Attenuation Potential of Clay Liner Carbon-in-Leach Tailings Storage Facilities – A Case Study at Gold Fields Ghana Limited, Tarkwa Mine (GFGL)

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Abstract This study presents research findings on cyanide attenuation potential of the substrata material of Tailings Storage Facilities (TSF) at Gold Fields Ghana Limited (GFGL), Tarkwa Mine. The attenuation properties of the substrata considered and evaluated were hydraulic conductivity (K), permeability characteristics and geochemical properties; pH, Organic Matter Content (OMC), Cation Exchange Capacity (CEC), Iron Oxide and Anion Exchange Capacity (AEC). Substrata material samples were taken before and after an insitu cyanide leaching test at five locations in and around the three TSF; TSF 1, TSF 2 and TSF 3. Total and Weak Dissociable Cyanide (WAD) were analyzed after leaching test.

Keywords Tailings Storage Facility, hydraulic conductivity, permeability, geochemical, organic matter content, cation exchange capacity

Introduction

The environmental fate of free cyanide and metal-cyanide complexes have been under intensive investigation over the last three decades. Cyanide is naturally occurring and natural mechanisms exit both geochemically and biogeochemically exist to retard or attenuate its movement in subsurface, and to degrade its compounds into low-hazard reaction products such as nitrogen gas, ammonia, nitrate, and carbon dioxide. The attenuation capacity of subsurface earth materials can be measured, quantified, predicted, and most importantly can be enhanced by rather simple and inexpensive procedures. The fact that natural earth materials have quantifiable and predictable ability to remove contaminant trace elements from migrating seepage has been documented for more than ten years (Griffin 1976, Griffin 1977). According to Griffin (1976), the overall pollution from contamination sources could be reduced if liners of natural earth material were designed for lower hydraulic conductivities. According to Ghosh *et al.* (2006a), various factors effluence the cyanide cycle in the environment and it includes but not limited to pH, temperature, sunlight intensity and OMC of soils.

Study Area

The study area comprised of the TSF at GFGL with specific emphasis on he substrata. The facility is located in the Tarkwa Nsuem Municipality in the Western region of Ghana. Tarkwa is on latitude 5°15′ N and longitude 2°00′ W and located within the South Western equatorial climatic zone. This zone is described as a moist tropical climate characterised by high year round temperatures and rainfall pattern. Rainfall peaks is from April to June and October to November. Average rainfall over the last 50 years at the mine site is 1600 mm per annum. The average daily temperatures range from 24.5 °C to 27.8 °C with peak readings in the months from February to April (Arthur *et al.* 2004). The three TSF's (TSF 1, TSF 2 and TSF 3)

Sample ID	pH	C.E.C (meq/100 g)	A.E.C (meq/L)	OMC (%)	Fe_2O_3 (ppm)
Station 1	4.5	2.01	1278.25	0.36	49.57
Station 2	4.5	2.89	1057.50	0.53	63.14
Station 3	4.8	2.34	881.25	0.78	66.43
Station 4	4.3	1.92	1057.50	0.43	22.86
Station 5	4.5	2.37	881.25	0.98	29.00

Table 1 *Geochemical parameters of sampled clays*

were substrata were the prime focus of the study.

Methodology

Field Leaching Test

Leaching test was carried out at five locations in the TSF basin. At each station, an auger drill was used to drill a hole to a depth of 1.5 m and fitted with a 2 m length Polyvinyl Chloride (PVC) pipe (101.6 mm diameter) which has been perforated. Four monitoring holes, at a distance of 3 m from the leaching point hole were also similarly constructed as the leaching point. A depth of 1.5 m was chosen to conform to the thickness of the clay in the TSF basin. Tailings slurry with 50 mg/L WAD concentration was introduced into the leaching points at the respective leaching sites, up to the 1.5 m level. Concentration of slurry conformed to GFGL mine limits for WAD in tailings discharged which averaged 48 mg/L from field sampling programme at various spigoting points.The leachates in the monitoring points at the respective leaching points were sampled and analyzed for Total and WAD cyanide after a month. Cyanide leachate in the monitoring holes surrounding the leaching points were sampled monthly and analyzed for WAD and Total cyanide. This was repeated over six month's period. Samples of the substrata were taken and analyzed to verify the impact of the leaching on the attenuation potential of the TSF clay liner.

Soil Sampling

A total of ten (10) clay soil samples were collected from the five leaching points in July 2010 prior to the leaching test. The same number of samples was taken in June 2011 to analyze for geochemical parameters after the leaching test. These disturbed clay samples of varied texture were taken from depths ranging from 1 to 1.5 m. The samples were coned and quartered on a clean polyethylene sample sheet and representative samples taken and transferred into a new, clean polyethylene sample bag. Samples earmarked for dry sieve analysis weighed 7 kg each, whiles that earmarked for hydrometer tests and geochemical tests weighed 1.5 kg each. The attenuation properties of the clay samples considered are the hydraulic conductivity, permeability characteristics and geochemical properties.

Results and Discussion

Geochemical Parameters

Geochemical investigations carried out on clay samples collected from five identified sites showed the results of the geochemical parameters as presented in Table 1.

Hydraulic Conductivity (K), Permeability (k_i) and Porosity (n) of Soil Samples

The Alyamani and Sen (1993) empirical formula and relevant parameters derived from grain size analyses were used to determine the hydraulic conductivity of the clay samples collected from the five respective stations. The field calculated hydraulic conductivity values were in the range of 6.2×10^{-3} to 1.41×10^{-2} m/d with a mean value of 8.3×10^{-3} m/d which is presented in Table 2. The maximum value of *K* was obtained from clay sample from Station 3, whiles the minimum value of K was obtained from clay sample from Station 5. Hydraulic conductivity values of silt, clay and mixtures of sand, silt and clay were in the orders of 10^{-2} and 10^{-4} m/d (Brassington 2007). Based on this

Sample ID	I_o (mm)	d_{10} (mm)	d_{50} (mm)	K (m/day)
Station 1	1.17×10^{-3}	4.1×10^{-3}	5.34×10^{-2}	7.5×10^{-3}
Station 2	1.12×10^{-3}	4.1×10^{-3}	5.40×10^{-2}	7.3×10^{-3}
Station 3	2.17×10^{-3}	4.0×10^{-3}	4.88×10^{-2}	1.4×10^{-2}
Station 4	1.15×10^{-3}	4.1×10^{-3}	4.86×10^{-2}	6.7×10^{-3}
Station 5	1.11×10^{-3}	4.0×10^{-3}	4.68×10^{-2}	6.2×10^{-3}
			Mean	**8.3×10^{-3}**

Table 2 *Summary of Hydraulic Conductivity of Clay Samples*

Sample ID	K (m/day)	Mean Dynamic Viscosity	K_i, (m²)
Station 1	7.5×10^{-3}	8.87×10^{-1}	7.72×10^{-12}
Station 2	7.3×10^{-3}	8.87×10^{-1}	7.50×10^{-12}
Station 3	1.4×10^{-2}	8.50×10^{-1}	1.39×10^{-11}
Station 4	6.7×10^{-3}	8.90×10^{-1}	6.91×10^{-12}
Station 5	6.2×10^{-3}	8.50×10^{-1}	6.10×10^{-12}
		Mean	**8.42×10^{-12}**

Table 3 *Estimated Permeability (k_i) of Clay Samples*

No: of Samples	Mean d_{10}(mm)	Mean d_{60}(mm)	Mean $U = d_{60}/d_{10}$	Mean $n = 0.255(1 + 0.83^U)$
5	4.1×10^{-3}	7.8×10^{-2}	19.2069	0.2621
				Percentage = 26.21 %

Table 4 *Estimated Mean Porosity (n) of Clay Samples*

Sample ID	K (m/day)	pH	C.E.C (meq/100g)	A.E.C (meq/L)	Total Cyanide (mg/L)	WAD Cyanide (mg/L)
Station 1	7.5×10^{-3}	4.5	2.01	1278.25	0.010	0.010
Station 2	7.3×10^{-3}	4.5	2.89	1057.50	0.020	0.011
Station 3	1.4×10^{-2}	4.8	2.34	881.25	0.030	0.010
Station 4	6.7×10^{-3}	4.3	1.92	1057.50	0.010	0.010
Station 5	6.2×10^{-3}	4.5	2.37	881.25	0.010	0.010

Table 5 *Summary of Major Attenuation Properties*

premise, the results can be said to be quite consistent with the hydraulic conductivity of clay. Permeability values (k_i) were calculated using Kresic (2007) equation. The k_i values as presented in Table 3, are very low ranging from 7.72×10^{-12} to 1.39×10^{-11} m² with a mean value of 8.42×10^{-12} m².

The estimated mean porosity value as shown in Table 4 is 26.21 %. Comparing this value with standard porosity values for clay (≈ 26-68 %; Kresic 2007), and studies conducted by Barnie (2010), on similar clay materials in the Atankwidi sub-basin of the White Volta Basin in Ghana, where he had a mean porosity of 26.24 %, the obtained mean porosity value is consistent with clayey soils in Ghana.

Table 5 gives a summary of the major attenuation properties of the TSF sub-strata material that influences cyanide attenuation.

Cyanide decay analyses of the sub-strata material of the TSFs

Within a working radius of 3 m, the sub-strata material at the respective leaching sites returned average Total cyanide concentrations ranging from 0.01 to 0.03 mg/L and WAD cyanide levels ranging from 0.01 to 0.011 mg/L. No concentrations of Free, WAD or Total cyanide were detected in the drilled holes prior

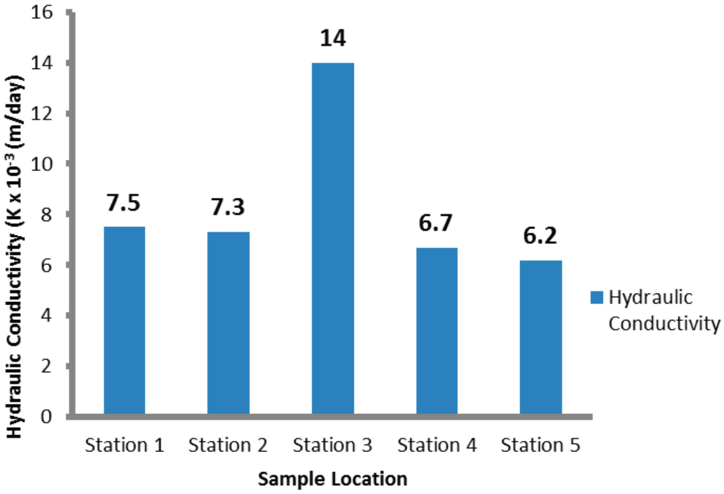

Fig. 1 *Hydraulic Conductivity Results from the respective stations*

to the leaching test.WAD cyanide results from the leaching test falls within limits stipulated, for TSFs with planned measures for cyanide degradation, where concentrations range from ≈1-10 mg WAD-CN/L (NICNAS, 2010). Moreover, the Total and WAD cyanide results falls within stipulated limits of EPA-Ghana, which states a Total and WAD cyanide limit of 1 mg/L and 0.6 mg/L respectively and hence, poses no threat to groundwater resource. However, the average cyanide detected with time at the five stations remained fairly constant as time increased.

Effect of hydraulic conductivity and permeability on cyanide attenuation

Total cyanide concentration from the leachate at Station 3 recorded the highest value due to the high hydraulic conductivity of the substrata. Clay material from Station 5 had the least hydraulic conductivity and attenuated 50 mg/L concentration of NaCN to 0.010 mg/L of Total cyanide and WAD cyanide respectively. Based on the geochemical results from the leaching stations, it was observed that clay material from Station 5 had unfavorable geochemical parameters which gave it a weak cyanide attenuation property. Such properties are; least AEC (881.25 meq/L), high CEC(2.37 meq/100 g) and low Iron-oxide content (29 ppm). However, it exhibited acidic (average pH is 4.5) values, high OMC (0.98 %), 0.010 mg/L Total and WAD cyanide concentration respectively. Clay material from Station 2 was able to attenuate the 50 mg/L NaCN to 0.020 mg/L of Total cyanide and 0.011 mg/L of WAD cyanide due to the fact that it was acidic (pH-4.5), had a high AEC (1057.50 meq/L) and high Fe-oxide content (63.14 ppm). The sample however, had the highest CEC (2.89 meq/100g) and low OMC (0.53 %), thereby rendering it ineffective in cyanide attenuation.Despite the fact that there was 0.01 mg/L of WAD cyanide in leachate samples of Station 3, Total cyanide values were the highest (0.030 mg/L) compared to leachate from Station 2 (0.020 mg/L) and Station 5 (0.010 mg/L). Although its clay material had the highest Fe-oxide content (66.43 ppm) and high OMC (0.78 %), the differences in cyanide attenuation was due to the fact that it had the least AEC (881.25 meq/L), high CEC (2.34 meq/100g) and had the highest pH (4.8).

Clay material from Station 4 attenuated both Total and WAD cyanide to 0.01 mg/L inspite of its low OMC (0.43 %) property and lowest Fe-oxide content (22.86 ppm). This could be attributed to the fact that clay material from Station 4 was highly acidic (4.3), had lowest CEC (1.92 meq/100 g) and high AEC of 1057.50 meq/L. Similarly, clay material from Station 1 also attenuated both Total and WAD cyanide to 0.01 mg/L, though having the lowest OMC (0.36 %) and a relatively lower CEC (2.01 meq/100 g). The cyanide attenuation in Station 1 was due to the fact that Station 1 was acidic (4.5), had the highest AEC (1278.25 meq/L) and Fe-oxide content of 49.57 ppm. An assessment of the hydraulic conductivity, permeability and geochemical results of clay material from the five leaching sites with respect to the Total and WAD cyanide concentrations from their leachate, revealed that low hydraulic conductivity and a combination of low acidic pH, relatively high AEC and low CEC were the major attenuation properties that influenced cyanide attenuation (Fig. 1). This agrees with studies conducted by Dzombak *et al.* (2006a)

Significant variations were recorded in all the geochemical parameters in samples taken after the leaching test and these are the pH, AEC, CEC, Fe_2O_3 and OMC. pH decreased significantly for all the five leaching sites with values ranging from 3.0 to 3.4 and a corresponding increase in AEC ranging from a minimum value of 1650 ppm to a maximum value of 2116.67 ppm. According to finding by Dzombak *et al.* (2006); Ghosh *et al.* (2006a) the substrata material after the leaching test increased effectiveness of the attenuation potential of the clay material but considering the higher CEC and OMC. OMC for Station 5 reduced from 0.98 % to 0.79 % rendering it less effective in attenuating cyanide and other minerals. Fe_2O_3levels for Stations 1(14.5 %), 2 (60.9 %) and 3 (49.5 %) decreased after the test whiles that of Station 4 (27.3 %) and 5 (8.0 %) were elevated. The pH reduced after the test at all the five stations ranging from 3.0 to 3.4 comparing to pre-leaching pH range of 4.3 to 4.8. Stations 1 and 3 reduced by 33.3 % with Stations 2, 4 and 5 reducing by 24.4 %, 23.3 and 27.8 % respectively.

Conclusion

The following conclusions were deduced from the studies carried out;

Estimated mean porosity values of the substrata material of the TSF basin establishes it as clayey with further classification of silty clay (TSF 1 and 2), laterite on slopes in TSF 3 and silty sand at low lying areas of TSF 3.

Mean calculated permeability and hydraulic conductivities of samples conforms to acceptable regulatory materials for the construction of tailings substrata. Station 5 exhibited the least attenuating geotechnical capabilities.

Confirmed geochemical parameters of the substrata effective in attenuating cyanide to tolerable and acceptable limits especially for stations 1, 2 and 3, with Station 5 being less effective.

The substrata material after the leaching test increased effectiveness of the attenuation potential of the clay material but considering the higher CEC and OMC. OMC for Station 5 reduced from 0.98 % to 0.79 % rendering it less effective in attenuating cyanide and other minerals.

pH for all the test stations became more acidic after the leaching test. Adsorption onclay particles and iron hydroxides can reduce metal and WAD cyanide concentrations. So can chemical reactions and ion replacement/exchange as the fluid infiltrates through the soil profile. Soils containing a clay component are especially effective in attenuating metals.

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