

Remediation of Acid Mine Drainage – A Review

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Abstract - Kopili hydroelectric project has suffered serious damage due to contamination of Kopili river by acid mine drainage from open cast coal mines and rat hole mines in Meghalaya. Acid mine drainage (AMD) forms when sulfide minerals deep in the earth are exposed to oxidizing conditions during mining, highway construction and other large-scale excavations. Upon exposure to water and oxygen, most sulfide minerals are oxidized to form sulfuric acid, metal ions and sulphate. Acid mine drainage enters surface or ground water and pollute it. Various biological, chemical treatment methods and AMD control methods are being used to reduce harmful effect of AMD. Comprehensive survey of the literature on acid mine drainage is done and various aspects related to the process of acid mine drainage formation, its hazardous impact on the environment and living organisms, preventative and control measures are being discussed in this review.

Key Words: Acid mine drainage, Kopili River, Acidic Water, AMD control, Chemical treatment, Remediation, Sulphate Reducing Bacteria, Permeable Reactive Barrier, Bioremediation, Phytoremediation, Reverse Osmosis

1. INTRODUCTION

Kopili River flows through the states of Meghalaya, Assam and is the largest tributary of Brahmaputra river. Acids from illegal rat-hole coal mines of neighbouring Meghalaya has polluted the Kopili river and its tributaries. The rivers run reddish due to a phenomenon called Acid Mine Drainage (AMD) which is caused by active and abandoned mines and coal storage sites [1-3]. Kopili hydroelectric power project is an important project because Assam, Arunachal Pradesh, Manipur, Meghalaya Mizoram Nagaland and Tripura are benefited from this project.

2. ENVIRONMENTAL ISSUE

The acidic water of Kopili river has been seriously affecting the performance of the Kopili Hydro Electric Project due to severe corrosion and damage of the water pipe and underwater parts of the generating units. Kopili hydropower station in Assam suffered major disaster on 7 October 2019 when it was submerged and flooded due to rupture in a pipeline. The pipe that burst had been repaired just a year ago. The pH level of the acidic water in the reservoir was 3.25. Burst pipe was designed to bring water at the rate of 12,000 liters per second. The fountain of water from the burst pipe rose several hundred feet and continued to do so

for hours. Huge loss of ₹6 billion due to this accident at Kopili hydropower station renews questions on rat-hole mining near dams.

Though water of Kopili river is unfit for human consumption but thousands of villagers living near Kopili river are using this water. National Green Tribunal (NGT) banned rat-hole mining in Meghalaya on 17 April 2014 but still it continues illegally. The pH level of water collected from the river emanating from Meghalaya was constant at 3.4 even a year after the rat-hole coal mining was banned by the NGT because the acidic water emanating from these mines continue to contaminate river downstream. The reason for this constant level could be that the rat holes through which the water seeped in were yet to be sealed and water got into the river system. It could take some more time for the acidic water to get neutralized.

Waste streams rich with sulphate and metallic ions is generated when sulfide minerals deep in the earth are exposed to oxidizing conditions during mining, highway construction and other large-scale excavations [4,5]. Upon exposure to water and oxygen, hydro-geochemical weathering of sulphide minerals generate acid mine drainage containing sulfuric acid, metal ions and sulphate. Pyrite and marcasite are most abundantly available sulphide minerals. Acid mine drainage (AMD) is prominent in both operating and abandoned mines. Composition of AMD can differ from one region to another due to local geology and source of water [6]. Due to highly acidic nature of AMD, vast array of metals and minerals get dissolved in it. Highly acidic and highly concentrated metallic streams are the characteristics of AMD. High concentrations of dissolved metalloids and metals, highly acidic pH and large amounts of sulphate in the toxic flow of AMD contaminate rivers and other surface water bodies that come in contact with it. Acid mine drainage pollutes groundwater on leaching into it. AMD causes corrosion and destruction of infrastructure. Highly acidic nature and heavy metals present in AMD are toxic to human health and plant physiology. Acid mine drainage (AMD) has hazardous impact on the environment and living organisms [7-9]. Acid mine drainage causes loss of biodiversity and deterioration of aquatic ecosystems [10-12]. Even colour of water changes when AMD enters into water bodies. Water contaminated with AMD often becomes unsuitable for domestic, agricultural and industrial uses. Industrial activities such as flue-gas scrubbing, streams of pulp and paper milling, chemical manufacturing also

produce effluents which have characteristics similar to that of AMD [13,14].

The acidity level and metal composition of a given AMD source depend on the type and quantity of sulphide minerals present and acid-neutralizing minerals contained in the exposed rock. The carbonate content of the area determines whether there is enough neutralization potential to counteract the acid produced from sulphide oxidation. Of the many types of acid-neutralizing compounds present in rocks, only carbonates occur in sufficient quantity to effectively neutralize acid-producing rocks. The ultimate acidity or alkalinity of AMD is determined by balance between the acid-producing potential and acid-neutralizing capacity of the disturbed area. The reaction rates of these materials are also important. Oxidation of sulphides tends to occur quickly while dissolution of limestone is a slower process.

3. AMD CONTROL METHODS

Problems related to AMD can be solved by preventative and control measures. Remediation of AMD is done either by source control and mitigation techniques [15]. Working principle of source controls involves the removal of oxygen and water to eliminate oxidation process of pyritic materials. Mitigation techniques are generally based on the neutralization of pH and the precipitation of metals of AMD [16]. Mitigation techniques can be classified as abiotic and biological treatment with sub-classes of active and passive treatment. Passive remediation systems are inexpensive to operate but require large land area and prolonged treatment period. Active remediation systems offer quicker treatment time but require higher investment costs.

Acid mine drainage can be chemically controlled by actively or passively treating acid-producing rock to stop or retard the production of acid. Active treatment of acid mine drainage is done by land reclamation, alkaline amendment, installation of alkaline recharge trenches, remaining of abandoned areas, oxygen barriers, water covers, etc. and passive treatment of acid mine drainage is done by forming alkaline leach beds, open limestone channels, anoxic limestone drains, vertical flow wetlands, constructed wetlands, etc. [17-19]. Low maintenance is required for passive treatment systems implemented on abandoned mine land and stream restoration projects. Over the long-term, maintenance of passive systems is necessary but it is not needed as frequently as for active treatment systems.

Acid-forming material can be compacted and capped. Caps and covers strategies that isolate pyritic materials from air and water are employed. Segregating and placing acid-producing materials above the water table in the backfill is also recommended. Diverting surface water above the mine site to decrease the amount of water entering the mine area is also practiced. The pit floor or material under the coal is

generally rich in pyrite. Incoming groundwater can be moved away from the pit floor by building high wall drains or placing impermeable barriers on the pit floor. Diversion and reclamation reduce the water flow from seeps. Surface diversion involving construction of drainage ditches to move surface water quickly off reclaimed surface mines by providing impervious channels to convey water across the disturbed area can also be done. Movement of water or oxygen into areas containing acid-producing rock can be retarded by oxygen barriers. These water control technologies include impervious membranes, dry seals, hydraulic mine seals and grout curtains/walls. Acid-producing rock and ground water can be separated by grouts. Ground water moving through backfills can be reduced by injection of grout barriers.

Backfilling and revegetation together can be effective methods of reducing acid loads from disturbed lands. Other technique to control AMD include injection of alkaline materials into abandoned underground mines and into buried acid material in mine backfills. Abandoned surface mines comprise huge volumes of contaminant of unknown composition and hydrology. Re-handling and mixing alkalinity into an already reclaimed backfill is generally expensive. Filling abandoned underground mine voids with non-permeable materials is one of the best methods to prevent formation of AMD. Underground mine voids are extensive so fill material and the placement method must be cheap, readily available and should have low transportation and pumping costs. Mixtures of class F fly ash and 3-5% Portland cement are used to control subsidence in mine in residential areas.

Re-mining of abandoned surface or underground mines is done for further coal removal. Re-mining reduces acid loads by decreasing recharge, covering acid-producing materials and removing the remaining coal which is the source of most of the pyrite.

Disposal of sulphide tailings under a water cover, such as in a lake is another way to prevent acid generation by excluding oxygen from sulphides. In past, mine wastes were disposed into the ocean or lakes but now many countries have banned this practice.

Alkaline recharge trenches are surface ditches filled with alkaline material which can minimize or eliminate acid seeps through an alkaline-loading process with infiltrating water. During reclamation alkaline recharge trenches can be installed on backfills or waste piles to add alkalinity to water. Pumping water into alkaline trenches can make acid seeps to turn alkaline.

4. CHEMICAL TREATMENT METHODS

4.1 Active Treatment of AMD

Chemical treatment system is commonly used if AMD problems develop during mining or after reclamation. AMD from acid-producing materials can be controlled by certain alkaline amendments. Blending acid-producing and acid-neutralizing rocks in the reclamation process to develop a neutral material is done. If sufficient alkalinity is not available at AMD site then external sources of alkalinity must be imported. Alkaline chemicals such as $\text{Ca}(\text{OH})_2$, CaCO_3 , CaO , NaOH , Na_2CO_3 , NH_3 are added to acidic water exiting the rock mass. The pH must be raised to between 6 and 9 by adding chemicals so that insoluble metal hydroxides form and settle out in treatment ponds. A simple chemical treatment system can consist of an inflow pipe, a storage tank holding the treatment chemical, a valve to control its application rate, a settling pond to capture precipitated metal hydroxides and a discharge point. Flow rate, pH and concentrations of metals in the AMD determine size and type of a chemical treatment system. For each specific condition a particular chemical is used to treat AMD adequately and cost-effectively.

Limestone (CaCO_3) is very safe, easy to handle, cheap and readily available source of alkalinity. Neutralization potential of limestone is between 75 - 100% and it has been used for decades to raise pH and precipitate metals in AMD. Use of limestone in AMD treatment is limited due to its low solubility. Hydrated lime ($\text{Ca}(\text{OH})_2$) is useful and cost effective for treating high-flow and high-acidity AMD. Hydrated lime treatment plant with large storage bins and a mixer/aerator is employed to help dispense and mix the chemical with the water [20]. Quicklime (CaO) is used with lime dosers and portable quicklime dispensing equipment machines. An average of 75% cost savings over NaOH systems and about 20 to 40% savings over NH_3 systems is possible if quicklime (CaO) is used for remediation of AMD. Soda ash (Na_2CO_3) is often used to treat AMD with low flow and low amounts of acidity and metals. Caustic soda (NaOH) is often used in remote low-flow ($<100 \text{ l min}^{-1}$) and high-acidity situations. The system can be gravity-fed by dripping NaOH solution directly into the AMD. Caustic soda is highly soluble, disperses rapidly and raises the pH quickly. The major drawbacks of using NaOH solution for AMD treatment are high cost and dangers in handling. Ammonia compounds are used to treat acid mine drainage but anhydrous ammonia is extremely hazardous. Ammonia is soluble, reacts rapidly and can raise the pH of water to 9.2. Injection of NH_3 into AMD is one of the quickest ways to raise pH of water. NH_3 is very cost effective and a cost reduction of 50% to 70% is generally realized when NaOH is substituted with NH_3 . For low flows of $<750 \text{ l min}^{-1}$, NaOH , Na_2CO_3 and ammonia have the lowest costs. Fluidized bed combustion ashes, flue gas desulphurization products and kiln dust are also suitable alkaline amendment materials for remediation of AMD.

After chemical treatment, the treated water flows into settling ponds so that metals in the water can precipitate. Metal hydroxide sludge is formed on using these AMD treatment chemicals. Sufficient residence time of the water is important for adequate metal precipitation or floc. Water quality and quantity determine the amount of metal floc generated. Ponds must be cleaned regularly. Flocs can be disposed by pumping onto land to get them age and dry because they become crystalline and behave like soil material. Remediation of AMD by neutralization is a fast and simple process but it requires large amount of neutralizing agents, generates large amount of sludge and Mo, Cr, and Hg cannot be insolubilized via pH control.

4.2 Passive Treatment of AMD

Active chemical treatment of AMD is generally expensive. Passive treatment systems have been developed that do not require continuous chemical inputs and natural chemical and biological processes treat contaminated mine water. Constructed wetlands, anoxic limestone drains, vertical flow wetlands, open limestone channels and alkaline leach beds are some of the passive technologies. Passive systems can be reliably implemented as low costs and low maintenance solution for many AMD problems in low-flow and low-acidity situations.

Aerobic constructed wetlands are used for AMD treatment which are shallow ponds ($<30 \text{ cm}$) with or without wetland plants. Aerobic wetlands are being used to slow down influent water to allow metal oxidation, hydrolysis and particle settling. Remediation efficiency and sustainability of remediation of AMD by constructed wetlands is depending on the climate and vegetation environment. Limestone can be used to facilitate neutralization. Aerobic wetlands are typically used as the final treatment step before discharge to receiving streams.

Anoxic limestone drain (ALDs) treats AMD by sending them through an underground passage that is filled with crushed limestone. ALD generate alkalinity when water passes through a limestone bed in a semi-closed system which have very little dissolved oxygen. CO_2 partial pressure is increased when limestone is buried in a semi-closed system which leads to additional limestone dissolution and alkalinity leading to precipitation of metals present in AMD. ALD can be operated effectively for more than 18 years without maintenance. Hydraulic head of AMD is forced down vertically through the organic substrate into a limestone bed with pipes to convey treated water to the next treatment stage in vertical flow wetlands (VFW).

In open limestone channels (OLC) when AMD passes over large ($>30 \text{ cm}$) pieces of limestone in relatively steep channels alkalinity is generated. Treatment effectiveness has been reported to be between 4 to 62% which is a very good response from a low-tech, low-maintenance and inexpensive system. Alkaline leach beds are opposite of open

limestone channel. These aerobic treatment systems use ponds instead of channels and are constructed with smaller pieces of limestone (2-10 cm). Limestone dissolves slowly and continually add alkalinity until the limestone gets coated with metal hydroxides and becomes less effective.

5. AMD REMEDIATION BY STEEL SLAG

Remediation of AMD by adsorption on high-efficiency, low-cost and readily available adsorbents such as steel slag, fly ash, and kaolin for removing heavy metals from wastewater of AMD is effective and flexible. These adsorbents have strong affinity and high loading capacity for pollutants.

Steel slag materials such as basic oxygen furnace slag, electric arc furnace slag and ladle furnace slag are the byproducts produced in the steelmaking process. Steel slag has excellent efficiency to decontaminate AMD. Steel slag is capable of removing pollutants from industrial effluents due to its excellent adsorption performance and strong alkali releasing capacity. Steel slag remediates AMD with pH 2.5, a sulphate concentration of 5000 ppm and iron concentration of 1000 ppm within 30 min by increasing its pH to 12.1, removing 99.7% of soluble iron and 75% of sulphate [11,12]. Dicalcium silicate (C_2S), Tricalcium silicate (C_3S) and calcium oxide (CaO) in steel slag have excellent alkalinity which is equivalent to 100–2000 ppm $CaCO_3$ [21]. Neutralization ability of steel slag in wastewater treatment can be as long as ten years. Steel slag is an inexpensive neutralizing adsorbent which can replace the traditional expensive alkaline chemicals to remediate AMD.

The type of steel produced and the quality of raw materials determines the composition of steel slags. Composition of Steel slag vary greatly and it contains 30–60% CaO, 2–35% FeO, 0–25% Al_2O_3 , 1–15% MgO and 0–35% SiO_2 . Basic oxygen furnace slag has high CaO content (>35%) [22]. Crystalline phases of steel slag such as Gehlenite ($Ca_2Al_2SiO_7$), Akermanite (Ca_2MgSiO_7), Bredigite ($Ca_5MgSi_3O_{12}$) and Merwinite ($Ca_3Mg(SiO_4)_2$) have vital role in the process of heavy metal ions sorption due to presence of active sites appearing during the isomorphous substitution of the type $Al^{3+} \rightarrow Si^{4+}$ in the crystalline phases. Excellent adsorptive performance of steel slag is due to its porous structure with a large specific surface area. Average pore diameter and specific surface area of steel slags are in the range of 17–27 nm and 0.8–1.9 m^2/g , respectively.

The physicochemical and surface properties of steel slag determine the performance and mechanism of steel slag in removing heavy metal ions in AMD. Parameters such as initial pH, dosage and particle size of steel slag, the initial concentration of heavy metal ions in AMD affect the entrapment of metal ions in AMD by steel slag. AMD remediation by steel slag is done by physisorption and chemisorption. Physisorption relies on the van der Waals force between steel slag and pollutants. Chemisorptions

plays a leading role in removing heavy metal ions which involves the transfer of electrons between the adsorbate and adsorbent. Remediation by chemisorption involves combination of multiple mechanisms such as surface coordination, ion exchange and chemical precipitation [23].

Removal of metal in AMD by steel slag is done due to the release of alkalinity. MgO, CaO and other alkaline substances in steel slag have hydration reaction which after hydrolysis release a large amount of alkalinity thus increasing the pH value of acidic wastewater which leads to precipitation of metals. Precipitate formed is separated from the wastewater to achieve the purpose of removing the heavy metals. Reduction of sulphate in AMD can be ascribed to the formation of gypsum ($CaSO_4 \cdot 2H_2O$).

Removal of heavy metal ions present in AMD is also achieved by the ion exchange between the Ca^{2+} in steel slag and heavy metal ions where Ca^{2+} is released from steel slag to create the active binding sites for metal ions. Most of the Ca^{2+} in steel slag is present in Ca_2SiO_4 and $Ca_2Fe_2O_5$ crystalline phase. Ca^{2+} in the lattice of Ca_2SiO_4 and $Ca_2Fe_2O_5$ can be replaced by the heavy metal ions present in AMD. Metal ions get adsorbed to the surface of steel slag by electrostatic attraction [24].

Ion coordination of silicon, aluminum, calcium, iron etc. present on the surface of steel slag is not saturated. These active sites available on the surface of steel slag get occupied by heavy metal ions present in AMD, form salts on the surface of steel slag and thereby get fixed on steel slag [25]. On contact with water, steel slag form hydroxylated M-OH group which react with the heavy metal ions present in AMD thus removing the heavy metal ions present in the wastewater by surface coordination reaction [26].

In comparison to other industrial wastes, Steel slag has unique advantages in the treatment of AMD because it can quickly release large amounts of alkaline substances which neutralizes the hydrogen ion of AMD thus raising the pH of AMD and has excellent removal efficiency for heavy metal ions and sulphate of AMD [27,28]. Activation technologies to improve the adsorption performance of steel slag are employed. Removal of metal ion from AMD by steel slag modified with aluminum hydroxide is enhanced significantly because active sites in the steel slag got increased, promoting the metal ions to diffuse to the surface of the slag. Bentonite-steel slag composite particles were employed as an adsorbent to treat AMD containing Pb^{2+} . Pb^{2+} was completely removed and acidic substances from AMD were effectively neutralize due to the strong alkali release capacity of steel slag and the excellent adsorption potential of bentonite for heavy metal ions [29].

Removal efficiency of metal ions from AMD is increased with the increase in steel slag mass because there is positive correlation between the dosage of steel slag and adsorption sites for removal of heavy metals from AMD. Increasing the dosage of steel slag increases the number of total available

active binding sites thereby increasing its adsorption efficiency. Optimum doses of steel slag are to be used to make the remediation process cost effective because size of the reactor increases with increasing the amount of steel slag which significantly increases the overall processing cost for wastewater treatment [30].

Efficiency for removal of metal from AMD by steel slag got increased on increasing the pH of AMD. One objective of remediation of AMD is to increase the pH level from acidic to neutral or basic. Various alkaline industrial wastes materials such as Fly ash, metallurgical slag, cement kiln dust can enhance the pH of AMD from 2 to the range of 8–12 [31].

On increasing pH of solution, concentration of OH⁻ ion is increased which is favorable for the adsorption or precipitation of metal ions. At higher pH, competition of H⁺ ions for free binding sites is attenuated and large amounts of positively charged metal ions hook up the free binding sites. On increasing pH during AMD remediation, the number of metal ions adsorbed on the surface of steel slag get increased and the removal efficiency of metal ions by steel slag exceeded 93% -99 % at pH 3 or more.

AMD generally contains multiple metal ions which have selectivity sequence of multi-ion competitive adsorption. In AMD containing Cu²⁺, Ni²⁺, and Zn²⁺, the adsorption sequence followed the selectivity sequence of Cu²⁺ > Zn²⁺ > Ni²⁺. In AMD consisting Pb²⁺, Zn²⁺, Cu²⁺ Cd²⁺, the selectivity sequence followed is Pb²⁺ > Cu²⁺ > Zn²⁺ > Cd²⁺. Higher preference for adsorption of Pb²⁺ can be correlated to its lower hydrate ion radius, lower hydration energy and higher electronegativity that contribute to more intense electrostatic interaction with the active binding sites available on the surface of slag.

6. BIOREMEDIATION

Compared to other chemical treatment methods for AMD remediation, biological treatments for AMD clean-up, also known as bioremediation are very promising remediation technologies [32-34] due to low operational costs and easy to operate for a wide range of acidic effluents with varying concentrations and better sulphate and metal recovery. Differential removal of metal ions is possible on remediation of AMD by microorganisms and does not results in secondary pollution.

Bioremediation techniques of AMD generally engage group of Sulphate Reducing Bacteria (SRB) as main working agents to control pH. In bioremediation of AMD, Sulphate Reducing Bacteria (SRB) reduces the excessive sulphate present in AMD to hydrogen sulphide which binds with the metals in the AMD stream to precipitate as metal sulphides. Metal sulphides are very stable and can be easily recovered and recycled. SRB remove sulphate from AMD and facilitate recovery of metals to generate non-toxic streams. Bioremediation of AMD can be done in active or passive

mode. Active bio-remediation system is usually a continuous process which requires constant resource input while passive bio-remediation systems require relatively low resource input. Hay, Manure, Woodchips, sludge and compost are being kept in bioreactor to sustain growth of SRB. SRB converts sulphate to adenosine-phosphosulphate which is metabolically reduced to biogenic-sulphite and then to biogenic-sulphide. The biogenic sulphide react with the metal present in the AMD stream to precipitate the metals as metallic sulphide.

Metal sulphide separation through precipitation technique is well pronounced in bioremediation techniques of AMD where pH of the system play critical role on the precipitation of metal. SRB generally thrive in pH ranges of 5.0 to 9.0 and have reduced activity rates at other pH levels. At low temperatures of 1-8 °C SRB assume normal activity rates but SRB generally do not tolerate high temperature conditions and at temperature above 40°C bacterial activity decreases drastically.

6.1 Passive Biological Treatment

Passive biological treatment systems based on SRB have minimal operation and maintenance cost. Passive bioremediation of contaminated groundwater is done by enhancing microbial activity through organic substrate injection or permeable reactive barriers methods. In situ remediation of AMD is done by injecting organic substrates into underground AMD. High removal efficiencies for metals and pH increment of mine water flowing through organic substrate enriched area were achieved but during high flow rate seasons this technique is not effective. Permeable Reactive Barrier (PRB) is another in situ remediation technique in which a reactive barrier is installed perpendicular to the contaminated water body. Neutralization of AMD and precipitation of metals took place on migration of AMD through the reactive barrier. Heavy metal precipitates produced during remediation get wrapped on the surface of the bacteria and hinder the remediation thus reducing the remediation efficiency of AMD by microorganisms. PRB allows water to flow easily and react with metal contaminant present in groundwater. PRB treat acid mine drainage consist of organic materials, such as municipal compost, leaf manure and wood chips/sawdust. Additions of organic substrates encourages the proliferation of sulphate reducing bacteria [35].

Passive bioremediation of surface water contaminated by AMD is done by infiltration beds and modified wetland systems. Infiltration beds is an extension of the concept of PRB which remediate surface and shallow sub-surface AMD to a depth of 50 cm. Organic materials are filled in trenches for efficient performance of SRB. Anti-clogging design and maintenance of constant hydraulic conductivity of the infiltration bed are essential for efficient remediation of AMD.

Aerobic and anaerobic wetlands are the most common and cost-effective remediation technique for AMD. Non-uniform water levels of AMD throughout the period of remediation reduce the efficiency of remediation [36]. Substrates are indispensable part of the wetlands and plays a crucial role in the effectiveness of the contaminants removal. Substrates influence the biological reactions and the metabolic pathways for the contaminant reduction [37]. Contaminant removal efficiency of the wetlands is affected by long-term performance and sustainability of the wetlands [38]. Substrate influences the long-term performance of wetlands while operational parameters such as hydraulic retention time, water depth and design affects the sustainability of the wetlands [39].

Anaerobic wetlands are relatively deep (>30 cm) with substrates of compost, sawdust, straw/manure, hay bales or other organic carbon-based materials which are generally mixed with limestone. Water becomes anaerobic due to the high biochemical oxygen demand on passing through the thick permeable organic subsurface layer. Anaerobic condition promotes bacterial reduction of sulphate to sulphides which then form insoluble metal precipitates. Reduction of sulphate increases alkalinity leading to metal precipitation as hydroxides.

6.2 Active Biological Treatment

Initially in comparison to passive treatment systems, capital and operating cost for active bioreactors was high but advancement in microbial technology has gradually made active bioreactors technology cost effective. Active bioremediation of AMD is done with biological reactors. Bioreactors for sulphate reduction treatment must have process design for consistent and long-term performance.

Biological sulphate reduction is being done using various reactor designs such as sequencing batch reactors, gas lift reactors, anaerobic filters/packed bed reactors, fluidized-bed reactors, anaerobic sludge blanket reactors, continuously stirred tank reactors, anaerobic hybrid reactors, membrane bioreactors [40]. Biological Sulphate reduction reaction and metal precipitation reaction are two main steps of biogenic H₂S-based process performed by SRB for AMD treatment. Sulphate reduction processes utilize sulphate in AMD solution as electron acceptor during anaerobic digestion of organic matter done by SRB. SRB generate alkalinity through production of H₂S which in turn precipitates metals. Excess sulphide is supplied to a separate oxidizing reactor to get elemental Sulphur. For AMD treatments, preliminary pH increment is required because highly acidic streams cannot be efficiently remediated. Alkaline materials are doped in organic substrates to protect SRB community against acidity and to maintain performance of bioreactors. Sulphide-containing effluent from biological sulphate reduction reactor can be recycled upstream so that SRB in downstream bioreactor is

protected from concentrated sulphide water because high dissolved sulphide content can be toxic to SRB, thus, reducing microbial activity. Functional groups such as carbonates, hydroxides and phosphates present in the AMD causes metal precipitation in a sulfate reducing bioreactor. These functional groups are produced due to the metabolic reaction of the microbial agent present in the reactor.

Bioremediation of AMD using algae is cost effective and have high efficiency of metal and sulphates removal. Algal strains such as Anabaena, Chlamydomonas, Chlorella, Cladophora, Oscillatoria, Phaeodactylum, Scenedesmus, Spirulina sp., etc. have been used for the bioremediation of AMD. These Algae generate high alkalinity which neutralizes the acidic nature of AMD and facilitate precipitation of metals [41].

7. PHYTOREMEDIATION

In phytoremediation, plants are being used for in situ remediation of AMD mainly by two main mechanisms: phytoextraction and phytostabilization. In phytoextraction, the plants uptake the contaminant metals present in the soil and accumulate them as a part of their biomass. Phytostabilization involves the immobilization of the metals within the plant rhizosphere and thus reducing the metal availability [42].

8. MEMBRANE TECHNOLOGY

Reverse osmosis (RO) and Nano-Filtration (NF) are the membrane based treatment being used for AMD remediation. Rejection efficiency of 93% to 98% is observed when NF membranes were applied and rejection efficiency as high as 99% is achieved on application of RO membrane. Sulphate content as low as 10 mg/l has been achieved on remediation of AMD by membrane technology [43-44]. Rejection efficiency of the membrane based AMD remediation is determined by pH, Feed concentration and Temperature.

9. CONCLUSION

Untreated AMD may have toxic effects on organisms in the river and the acidic water of AMD can erode the soil. Effective treatment methods to neutralize the acidity of the AMD and removal of heavy metals from AMD will help in conserving the ecosystem. Remediation of AMD convert pollutants to an acceptable form in which they have least negative impact on environment. Metal recovery from AMD remediation may be perceived as generation of renewable raw materials [45,46].

AMD require site-specific treatment because each AMD is unique. Certain systems are better suited to specific water quality and can provide good treatment success. Some of the treatment methods are suitable for abandoned mines while others are best suited for active operations. Other methods can be used in either setting. Costs for treating AMD are site

and case specific. Cost of AMD treatment methods are generally high. Cost-effective methods which prevent the formation of AMD at its source are preferable [47].

There is no single reliable method for AMD treatment so efforts must be done to avoid the generation of AMD and prevention of contamination of water sources by existing AMD must be done by avoiding surface water and ground water to come in contact with existing AMD. Mining companies must predict AMD before mining. On sites where a potential exists, quick coverage of acid-producing materials in the backfill should be practiced [48].

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