Implicacoes Ambientais. Tese de Disertacao de Mestrado. Escola Politecnica da Universidade de Sao Paulo, SP. 143 pp.

Sencindiver, J.C. and D.K. Bhumbla. 1988. Effects of cattails (Typha) on metal removal from mine drainage. In Mine drainage and surface mine reclamation (vol 1). Info. Circular no. 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 359-366.

Spratt, A.K. and R.K. Wieder. 1988. Growth responses and iron uptake in Sphagnum plants and their relation to acid mine drainage treatment. In Mine drainage and surface mine reclamation (vol 1). Info. Circular no. 9183. U.S. Bureau of Mines, Pittsburgh, PA. pp 279-285.

Sastri, V.S. 1979. Reverse osmosis separation of metal ions in acid mine water. *Sep. Sci. Tech.*, 14 (8):711-719.

Tiwary, R.K. 2001. Environmental impact of coal mining on water regime and its management. *Water, Air, Soil Poll.*, 132:185-199.

Tsukamoto, T.K., H.A. Killion and G.C. Miller. 2004. Column experiments for microbiological treatment of acid mine drainage : Low temperature, low-pH and matrix investigations. *Water Res.*, 38:1405-1418.

Tsukamoto, T.K. and G.C. Miller. 1999. Methanol as a carbon source for microbiological treatment of acid mine drainage. *Water Res.*, 33:1365-1370.

Turner, D. and D. McCoy. 1990. Anoxic alkaline drain treatment system, a low cost acid mine drainage treatment alternative. National Symp on Mining. Univ of KY, Lexington, KY.

Tuttle, J.H., P.R. Dugan and C.I. Rendles. 1969. Microbial sulphate reduction and its potential utility as an acid mine water pollution abatement procedure. *Appl. Microbial.*, 17:297-302.

Warner, R.W. 1971. Distribution of biota in a stream polluted by acid mine drainage. *Ohio J. Sci.*, 71:202-215.

Wieder, R.K. 1993. Ion input/output budgets for wetlands constructed for acid coal mine drainage treatment. *Water, Air, Soil Poll.*, 71:231-270.

Webb, J.A. and I.D. Sasowsky. 1994. Interaction of acid mine drainage with a carbonate terrane : Evidence from the Obey river, north-central Tennessee. *J. Hydro.*, 161 (1-4) : 327-346.

Watzlaf, R.R., K.T. Schroeder and C.L. Kairies. 2000. Long-term performance of anoxic limestone drains. *Mine Water Env.*, 19:98-110.

Widdle, F. 1988. Microbiology and ecology of sulphate and sulphur-reducing Bacteria. In Biology of anaerobic microorganisms. Ed A.J.B. Zehnder. Wiley Interscience, New York. pp 469-586.

Younger, P., S.A. Banwat and R.S. Hedin. 2002. Mine Water : Hydrology, pollution, remediation. Academic Press, Kluwer, The Netherlands.

Zeballos F. C. 2001. Modelagem matematica da Lixiviacao Quimica e Bacteriana de Minerios de Cobre em Pilha. Tese de Dissertacao de Mestrado. Pontificia Universidade Catolica do Rio De Janeiro, Department de Ciencias dos Materiais e Metalurgia, RJ. 115 pp.

Ziemkiewicz, P.F., J.G. Skousen and R.J. Lovett. 1994. Open limestone channels for treating acid mine drainage : A new look at an old idea. *Green Lands*. 24(4):36-41.

Ziemkiewicz, P.F. and D.L. Brant. 1996. The Casseliman river restoration project. Eighteenth West Virgina Surface mine draiange task force Symposium. Morgantown, WV.

Ziemkiewicz, P.F., *et al.* 1997. Acid mine drainage treatment with armored limestone in open limestone channels. *J. Env. Qual.*, 26:1017-1027.

Ziemkiewicz, P.F. J.G. Skousen and J. Simmons. 2003. Long term performance of passive acid mine drainage treatment systems. *Mine Water Env.*, 22 (3):118-129.

Zaluski, M.H., *et al.* 2000. Performance of field-bioreactors with sulphate-reducing bacteria to control acid mine drainage. 5th International Conference on Acid rock drainage. Denver, Co. Proceedings, pp 1169-1175.

Zhong, C.M., *et al.* 2007. Treatment of acid mine drainage (AMD) by ultra-low-pressure reverse osmosis and nanofiltration. *Env. Eng. Sci.,* 24 (9):1297-1306.

Zurbuch, P.E., *et al.* 1997. Restoration of two West Virginia rivers from effects of acid mine drainage. 19th Annual Conference of the Association of Abandoned Mine Lands Programmes. Canaan Valley, WV.

Proceedings, pp 19-28.

AUTHOR

1. Ms. Sangita, Senior Research Fellow, Central Institute of Mining and Fuel Research, Barwa Road, Dhanbad-826 015.

2. Dr. G. Udayabhanu, Associate Professor, Department of Applied Chemistry, Indian School of Mines University, Dhanbad-826 015.

3. Dr. (Mrs.) Bably Prasad, Scientist EII, Environmental Management Group, Central Institute of Mining and Fuel Research, Barwa Road, Dhanbad-826 015.