

RESEARCH ARTICLE

ASSESSING THE ACID MINE DRAINAGE POTENTIAL OF A STOCKPILED GOLD BEARING SULPHIDE ORE

Bennetta Koomson^{a*}, Shadrack Fosub, Blestmond Afrifa Brako^a, Elias Kwasi Asiam^a, Ernest K. Yanful^c^a*Kwame Nkrumah University of Science and Technology, Department of Materials Engineering*^b*University of Mines and Technology, Department of Environmental and Safety Engineering*^c*Department of Civil and Environmental Engineering, Western University, London, Ontario, Canada**Corresponding Author Email: bkoomson.coe@knust.edu.gh; bennybiney@yahoo.com

This is an open access journal distributed under the Creative Commons Attribution License CC BY 4.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

ARTICLE DETAILS

Article History:

Received 01 June 2021
Accepted 03 July 2021
Available online 29 July 2021

ABSTRACT

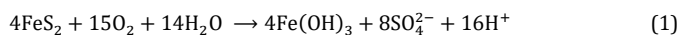
This work seeks to assess the acid mine drainage (AMD) potential of stockpiled sulphidic gold bearing ore that was left untreated for a period of four (4) years. The mineralogical composition of the stockpiled sulphidic gold ore was determined using X-Ray Diffractometry (XRD) and Reflected Light Microscope. The AMD potential and kinetic studies on the ore sample were determined using Acid Base Accounting (ABA) and Humidity Cell (ASTMD 5744). The XRD and microscope analyses showed that the gold ore contain arsenopyrite and pyrite as the major sulphide minerals. The ABA confirmed that the gold sulphide ore could be a potential source of AMD with respect to AMD marginal of safety if the ore is left untreated for a very long period. Humidity Cell kinetic analysis showed a possibility of mobilizing Arsenic (As) into the geo-environment when there is a long period of oxidation of abandoned sulphide run-of-mine (ROM) ore.

KEYWORDS

Acid Base Accounting, Arsenic, Sulphate Concentration, Heavy Metals Concentration, Conductivity

1. INTRODUCTION

Natural geochemical processes that oxidize metal sulphides exposed at the earth's surface by anthropogenic activities such as mining, results in acid mine drainage (AMD). AMD occurs when mine rocks or mine waste rocks and tailings containing sulphide-bearing minerals such as pyrite, arsenopyrite, chalcopyrite and pyrrhotite are exposed to molecular oxygen-rich environment and water (Warhurst and Noronha, 2000; Simate and Ndlovu, 2014). Iron and sulphur oxidizing bacteria are also known to catalyze these reactions at low pH thereby increasing the rate of reaction by several orders of magnitude (Nordstrom and Southam, 1997). These reactions however, occur naturally but at a rather slow rate. The reaction of pyrite with oxygen and water produces a solution of ferrous ion (Fe²⁺), sulphate ion (SO₄²⁻) and protons (H⁺ acid) (Jennings *et al.*, 2008; Simate and Ndlovu, 2014). The sulphur oxidation produces the sulphuric acid and the ferrous ion is further oxidized to ferric ion, which forms the orange ferric hydroxide precipitate (Fe(OH)₃) as summarized in Equation.1. As at today, AMD has been recognized as one of the main environmental challenges derived from mining activities (Dold and Fontbote, 2001; Holmstrom *et al.*, 2001; Romero *et al.*, 2010; Naidu *et al.*, 2019). The resultant acidic leachate may be transported to the surrounding environment and contaminate soils, sediments, ground and surface waters (Bain *et al.*, 2000; Armienta *et al.*, 2001; Jung, 2001; Romero *et al.*, 2010; Dong *et al.*, 2018; Skousen *et al.*, 2019). Often, the chemical characteristics associated with AMD are low pH values (high acidic water), high concentration of metals (iron, aluminium and manganese and other heavy metals) and metalloids (of which arsenic is generally of great concern) and sulphate ions in solution (Johnson and Hallberg, 2005; Mendez-Ortiz *et al.*, 2007).



Due to the above stated detrimental effects, AMD generation associated with sulphide bearing waste rocks and tailing material have been studied in detail over the past years (Dold, 2010; 2014; Banerjee, 2014; Simate and Ndlovu, 2014; Çelebi and Öncel, 2016; Zhou *et al.*, 2017; Fosub *et al.*, 2020). Kuma (2003) and Asamoah *et al.* (2007) reported the occurrence of AMD in the Tarkwa mining area in Ghana. Ndur *et al.* (2010) assessed AMD potential of the Coral Snake Waste Rock Dump located close to the Enkansu and Kaw streams in Obuasi, Ghana. With the above notwithstanding, little has been done on the AMD potential of sulphide bearing Run of Mine (ROM) ore which stays on the ROM pad/ Stockpile for several years and interact chemically with oxygen and rain water. For instance, Brierley and Brierley (2001) reported that 1.1 million dry-tons of about 80% pyrite of cobaltiferous pyrite concentrate (grading 1.38 % cobalt) produced from the Kilembe mine had been stockpiled for over 30 years before the cobalt recovery. Also, the Escondida Low-Grade Sulphide bioleach project began after the ore had been stockpiled for 2 years (Clark *et al.*, 2006).

Storing these sulphide bearing ores for such long periods before the beneficiation process causes the oxidation of unstable sulphides (Wills, 1997) resulting in AMD. Impoundments have been categorized as main sources of AMD although open pit high walls, underground workings and ore stockpiles contribute significant volumes of AMD (US-EPA, 2005; Romero *et al.*, 2010). As stated by Asare-Donkor *et al.* (2015), the Anglogold Ashanti Mine, Obuasi which was shut down from 2014 to 2019 (Ghanaian times, 2020) had large deposits of mine wastes, ore stockpiles and waste rocks that have become a heap around the extraction plants. Also, illegal miners in Ghana strip about 28 million tons

Quick Response Code



Access this article online

Website:
www.earthsciencesmalaysia.com

DOI:
10.26480/esmy.01.2021.58.64

of ore annually (Agbesi, 2017). In 2017, activities of these miners were brought to a halt by a directive from the government due to environmental issues. Hence, resulting in abandoned stockpiles of ROM ore in most illegal mining areas in Ghana for over two years. It is therefore important to ascertain the mineralogy of ROM ore and assess its AMD potential. This work attempts to investigate the AMD potential of sulphide rich ROM ore at Obuasi Ghana. Findings from the investigations will assist in managing seepage from the ROM/stockpile area.

1.1 Geology of the Study Area

The geology of Ghana can be divided into four distinct geotectonic units namely: the West African Craton, Platform, Pan-African mobile belt and coastal basins. The West African Craton was stabilised towards the end of the Eburnean Orogeny at approximately 2 Ga (Leube et al., 1990) and comprises the Paleoproterozoic Birimian Metasedimentary and Metavolcanic rocks which have been intruded by basin and belt type granitoids respectively. Overlying the Birimian Metavolcanic belt is the Tarkwaian Group which is believed to be of shallow water continental origin derived from the Birimian and its associated granitoids. The Platform area is dominated by the Neoproterozoic to Paleozoic Voltaian basement complex which is from the base made up of Kwahu (Morago) group, Oti-Pandjari group and Obosum group. The Pan-African Mobile belt is also made up of Buem, Togo and Dahomeyan structural units. The Buem structural unit consists of a thick, lower sequence of clastic sediments with some carbonate and tillite units succeeded by clastics and volcanics that include mafic flow units and pyroclastics (Kesse, 1985). Also, the highly metamorphosed Togo structural unit is predominantly composed of quartzite, chert, mica schist and phyllite while the Dahomeyan is predominantly gneissic in composition (Duodu et al., 2009). The coastal basin comprises the Phanerozoic units are also made Paleozoic coastal sediments, Mesozoic -Tertiary sediments and basins and Mesozoic intrusives.

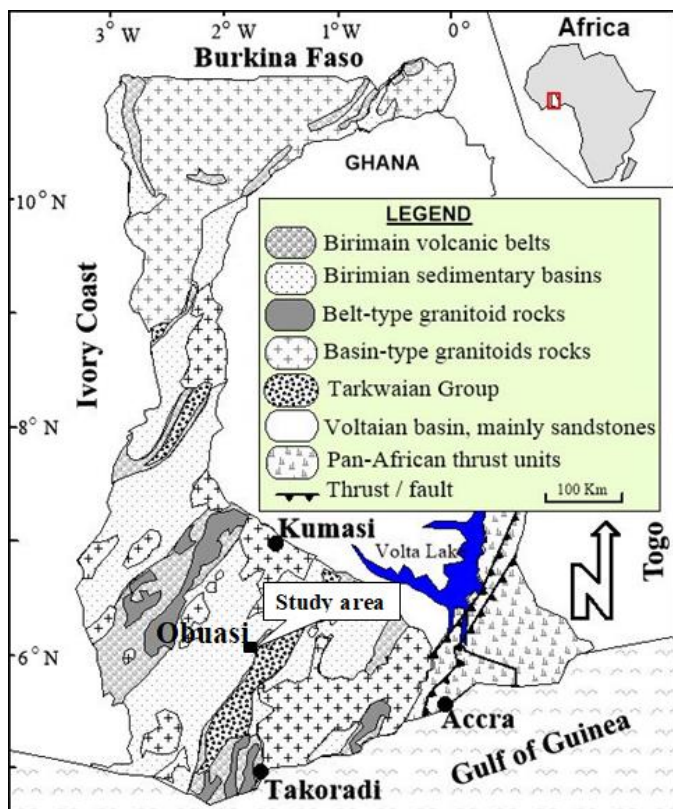


Figure 1: Geological map of Ghana showing the study area (modified after Davis et al. 1994)

The study area (Obuasi) falls within the Birimian of Ghana, precisely at the contact between the Ashanti belt and Kumasi basin (Fig.1) where gold-bearing quartz veins and sulphides are the two dominant ore types (Fougerouse et al., 2013). The area is underlain by Paleoproterozoic Birimian Metasedimentary (argillites, carbonaceous schist, wackes and chemical sediments), Metavolcanic rocks (basic to intermediate volcanic rocks) and the Tarkwaian sediments to the SE (Osae et al. 1999). Deformation within the area is marked by the carbonaceous shear zones that follow the general strike of the Birimian rocks (ie. NE). The shear zone is characterized by different generations of quartz veins (smoky

blue-gray quartz veins, ribboned milky white quartz veins and quartz-calcite veins) which are usually mined as stockwork. Sericitization, carbonitization and sulfidation are predominant alterations in the area (Osae et al. 1999).

2. MATERIALS AND METHODS

2.1 Sampling

Run of Mine (ROM) ore samples (predominantly carbonaceous schist and quartz veins) were collected from six different locations of a stockpile. The samples were homogenized with a shovel and then further sampled using coning and quartering method to obtain 5 kg of the ore material. The prepared sample was then preserved at a temperature of 4 °C for further analysis.

2.2 Mineralogical Investigations

The mineralogy of the ROM ore was determined by using physical observation, reflected-light microscopy (RLM) and X-ray diffractometry (XRD). Before bulk characterization, the sample was washed with distilled water to get rid of fine particles sticking on the rock surfaces. Polished mounts (< 45 µm) were prepared for RLM analysis using conducting graphite doped epoxy. The samples for the XRD analysis were pulverized and processed by placing on a powder plate and compacting with a glass slide. The XRD powder patterns (scans) were obtained using a Rigaku D/MAX 2500 rotating anode powder diffractometer using monochromatic CuKα radiation. Phase identification was achieved using the JADE version 9.0 coupled with the ICSD and ICDD diffraction databases. The measurement was done with two theta angular range of 5 – 70°, step size of 0.020°, scan speed of 1°/min, voltage of 50 kV and current of 260 mA.

2.3 Acid Base Accounting (ABA)

The most commonly and dependable static test used to predict AMD from most sulphide rock-bearing mineral is the standard acid-base accounting (ABA) (Yeheyis et al., 2009; Skousen, 2017). The ABA test determines the balance between maximum acid-generating processes (oxidation of sulphide minerals) and acid-neutralising processes (dissolution of alkaline carbonates, displacement of exchangeable bases and weathering of silicates) (Sobek et al., 1978; Ritcey, 1989; Skousen et al., 2002; Yeheyis et al., 2009; Banerjee, 2014; Yucel and Baba, 2016). Acid Base Accounting (ABA) of the ROM ore samples was carried out using the MEND method (1991). In this experiment, modified Sobek method was employed in the ABA analysis. Results of the experiment were computed using Equations (2), (3) and (4). Finely ground ROM ore sample (2 g; < 45 µm) was soaked in 40 ml 0.1 N HCl for 24 hrs and then the resulting solution was titrated with 0.1 N NaOH until a pH of 7 was obtained. The sample was also analyzed for total sulphur content using the LECO sulphide analyzer.

$$NP = \frac{50a \left[x - \left(\frac{b}{a} \right) y \right]}{c} \quad (2)$$

$$MPA = 31.25 \times \% S_{\text{sulphide}} \quad (3)$$

$$NNP = NP - MPA \quad (4)$$

where: NP is the Neutralization Potential (kg CaCO₃/t), MPA is the maximum potential acidity (kg CaCO₃/t), NNP is the Net Neutralization Potential (kg CaCO₃/t), 'a' is the normality of HCl, 'b' is the normality of NaOH, 'x' is the volume of HCl (mL), 'y' is the volume NaOH (mL) and S is the sulphur content of the sulphide.

2.4 Laboratory Weathering of ROM Ore

The ROM ore was subjected to standardized laboratory weathering analysis using the humidity cell test procedure (ASTM D 5744 – 07; Anon, 2007). This was to enhance the study of the kinetics involved in the rate at which weathering product mass (SO₄²⁻) is released from a known mass (250 g) of the ROM ore when it is leached every week using a fixed volume (500 mL) of de-ionised water. About 2 kg of the material was homogenized; hand crushed using a laboratory mortar and pestle and sieved to obtain a particle size range of 80 % passing a 4.76 mm aperture size sieve. The sample was then thoroughly washed several times with distilled water until the conductivity of the spent rinsing water was almost the same as that of the fresh distilled water. The residue was then dried with paper towels and further sampled using a Jones riffle to obtain

two sets of 250 g of ROM ore. The material (250 g) was transferred into a humidity cell column of height, internal diameter and wall thickness of 20.3 cm, 10.2 cm and 0.635 cm respectively lined with a geotextile (Fig. 2). The experiment was conducted for ten weeks at an average temperature and humidity of $22 \pm 1^\circ\text{C}$ and 21 % RH respectively. An EXTECH 45160 was used for the temperature and humidity measurements. The setup was supplied with air using a standing table fan. Sulphate analysis on resulting weekly leachate solutions was obtained using the Waters High Pressure Liquid Chromatogram (HPLC) with a flow rate of 1.2 ml/min. The column and detector types were IC Pack anion 4.6 x 50 mm and Waters 432 Conductivity Detector respectively. The resulting weekly leachates were also analyzed for selected heavy metals using inductively coupled plasma-optical emission spectroscopy (ICP-OES).

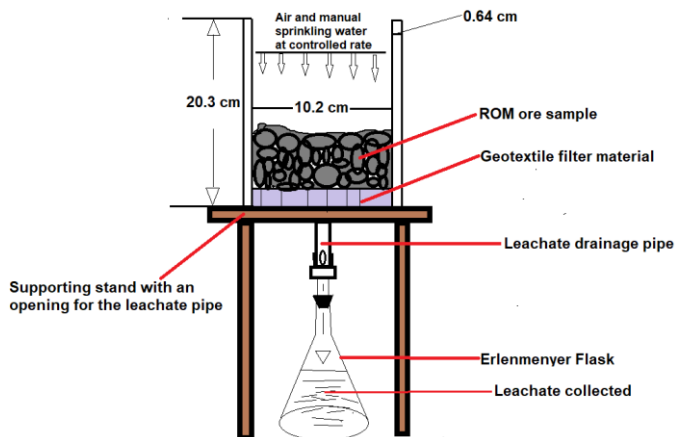


Figure 2: Schematic set-up for weathering of ROM ore in Humidity Cell

3. RESULTS AND DISCUSSION

3.1 Mineralogical Investigations

Macro and microscopic examinations of hand specimen and polished sections as shown in Fig. 3 and Fig. 4 respectively revealed that the ROM ore contained arsenopyrite and pyrite as major sulphides minerals. Fig. 3a is a highly sheared and foliated mineralized carbonaceous schist with deformed pyrite. Fig. 3b is a typical texture of "classic" crush zone of finely disseminated grains of deformed pyrite and needle-like arsenopyrite. Figs. 3c1 and 2 are grains of arsenopyrite and pyrite with quartz vein and microfracture respectively. The size of the sulphides in the ROM ore was between 100 and 3000 μm . The sulphide grains were observed to be sub perpendicular to foliation in some sections of the ore. In some instances, finely disseminated grains were observed to be occurring along microfractures and shear planes. Arsenopyrite grains in the ROM ore were idiomorphic crystals with a rhomboidal shape as shown in Fig. 4a. They had well-defined straight edges and appeared whitish. Also, some large crystals of arsenopyrite in the ROM ore were observed to be massively fractured. Other arsenopyrite grains, however, appeared elongated with both rough and smooth edges (Fig. 4b). Their sizes ranged from 200 to 1200 μm with few fractures.

Pyrite in the ROM ore appeared as brassy yellow to yellowish-white in air when viewed using a microscope. The sizes range from 40 to 2000 μm in a range of textures and crystal forms. The Pyrite grains appeared predominantly as spongy or porous masses with intergrown material as well as framboids at the rough ends of some of the crystals (Fig. 4a). Qualitatively, few framboids occurred as discrete particles. Most of the framboids majorly occurred as aggregates but are found at the edges of the pyrite crystals. The pyrites are more deformed compared to arsenopyrite due their spongy nature.

The X-ray diffractograms (XRD, Fig. 5) showed that the ROM ore was made up of quartz, illite, dolomite, chlorite-serpentine, albite, muscovite, paragonite, rutile, pyrite, arsenopyrite and pyrrhotite in order of decreasing abundance. The average composition of the main ore types at the mines are made up of about 35% quartz and 60 – 70% sulphide material. The run of mine taken for this analysis has key geochemical compositions in relative proportions such as: Fe (45.3%); As (32.6%); S (20.0%) and other base metals constitute about 2.1% dry weight (Oberthur *et al.*, 1994; Osae *et al.*, 1995; Foli *et al.*, 2015).

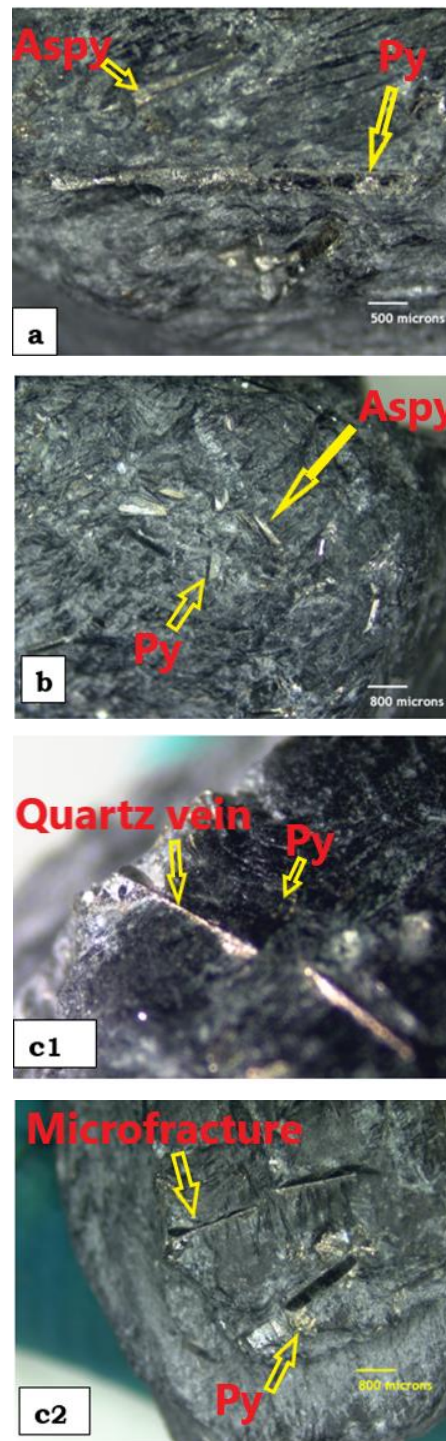


Figure 3: Hand specimen of ROM ore showing (a) a Highly sheared and foliated Mineralised carbonaceous schist (b) a Typical Texture of "Classic" Crush Zone of Finely Disseminated grains of Pyrite (Py) and Arsenopyrite (Aspy) (c1) Quartz vein within the Mineralised carbonaceous schist (c2) Pyrite (Py) along Microfractures and Shear Planes

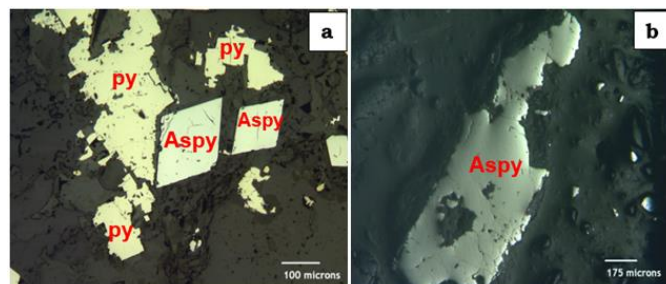


Figure 4: Photomicrographs of polished sections of rhomboidal arsenopyrite (Aspy) and deformed pyrite (py) crystals b) elongated grain of arsenopyrite

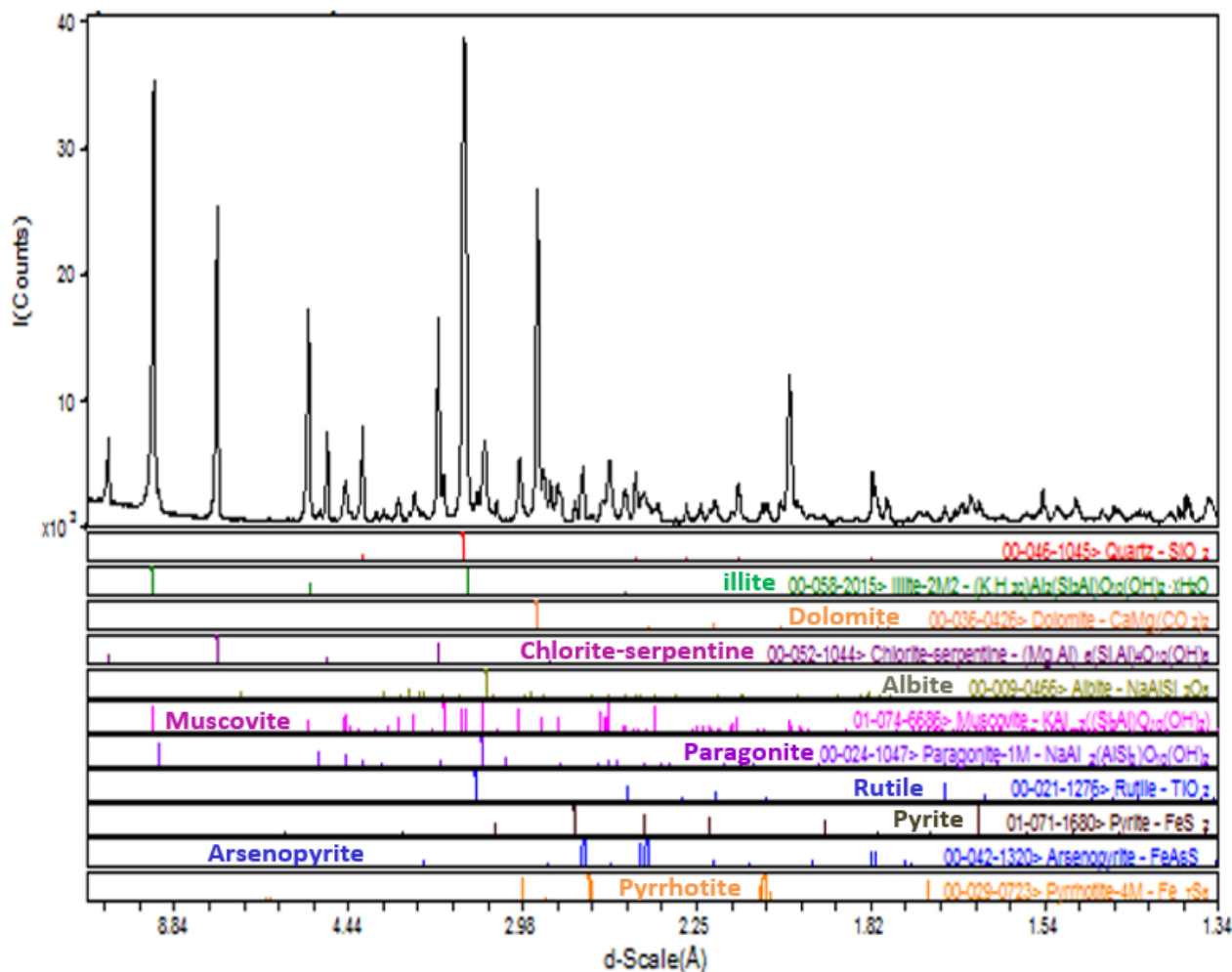


Figure 5: X-ray Diffractogram of Bulk Material Mineralogy (ROM Ore) showing the presence of quartz, illite, dolomite, chlorite-serpentine, albite, muscovite, paragonite, rutile, pyrite, arsenopyrite and pyrrhotite in order of decreasing abundance.

3.2 Acid Base Accounting

The result of acid base accounting (ABA) on the ROM computed using Eqns (2), (3) and (4) is presented in **Table 1**. ABA was conducted to help assess the acid producing and acid neutralising potential of the ROM ore prior to mineral processing. The calculated maximum potential acidity (MPA) of the ROM ore was $30.53 \text{ kg CaCO}_3\text{t}^{-1}$ while the neutralisation potential (NP) is $39.52 \text{ kg CaCO}_3\text{t}^{-1}$. The MPA value is attributed to the presence of few reactive sulphide minerals (pyrite, arsenopyrite and pyrrhotite). Again, the maximum NP value could be attributed to the following acid neutralising minerals such as slightly soluble dolomite, intermediate weathering chlorite-serpentine, very slow weathering muscovite (Sverdrup, 1990). The net neutralization potential (NNP) was found to be $8.99 \text{ kg CaCO}_3\text{t}^{-1}$. This means that there is enough NP (carbonate = calcite) to maintain the ROM ore neutral should it become chemically reactive leading to AMD. The neutralisation potential ratio (NPR) defined as (NP/MPA) was also found to be 1.2943. One of the criteria used to determine the acid producing potential of a rock-bearing mineral is the NNP value (Lottermoser, 2010). Conceptually, rocks with positive NNP values have no potential to generate acid, whereas rocks with negative NNP values do. A factor of safety is used in practice and rocks with significantly positive NNP values are generally considered as having no potential to generate acid ($> +20 \text{ kg CaCO}_3\text{t}^{-1}$); rocks with a significant negative NNP value ($< -20 \text{ kg CaCO}_3\text{t}^{-1}$) are potentially acid generating (Yucel and Baba, 2016). Rock-bearing sulphide minerals with intermediate NNP values have uncertain acid generation potential ($-20 \text{ kg CaCO}_3\text{t}^{-1} < \text{NNP} < +20 \text{ kg CaCO}_3\text{t}^{-1}$) (Ferguson and Morin, 1991; Miller *et al.*, 1991; Lottermoser, 2010, Yucel and Baba, 2016).

The ROM ore as examined for AMD potential in this study can hence be said to be uncertain since the value of $8.99 \text{ kg CaCO}_3\text{t}^{-1}$ falls in the uncertain range and this can be investigated using kinetic leaching studies to establish the domains. The NPR also indicates the relative margin of safety within a rock-bearing mineral for AMD. If NPR value is less than 1, the sample is said to be acid generating and if the NPR is between 1 and 2 ($1 < \text{NPR} < 2$), the sample is considered to be potentially acid generating, if the NPR is 2 or more, the indication is that the rock-

bearing mineral would have a higher probability to remain near-neutral and should not be problematic with respect to AMD (Price *et al.*, 1997; Price and Errington, 1998; Skousen *et al.*, 2002; Yucel and Baba, 2016). Again, according to Brodie *et al.* (1991), NPR less than 1 of a sample is said to be acid generating, NPR value of sample between 1 and 3 is said to be uncertain and NPR greater than 3 is said to be non-acid generating. Using the NPR marginal safety condition with respect to AMD, then ROM ore is said to have a possible AMD potential since a value of 1.295 falls between NPR values 1 and 2 according to Price *et al.* (1997), and uncertain since a value of 1.295 falls between NPR values 1 and 3 according to Brodie *et al.* (1991).

Table 1: Summary of Acid Base Accounting (ABA) Results

ABA Parameter	ROM
Paste pH	7.58
Total Sulphur (%)	0.977
Neutralisation Potential (NP) $\text{kg CaCO}_3\text{t}^{-1}$	39.52
Maximum Potential Acidity (MPA) $\text{kg CaCO}_3\text{t}^{-1}$	30.53
Net Neutralisation Potential (NNP) in $\text{kg CaCO}_3\text{t}^{-1}$	8.99
Neutralisation Potential Ratio (NPR)	1.295

3.3 Weathering of ROM ore Results

The results of the leaching (weathering) test conducted on the ROM indicate that there is averagely low heavy metal concentration release from the ROM ore with slightly acidic to neutral pH (6.64 – 7.98) solution as shown in Table.2. An average oxidation-reduction potential (Eh) value of about $600 \pm 63 \text{ mV}$ indicates moderate oxidation of the ROM ore sample during the leaching process which allowed moderate reactivity and smaller electrical conductivity in the leachate. Ferguson and Morin

(1991); Patterson and Ferguson (1994) however established that rocks with NNP greater than 0 kg CaCO₃t⁻¹ do not produce acid. This confirms the leaching test since the NNP value of the ROM is 8.99 kg CaCO₃t⁻¹. If the sample is strongly generating acid then the pH of the leachate solution is expected to be < 6 with high or significant concentrations of metal contaminants. The low metal concentration is also confirmed by the low average electrical conductivity (21 ± 9 µS/cm) of the leachate (Table. 2). If ROM ore sample is generating acid strongly, electrical conductivity levels between 1000 to 20000 µS/cm are expected (Sephton and Webb, 2017). Notwithstanding that, the ROM ore could have a low AMD potential but AMD can occur over long exposure periods of interaction between the ore and water in an atmosphere if the ore is left untreated for a very long time since there is a slight potential for AMD. The AMD produced will depend on the size of the exposed surface area of the type and quantity of sulphide minerals present as well as the host rock composition (Ziemkiewicz et al., 2003).

From Fig. 6, it can be seen that the release of sulphate from the leaching process increased with increasing time with a slow-release rate of approximately 0.423 mgL⁻¹day⁻¹ for every 250 g of the ore under the test conditions. AMD is characterized by a high sulphate concentration in the range of 500 – 10, 000 mg/L (Hill, 1968). In extrapolating for the limit of the sulphate ion concentration, it will take approximately 3 years for a sulphate ion concentration of 500 mg/L to be produced and 65 years for sulphate ion concentration of 10, 000 mg/L to be produced in the leachate. From Table. 2, concentrations of Fe, Pb, Zn and Cu were within the effluent permissible limits set by the Ghana EPA (2007) and (2010). However, concentration of Arsenic (As) was slightly above Ghana EPA (2007) and (2010) permissible limit for the 56th day. This indicates that sulphide contained in stockpiled ores must be properly managed to prevent contamination of the geo-environment. The low concentration of Fe and As release may be due to the fact that the leachate samples had pH higher than 6. This is because low pH (< 4) accelerates the acid generation, dissolving Fe oxyhydroxides and releasing As (Andrade et al.,

2008). Again, the presence of carbonate in the form of dolomite as shown in Fig. 5 could reduce the oxidation rates and Arsenic (As) mobilisation as seen in the work of Andrade et al. (2008). All these can be attributed to low oxidation rate of the sulphide, since the amount of leached sulphate was also low in the leachate samples (Fig. 6). This is in agreement with the authors (Nicholson et al., 1990; Jones et al., 2003) who reported that the rate of sulphide oxidation is reduced by increasing pH of the medium. Also, there could be retention of As by iron (hydroxides) which precipitate just after sulphide oxidation at high pH (> 4) (Pierce and Moore, 1982; Sun and Doner, 1998; Ladeira and Ciminelli, 2004; Gupta et al., 2005).

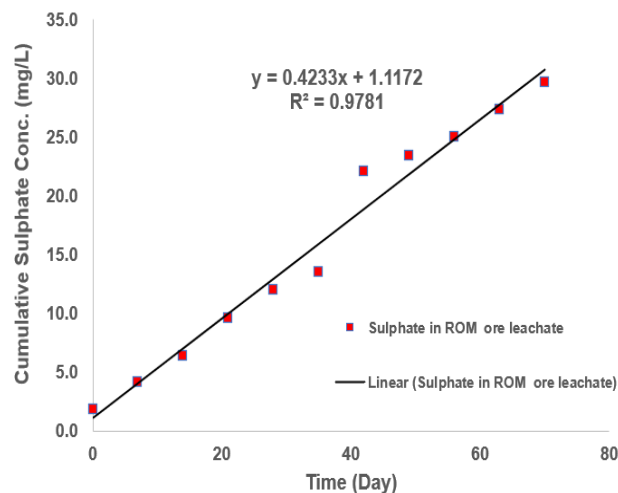


Figure 6: Plot of Cumulative sulphate concentration release from ROM Ore in days during a laboratory weathering analysis.

Table 2: pH, mean concentrations, conductivity and redox potential of metal species in leachate from laboratory weathering analysis

Time	Heavy Metal Concentration (mg/L)						Cond. (µS/cm)	Eh vs. SHE (mV)
	Day	pH	Fe	As	Cu	Pb		
0	6.64	0.07	0.02	0.01	0.01	0.03	38	622
7	6.94	0.09	0.02	0.01	0.01	0.02	39	620
14	7.10	0.15	0.02	0.00	0.01	0.01	25	648
21	6.94	0.07	0.02	0.00	0.01	0.02	18	649
28	7.63	0.04	0.01	0.00	0.01	0.02	20	722
35	7.05	0.04	0.01	0.00	0.01	0.02	15	649
42	7.55	0.05	0.02	0.00	0.01	0.02	17	557
49	6.89	0.08	0.01	0.00	0.01	0.01	13	548
56	7.98	0.10	0.22	0.00	0.01	0.02	15	519
63	7.55	0.04	0.01	0.00	0.00	0.02	16	542
70	7.39	0.07	0.01	0.00	0.00	0.01	15	522
Ghana EPA Effluent Permissible Limit	6.0 – 9.0	2.0	0.2	1.0	0.1	2.0	750	

4. CONCLUSIONS

The net neutralisation potential (NNP) and neutralisation potential ratio (NPR) of the acid base accounting (ABA) were used to assess the possible AMD potential of stockpiled gold-bearing sulphide ore. The mineralogical analysis carried out on the gold ore showed that arsenopyrite and pyrite are the most common sulphide minerals present in the stockpiled material (predominantly composed of carbonaceous schist and quartz veins). Quartz, illite, dolomite, chlorite-serpentine, albite, muscovite, paragonite and rutile were the non-sulphide gangue minerals identified in the ROM ore. Some of these non-sulphide minerals could play a major or a minor role in the acid neutralisation due to their differences in relative reactivity.

The maximum potential acidity (MPA), neutralisation potential (NP), NNP and NPR associated with the ROM ore were 30.53 kg CaCO₃t⁻¹, 39.52 kg CaCO₃t⁻¹, 8.99 kg CaCO₃t⁻¹ and 1.295 respectively. Considering the ROM ore sample, the NP exceeded the MPA, indicating that the ore sample generally has a low AMD potential or uncertain. Decisively, the pH from the weathering test were slightly acidic to neutral pH values. Very low

metal concentrations which were uncharacteristic of a strong acid generating material were obtained. The pH condition, slow release and low concentration of sulphate suggest low oxidation of sulphide mineral in the ROM ore per the conditions provided in the leaching test work.

There is a possibility of mobilizing Arsenic (As) into the geo-environment by ROM ore oxidation since the concentrations slightly increased above the Ghana EPA permissible limit on particular day. Subsequently, AMD could occur over a long period of exposure of interaction between the ROM ore and water under right atmospheric conditions if the ore is left untreated or abandoned for a very long period.

5. RECOMMENDATIONS

In order to expand the frontiers of knowledge in potential AMD pollution of sulphidic run of mine ore, it is strongly recommended that all other AMD indicators in the ore be ascertained by prolonging the study time for six plus years.

Also kinetic net acid generation tests must be developed to provide a qualitative indication of the lag to onset of AMD from the sample.

ACKNOWLEDGEMENTS

The authors wish to appreciate the Chamber of Mines - Ghana, AngloGold Ashanti, Ghana and Newmont Ghana for the invaluable support towards the success of this research. Special thanks also go to Dr. Allen Pratt, Dr. Brian Hart and Tim Stephens for their support in the mineralogical analysis.

REFERENCES

- Agbesi, K.M., 2017. Galamsey menace: Causes, effects and solutions. GhanaWeb. <https://www.ghanaweb.com/GhanaHomePage/features/Galamsey-menace-Causes-effects-and-solutions-538404> (Accessed 5.5.21).
- Andrade, R. P. D., Santana Filho, S., Mello, J. W. V. D., Figueiredo, B. R. D. and Dussin, T. M. 2008, Arsenic mobilization from sulfidic materials from gold mines in Minas Gerais state, *Química Nova*, Vol. 31(5), pp. 1127-1130.
- Anon, 2007, Standard Test for Laboratory Weathering of Solid Materials Using a Humidity Cell, D 5744 - 07, pp. 1- 19.
- Armienta, M.A., Villasenor, G., Rodriguez, R., Ongley, L. K. and Mango, H. 2001, The role of arsenic-bearing rocks in groundwater pollution at Zimapan Valley, Mexico, *Environmental Geology*, Vol. 40, pp. 571-581.
- Asamoah, V. E., Asiam, E. K. and Kuma, J. S. 2007, Assessment of a Natural Wetland for the Remediation of Acid Mine Drainage (AMD) at Tarkwa, Ghana, Presented at the First International Conference on Environment Research, Technology and Policy, Accra, Ghana, (16-19 July 2007), pp. 27-28.
- Asare-Donkor, N.K., Kwaansa-Ansah, E.E., Opoku, F. and Adimado, A.A., 2015. Concentrations, hydrochemistry and risk evaluation of selected heavy metals along the Jimi River and its tributaries at Obuasi a mining enclave in Ghana. *Environmental Systems Research*, 4(1), p.12.
- Bain, J. G., Blowes, D. W., Robertson, W. D. and Frind, E. O. 2000, Modeling of sulphide oxidation with reactive transport at a mine drainage site, *Journal of Contaminant Hydrology*, Vol. 41, pp. 23-47.
- Banerjee, D. 2014, Acid drainage potential from coal mine wastes: environmental assessment through static and kinetic tests, *International Journal of Environmental Science and Technology*, Vol.11, no. 5, pp. 1365-1378.
- Brierley, J. A. and Brierley C. L. 2001, Present and future commercial applications of biohydrometallurgy, *Hydrometallurgy*, Vol. 59 (2-3), pp. 233-239.
- Brodie, M. J., Broughton, L. M. and Robertson, A. M. 1991, A conceptual rock classification system for waste management and a laboratory method for ARD prediction from rock piles, In: Second International Conference on the Abatement of Acidic Drainage, Conference Proceedings, Sept. 16, Vol. 1, p. 4.
- Çelebi, E. E., and Öncel, M. S. 2016, Determination of acid forming potential of massive sulfide minerals and the tailings situated in lead/zinc mining district of Balya (NW Turkey), *Journal of African Earth Sciences*, 124, 487-496.
- Clark, M. E., Batty, J. D., Van Buuren, C. B., Dew, D. W. and Eamon, M. A. 2006, Biotechnology in minerals processing: Technological breakthroughs creating value, *Hydrometallurgy*, Vol. 83(1-4), pp. 3-9.
- Dold, B. 2014, Evolution of acid mine drainage formation in sulphidic mine tailings. *Minerals*, Vol. 4(3), pp. 621-641.
- Dold, B. and Fontboté, L. 2001, Element cycling and secondary mineralogy in porphyry copper tailings as a function of climate, primary mineralogy, and mineral processing, *Journal of Geochemical Exploration*, Vol. 74(1-3), pp. 3-55.
- Dold, B., 2010. Basic concepts in environmental geochemistry of sulfidic mine-waste management. *Waste management*, 24, pp.173-198.
- Dong, Y., Liu, F., Qiao, X., Zhou, L. and Bi, W., 2018. Effects of acid mine drainage on calcareous soil characteristics and *Lolium perenne* L. Germination. *International Journal of Environmental Research and Public Health*, 15(12), p.2742.
- Ferguson, K. and Morin, K. 1991, The prediction of acid rock drainage-lessons from the data base. In Proceedings Second International Conference on the Abatement of Acid Drainage, Vol. 3, CANMET, Ottawa, Ontario, pp. 83 - 106.
- Foli, G., Gawu, S. K. and Nude, P. M. 2015, Arsenic contamination and secondary mineral evaluation in mine drainage using integrated acid-base accounting and toxicity characterisation leaching procedure: the case of Obuasi Mine, Ghana, *Environmental Earth Sciences*, Vol. 73(12), pp. 8471-8486.
- Fosu, S., Owusu, C., Ntsiful, F. and Ackah, K. 2020, Determining Acid and Metalliferous Drainage Potential of Waste Rock on a Mine. *Ghana Mining Journal*, Vol. 20(2), pp. 49-59.
- Ghana EPA, 2007, Annual report: industrial effluent monitoring. Environmental Protection Agency, Accra, Ghana.
- Ghana EPA, 2010 Environmental performance rating and disclosure: report on the performance of mining and manufacturing companies. Environmental Protection Agency, Accra, Ghana.
- Gupta, V. K., Saini, V. K. and Jain, N. 2005, Adsorption of As (III) from aqueous solutions by iron oxide-coated sand, *Journal of Colloid and Interface Science*, Vol. 288(1), pp. 55-60.
- Hill, R. D. 1968, Mine drainage treatment: State of the art and research needs. *Mine Drainage Control Activities*, Federal Water Pollution Control Administration, U.S. Department of the Interior, Cincinnati (Ohio), 99 pp.
- Holmstrom, H., Salmon, U. J., Carlsson, E., Petrov, P. and Ohlander, B. 2001, Geochemical investigations of sulphide-bearing tailings at Kristineberg, northern Sweden, a few years after remediation. *Science of the Total Environment*. Vol. 273, pp. 111-133.
- Jennings, S. R., Neuman, D. R. and Blicker, P. S. 2008, Acid Mine Drainage and Effects on Fish Health and Ecology: A Review, Reclamation Research Group Publication, Bonzeman, MT, 22 pp.
- Johnson, D. B. and Hallberg, K. B. 2005, Acid mine drainage remediation options: a review, *Science of the Total Environment*, Vol. 338(1-2), pp. 3-14.
- Jones, R. A., Koval, S. F. and Nesbitt, H. W. 2003, Surface alteration of arsenopyrite (FeAsS) by *Thiobacillus ferrooxidans*, *Geochimica et Cosmochimica Acta*, Vol. 67(5), pp. 955-965.
- Jung, M. C. 2001, Heavy metal contamination of soils and waters in and around the Imcheon Au-Ag mine, Korea. *Applied Geochemistry*, Vol. 16, pp. 1369-1375.
- Kuma, J. S. 2003, Passive Treatment of Acid Mine Drainage - Laboratory Studies on a Soil Heap from the Tarkwa Area, Ghana, *Ghana Mining Journal*, Vol. 7, pp. 46.
- Kwabea F. 2020. 'After six years shut down: AngloGold Obuasi mine back! ...pours first gold as it begins production.' Ghanaian Times, 30 January. Available at <https://www.ghanaiantimes.com.gh/after-six-years-shut-downanglogold-obuasi-mine-back-pours-first-gold-as-it-begins-production/> (Accessed : 20 January 2021).
- Ladeira, A. C. and Ciminelli, V. S. 2004, Adsorption and desorption of arsenic on an oxisol and its constituents, *Water Research*, Vol. 38(8), pp. 2087-2094.
- Lottermoser, B. G., 2010, Mine waste: characterisation, treatment and environmental impacts, 3rd Ed., Springer, Berlin, Heidelberg.
- MEND. 1991, Acid Rock Drainage Prediction Manual, Mine Environment Neutral Drainage Program Report 1.16.1b, March 1997, 71 pp.
- Méndez-Ortiz, B. A., Carrillo-Chávez, A. and Monroy-Fernández, M. G. 2007, Acid rock drainage and metal leaching from mine waste material (tailings) of a Pb-Zn-Ag skarn deposit: environmental assessment through static and kinetic laboratory tests, *Revista Mexicana de Ciencias Geológicas*, Vol. 24(2), pp.161-169.
- Miller S. D., Jeffery J.J. and Wong, J. W. C. 1991, Use and misuse of the acid base account for "AMD" prediction, In: Proceedings of the 2nd

- ICARD, vol 3. Montreal, QC, Canada, pp 489–506.
- Naidu, G., Ryu, S., Thiruvengkatahari, R., Choi, Y., Jeong, S. and Vigneswaran, S., 2019. A critical review on remediation, reuse, and resource recovery from acid mine drainage. *Environmental pollution*, 247, pp.1110-1124.
- Ndur, S., Amegbey, N., Aggyeman, J. and Frempong, V. 2010, Acid Mine Drainage Potential of the Coral Snake Waste Dump, AngloGold Ashanti, Obuasi Mine, Ghana Mining Journal, Vol.12, pp. 32-37.
- Nicholson, R. V., Gillham, R. W. and Reardon, E. J. 1990, Pyrite oxidation in carbonate-buffered solution: 2. Rate control by oxide coatings, *Geochimica et Cosmochimica Acta*, Vol. 54(2), pp. 395-402.
- Nordstrom, D. K., and Southam, G. 1997 *Geomicrobiology – interactions between microbes and minerals*, Mineral Society, Am 35: 261-390.
- Oberthur T., Vetter U., Schmidt M. A., Weiser T., Amanor J. A., Gyapong, W. A., Kumi R. K. and Blenkinsop T. G. 1994, The Ashanti Gold mine at Obuasi, Ghana: Mineralogical, Geochemical, Stable Isotope and fluid inclusion studies on the metallogenesis of the deposit *Metallogenesis of Selected Gold Deposits in Africa* pp 44–79, 101–113.
- Osae, S., Kase, K., and Yamamoto, M. 1995, A geochemical study of the Ashanti gold deposit at Obuasi, Ghana, *Okayama University Earth Science Report*, 2(1), pp.81-90.
- Patterson, R J. and Ferguson, K. 1994, The Gibraltar North Project assessing acid rock drainage, In: *International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage*, U.S. Bureau of Mines Special Publication SP 06B-94, Vol.1, pp. 12-21.
- Pierce, M. L. and Moore, C. B. 1982, Adsorption of arsenite and arsenate on amorphous iron hydroxide, *Water Research*, Vol.16(7), pp. 1247-1253.
- Price, W. A. and Errington, J. C. 1998, Guidelines for metal leaching and acid rock drainage at mine sites in British Columbia, Ministry of Energy and Mines. In *mine drainage and surface mine reclamation, 1: mine water and mine waste*. April 19-21. Pittsburgh, USA.
- Price, W. A., Errington J. and Koyanagi V. 1997, Guidelines for the prediction of acid rock drainage and metal leaching for mines in British Columbia: part I. General procedures and information requirements, In: *Proc, 4th ICARD, Natural Resources Canada, Ottawa*, Vol. 1, pp 1–14.
- Ritcey, G. M. 1989, *Tailings management: problems and solutions in the mining industry*, Amsterdam: Elsevier Science Publishers.
- Romero, F. M., Prol-Ledesma, R. M., Canet, C., Alvares, L. N., and Pérez-Vázquez, R. 2010, Acid drainage at the inactive Santa Lucia mine, western Cuba: Natural attenuation of arsenic, barium and lead, and geochemical behavior of rare earth elements, *Applied Geochemistry*, Vol. 25(5), pp. 716-727.
- Sephton, M.G. and Webb, J.A. 2017, Application of Portland Cement to Control Acid Mine Drainage Generation from Waste Rocks, *Applied Geochemistry*, pp. 143-154.
- Simate, G.S. and Ndlovu, S., 2014. Acid mine drainage: Challenges and opportunities. *Journal of Environmental Chemical Engineering*, 2(3), pp.1785-1803.
- Skousen, J., 2017. A methodology for geologic testing for land disturbance: Acid-Base Accounting for surface mines. *Geoderma*, 308, pp.302-311.
- Skousen, J., Simmons, J., McDonald, L. M. and Ziemkiewicz, P. 2002, Acid-base accounting to predict post-mining drainage quality on surface mines, *Journal of Environmental Quality*, Vol. 31(6), pp. 2034-2044.
- Skousen, J.G., Ziemkiewicz, P.F. and McDonald, L.M., 2019. Acid mine drainage formation, control and treatment: Approaches and strategies. *The Extractive Industries and Society*, 6(1), pp.241-249.
- Sobek, A. A., Schuller, W. A., Freeman, J. R. and Smith, R. M. 1978, *Field and laboratory methods applicable to overburdens and mine soils*, Cincinnati, OH, USEPA Environmental Protection Technology. EPA-600/2-78-054. USEPA, Washington, DC.
- Sun, X. and Doner, H. E. 1998, Adsorption and oxidation of arsenite on goethite, *Soil Science*, Vol. 163(4), pp. 278-287.
- Sverdrup, H. U., 1990, *The kinetics of base cation release due to chemical weathering*, Lund University Press, Lund.
- US-EPA, 2005, *Prevention of Acid Mine Drainage Generation from Open Pit Highwalls – Final Report*, EPA / 600/ R-05/060, Mine Waste Technology Program Activity III, Project 26.
- Warhurst, A. and Noronha, L. 2000, *Environmental Policy in Mining: Corporate Strategy and Planning for Closure*, Lewis Publishers, Washington DC, pp. 118 - 139.
- Yeheyis, M. B., Shang, J. Q. and Yanful, E. K. 2009, Long-term evaluation of coal fly ash and mine tailings co-placement: a site-specific study, *Journal of Environmental Management*, Vol. 91(1), pp. 237-244.
- Yucel, D. S. and Baba, A. 2016, Prediction of acid mine drainage generation potential of various lithologies using static tests: Etili coal mine (NW Turkey) as a case study, *Environmental Monitoring and Assessment*, Vol. 188(8), p. 473.
- Zhou, J., Nyirenda, M. T., Xie, L., Li, Y., Zhou, B., Zhu, Y., & Liu, H, 2017, Mine waste acidic potential and distribution of antimony and arsenic in waters of the Xikuangshan mine, China, *Applied Geochemistry*, 77, pp. 52-61.
- Ziemkiewicz, P. F., Skousen, J. G. and Simmons, J. 2003, Long-term performance of passive acid mine drainage treatment systems *Mine Water and the Environment*, Vol. 22(3), pp. 118-129.

