Desalination and Water Treatment
www.deswater.com

doi: 10.1080/19443994.2016.1146921

57 (2016) 24755–24764
November

Taylor & Francis
Taylor & Francis Group

Treatment of mining-influenced water at Malanjkhand copper mine

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Received 7 September 2015; Accepted 21 January 2016

ABSTRACT

The chemical precipitation technique has been successfully utilized to treat the mine water. The copper concentration in mine water was below 50 mg per liter in majority of samples collected for the study. Iron concentration varied between 0.02 and 4.55 mg per liter. It was 0.674–3.83 mg per liter for manganese and fluoride concentration of 0.18–6.6 mg per liter was found. The pH range of mine water was 4.1 and 7.4. The study investigated the effect of pH adjustment and lime dosage on the mine water. Sample after treatment were analyzed for pH, chemical oxygen demand (COD), suspended solids (SS), total dissolved solids (TDS), and copper and fluoride ion concentration. The copper concentration reduction was found to be >99% over a treatment pH range of 8.0–9.5 using lime dosage of 140–170 mg/L at 56% purity of lime but the fluoride removal efficiency was approximately 40% at a treatment pH of 9.0. Thus, the study indicates the requirement of elevated pH (10.5) for better fluoride removal efficiency of 70%. It was also observed that lime with higher purity is better in terms of copper and fluoride removal effectiveness. Finally, the treated water pH (after settlement of sludge) was in the range recommended for discharge in inland surface waters bodies.

Keywords: Mine water treatment; Copper removal; Chemical precipitation; Lime treatment

1. Introduction

When mined materials (such as the walls of open pits and underground mines, tailings, waste rock, and heap and dump leach materials) are excavated and exposed to oxygen and water, acid can form if iron sulfide minerals (especially pyrites) are abundant and there is an insufficient amount of neutralizing material to counteract the acid formation (acid rock drainage/acid mine drainage). The acid will, in turn, leach or dissolve metals and other contaminants from mined materials and form a solution that is acidic, high in sulfate, and metal-rich (including elevated concentrations of cadmium, copper, lead, zinc, arsenic, etc.) [1]. The metal-rich solution can be considered for metal extraction from the sludge obtained after chemical precipitation. Although the chemistry of AMD generation is straightforward, the final product is a function of the geology of the mining region, presence of micro-organisms, temperature and also of the availability of water and oxygen [2].

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Malanjkhand copper project is a base metal mine which contains copper, iron, manganese along with fluoride and some toxic elements like arsenic, lead, and cadmium in the host rock. The active chemical treatment of mine-influenced water investigated in this paper, works by collecting and chemically treating mine water in a centralized treatment plant followed by precipitation of suspended/dissolved solids with copper recovery. Seasonal variations also affect critical parameters such as pH and contents of Cu, Fe, Mn, and F in mine water. The mine water samples were systematically collected in all three seasons for treatability studies from various drainage/seepage locations in and around the project. Jar test experiments were also performed to optimize the chemical dosage for effective removal of copper and fluoride from the acid mine drainage.

2. Process description

The process of chemical precipitation involves the addition of chemical reagents, followed by the separation of the precipitated solids from the cleaned water. Precipitation can be induced by addition of an alkali, sulfide, coagulant, or other reagent that will bond with dissolved metal ions. Alkali sources include caustic sodium hydroxide (NaOH), hydrated lime ($Ca(OH)_2$), quick lime (CaO), limestone ($CaCO_3$), and magnesium hydroxide ($Mg(OH)_2$). Sulfide reagents used to cause precipitation of contaminants include iron sulfide (FeS), sodium hydrosulfide (NaHS) (Wellington—Oro Water Treatment Plant), sodium sulfide (Na_2S), calcium sulfide (CaS), and biogenic sulfide generated *in situ* by sulfate reduction. Coagulants can include alum $KAl(SO_4)_2$, iron hydroxide ($Fe(OH)_3$),or ferric chloride $FeCl_3$. Carbonates can also be used in chemical precipitation, including sodium carbonate Na_2CO_3), calcium carbonate ($CaCO_3$), or CO_2 under pressure (Toby Creek Mine). Some additional methods that are being used for neutralization include the rotating cylinder treatment system (RCTS) (Leviathan Mine, Sunshine Mine, Cement Creek, American Tunnel, Inactive Copper Mine in Vermont, Zortman Landusky), $FeCl_3$for arsenic removal (Lava Cap Mine), use of CO_2 under pressure (Toby Creek Mine), and a limestone/steel slag system (Ohio Mines) [3].

Due to the low pH, the solubility of the toxic metals contained in the AMD keeps up at a high level, thus permits their dispersion into the environment [4]. The most generally applied treatment of AMD involves the addition of alkaline reagents to increase the pH and precipitate the dissolved metals as hydroxides [5]. Although this treatment can provide effective remediation, it has the disadvantages of high operational costs and problems related to the disposal of the bulky sludge that is produced [5–7]. Various techniques are being used worldwide successfully or with partial success; some of the commonly used reagents used for chemical precipitation are summarized in Table 1.

2.1. Sulfide precipitation

The precipitation of dissolved metals as metal sulfides can be induced by addition of a sulfide. The suitable alternative methods recover metals from AMD (acid mine drainage) in the form of sulfides using precipitating agent as H_2S, Na_2S, and NaHS. The superior sulfide precipitation is reasoned by the sparingly soluble nature of sulfide precipitates, better thickening and dewatering characteristics as corresponding metal hydroxides, the production of lower sludge volumes (6–10 times) and stability of formed sulfides over a wide pH range. Additionally, sulfide precipitates can be processed by existing smelters for metal recovery. Chemical sulfide precipitation has not been widely used for AMD treatment due to high cost of chemicals and the hazard associated with their manipulation [8].

The Wellington-Oro is located in Breckenridge, Summit County, Colorado. It uses a sulfide precipitation process to cause the precipitation of zinc and cadmium sulfides. A small amount of soda ash is added into the process to control the pH to the optimal range for sulfide precipitation. Sulfides, in the form of sodium hydrosulfide, are added in a controlled dose. The process removes 99.8% of the zinc and cadmium and has been able to achieve the discharge limits—225 ppb for zinc and 4 ppb for cadmium [9].

2.2. Surface pool water

Pooled water (i.e. pit lakes, mine pools) can be treated with chemical precipitation in a batch mode, as opposed to the continuous-flow treatment schemes discussed above. The hybrid treatment involves both hydroxide and sulfide precipitation is generally preferred. An alkali is added to increase pH and cause some precipitation of dissolved metals. A carbon source (dried fish and decomposed weeds) is also added to boost growth of sulfate-reducing bacteria and induce sulfide precipitation as well.

2.3. Hydroxide precipitation

Precipitation using alkaline reagents is the most widely used treatment method for removing metals as hydroxides [10,11]. A polymer may be added to enhance flocculation, and the solution may be

Table 1
Reagents used for chemical precipitation

Alkali reagents	(1) Caustic sodium hydroxide (NaOH) (2) Hydrated lime ($Ca(OH)_2$) (3) Quick lime (CaO) (4) Limestone ($CaCO_3$) (5) Magnesium hydroxide ($Mg(OH)_2$)
Sulfide reagents	(1) Iron sulfide (FeS) (2) Sodium hydrosulfide (NaHS) (Wellington-Oro Water Treatment Plant) (3) Sodium sulfide (Na_2S) (4) Calcium sulfide (CaS) (5) Biogenic sulfide generated in situ by sulfate reduction
Coagulant reagents	(1) Alum ($K_2SO_4 \cdot Al_2(SO_4)_3 \cdot 24H_2O$) (2) Iron hydroxide ($Fe(OH)_3$) (3) Ferric chloride ($FeCl_3$)
Carbonate reagents	(1) Sodium carbonate (Na_2CO_3) (2) Calcium carbonate ($CaCO_3$) (3) CO_2 under pressure (Toby Creek Mine)

transferred to a clarifier to separate the solids from the cleaned overflow effluent. However, the resultant hydroxide sludge tends to be voluminous and typically only settle to between 2 and 4% (w/w) dry solids [12]. The high-density sludge process was developed in the 1960s to counter this problem. The process begins by mixing incoming effluent with a neutralizing agent (limestone/lime) and recycled sludge from a clarifier/thickener unit. After neutralization, this mixture is fed to the main lime reactor where a combination of aggressive aeration and high shear agitation ensures optimum process chemistry and clarifier performance. The discharge from the lime reactor is then treated with flocculent in the flocculation tank to promote precipitation and sent to the clarifier/thickener unit. The clarifier separates the treated effluent from the sludge, a portion of which is recycled to the head of the process [13].

Water affected by ARD (acid rock drainage)/AMD are usually treated by low-density or high-density sludge (LDS or HDS) lime plants, whereby lime is mixed with the contaminated water, effectively neutralizing the acid and precipitating the soluble metals as metal hydroxides. However, as effluent metal discharge limits become stricter, it is becoming more difficult for a simple lime plant to meet these regulations. This is due to the solubility of metal hydroxides being strongly pH dependent, and with the pH of the lowest metal solubility being different for the various heavy metals [14].

Hydrated lime ($Ca(OH)_2$) is typically procured in bulk powder form and it can be added either as a controlled dispersion of powder into the water or as a lime slurry. Hydrated lime is particularly useful and cost effective in large-flow, high-acidity situations where a lime treatment plant with a mixer/aerator is constructed to help dispense and mix the chemical with the water [15].

Limestone has been used for decades to raise pH and precipitate metals in CMD (Coal Mine Drainage). When pH is low and the metal concentrations are also relatively low, finely ground limestone may be dumped into drainage directly (limestone sand application) or limestone gravel may be ground into powder by water-powered rotating drums (limestone drum stations) and metered into the drainage. Sand-sized limestone has also been placed in a large cylindrical tank and mixed with the ARD which is introduced into the bottom of the tank [16]. The peak removal of copper using lime would require a pH of approximately 8.5; however, peak removal of lead requires a pH closer to 10.5 [17].

3. Applications

This technology can be used in conjunction with other treatments or by itself, depending on site conditions. The treatment system can be designed to deal with a variety of site conditions. The optimal process and its efficiency depend on several factors, including flow rate or volume, contaminants and their concentrations, other water parameters, discharge criteria, site access, and sludge disposal options. Being a flexible permanent technology, it can address metal contamination in mining-influenced water at mine sites. Besides, it finds application in situations like high or low volume of material, solo technology or in conjunction with others and in case of multiple contaminants.

4. Malanjkhand copper mine–the case study

4.1. Approach

Malanjkhand is situated in the deep, dense, green forests of Baihar subdivision of the Balaghat district in central Indian state of Madhya Pradesh and in the southern vicinity of the world famed Kanha National Park, known for large population of tigers and hard ground barasingha**.** All these places are well connected to the district town of Balaghat with a network of all-weather roads. The Chhattisgarh state capital city of Raipur is 180 km southeast from here, whereas Jabalpur is 200 km northwest. Nagpur is 300 km southwest from this place. Sprawling cultivated rice lands are found over the basins and around the inaccessible dense forests infested with scores of wild animals.

4.2. Geology

General relief is flat. The area in and around Malanjkhand is a part of the Baihar Plateau and is characteristically an undulating terrain comprising narrow basins and hills with dendritic drainage pattern. Malanjkhand copper mine is located over the erstwhile Malanjkhand hill which, before the commencement of mining, had seven peaks, rising 50–70 m, with intervening saddles forming a 2.6-km long arcuate chain having an eastward convexity. Quartz reef is the principal host of mineralization and varies in composition from pure quartz to quartz feldspathic rock. Besides quartz reef, silicified altered granitic rocks are also seen hosting the sulfide mineralization.

The reef was exposed on the erstwhile Malanjkhand hill ridges. It was positioned in an arcuate shape over a length of 2.6 km in north-south direction dipping 60˚–70˚ due east with an average width of 65–70 m. It was found emplaced along the fracture and fissure planes in the granitoids, subsequently sheared and fractured, permitting sulfide-rich hydrothermal fluids to precipitate giving rise to a rich copper deposit. This reef is being mined since 1982 and the open pit now exists in place of the hill. The highest elevation during the time was then 652 m w.r.t. mean sea level. The E–N–E (East–North–East) trending Son–Narmada Lineament along the Narmada River cuts across the Indian Precambrian Shield. The Malanjkhand copper deposit is located in the southern part of the Central Indian Precambrian Shield which is bordered by Pranhita-Godavari valley and Son–Mahanadi valley. The geology of the Malanjkhand area comprises the Basement complex and weakly metamorphosed sedimentary rocks of the Chilpighat series ranging from middle to upper Proterozoic ages, separated by an unconformity. The most predominant minerals occurring in quart reef and granitoids in order of abundance are chalcopyrite, chalcocite, and malachite. Malachite, azurite, cuprite, and native copper were the major oxide ores which were found initially during initial stripping of the Malanjkhand hill. This was gradually followed with depth by presence of secondary chalcocite, covellite, and bornite ore minerals that were, in turn, followed by primary chalcopyrite, pyrite, and bornite ore minerals.

Since 1982 and till date, the mine has produced and milled more than 60 million tonnes of 1.14% Cu grade ore. Accumulated tailings are estimated to be more than 62 million tonnes at 0.11% Cu grade. Waste rocks have been staked as the overburden dumps and are estimated to be more than 260 million tones [18].

4.3. Mine water of the Malanjkhand copper mine

The estimated quantity of mine water pumped out of Malanjkhand mine during the summer months averages to 2,000 m^3 per day and during winters it rises to an average of 3,000 m^3 per day. During the monsoon months, Malanjkhand area experiences heavy rainfall leading to rise in the average quantity of 13,500 m^3 per day of mine water being pumped out of the mine**.** At present, the mine water is reused in tailing slurry preparation and in concentrator plant operations.

4.4. Physicochemical characteristics of Malanjkhand mine water

Malanjkhand mine water is generally found to have high concentrations of copper among the heavy metals, but the copper concentration has rarely been observed to have reached above 50 mg per liter. Iron concentration varies between 0.02 and 4.55 mg per liter. It is 0.674–3.83 mg per liter for manganese. In addition, relatively higher fluoride concentration (0.18–6.6 mg per liter) is always observed. The pH of Malanjkhand mine water has been found to range between 4.1 and 7.4 varying from place to place. Seasonal variations have always increased or decreased the critical parameters such as pH and contents of Cu, Fe, Mn, and F in mine water.

4.5. Chemical precipitation–A viable option

The Malanjkhand copper mine water quality assessment along with the mine dump seepage and tailing dump seepage has always revealed it is acidic in nature with substantial presence of Cu, Fe, Mn, and fluorides. Acid mine drainage (AMD) may, thus, prove to be highly detrimental to aquatic life, and therefore is never released untreated in to the natural drainage system.

Two viable options are being practiced in Malanjkhand. One is the treatment of mine water including solid waste disposal and the other is the copper recovery with recourse to recycle and reuse of renovated water. Viability of these options has been assessed in the laboratory that has helped in arriving at an effective techno-economic alternative.

4.5.1. Acidic mine water treatment

The most conventional solution is to collect and chemically treat mine water in a centralized treatment plant followed by precipitation of suspended/dissolved solids. Active treatment requires a constant maintenance including supply of chemicals and translation of waters. A few active acidic mine water treatment methods and passive treatment methods are shown in Table 2. Some passive systems utilize the dissolution of limestone in ponds or channels to neutralize AMD. Typically, they incorporate anoxic limestone drains, limestone ponds or open limestone channels.

These systems work for a few years, but coating by Fe and Al hydroxides reduce limestone dissolution and plug the system in the long run. Since the limestone must be renewed, such systems are not truly passive or self-sustaining. Passive treatment system like natural or constructed wetlands within which microbial communities perform the same function meets the definition of sustainability. It is economical, non-polluting, and is not a source of secondary wastes. However, use of passive system of wetlands is liable to be adversely affected by fluctuations in flow and chemical parameters and may require long time to stabilize without any possible recovery of copper. The space requirement would also be more in case of wetlands.

4.5.2. Sample collection

Systematic collection of mine water samples was done from the south, north, and central pit bottom ponds including the seepage channels of tailing dam and south and central waste rock dumps. Samples were collected in a 15-L polyethylene bucket. Samples were placed directly into acid-rinsed polyethylene bottles with no filtration. Measurements for pH, dissolved solids, and dissolved oxygen were made in the field. All other analyses were performed in laboratories. Sample preservation was performed immediately after sample collection. The collected samples were preserved, processed, and analyzed for major ions, trace elements, and nutrients according to Standard Methods for The Examination of Water and Wastewater, 21st ed., American Public Health Association, American Water Works Association, and Water Environment Federation, Washington, DC, 2005. Heavy metals were quantified using inductively coupled plasma optical emission spectrometry (ICP-OES). In most case, flow of discharges was measured by the area-velocity method. A portable cutthroat flume was used at sites with unidentified channel and velocity to measure the flow accurately.

The coagulant was subjected to rapid mixing (coagulation) with the sample water at 110 rpm for 20 min followed by 40 min slow mixing (flocculation) at 30 rpm, followed by settling for 60 min. In order to obtain basic data Jar test experiments were performed for optimizing the chemical dosing for effective and efficient removal of copper and fluoride.

The characteristics of various mine water samples collected for treatability studies with respect to pH, chemical oxygen demand (COD), suspended solids (SS), total dissolved solids (TDS), copper and fluoride are tabulated in Table 3. The treatability studies were conducted by obtaining samples of mine dump seepage because of high concentration of copper and fluoride in seepage water.

4.5.3. pH optimization

In order to determine the optimum pH for maximum precipitation of copper from the mine water an experiment was carried out where the pH value of raw mine-influenced water sample was gradually increased. The treatment pH was raised to 9.0, 9.5, 10.0, and 10.5 using lime slurry (5%; w/v). The lime dose was calculated from the volume of lime slurry added. After the completion of jar test experiments, the supernatant water samples were analyzed for pH, COD, SS, TDS, Cu, and F (Table 4).

Table 2
Mine water treatment methods

Active methods	Passive methods
Chemical precipitation	Aerobic/anaerobic wetlands
Electro-chemical treatment	Surface flow wetlands
Neutralization precipitation	Vertical flow wetlands
Ion exchange and physiochemical adsorption	AMD treatment ponds
	Bioreactors and permeable reactive barriers

It was observed that addition of lime caused increase in sample pH and a sharp decrease in copper concentration. The copper removal efficiency of more than 97% was achieved over a treatment pH range of 9.0–10.5. At a treatment pH value of 9.0 the fluoride removal efficiency was approximately 40%. However, when the treatment pH was raised to 10.5 the fluoride removal efficiency significantly increased to more than 70%. It is also interesting to note that though initially the pH value of the sample water was increased to 10.5, the treated water pH (after settlement of sludge) was in the range recommended for discharge in inland surface waters bodies.

After assessing the copper removal efficiency, a two-stage experiment was further planned to determine the pH value required for optimum removal of fluoride from the raw mine-influenced water sample. During the first stage, the treatment pH was adjusted to 5.5–6.5 and jar test experiments were performed. Similarly, during the second stage of the experiment supernatants obtained from the first stage of the experiment were further subjected to the treatment pH value of 11.0 (Refer: Tables 5 and 6).

During the first stage, when the treatment pH was adjusted to 6.0–6.5, a decrease in fluoride content of approximately 6% was achieved. At further lower treatment pH (>6.0), no significant fluoride reduction was observed. However, during the second stage, when the treatment pH was increased to alkaline range by further addition of lime, more than 60% removal of fluoride was observed.

It can, thus, be construed that although significant removal of copper from acidic mine-influenced water can be achieved through chemical treatment by lime at pH range of 9.0–10.5, for effective removal of fluoride, pH value of more than 10.0 is required. A comprehensive mixing of lime and sufficient settling time is also necessary for effective precipitation.

4.5.4. Treatability of mine waters composites for copper recovery

It has been observed during the pH optimization studies that copper can be effectively precipitated and recovered from the acidic copper mine water as insoluble hydroxide by simple pH adjustment through lime addition. The possibility of recovering copper from composites of various mine waters by lime addition and to estimate the efficiency of such recovery over a working pH range of 8.0–9.5 was also explored. A set of experiments were designed, wherein different mine waters, were first composited in different volume ratios, and then the pH of the composites, initially in acidic range, was adjusted to different values (8.0, 8.5, 9.0, and 9.5) by adding a 5% (w/v) lime (56% purity) slurry. The required lime dose was calculated from the volume of lime slurry added. The volume and dry weight of the settled precipitate were also recorded (Tables 7 to 10) immediately after pH adjustment jar testing was conducted and the supernatant water samples were analyzed for Cu, Fe, and Mn in addition to pH. In all cases the copper recovery was found to be more than 99% over a treatment pH range of 8.0–9.5.

A composite of TDS (Tailing Dam Seepage) and MDS (Mine Dump Seepage) resulted in a pH value of 2.9 and the dosage of lime required to bring up this pH to 8.0–9.0 was 140–170 mg/L (Table 7). The dry weight of the precipitate was estimated to be 0.36–0.40 g/L.

A composite of tailing dam seepage (TDS), mine dump seepage (MDS), and mine water (MW) (mixed in a ratio of 3.25:1:1) was found to have pH 2.8. The lime dose required to bring up this pH to the working range of 8.0–9.0 was 230–250 mg/L. The estimated dry weight of precipitate was 0.34–0.40 g/L (Table 8).

The pH of a composite of MDS and MW (1:1) was relatively higher (~5.5). The lime requirement for adjustment of pH to 8.0–9.0 was less than 15 mg/L (Table 9). The estimated dry weight of the precipitate was also found to be on the lower side (0.07–0.09 g/L).

The effect of raw mine-influenced water addition to already reclaimed water (having pH in the range of 8.0–9.0) was investigated in subsequent experiments. Supernatants of jar test experiments (Table 9) were mixed with raw mine-influenced water in a ratio of 3:1. The jar testing after pH correction through lime addition (Table 10) was done keeping the pH of the

Table 3
Mine water sources in the mine

Mine Waters	pH	COD	SS	TDS	Fluoride	Copper
Tailing dam seepage	3.0	32	32	4,400	4.7	21.676
Mine water (South pit bottom pond)	4.7	16	BDL	3,220	6.3	43.901
South and Central mine dump seepage	5.0	12	10	3,060	7.3	48.600
Mine water (North and Central pit bottom ponds)	6.2	8	BDL	3,360	3.2	12.711

All parameters in mg per liter except pH, BDL = Below detectable limit

Table 4
Treated water properties, lime dosages, and sludge generated

Sample	Lime dose	pH after adjustment	pH after settling	COD	SS	TDS	Fluoride	Copper	Sludge volume (mL/L)
Control	–	5.0	4.8	<5	6	2,214	7.3	43.153	–
1	100	9.0	6.9	BDL	BDL	2,278	4.1	0.219	20
2	110	9.5	7.2	BDL	BDL	2,258	4.0	0.056	40
3	125	10.0	7.4	BDL	BDL	2,212	3.6	0.076	45
4	150	10.5	8.0	BDL	BDL	2,190	1.8	0.148	70

All parameters in mg per liter except pH and sludge volume

Table 5
Stage–I: treated water, lime dosages, and sludge generation

Sample	Lime dose	pH after adjustment	pH after settling	COD	SS	TDS	Fluoride	Copper	Sludge volume (mL/L)
Control	–	5.2	4.8	<5	6	2,214	7.3	43.153	–
1	15	5.5	5.4	<5	<5	2,228	7.3	1.121	15
2	20	6.0	6.0	BDL	BDL	2,240	6.8	0.771	17
3	30	6.5	6.0	BDL	BDL	2,256	6.8	0.788	20

All parameters in mg per liter except pH and sludge volume

Table 6
Stage–II: treated water, lime dosages, and sludge generation

Sample	Initial treatment pH	Lime dose	pH after lime addition	pH after settling	COD	SS	TDS	Fluoride	Copper	Sludge volume (mL/L)
Control	–	15	6.0	6.0	BDL	BDL	2,240	6.8	0.771	17
1	6.0	45	11.0	5.4	<5	<5	2,218	2.8	0.126	13
Control	–	30	6.5	6.0	BDL	BDL	2,256	6.8	0,788	20
2	6.5	40	11.0	9.8	BDL	<5	2,190	2.5	0.119	10

All parameters in mg per liter except pH and sludge volume

resultant composite at value lower than 8.5. When the "supernatant A," having pH value of 7.8 was mixed with raw water, no change in the resultant pH was observed. However, in order to reach a targeted pH of 8.5, around 2.5 mg/L lime was used. For a 3:1 composite of "supernatant B" and raw water, the pH dropped to 8.10. Only 2.0 mg/L lime was used to increase the pH to 8.5. When "supernatant C" was

Table 7
TDS and MDS composite, reclaimed water, and settled precipitate

Parameters	TDS	MDS	TDS:MDS = 1.8:1	Supernatant (after jar test)		
Initial pH	2.7	5.2	2.9	–	–	–
Lime dose	–	–	–	140	150	170
pH (after lime addition)	–	–	–	7.8	8.7	9.2
pH (after setting)	–	–	–	7.2	8.1	8.8
Copper	47.28	33.65	41.564	0.057	0.054	0.076
Iron	15.33	0.013	9.661	0.041	0.026	0.068
Manganese	13.01	3.660	9.473	3.79	2.016	0.242
Precipitate volume (mL/L)	–	–	–	32	34	36
Dry weight of precipitate (g/L)	–	–	–	0.356	0.372	0.385
All parameters in mg per liter except pH and sludge						

Table 8
TDS, MDS and MW composite, reclaimed water and settled precipitate

Parameters	TDS	MDS	MW	TDS:MDS:MW = 3.25:1:1	Supernatant		
Initial pH	2.69	5.23	6.65	2.83			
Lime dose	–	–	–	–	234	240	250
pH (after lime addition)					8.1	8.6	9.2
pH (after setting)	–	–	–	–	8.0	8.5	9.1
Copper	47.28	33.65	0.099	34.780	0.068	00.079	0.120
Iron	15.33	0.013	0.013	9.252	0.384	0.0348	0.047
Manganese	13.01	3.660	2.022	8.903	4.341	3.695	1.345
Precipitate volume (mL/L)	–	–	–	–	26	30	36
Dry weight of precipitate (g/L)	–	–	–	–	0.338	0.343	0.398
All parameters in mg per liter except pH and sludge							

mixed with RW in the same proportion (3:1) the pH of the resultant composite was >8.55, and thus did not require any lime addition.

4.5.5. Comparison between different lime forms

Purity of lime is usually defined as available lime expressed as CaO. However, chemically lime refers to either calcium oxide or calcium hydroxide, therefore, it is necessary to assess the purity of lime before fixing the dose for chemical treatment. Jar test experiments were carried out to find out the effectiveness of different forms of lime in the treatment of acidic mine water, where the lime of varying form and purity was used to adjust the treatment pH at 10.5 (Table 11).

It is observed that lime with higher purity has proved to be better in terms of copper and fluoride removal. These experiments evidently demonstrate that, higher the quantity of CaO available as lime, lesser the quantity is required to raise the pH to a specified value.

4.6. Recommendations

The most widely used method for removing copper and fluoride is precipitation as insoluble hydroxide or salt at alkaline pH. Active chemical treatment is preferred for treating the acidic mine water because of its simplicity and robust nature. Chemical precipitation offers many advantages as a treatment alternative as it has been used effectively for many years. It is able to meet stringent discharge criteria as it is efficient, easy to monitor and implement and it also gives immediate results. It can be used in a variety of situations and the design of the treatment process can be customized. This treatment can address both acute as well as chronic risks to human and ecological receptors. It provides a comparatively speedy effect in the reduction of contamination in down gradient surface water bodies. The ability for chemical precipitation to be used in prohibitive locations has increased due to advances in remote monitoring systems. Passive ecological system is time-consuming and consumes a larger territory for experimentation as well as implementation

Table 9
MDS and MW composite, reclaimed water and settled precipitate

Parameters	MDS	MW	MDS:MW = 1:1	Supernatant (after jar test)		
				A	*B*	*C*
Initial pH	5.23	6.65	5.51	–	–	–
Lime dose	–	–	–	5	10	12.5
pH (after lime addition)	–	–	–	8.2	8.7	9.2
pH (after setting)	–	–	–	7.8	8.4	8.8
Copper	33.65	0.099	16.556	0.073	0.055	0.498
Iron	0.013	0.013	0.013	0.024	0.033	0.026
Manganese	3.660	2.022	2.786	1.593	1.636	0.356
Precipitate volume (mL/L)	–	–	–	10	11	13
Dry weight of precipitate (g/L)	–	–	–	0.064	0.067	0.088
All parameters in mg per liter except pH and sludge						

Table 10
Composites of raw water, supernatant *A*, *B*, and *C*, reclaimed water and settled precipitate

Parameters	A:RW = 3:1	Supernatant	B:RW = 3:1	Supernatant	C:RW = 3:1
Initial pH	7.85	–	8.11	–	8.55
Lime dose	–	2.5	–	2.5	–
pH (after lime addition)	–	8.50	–	8.50	–
pH (after setting)	–	8.47	–	8.48	–
Copper	0.050	0.031	0.058	0.026	0.088
Iron	0.282	0.017	0.026	0.021	34.563
Manganese	3.191	2.898	2.719	2.456	0.989
Precipitate volume (mL/L)	–	–	–	–	–
Dry weight of precipitate (g/L)	–	–	–	–	–
All parameters in mg per liter except pH and sludge					

Table 11
Stage–II: treated water with different lime forms and purity

Lime form	Available lime (as % Ca0)	Lime dose	pH after lime addition	pH after settling	COD	SS	TDS	F−	Cu	Precipitate	
										Vol ml/L	Dry Wtgm/L
Control	–	–	5.0	4.8	12	10	3,060	7.30	48.153	–	–
Lime (Ex MCP)	56	156	10.5	9.3	<5	<5	2,219	2.40	0.302	80	5.2
Slaked lime (LR) (Ca hydroxide)	73	100	10.5	9.0	<5	<5	2,178	2.05	0.256	74	10.8
Quick lime (LR) (Ca oxide)	84	75	10.5	9.8	<5	<5	2010	1.50	0.131	88	6.6
All parameters in mg per liter except available lime, pH and sludge											

4.7. Limitations

The chemical precipitation process, although relatively simple in concept, requires various ingredients which makes it dependent on various economic parameters. High cost of operation and maintenance, chemical reagents, power consumption, and possible generation of waste stream are some of the disadvantages or limitations of chemical precipitation. These can equate to a relatively high cost for treatment. As no method is applicable to all situations, similarly chemical precipitation method is also not applicable/viable for all cases.

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