Immobilisation of Hazardous Substances from Mine Tailings using Mineral Reservoir Technology: Case of Mineral Processing Tailings from Ghana

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Abstract The chemical stability of tailings from mineral processing is an important subject for study within the research field regarding the possible impacts for the environment, especially groundwater pollution and acid mine drainage (AMD). Tailings generated from processing metal ores can be classified as fined-grained sediment-water slurry. The solids are composed of minerals such as silicates, oxides, hydroxides, carbonates, and sulphides (Lottermoser 2003). The mineralogical and geochemical studies of tailings from metal ores are key factors used in the investigation of the chemical reactions and chemical 'systems' that result in AMD. However, rigorous and total characterisation of tailings has been cited in Lottemoser (2003).

The scope of this study includes investigation of the chemical properties of tailings liquid and the mineralogical properties of tailings sediment of quartz conglomerates ores from Goldfields Ghana Ltd (GFGL), Tarkwa as well as, sulphide ores from AngloGold Ashanti (AGA), Obuasi Mine.

Key Words mine tailings, AMD, tailings liquid/sediment investigation, heavy metals, mineral/metal speciation

Introduction

Mining activities can be considered a major economic contributor for many nations, particularly in countries such as Ghana, South Africa and Guinea. For example, 25% of Guinea's and 5.9% of South Africa's GDP as well as the majority of foreign revenues of these countries are mining related. The inception of an Economic Recovery Programme (ERP) by the government in 1983 has caused a major resurgence in Ghana's minerals and mining sector over the past decades, leasing permits for 12—16 large scale mining operations by the end of 1998 (Aryee 2001). About 12% of all land in Ghana is currently under some form of concession for mineral exploration (Ghana Chamber of Mines 2006), with more than 250 companies engaged in surface mining as of 2001 (E.A.G. 2001). The economic contributions of mining in Ghana, as of 2008 stood at 6.6% of the total GDP (2007), 12% of government revenue, 7% of Ghana's total corporate tax, and 41% of total export earnings, generating employment for over 20 000 people in the large-scale mining sector and about 500,000 people in the small-scale mining sector (Aryee and Aboagye 2008).

Although mining has significant potential to make a positive impact, it ends up depleting the resource and it is characterized by some negative impacts. Gold mining in Ghana has resulted in widespread land use change (Schueler and Kuemmerle 2011), and in most cases rarely benefits local workers, even though mining has widespread and drastic environmental and social effects (Kumah 2006). Inefficient mineral processing techniques and poor metal recovery has generated mine tailings with high metal concentrations. The problem is compounded by the presence of sulphide minerals, which, upon exposure to the atmosphere or oxygenated water, oxidize to produce acid water with high amounts of sulphate, heavy metals and metalloids. An understanding of the complex chemical reactions within sulphidic wastes is essential, as the reactions can cause and influence AMD (Lottermoser 2003).

Soils and sediments represent the major sinks for anthropogenic metals released to the environment with regards to their interface between the geosphere, the atmosphere, the biosphere and the hydrosphere. While some organic contaminants can undergo biodegradation, heavy metals remain in the environment. Fortunately, the toxicity of metals largely depends on their speciation; the less soluble form is usually less toxic (Manceau *et al.* 2011). A particular mine waste may be changed into a valuable commodity at changing circumstances to recover metals of interest. The current situation does not make mine tailings and mine wastes chemically safe at the dams. To a large extent, they inevitably pose the greatest potential source of environmental pollution, if inadequate management and monitoring are conducted on regular basis.

The subject of the investigation presented here are the tailings of gold mines in Ghana. In general, there is a possible difference in the chemical behaviour or chemical stability of tailings from sulphide ores and ores from conglomerates, respectively. Results of the chemical investigation on tailings liquid collected from piezometers and observation wells around the tailing dam show different chemical leaching behaviours. The chemical investigation of the tailings sediment is the topic of this ongoing work. The results obtained from chemical and mineralogical analyses of the tailings (liquid and solids contents) will be interpreted and a technique for the immobilisation of the dissolved hazardous substances using mineral reservoir technology will be developed in relation to the former work (Lottermoser 2003 and Poellmann 2007).

With an area of 11,400 ha, the Tarkwa concession currently being operated by GFGL is one of the oldest surface mines dating back to the 1980's (Agbesinyale 2003).

The company is located in the Wassa West District in the Western Region of Ghana, which has a total population of about 254,100 (in 2002) and an annual population growth estimated at 2.9% (Wassa West District Assembly 2004). It has a mean annual rainfall of 187.8 cm. The maximum rainfall is recorded during the main rainfall season from March to September and the dry season is from October to February. Therefore, the region therefore has fairly uniform temperatures, ranging between 26 °C in August and 30 °C in March (Tarkwa Nsuaem Municipal Assembly 2006). Gold is extracted from the gold-bearing quartz-pebbles conglomerates of the Tarkwaian series by heap leaching methods, and was further developed into Carbon-In-Leach (CIL) operations from 2003—2004. The GFGL TSF1 was constructed to receive tailings from the CIL operations. The site is situated in Tarkwa, in the south-western part of Ghana, at 5° 18' 0" North, 1° 59' 0" West, 300 km west of Accra by road and a 92.1km drive from Takoradi (GFGL 2010 and Kumah 2010).

Similarly, the AGA, Obuasi Mine is located some 160 km Northeast of Accra in the Obuasi Municipal District of the Ashanti Region of Ghana. The district covers a land area of 1624 km². The population of the municipality is estimated at 205,000, based on the 2000 Housing and Population Census and applying a 4% annual growth rate. Mean annual rainfall ranges between 1250 mm

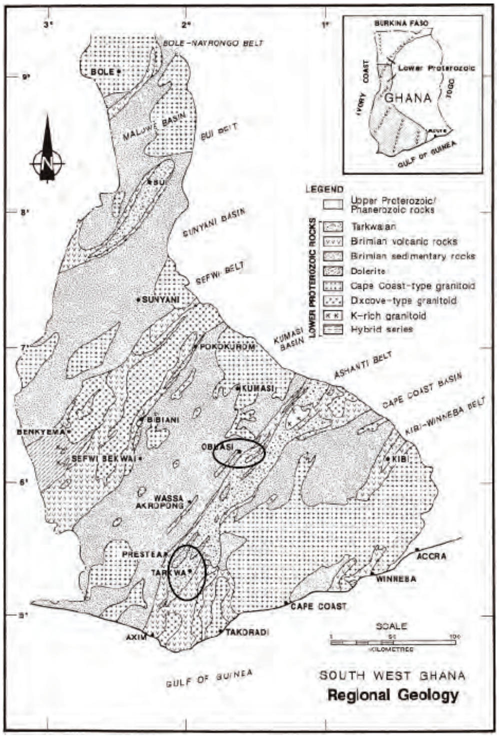


***Figure 1** Geological Map of southwest Ghana showing Birimian, Tarkwaian and distribution of Granitoid types from the Ashanti Belt Gold mineralisation (Eisenlohr, B. N. & Hirdes, W. 1992). Study areas: Sansu TSF (AGA, Obuasi) and GFGL TSF1 (Tarkwa).*

***Figure 2** Pictures of the TSFs from Study Areas, (Above)Aerial view of SANSU TSF AGA, Obuasi (Projects Department). Location: 500m SW of Dokyiwa village, Obuasi, (Below) Top view of GFGL TSF1, Tarkwa. Location: 5° 18' 0" North, 1° 59' 0" West 300 km west of Accra (GFGL 2010).*

and 1750 mm. Mean average annual temperature is 25.5 °C. Gold mining is extensive, and carried out by underground and open pit operations in the Birimian Series, which is made up of phyllites and greywackes with some quartz intrusions. The mine tailings at old dams are also mined by mechanic and hydraulic means. The Sulphide Treatment Plant processes sulphide ores from underground whereas the Oxide Treatment Plant processes surface oxide ores and old tailings material. The Sansu TSF, commissioned in 1992, is an approximately square dam that serves the Sulphide Treatment Plant (STP) (throughput of 200,000 ton per month) and Oxide Treatment Plant (OTP) (throughput of 80,000 tons per month) and contained some 56Mt of tailings by late 2008. Both the Sansu TSF and GFGL TSF1 have been designed to comply with the requirements of the PNDC Law (1986) and Parliament of Ghana (1994). Sansu Tailings Storage Facility (2009).

Experiments and Results

The tailings liquid obtained from piezometers at depth shows the leaching front and precipitation of mineral phases. The quantitative metal speciation is analysed using ICP-OES and IC. The major ion concentrations (mg/L), measured in tailings liquid from piezometers, were: Ca (3—239); K (1—46); Mg (1—267); Na (2—389); Zn (1—52); Cl (5—139); SO_4^{2-} (2—2937); NO_3 (1—11) and HCO_3^- (3—590) from AGA TSF and Ca (2—22); K (1—3); Mg (1—6); Na (5—105); Cl (4—50); SO_4^{2-} (8—100); NO_3^- (2—27) and HCO_3^- (3—78) from GFGL TSF1 and observation well water. Further modelling reactions of the tailings water with acidic rainwater or pure water are tested in the ongoing research. Similar analyses will be conducted on the eluate obtained from leaching tailings sediments sampled at different depths, up to about 1m, on the soil profile using the ‘pH-Stat’ method. The implementation of the elution is based on the LAGA (2002).

Modelling of these ion concentrations with the PHREEQC-Interactive software (Parkhurst and Appelo 1999) shows the redox conditions and possible mineral precipitation of the dissolved ions. The results are shown in Table 1.

The workflow for the investigation of the tailings sediments as part of the ongoing study, is given for the investigation of the chemical and mineral phases using XRF, -XRD, -SEM (EDX) – analysis.

The results of X-Ray Fluorescence (XRF) analysis from the two tailings materials are given in Table 2.

The XRD diffractograms of the tailings samples show a high composition of quartz and feldspars with some clay minerals. The clays serve as a possible reservoir for the incorporation of heavy metals and the trace minerals.

Discussions and Conclusions

The tailings materials from both mines show a very slight degree of weathering, despite the high rainfall patterns in both districts. The tailings materials from the AGA TSF show a secondary precipitation of gypsum at various depths from the soil profiles (Fig. 3). This may be attributed to the reaction of sulphate ions with dissolved calcium ions, as seen from the low CaO composition in the XRF analysis (Table 2). However, due to the early stage of this research, it may be too early to draw useful

***Table 1** Results of Mineral speciation of Tailings water from GFGL TSF1 and AGA TSF.*

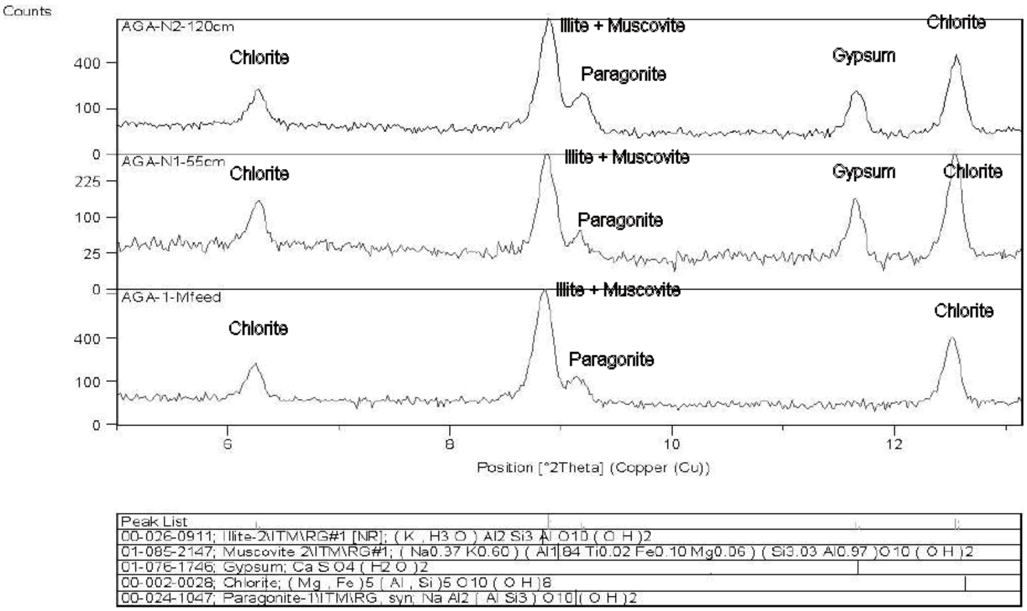
Sample	Depth (m)	Saturation indices (SI) of mineral phases with positive SI of precipitation
AGA-Discharge Tailings	Surface	$Fe(OH)_3$ (1.7-1.8), FeOOH (7.6-7.7), Fe_2O_3 (17.2-17.3)
AGA-E-1	30.5	$Fe(OH)_3$ (1.0); FeOOH (6.9); Fe_2O_3 (15.8)
AGA-E-2	30.7	Unlikely
AGA-N-1	14.1	Unlikely
AGA-N-2	10	$Fe(OH)_3$ (1.5), FeOOH (7.4); Fe_2O_3 (16.8)
AGA-W-1	11.4	$Fe(OH)_3$ (1.0), FeOOH (6.9), Fe_2O_3 (15.8)
AGA-W-2	11-4	Unlikely
AGA-W-3	8.9	$Fe(OH)_3$ (0.8), (6.7), Fe_2O_3 (15.4)
GFGL-A1	12.1	Unlikely
GFGL-5A	12.2	$Fe(OH)_3$ (1.3); FeOOH (7.2); Fe_2O_3 (14.4)
GFGL Well	1.8	$Fe(OH)_3$ (1.1); FeOOH (6.95); Fe_2O_3 (15.9)

SI- Saturation Index; E, N, and W- East, North and West Embankments; A- identification names

***Table 2** Results of major minerals ions identified by XRF analysis of tailings sediments and ores from AGA TSF and GFGL TSF1.*

Sample Description		AGA TSF			GFGL TSF1			
		Ore	Profile 1	Profile 2	Ore	Profile 1	Profile 2	Profile 3
Depth(s) (cm)			15,45,55, 154	8,15,44,7 8,120		15,40,86, 120	30.7	15,21,62, 123
Element Oxide (%)	LOI	5.8-6.5	7.1-8.7	7.8-11	0.9-1.2	0.2-0.6	0.77	0.4-0.6
	SiO_2	58-61	53-61	5.6-60.1	80-81.7	81.5-89	83	83.9-88
	Al_2O_3	17-18.5	12.7-16	12.2-15.6	10.5-12	5-7.6	8.8	6-7
	Fe_2O_3	4.1-4.6	4.2-4.6	4.6-6.4	2.8-3	2-7.1	3.8	2.4-5.6
	MgO	1.7-1.8	1.6-1.8	1.4-1.8	0.1-0.2	0.1-0.2	0.2	0.1-0.2
	K_2O	2.6-2.8	2-2.6	2-2.5	1.5-1.9	0.8-1.2	1.5	0.9-1
	CaO	2.8-3	3.3-4.2	3.6-5.2	0.1	0.1-0.14	0.2	0.1-0.2
	Na_2O	2-2.5	1.6-1.8	1.5-1.8	1.03-1.1	0.4-0.71	0.8	0.6-0.7
	SO_3	1.2-1.7	2.7-4	3-9	0.04	0.03-0.04	0.05	0.04
	As_2O_3	0.7	0.3-1.0	0.4-1.9	0	0	0	0
	TiO_2	0.5	0.4-0.5	0.5	0.2-0.3	0.2-0.5	0.3	0.2-0.4
	MnO	0.13	0.15	0.1-0.2	0.2-0.4	0.1-0.2	0.11	0.2-0.4
	P_2O_5	0.17	0.1-0.2	0.1-0.2	0.1	0.02-0.1	0.04	0.04
	BaO	0.1	0.1	0.1	0.08-0.1	0.04-0.1	0.09	0.05

LOI(loss on ignition) = "combined water" (hydrates and labile hydroxy-compounds) and carbon dioxide from carbonates. Also present were traces of Cr_2O_3 (0.02%),CoO (0.02%, NiO (0.09%), ZnO (0.02%), SrO (0.03%), Rb_2O (0.08%), ZrO_2 (0.02%), Y_2O_3 (0.002%), V_2O_5 (0.02) and Ga_2O_3 (0.002%)from AGA and some GFGL samples.



Peak List
00-026-0911; Illite-2\ITM\RG#1 [NR]; (K , H3 O) Al2 Si3 Al O10 (O H)2
01-085-2147; Muscovite 2\ITM\RG#1; (Na0.37 K0.60) (Al1.84 Ti0.02 Fe0.10 Mg0.06) (Si3.03 Al0.97)O10 (O H)2
01-076-1746; Gypsum; Ca S O4 (H2 O)2
00-002-0028; Chlorite; (Mg , Fe)5 (Al , Si)5 O10 (O H)8
00-024-1047; Paragonite-1\ITM\RG, syn; Na Al2 (Al Si3) O10 (O H)2

***Figure 3** XRD powder diffractogram of AGA-and GF-TSF tailings sediments at different depths of the soil profile. Quartz (26.6 °2θ) occurs as main mineral in both tailings with few compositions of chlorite and muscovite. Precipitation of gypsum (11.9 °2θ) occurs in the AGA tailings sediments only.*

and critical conclusions. The characterisation of the clay composition of the tailings, especially material from AGA TSF, will be performed by XRD and other methods. From the XRF analysis (Table 2), the oxides of some identified minerals, especially the arsenic element, is incorporated in minerals that require special identification methods in order to describe their chemical behaviour and chemical forms. The complete leaching results from the 'pH-Stat' Method run parallel to the characterisation of the clays. The chemical behaviour and speciation of the total leachable hazardous substances from the tailings is still too early to conclude. The concluding section of this work will focus on the use of mineral reservoir technology to incorporate the identified hazardous substances into an immobile barrier based on reservoir minerals (Poellmann 2007). However, with such a high composition of SiO_2 and Al_2O_3, the possible application of the tailings as raw materials in the cement and construction industry is highly recommended, if the barrier created by their toxicity is to be overcome. The chemical and mineral investigations conducted on the tailings sediments and water alone may not be enough to predict their impact on the groundwater in totality. Further groundwater hydrochemistry is recommended.

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References

Agbesinyale, P. (2003): Ghana's Gold rush and Regional Development-The Case of the Wassa West District, 357. PhD. thesis, University of Dortmund, Spring centre, Dortmund.

Aryee, B. N. A. (2001). Ghana's mining sector: Its contribution to the national economy. Resources Policy 27(2): 61–75.

Aryee, B. N. A. and Aboagye, J. Y. (2008): Mining and Sustainable Development in Ghana. Developing Messages for the UN Conference on Sustainable Development Review – Developing Country Perspective.

E.A.G. (2001): Information, Education and Communication on the Environmental and Socio-economic Effects of Surface Mining. Article from the Environmental Action Group: www.rainforestinfo.org.au/projects / ghana. htm.

Eisenlohr, B. N. & Hirdes, W. (1992): Structural Development of the early proterezoic Birimian and Tarkwaian rocks of southwest Ghana.

GFGL (2010): Site Investigation for the Tailings Dam Facility, GFGL, Tarkwa Mine. Knight Piesold Consulting. Reference: 2176 – PMI – RPT 026 REV 01; unpublished report.

Ghana Chamber of Mines (2006): Facts and figures. Accra: Ghana Chamber of Mines.

Kumah, A. (2006). Sustainability and Gold Mining in the Developing World. Journal of Cleaner Production 14(3–4): 315–323.

Kumah, J. S. *et al.* (2010): Gold Potential of the Ashanti Belt of Ghana. Journal of the School of Marine Science and Technology, Tokai University, Vol. 8, No. 3, pp. 25—39.

LAGA (2002): Mitteilung der Länderarbeitsgemeinschaft Abfall (LAGA) Nr. 33. Guideline EW 98 P (05).

Lottermoser, B. G. (2003): Mine Wastes - Characterization, Treatment and Environmental Impacts. Springer-Verlag Berlin Heidelberg, pp. 143—250.

Manceau, A., Marcus, M. A. & Tamura N. (downloaded June 2011): Quantitative Speciation of Heavy Metals in Soils and Sedments by Synchroton X-ray Techniques. Article from http://lgca.obs.ujf-grenoble.fr/perso/amanceau/pdf/RiMG.pdf.

Parkhurst, D.L, Appelo, C.A.J (1999): User's guide to PhreeqC (version 2) — a computer program for speciation, batch reaction, one dimensional transport, and inverse geochemical calculations. Water-Resources Investigations Report 99—4259, p 326, Denver.

PNDC Law (1986): Ghana Minerals and Mining Law. PNDCL 153.

Parliament of Ghana (1994): Guidelines on Ghana's Mining Environment Regulations, Final Draft 1994. Ammendment Act 475.

Poellmann, H. (2007): Immobilisierung von Schadstoffen durch Speichermineralbildung. Berichte aus der Geowissenschaft, Shaker-Verlag Aachen.

Sansu Tailings Storage Facility (2009): AGA Geotechnical Department. AngloGold Ashanti, Obuasi Mine; unpublished report.

Schueler, V., Keummerle, T. and Schröder H. (2011): Impacts of Surface Gold Mining on Land Use Systems in Western Ghana. AMBIO DOI 10.1007/s13280—011—0141—9, Royal Swedish Academy of Sciences, Springer, pp. 1—12.

Tarkwa Nsuaem Municipal Assembly (2006): Municipality Information. Tarkwa Nsuaem Municipal Assembly.

Wassa West District Assembly (2004): Medium Term Development Plan 2002—2004. District Development Plan, 140. Tarkwa: Wassa West District Assembly.