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Distribution of Arsenic and Heavy Metals from Mine Tailings dams at Obuasi Municipality of Ghana

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Abstract: This present study investigated the issue of gold mine tailings dams as a potential source of arsenic and other trace elements contamination and their dissolution into the adjoining environmental media in Obuasi Municipality of Ghana. One active (Sanso tailings dam) and two abandoned (Pompora and Dokyiwa) mine tailings dams in Obuasi gold mine site, were selected for the collection and analysis of the tailings. The concentrations of As, Fe, Mn, Cu and Zn were determined using an atomic absorption spectrometer (AAS, Varian Models 240FS). The total concentrations of elements in the mine tailings were up to 1752 mg/kg As, 75.16 wt.% Fe, 1848.12 mg/kg Mn, 92.17 mg/kg Cu and 7850 177.56 mg/kg Zn. Sulfate was the dominant anion throughout the leachate, reaching a maximum dissolved concentration of 58.43 mg/L. The mine tailings were contaminated with much higher concentrations of As and heavy metals than the Netherlands soil protection guideline values. Leaching levels of As were in the range of 0.04–0.56 %, presenting high proportions for the total arsenic content in the mine tailings.

Keywords: *Arsenic, heavy metals, mine tailings, gold mining, Obuasi, Ghana*

I.   INTRODUCTION

Ghana, formerly the Gold Coast, is an important gold mining country located in the western part of Africa. Commercial scale gold mining predates the late 19th century. The Ashanti and Western regions are the major gold mining locations. The gold (Au) is associated with sulphide mineralization, particularly arsenopyrite (Griffis et al., 2002). The belief is that the Birimian formation has over ten times the average crystal abundances of gold and arsenic (Kesse, 1985). Due to the nature of the gold ore and the previous method of mining and processing of the metal, environmental degradation and metal pollution are restricted to only mining areas especially Obuasi, Prestea, and Tarkwa. Hence arsenic mobilizes in the environment as a result of arsenopyrite oxidation induced by mining activities (especially dispersal of tailings). The degeneration of the Ghanaian mining environment by mine chemical wastes is principally the consequence of poor management of mine spoil facilities and the reckless manner in which alluvial and open pit activities are carried out.

Mining operations generally produce many types of mine wastes, including mine tailings, waste rock and slag. Mine tailings out of those, in particular, act as a main source of environmental contamination (Roussel et al., 2000). Arsenic (As) and heavy metals may be released from the mine wastes to the ground and surface water systems, as well as the geological environment due to their solubility and mobility (Jang et al., 2005). A large amount of mine wastes including mine tailings, slag, and waste rock were also produced by the mining

operation and are usually passed into the tailings. Also, flood damages and ground subsidence have occurred at the mine several times because it was not equipped with any facility for the prevention of the damage. During the year 2005, there were three recorded incidents of tailings spillage, each of it resulted in serious environmental problems at Obuasi. This spillage from the dams would be the cause of reduced production levels of farm products and reddish color of vegetation in the area as well as the bare nature of some portions of the land (Kumi-Boateng, 2007). Arsenic in mine tailings usually exists in sulfide minerals such as pyrite (FeS2), arsenopyrite (FeAsS), galena (PbS), chalcopyrite (CuFeS2), and sphalerite [(Fe, Zn)S] (Roussel et al., 2000). Oxidation, dissolution, precipitation, adsorption, and desorption mainly occur in mine tailings exposed to the air. Oxidation of sulfide minerals results in contamination of the surrounding soil and groundwater by allowing release of As and heavy metals in sulfide-bearing minerals (Kim et al., 2004; Lim et al., 2009). Furthermore, As and heavy metals from mine tailings may cause fatal diseases in humans through crops and water due to the characteristic easy accumulation in internal organs (Lee et al., 2007). Hence, tailings need to be properly managed because they constitute a major source of release of many trace elements into the environment. Gold mine tailings at Obuasi, for instance, contain very high amount of As, averagely 8305 mg/kg (Ahmad and Carboo, 2000). The preferred approach to tailings management is to pump the tailings, usually in slurry form, into impoundments or dams designed to hold the tailings and perform a number of functions, including treatment functions. Around the town of Obuasi, Prestea and Tarkwa studies in these locations revealed high As concentration in water, soil, fruits, food crops, biological tissues, rivers, school compounds, farmlands and settlements close to the mine sites (Smedley et al., 1996; Amonoo-Neizer et al., 1996; Golow et al., 1996; Carboo and Sarfor-Armah, 1997; Ahmad and Carboo, 2000; Boadu et al., 2001; Akabzaa et al., 2005; Asklund and Eldvall, 2005; Ansong Asante et al., 2005). In cognizance of the above, it is apparent that, the As research in the Ghanaian environment focused primarily on surface waters, soils, food crops, fruits and biological samples with limited studies on mine tailings, identified as one of major source of As poisoning. More so, the few studies performed in some parts of Obuasi were restricted to only few sites with most communities unattended. Unfortunately, gold mining is progressing steadily in Obuasi environment known to have geology rich in arsenopyrite. Yet, the impact of this element in the Ghanaian environment has not received the fullest attention.

This present study investigated the issue of gold mine tailings dams as a potential source of arsenic and other trace elements contamination and their dissolution into the adjoining environmental media in Obuasi Municipality. The study considered two types of tailings dams - one active and two decommissioned - and assessed the distribution of these heavy metals. In addition, leaching test was conducted with rain water to ascertain a way to preserve arsenic species without change of their oxidation states and to prevent added chemicals from affecting dissolution process.

II. PHYSIOGRAPHY, GEOLOGY AND HYDROGEOLOGY

Obuasi is located in the Ashanti region of Ghana (Fig. 1) and is about 64 km south of Kumasi, the regional capital and 300 km north-west of Accra, the capital of Ghana. It is situated at latitude 6° 12' 00'' North and longitude 1° 40' 00'' West. It is located in the tropical evergreen rain forest belt. It covers an area of about about 162.4 km^2 and is bounded on the south by Upper Denkyira District of the Central Region, east by Adansi South District, west by Amansie Central District and north by Adansi North District (Mensah, 2012). The climate is of the semi-equatorial type with a double rainfall regime. Total annual rainfall is about 1700 mm. Mean average annual temperature is 25.5 ℃ and relative humidity is 75-80 % in the wet season (Fig. 2).
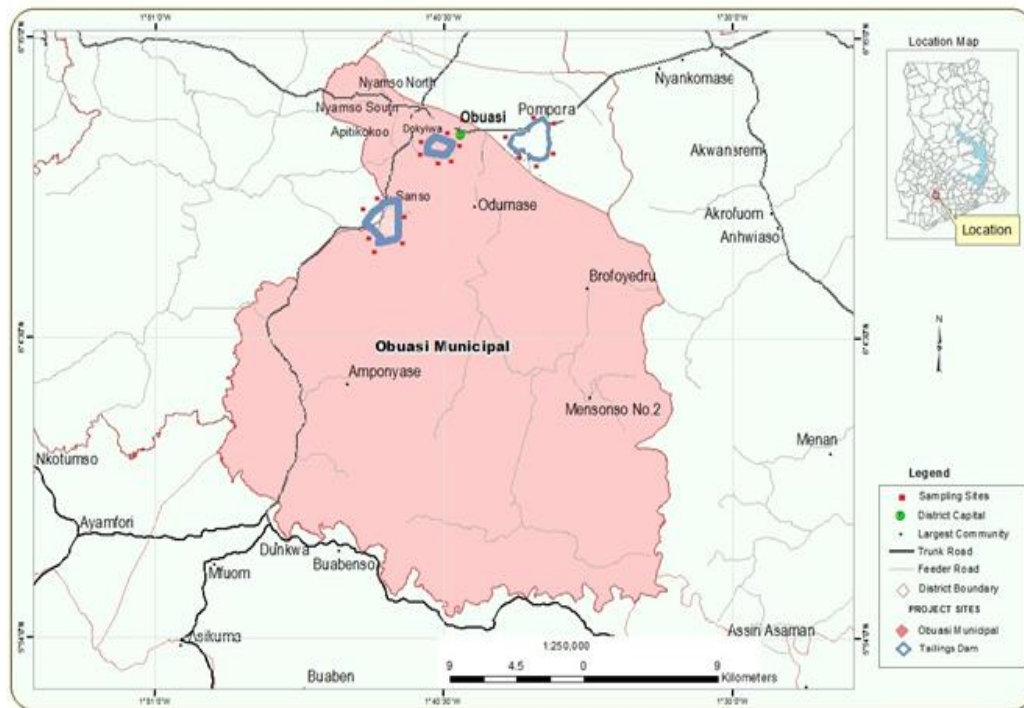
Fig. 1 Map of Obuasi Municipality showing the Sansu, Dokyiwa and Pompora tailing dams
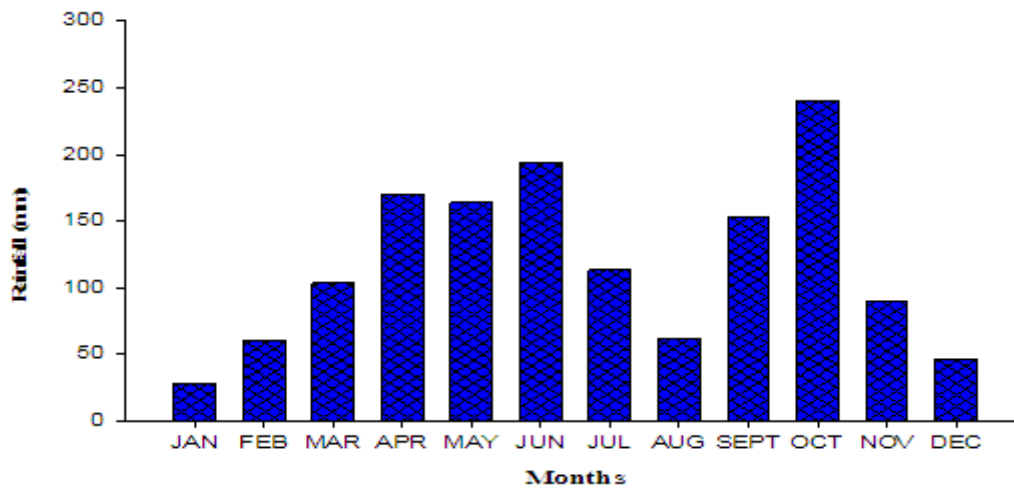
Fig. 2 Monthly rainfall pattern in Obuasi Municipality of Ghana

The area is underlain by metavolcanic, pyroclastic and metasedimentary rocks (Fig. 3). The metavolcanic rocks are of basaltic and gabbroic in compositions whereas the metasedimentary rocks are mainly tuffaceous and carbonaceous phyllites, tuff, cherts and manganeferous sediments. These two units are contemporaneous and separated by a major shear zone. Intruding the metavolcanic and metasedimentary rocks are magmatic bodies and porphyritic granitoids consisting of hornblende-rich varieties that are closely associated with the volcanic rocks, and mica-rich varieties which are found in the metasediment units (Kesse, 1985). The Birimian is overlain by the Tarkwaian rocks made up of sedimentary units and also recent alluvial deposits. Gold ores contain high sulphide minerals, made up mainly of arsenopyrite and pyrite (Osae et al., 1995). The top 30-80 m of the subsurface is made up of porous rocks that mark the water table in the area (Foli and Nude, 2012). Rock porosity ranges from $1.0\text{-}5.0\times10G7$ m/s (Kumapley, 1993). These rocks have undergone some degree of weathering and consist mainly of clay deposits which have subsequently been hardened and altered. A cross section of the hills along the roads reveals the presence of an uneven distribution of quartz veins injected into the phyllites which break up on weathering to give rise to pisolithic and gravely pebbles (Boateng et al., 2012). The topography of Obuasi and its environs varies from gently undulating to hilly. There

are moderately high-elevated lands with lowlands and valleys between them. The highlands trend in different directions; they have flat and plateau tops and are generally amorphous in their shapes.
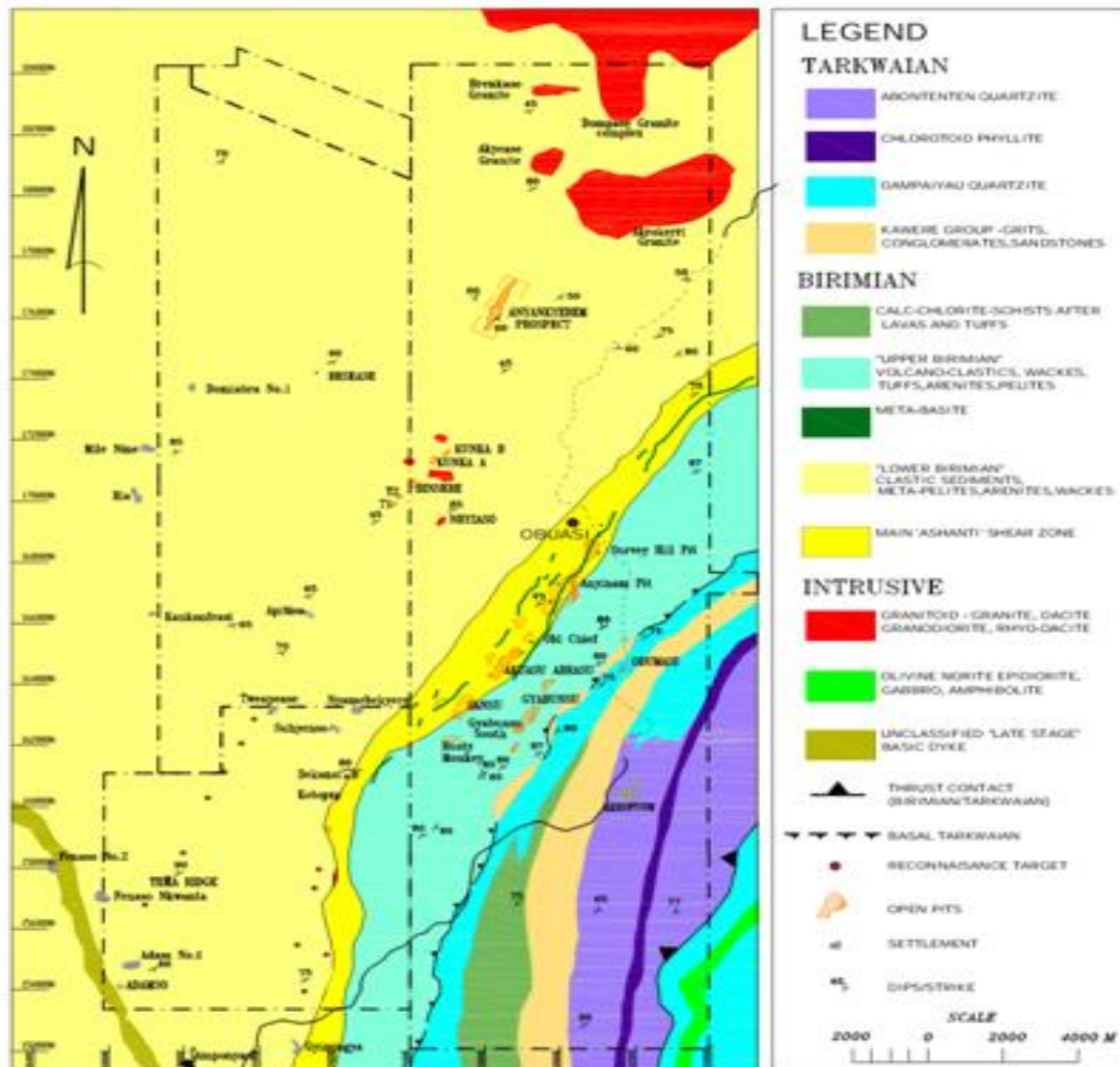

Fig 3 The geological map of Obuasi

III.   MATERIALS AND METHODS

Sample Collection

        Active and abandoned gold mine tailings dams (Fig. 1) were selected for the sample collection and analysis in the present study: they are Sansu active tailings dam, abandoned tailings dams at Pompora and Dokyiwa communities, respectively. The active tailings dams were built some two decades ago with the decommissioning of the old dam, which was used for several decades. Six spots were selected randomly at each study site for sampling using soil auger and chisel hoe. Mini pits were dug at selected points, the soils were identified by the series name and sampled at a depth of 0-20 cm. At each demarcated selected point within every site, three 1 kg soil samples were collected at a depth of 20 cm from six different locations apart by about 15 m (Fig. 1). Samples were however, not taken from locations that were difficult to access. The samples were placed into plastic bag, and then stored in a cooler in the field. The samples were transported to the laboratory for analysis. The concentrations of As, Fe, Mn, Cu and Zn were determined using an atomic absorption spectrometer (AAS, Varian Models 240FS). Particle size distribution was determined using the modified Bouyoucos hydrometer (Day, 1965). Soil pH and electrical conductivity (EC) were also determined by glass electrode in a soil-water ratio of 1:2.5. Dissolved oxygen (DO, YSI model 58) was measured. The values of several anions (Cl^-, F^-, NO_3^-, and SO_4^{2-}) were determined by an ion chromatography (as described below).

Laboratory Analysis

In order to determine the total concentrations of arsenic and metals (Fe, Cu, Mn and Zn) in the mine tailings, the samples were dried using a freeze-drier for 3–4 days and homogenized by thorough mixing. The homogenized dried samples were sieved through a 0.2 mm sieve and were digested using EPA method 6010 (Roy-Keith, 1998). A total of 18 samples were digested separately and replicate results for each sample were obtained by repeating the same process on two different days. The final suspended mixture was filtered through a 0.45 μm membrane filter. The same procedure was performed with a blank and a standard reference material (2711, Montana Soil Moderately Elevated Traces) in each batch of digestion. The concentrations of arsenic and the trace metals in the leachate were determined using atomic absorption spectrometer (AAS) whereas those of anions were by ion chromatograph (IC).

Lastly, leaching concentrations of arsenic from the mine tailings were evaluated. Leaching tests of the mine tailings were performed to indirectly evaluate release and mobility of contaminants to the surrounding environment by normal rainwater (approx. pH 5.8). The leaching test was conducted with rainwater in order to preserve arsenic species without change of their oxidation states and to prevent added chemicals from affecting As dissolution process.

Quality Control Parameter for Mine Tailings Arsenic Determination

Quality control measures were incorporated into the analytical scheme. Instrumental calibration, replicates and field blanks were prepared according to Knödel et al., (2007). A quality control (QC) standard was run routinely during the sample analysis to monitor instrument drift and overall quality of the analysis. For instrument calibration, a 100 μg/L As standard was prepared from serial dilutions of a 1000 μg/L stock standard. A calibration curve of 0.1, 0.5, 1.0, 1.5 and 2.0 ppm was prepared from that 100 μg/L arsenic standard. To detect possible interferences and matrix effects, which are considered important for arsenic determinations, the standard addition method was used with five arbitrarily chosen samples (Table 1).

Table 1 Calibration plots corresponding to the standard of arsenic and the standard addition method of different samples

Standard of As	r (correlation coefficient)	a (intercept)	b (slope)	Slope ratios of As standard/sample
Standard of As	0.9998	0.0001	0.049	1.000
BK1	0.9979	0.0390	0.045	1.365
OB2	0.9999	0.0026	0.040	1.333
AW3	0.9995	0.0135	0.041	1.304
AC4	0.9993	0.0860	0.014	4.305
AN5	0.9989	0.0018	0.026	2.000

Absorbance = a+b (As, ppb).

The analytical characteristics for arsenic determination in mine tailings leachate samples were done by spiking three leachate samples from their respective tailings dam with 10 μg arsenic to three equal fractions of leachate samples, respectively. A matrix modifier of 5 μg of Pd and 3 μg of $Mg(NO_3)_2$, was used for each 20 mL of sample and was added into the blank, standard and samples. All samples and blanks were digested and diluted using the same procedure as described above. Reagent blank determinations were used to correct the instrument readings which were usually very low for this method.

Table 2 shows the analytical characteristics for arsenic determination in mine tailings leachate samples by AAS.

Table 2 Analytical recoveries (%) ± SD of As metal in mine tailings leachate samples at 10.0 μg/L fortification levels (n=3)

Leachate samples	SpikedAs (mgL^{-1})	Recovered As (%)
Dokyiwa	10	98.4± 0.3[a]
Pompora	10	94.9± 1.7
Sansu	10	88.3 ± 1.2

[a] Average ± standard deviation.

Mean recovery for the several added samples considered was 97.21±2.83 % (n=6). Mean relative standard deviations were lower than 7.00 %.

The arsenic concentrations determined in the certified reference material NIST CRM 1643d (National Institute of Standard and Technology) containing trace elements in water and total arsenic at a certified

concentration of 56.02 ± 0.73 μg/L, was also analyzed (n=10) and was not significantly different from certified levels (p > 0.05) (Table 3).

Table 3 Accuracy and precision of the proposed method for arsenic determination against standard reference materials.

Reference material	Mean total As ± SD (μg/L)		Accuracy (%)	Precision RSD (%)
	Certified value[a]	Measured value[a]		
NIST CRM 1643d	56.02 ± 0.73	54.67 ± 0.89	96.41	5.33

IV.   RESULTS AND DISCUSSION

Data on particle size distribution are presented in Table 4. Generally mine tailings from Sanso, Pompora and Dokyiwa tailings dams were reddish-brown to dark-gray coloration and sticky. The samples were in a slightly wet state containing 9.6 %, 6.2 % and 4.5 % water from the mine tailings from Sanso, Pompora and Dokyiwa tailings dam, respectively. The texture of the mine tailings at Sanso is silty clay loam whereas those of Pompora and Dokyiwa are clay.

Table 4 Particle size distribution (mean of three samples) and texture of the tailings mud

Sampling location	Depth (cm)	Particle size distribution (%)			Texture	Moisture content
		Sand	Silt	Clay		
Sanso	0-20	12	56	32	Silty clay loam	9.6
Pompora	0-20	20	29	51	Clay	6.2
Dokyiwa	0-20	30	20	50	Clay	4.5

Data represent means of 6 samples per site

Table 5 shows pH, DO and the concentrations of fluoride, chloride, nitrate and sulfate in the leachate of mine tailings. The pHs of leachate in the analyzed samples were alkaline in nature which are not so low (not so acidic). In many cases, the mine leachate where acid mine drainage occurs would show very low pH values such as 2-4 (Jambor et al., 2003; Alvarez, et al., 2006). These neutral or slightly alkaline conditions greatly affected mobility of arsenic in the tailings mud. Relatively high pH values in this tailings mud may be derived from deficiency or less abundance of sulfide minerals in the tailings dam. Thus not much sulfate was generated from oxidation of the sulfide minerals, which did not substantially lower the pHs of the tailings mud, however, sulphate was the dominant anion among the other anions determined, reaching a maximum dissolved concentration of 58.43 mg/L. The high concentration of sulfate indicates that the oxidation of sulfide minerals had occurred in the mine tailings, so that sulfate had been produced.

Table 5 Values of several chemical constituents in leachate of mine tailings (n=18)

Sampling location	pH	Chemical constituent (mg/L)					
		EC (μS/cm)	DO	F⁻	Cl⁻	NO₃	SO₄⁻²
Sanso 1	7.13±1.23[a]	686±48.36	3.32±1.12	0.04±0.02	1.42±0.96	0.35±0.09	53.17±7.74
Sanso 2	7.53±0.98	690±52.68	3.76±1.42	0.06±0.03	0.39±0.13	0.57±0.36	58.43±9.64
Pompora 1	6.12±2.34	798±79.22	3.83±1.08	0.28±0.14	0.19±0.07	0.48±0.84	32.73±6.46
Pompora 2	7.85±2.02	773±0.74.64	3.67±1.03	0.15±0.09	0.23±0.17	0.76±0.62	40.13±7.15
Dokyiwa 1	7.17±1.42	665±35.46	4.95±1.72	0.78±0.16	4.44±1.24	0.13±0.07	29.64±5.33
Dokyiwa 2	7.94±1.06	732±42.83	5.03±2.08	1.26±0.84	3.97±1.03	0.17±0.03	56.87±9.14

[a]Mean ±standard deviation.

As shown in Fig. 4, the concentration of sulfate is inversely related to pH, showing that the sulfuric acid is the main source of large amounts of hydrogen ions. The EC values of the tailings mud ranged from 665 to 798 μS/cm , which were considered quite similar values compared with those in other abandoned metal mines (Kim *et al*., 1995). The highest EC values were measured at mine tailings (Pompora 1=798 and Pompora 2=773 μS/cm).
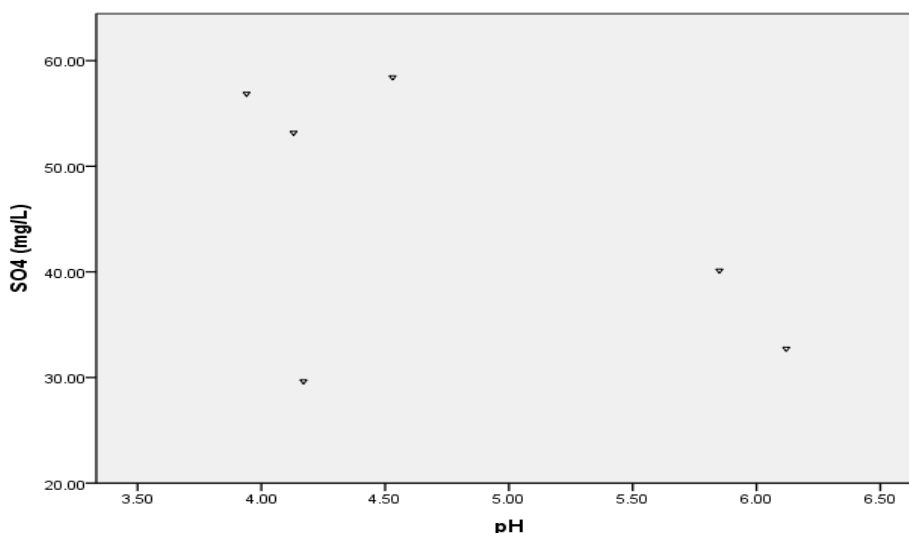
Fig. 4 Relation between pH and sulfate concentration in leachate of mine tailings.

The concentrations of other anions in the leachate were very low (<1.5 mg/L, with an exceptional value 4.5 mg/L for Cl⁻). The values of DO were relatively low (3.32–5.03 mg/L at 25 ^{0}C).

Table 6 shows the total concentrations of arsenic and other trace metals (As, Fe, Mn, Cu and Zn) in the mine tailings and arsenic leaching rates in rainwater. The results showed that the mine tailings were heavily polluted with arsenic, and total concentrations of each element were diverse. The total concentrations of elements in the mine tailings were up to 1752 mg/kg As, 75.16 wt.% Fe, 1848.12 mg/kg Mn, 92.17 mg/kg Cu and 7850 177.56 mg/kg Zn. The order of abundance of the trace elements was Fe>As>Mn>Zn>Cu in the analyzed mine tailings (Table 6).

Table 6 Concentrations of arsenic and metals in mine tailings, and arsenic leaching rates in rainwater (n=18)

Sampling location	Concentrations of arsenic and metals in mine tailings					Leaching rate in rainwater
	As (mg/kg)	Fe (wt. %)	Mn (mg/kg)	Cu (mg/kg)	Zn (mg/kg)	As (%)
Sanso 1	542±21.34[a]	7.87±4.34	154.63±21.35	33.42±6.32	88.67±33.58	0.04
Sanso 2	622±35.46	4.14±0.53	129.56±34.57	24.16±7.32	79.47±17.94	0.06
Pompora 1	1634±124.53	33.26±14.32	846.13±77.34	82.44±13.57	185.13±24.87	0.43
Pompora 2	1752±154.34	46.41±16.46	1204.63±127.46	79.12±18.3	204.56±43.65	0.36
Dokyiwa 1	1412±112.78	57.23±21.02	1848.12±168.96	92.17±11.35	165.48±54.86	0.56
Dokyiwa 2	1292±175.49	75.16±31.21	1653.43±143.62	88.64±7.34	177.56±33.42	0.55

[a]Mean ±standard deviation.

Arsenic concentrations in soils from the decommissioned tailings dam site (Pompora and Dokyiwa tailings dam) far exceeded that from the active tailings dam (Sanso tailings dam). In relation to the Netherlands soil protection guidelines, As levels in soil beyond 55 mg/kg dry weight requires remediation (VROM, 2000). At this threshold, all the soils tested, especially soils from decommissioned and active tailings dams sites, showed poor quality with respect to As and may pose environmental health concern. Potential intrusions of As from the decommissioned tailings dam was approximately three fold that from the active tailings dams.

The Fe content in all the analyzed samples was far above the soil protection guideline value of 21,000 mg/kg, which meant that the presence of the tailings dams, both active and decommissioned probably impacted the surrounding soils with significant amount of Fe. Soils in Obuasi are rich in iron, associated with gold ore deposits principally characterized by sulphide minerals in arsenopyrite form (Osae et al., 1995; Amonoo-Neizer et al., 1995; Asiam, 1996; Smedley, 1996; Smedley et al., 1996; Ahmad and Carboo, 2000; Kumi-Boateng, 2007).

Mn contamination from the active tailings dams is only marginal, as the Mn levels from the active tailings dam were within the permissible range of values of 320 mg/kg for soil protection guideline. However, the levels of Mn in the decommissioned tailings dam were far above the intervention limit of 320 mg/kg. Factors contributing to the differences in Mn concentration between soil samples from the two tailings dam sites are not clear, however, the possible cause for this might be poor mobility of Mn in soils. Mn contamination from the

dams via movement through soil might take considerably long time to manifest, probably, a reason why the Mn contamination was more pronounced in the decommissioned dam compared to the more recent active dam. Another reason might be the susceptibility of old dried tailings of the decommissioned dam to transport by air, in view of the fact that it was not capped.

The mean concentrations of Cu in soils from the active and decommissioned tailings dams exceeded the recommended limit of 36 mg/kg for a typical uncontaminated soil, however, the values were still within Cu intervention limit of 190 mg/kg for contaminated sites (VROM, 2000).

Zn contamination from the active tailings dams is also marginal, as in the Mn levels from the active tailings dam. The mean levels of Zn from the active tailing dam were within the recommended limit of 140 mg/kg for a typical uncontaminated soil. However, Zn levels of soil samples from the decommissioned tailings dam site fell short of recommended background level of 140 mg/kg, but were still within intervention limit of 720 mg/kg (VROM, 2000).
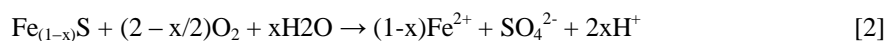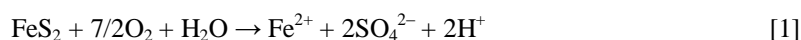
With regards to the site with the highest concentrations of trace elements, the following observation was made: decommissioned tailings dam site (Dokyiwa) > decommissioned tailings dam site (Pompora) > active tailings dam site (Sanso). The high level of trace elements contamination potentially associated with the decommissioned tailings dam in this study could be a function of dust, since the tailings were dried and uncapped, and easily prone to the effect of wind. Hence the tailings dam will release a considerable amount of these contaminants into the surrounding soils.

The low levels of As and trace metals observed in the active tailings dam might be as a result of the active tailings dams, being relatively recent (built in 1991), have benefited from substantial technological improvement over the decommissioned one, which was one of the earliest to be operated at the AngloGold Ashanti mines. Coupled with recent implementation of an environmental management system that is ISO 14001 compliant (since December 2006), there has been great institutional commitment to keep contamination from mining operations very low at the AngloGold Ashanti mines (Antwi-Agyei et al., 2009). In addition the presence of security around tailings facilities has prevented vandalization of these facilities, perhaps, constituted a network of management activities that altogether might have worked to ensure the reduced level of contamination around the active tailings dams. Indeed, provision of improved security to protect tailings facilities has substantially reduced deliberate damages to tailings transmitting lines by small-scale artisanal miners, who often seek to obtain and reprocess these tailings.
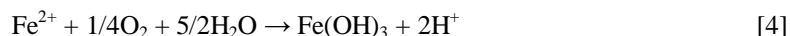
Hitherto, such damages to tailings lines resulted in spillage problems that affected land, vegetation and nearby rivers (AngloGold Ashanti, 2006). The active tailings dams are also presently equipped with facility for draining and re-treatment of effluent, which did not exist during operation of the old decommissioned dam. Leaching tests of the mine tailings were performed to indirectly evaluate release and mobility of contaminants to the surrounding environment by normal rain. Thus rain water (approx. pH 5.8) was selected for the leaching test.

Table 6 shows leaching concentrations of As from the mine tailings. Especially, the leaching levels of As were in the range of 0.04–0.56 %, presenting high proportions for the total arsenic content in the mine tailings. Kim et al., (2000) and Lim et al., (2009) reported a similar result on leaching of As from mine tailings. In their study, As leaching levels were in the range of 0.0017–0.37 % and 0.014–0.026 %, respectively, when mine tailings of six types were mixed with water for 1 hr at a ratio of 1:5 as mass and 1:10 wt:wt, respectively. Even though the test conditions such as leaching solution and shaking time do not correspond to those in our study.

This result is also comparable with results conducted elsewhere (Jang et al., 2005; Ribit et al., 1995; Johnson et al., 2000). Although the mine tailings used in this study were sampled from the surface (0-20 cm) of the uncovered mine tailings pile at active and abandoned mine tailings dam which had been allowed to be in contact with oxygen. This condition might have resulted in the oxidation of sulfide minerals in the mine tailings. The oxidation of sulfide minerals which combine with As can also result in the dissolution of As by water (Lim et al., 2009). Based on the presence of sulfide minerals, high contents of As, potential of oxygen contact, and high sulfate concentration in the mine tailings, the equations 1–3 related to dissolution of iron and arsenic, as an example, could have occurred in the mine tailings (Kim et al., 2004; Lim et al., 2009; McGregor et al., 1998; Johnson et al., 2000):

$$FeS_2 + 7/2O_2 + H_2O \rightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad [1]$$

$$Fe_{(1-x)}S + (2 - x/2)O_2 + xH_2O \rightarrow (1-x)Fe^{2+} + SO_4^{2-} + 2xH^+ \qquad [2]$$

$$4FeAsS + 13O_2 + 6H_2O \rightarrow 4Fe^{2+} + 4H_2AsO_4^- + 4SO_4^{2-} + 4H^+ \qquad [3]$$

Here, ferrous ions precipitate in the form of ferric hydroxide by oxidizing or hydrating, as shown in the equation (4):

$$Fe^{2+} + 1/4O_2 + 5/2H_2O \rightarrow Fe(OH)_3 + 2H^+ \qquad [4]$$

As and heavy metals released by oxidation can be re-adsorbed onto the surface of ferric hydroxide, and also adsorbed As and other heavy metals can be separated from the surface of ferric hydroxide by water (Lim et al., 2009; Holmstrom et al., 1999).

V.   CONCLUSIONS

Considerable amount of As and trace elements (Fe, Cu, Mn and Zn) contamination was associated with gold mine tailings dams, irrespective of whether the dam was active or decommissioned. This potential impact was greater for decommissioned tailings dam since the tailings were dried and uncapped, and easily prone to the effect of wind. Hence the tailings dam will release a considerable amount of these contaminants into the surrounding soils. Arsenic contents of soils from the vicinity of the active and decommissioned tailings dams far exceeded recommended Netherlands intervention value of 55 mg/kg, hence, constituted significant environmental health threat. However, Cu and Fe contents of the mine tailings from both active and decommissioned tailings dams within the study area were also far above the Netherlands soil protection guideline values. Similar pattern was exhibited in the Mn and Zn levels in the abandoned tailings dams but not in the case of active tailings dam which might not present direct environmental threat, although potentially, they could remobilize (with rainfall) and affect aquatic systems. The leaching concentration level of As observed in this study indicates that easily soluble fraction of As might be already released by the oxidation of sulfide minerals with air and water for a long period at the tailings deposition site. Based on the potential that As could be already released from the mine tailings, investigations on the status of contaminants in nearby environmental media (lands, plants, nearby streams and rivers as well as groundwater) are needed. In addition, mine tailings treatment is needed to prevent additional oxidation of sulfide minerals in mine tailings by oxygen contact which releases As and heavy metals by water.

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