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THE EFFECTIVENESS OF SOME TROPICAL SOIL LINERS IN THE RETENTION OF HEAVY METALS RELEASED FROM ARD

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ABSTRACT

The long-term interaction between acid rock drainage (ARD) and two tropical clayey soils, potential liner materials for mine waste containment, with particular reference to the retention of heavy metals is reported. A constant-flow flexible wall permeameter was used to measure the soil hydraulic conductivity under an effective confining stress of 60 kPa. During the tests, the concentrations of Fe and Al in the effluents continued to increase steadily above the influent concentrations suggesting the dissolution of aluminum and iron hydroxides and aluminosilicates in the soils. At the end of permeation the breakthrough curves of only K and Pb in both the lateritic and non-lateritic soil and those of As, Zn and Cd in the latter showed effluent/influent concentration ratios less than unity. This suggests that the non-lateritic soil would be a more effective barrier material in controlling the migration of heavy metals present in ARD than the lateritic soil.

RÉSUMÉ

L'interaction à long terme entre le fluide de drainage acide de roche (ARD) et deux sols argileux tropicaux, les matériaux potentiels de membranes pour le confinement de résidus miniers, avec la référence particulière à la soutenemènt des métaux lourds est rapportée. Une constant-coulent perméamètre à paroi filexible a été employé pour mesurer la conductivité hydraulique de sol sous la contrainte de confinement de 60 kPa. Durant les essais, les concentrations du fer et aluminium dans les effluents ont continué à augmenter solidement au-dessus des concentrations dans l'affluent suggérant la dissolution des hydroxydes d'aluminium et de fer et des aluminosilicates dans les sols. À la fin de la percolation des sols avec le ARD, les profiles d’effluents chiminiques obtenu pour le potassium et le plomb seulement dans les sols latéritique et non-latéritique et ceux de arsenic, le zinc et cadmium dans les derniers ont montré les taux de concentration d'effluent/influent moins que l'unité. Ceci suggère que le sol non-latéritic serait un matériel plus efficace de barrière en commandant la migration des métaux lourds actuels dans ARD que le sols latéritique.

1. INTRODUCTION

Acid Rock Drainage (ARD) occurs in some mine wastes because of the oxidation of iron sulphides, especially pyrite (FeS_2), pyrrhotite (FeS) and marcasite (FeS_2) which leads to the formation of several soluble hydrous iron sulphates, the production of acidity and the subsequent leaching of metals (Nordstrom, 1982). With typically low pH and the presence of deleterious elements such as heavy metals and arsenic, ARD has the potential to pollute potable water resources. Most of the groundwater contaminants emanating from mine wastes have negative impact on terrestrial and aquatic life and the environment. Globally, ARD has been considered as perhaps the predominant mode of groundwater contamination by mine wastes (Gray 1996, Korkka-Niemi et al. 1998). Where it cannot be prevented or controlled, it must be treated to eliminate acidity, and reduce heavy metals and suspended solids before these contaminants are released into groundwater. Attempts are therefore usually made to mitigate their harmful effects by storing mine wastes in impoundments that may be lined with natural clayey or composite barrier materials. At some sites, natural clay or bentonitic clay may also be used to line acid water containment ponds.

There has been an increased exploitation of mineral resources, particularly gold, in Ghana, West Africa in recent times. This has resulted in the generation of several tonnes of waste rock and mine tailings. In some of the active and historical Ghanaian gold mines arsenopyrite ($FeAsS$), pyrite and rarely chalcopyrite ($CuFeS_2$) are associated with gold mineralisation. The extraction and processing of gold from these sulphidic ores has resulted in the generation of several tonnes of crushed and milled waste as well as mine tailings. Many of these mines are located in high rainfall regions of the country. This tropical environment is conducive to the oxidation of sulphidic mine waste and soil/rock slope excavations in some mine environments, thereby facilitating the generation of ARD. Available field evidence from some ancient and operating local mines that exploit sulphide-bearing ores in Ghana indicates the occurrence of ARD. The acid drainage is observed in such mine environments as precipitation of brown-red deposits at, and close to, the exit points of leaching waters. Mitigating the effects of the release of ARD from Ghanaian mines is important as most of the mining areas are densely populated and are also covered by tropical rainforests.

This study was undertaken to evaluate the geotechnical and geoenvironmental properties of two candidate tropical clayey soils for lining mine tailings impoundments and acid water containment ponds at mine sites. Another objective was to study the interactions between the soils and ARD and consequently assess the effectiveness of the soils as barrier materials, with particular reference to the retention of heavy metals.

The effectiveness of the soils in retarding ARD migration was assessed using a constant-flow flexible wall permeameter to measure the soil hydraulic conductivity, K. In such permeation studies, backpressure saturation and the control of effective stresses across compacted specimens as well as the minimization of the potential for sidewall leakage are also important requirements. A flexible-wall permeability cell is considered to be more effective in meeting these requirements than a fixed wall permeameter. In order to obtain representative values of the hydraulic conductivity of the soils, low hydraulic gradients that simulate the field hydraulic gradients across constructed hydraulic barriers such as liners are required. In assessing the impact of ARD on these clayey soils several pore volumes of flow are also required so that effluent breakthrough curves can be obtained and analysed. A flow pump is usually necessary to provide several pore volumes of permeant flow within reasonable time. Among the many documented advantages of using a flow pump system in hydraulic conductivity measurements are: rapid determination of hydraulic conductivity; generation of very low but accurate flow rates of permeant which results in the generation of realistically low hydraulic gradients across the specimens (Olsen et al. 1988; Redmond and Shackleford 1994 and Kashir and Yanful 1997). Thus, a constant-flow flexible wall permeameter was used to infuse ARD through the soil specimens.

2. MATERIALS AND METHODS

A detailed description of the constant-flow flexible wall permeameter used in this study is provided by Kashir and Yanful (1997). The soils were compacted and sequentially permeated with at least 2 pore volumes of 0.01N $CaSO_4$ and then 19-24 pore volumes of ARD, under an effective confining stress of 60 kPa. The pH, electrical conductivity and composition of the effluents were monitored. The mineralogical compositions of the soils, before and after permeation, were assessed to determine any changes that might have occurred in the soils as a result of the interactions with the permeant.

2.1 Materials

Two tropical soils were sampled in Ghana, West Africa and shipped to Canada for the study. Disturbed soil samples were collected for classification and strength (compaction) tests. One sample, a residual weathered product of phyllite, was obtained from a well-drained upland area and designated Sample HW. The other sample was however, obtained from a low-lying area with poor drainage. The bedrock at the location of the second sample is massive quartzite of Middle to Late Precambrian age. The soil sampled is designated Sample KWB. Acid mine water was generated in the laboratory for the study, by using a Haake Model E52 Constant Temperature Circulator to warm and circulate a water bath of a submerged mixture of sulphide-rich mine waste rock and tailings.

2.2 Laboratory Tests

Geotechnical tests performed on the soils included natural moisture content, Atterberg Limits, shrinkage characteristics, particle size distribution, specific gravity of solids and the standard Proctor moisture - density relationships. These tests were generally performed using procedures outlined in the relevant American Society for Testing and Materials (ASTM) specifications (ASTM 2002). Approximately 3.5cm of compacted sample at a placement moisture content of 2% above optimum was used for this study.

The chemical tests performed included the reactivity and conductance of the soil and water samples as well as the carbonate content, the cation exchange capacity (CEC), total organic matter content and the specific surface (glycol retention) of the soils. Others were the elemental and trace metal compositions of the soil and water samples. The carbonate (calcite and dolomite) content of the soils was determined by a gasometric method using the Chittick apparatus and procedures described by Dremanis (1962). The organic carbon and total organic matter content of each soil was determined using a titrimetric dichromate redox (the Walkley–Black) method (Walkley and Black 1934). The specific surface of each soil was determined by the glycol retention procedure on the <#200 mesh air-dried sample (Martin 1955). The cation exchange capacity (CEC) of the air-dry soil was determined using KCl and Silver Thiourea (AgTh) exchange procedures. The concentration of the cations Ca^{2+}, Mg^{2+}, K^+ and Na^+ in the supernatants were then determined by atomic absorption spectrophotometry using Philips Atomic Absorption Spectrometer PU9100X. The mineralogical compositions of the soils were determined using X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) techniques.

The quantity of water samples especially the effluents and porewaters was small and a mini-probe was necessary to enable the pH to be determined. To ensure consistency in the interpretation of the results this probe was also used for all other pH tests. A Metrohm 712 Conductometer was used to measure the conductivity of the soil (soil suspension) and water samples. The cationic composition of the permeant and effluents were determined using Inductively Coupled Plasma– Atomic Emission Spectroscopy (ICP-AES).

3. RESULTS AND DISCUSSION

3.1 Index Classification Tests

A summary of the test results is provided in Table 1. The natural moisture contents of the samples were 27% and 29% for Samples HW and KWB respectively. Texturally, Sample HW can be described as silty sandy clay while Sample KWB is sandy silty clay. The specific gravity of both samples was 2.78, which is in the upper bound range (2.65-2.80; Holtz and Kovacs 1989) for most clay soils. The high specific gravity is typical of some tropical soils that contain iron minerals and concretionary gravels. Since the specific gravities exceed 2.50 the soils cannot be considered as organic.

Under the Unified Soil Classification System the soils classify as inorganic clays of high plasticity (CH). With Activity A<0.75, Sample HW is an inactive clay while Sample KWB, which has A>1.25, is an active clay (Holtz and Kovacs 1989). Both soils had high but different shrinkage properties. Although they contain 39% clay-size particles the wide variation in the range of values for the shrinkage parameters suggest that smectite, which is present in Sample KWB, has a more dominant influence on the shrinkage properties of this soil than kaolinite has on Sample HW. In addition, the varying amounts of sand in the soils partially accounts for the observed differences in shrinkage parameters.

In a study on the effect of desiccation cracking on the hydraulic conductivity of compacted clay liners, Omidi et al. (1996) observed that the hydraulic conductivity of soils with volumetric shrinkage greater than 11% are markedly increased due to desiccation, expansion and cracking. The results of the present study show that the hydraulic conductivity of a liner constructed with Sample HW is unlikely to be adversely affected by shrinkage changes. However, there is the potential for undesirable excessive increase in hydraulic conductivity of a liner constructed with Sample KWB. With maximum Proctor dry densities of 1592 kg/m^3 for Sample HW and 1632 kg/m^3 for Sample KWB at optimum moisture contents of 20.8% and 19% respectively, both soils would have adequate strength when compacted.

Table 1: Characteristics of soils studied

Property	Sample	
	HW	KWB
Natural Moisture Content (%)	*27*	*29*
Atterberg Limits, %		
Liquid Limit	47	87
Plastic Limit	26	27
Plasticity Index	21	60
Shrinkage Characteristics		
Shrinkage Limit, SL	*22*	*8*
Shrinkage Ratio, R	*1.70*	*2.80*
Volumetric Shrinkage, Vs at w = OMC + 2%	*1.0*	*36.7*
Linear Shrinkage, L_s	*20.9*	*64.5*
Specific Gravity	2.78	2.78
Particle Size Distribution, %		
Clay	39	39
Silt	28	49
Sand	33	12
Activity, A	0.55	1.54
Liquidity Index, LI	0.06	0.04
Standard Proctor Compaction		
MDD, kg/m^3	1592	1632
OMC, %	20.8	19.0

3.2 Composition of Soils and ARD

3.2.1 Soils

The results of the chemical tests are summarized in Table 2. Based upon the descriptive classification of soil reactivity proposed by Young (1976), with pH (soil: water ratio of 1:2) of 4.82 at 25^{o}C, Sample HW may be described as strongly acidic. Similarly, with a pH of 7.25, Sample KWB may be described as either weakly alkaline or neutral. The loss on ignition of the soils at 105^{o}C was high, approximately 12-13%. These high losses on ignition suggest the presence of appreciable amounts of free or molecular water and also reflect the amounts of organic matter present in the soils. With silica: sesquioxide ratio of 1.86, Sample HW can be described as a laterite or lateritic soil while Sample KWB, which has silica: sesquioxide ratio of 2.87 is non-lateritic.

Table 2: Summary of some chemical properties of the soils

Property	Sample	
	HW	KWB
Standard pH (air-dried soil: water; 1: 2)	4.82	7.25
Total Organic Matter, %	0.9	1.7
Glycol Retention, mg/g clay	33.7	83.8
Cation Exchange Capacity (CEC), meq/100g	2.8	22.6
Carbonates, %	2.6	4.5
Dolomite	1.63	1.56
Calcite	0.97	2.94
Major Oxides, %		
SiO_2	55.0	60.7
Al_2O_3	21.4	13.9
Fe_2O_3	8.1	7.3
TiO_2	1.3	1.3
K_2O	0.13	0.26
MnO	0.04	0.19
MgO	0.21	0.87
CaO	0.11	2.23
Na_2O	<0.01	0.73
P_2O_5	0.07	0.04
Cr_2O_3	0.02	0.02
Silica: Sesquioxide Ratio [$SiO_2/(Al_2O_3 + Fe_2O_3)$]	1.86	2.87
Loss On Ignition (%)	12.9	12.00
Trace Metal Concentration, μg/g		
Vanadium	152	174
Chromium	86	125
Zinc	47	62
Nickel	45	41
Copper	27	42
Lead	16	24
Arsenic	7	3
Cobalt	11	40

Chemical and semi-quantitative XRD analyses of the soils indicated that Sample HW consisted of 46% quartz, 35.7% kaolinite, 8.1% iron oxyhydroxides (goethite, ilmenite and magnetite), 5.4% bayerite, 2.1% Mgvermiculite and 1.8% potassium feldspar. Similar analyses showed the composition of Sample KWB to be 40% quartz, 36.6% Fe-chlorite - Al-interlayered smectite, 8.3% aluminum oxyhydroxides (gibbsite, bayerite and diaspore), 6% iron oxyhydroxides (goethite, haematite and magnetite), 2.8% dolomite, 1.6% iron and/or titanium oxides (ilmenite and anatase), 1.3% kaolinite and traces of potassium and plagioclase feldspars.

Glycol retention values (whole soil) were 33.7 mg/g for Sample HW and 83.8 mg/g for Sample KWB and cation exchange capacity (CEC) was 2.8 meq/100g for Sample HW and 22.6 meq/100g for Sample (Table 2). These glycol retention and CEC values reflect the predominance of kaolinite, a 1:1 layer silicate mineral, in Sample HW and smectite, a 2:1 low charge clay mineral, in Sample KWB.

3.2.2 ARD

The chemical composition of the ARD is presented in Table 3. The ARD had pH of 2.6, electrical conductivity of 7600 μS/cm, and sulphate concentration of 5200 mg/L.

According to Gray (1996), pH value, sulphate, iron, zinc, aluminum, copper and cadmium are the seven parameters most indicative of ARD contamination. The low reactivity, high electrical conductivity, the high sulphate, aluminum and iron contents as well as the high amounts of heavy metals such as zinc, manganese, cobalt, copper and lead are parameters that indicate that the laboratory-generated acid water is similar in composition to typical ARD.

Table 3: Chemical composition of ARD

Analyte	Value (mg/L)	Analyte	Value (mg/L)
Sulphur	1730	Copper	2.36
Iron	654	Lead	1.88
Calcium	321	Vanadium	0.84
Magnesium	287	Phosphorous	0.66
Nickel	182	Arsenic	0.38
Zinc	163	Cadmium	0.31
Aluminum	130	Chromium	0.28
Manganese	65.9	Barium	0.05
Silicon	64.3	Zircon	<0.01
Sodium	29.4	Molybdenum	nd*
Cobalt	7.11	Titanium	nd*
Potassium	4.95		

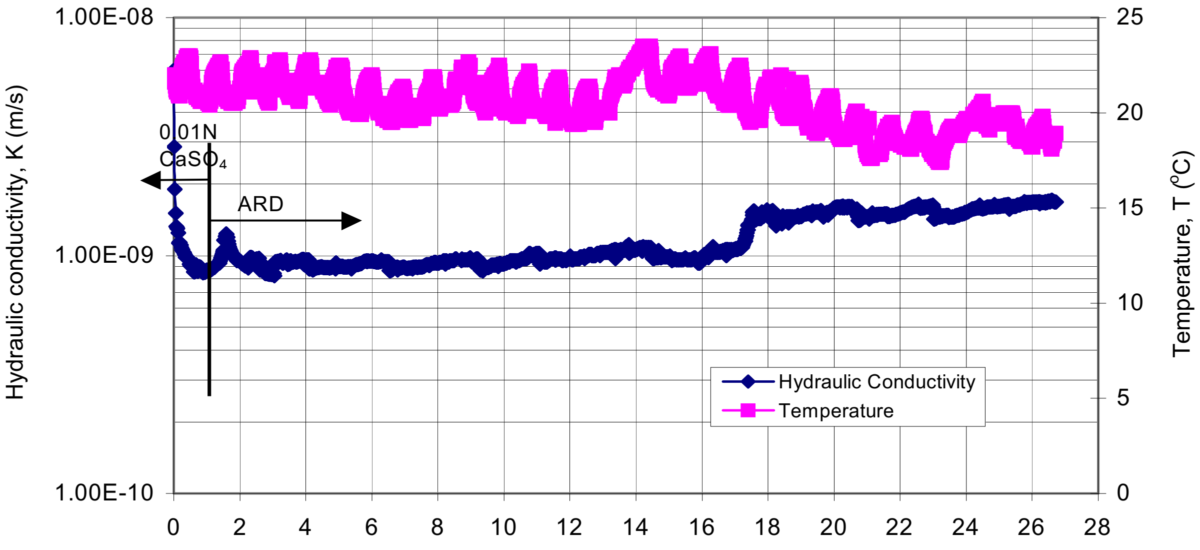
nd * - not detected

3.3 ARD Interaction With Soils

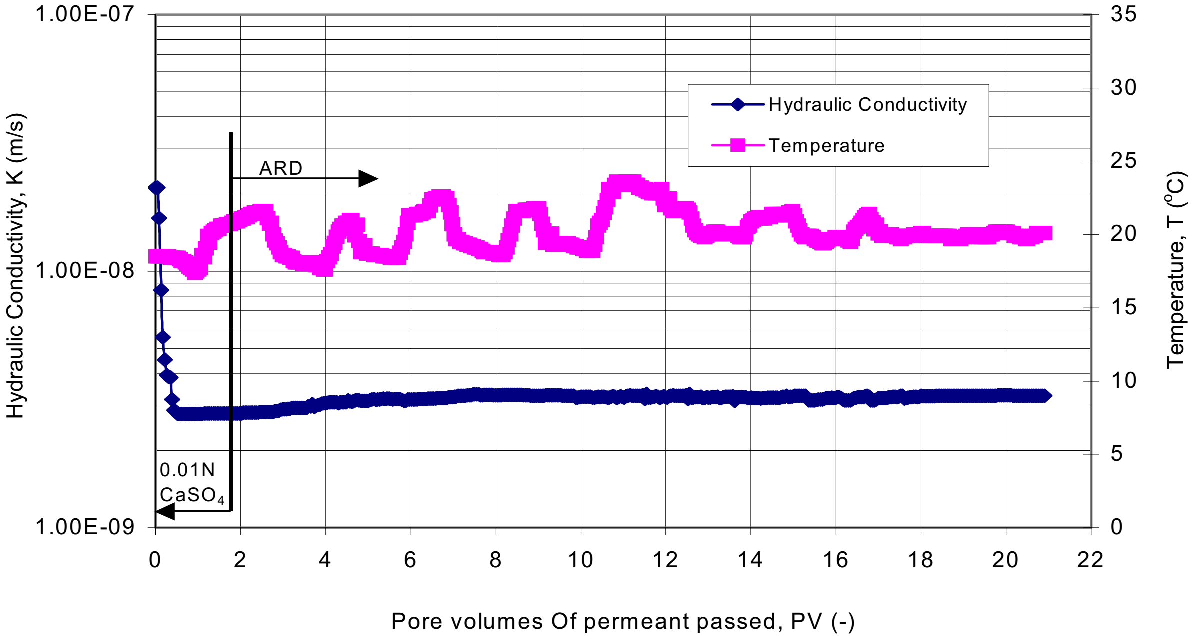
3.3.1 Hydraulic Conductivity

The hydraulic conductivity of the non-lateritic soil (Sample KWB), which also contained a relatively high proportion of active clay mineral (interlayered Fe-chlorite-Al-smectite), increased slightly from 8.5 x 10^{-10} m/s reaching a stabilized value of 9.5 x 10^{-10} m/s after permeation with approximately 2 pore volumes of ARD. However, after passing of 25 pore volumes of ARD, the hydraulic conductivity increased by nearly half an order of magnitude (8.5 X 10^{-10} m/s to 1.7 X 10^{-9} m/s) (Figure 1a). The increase in hydraulic conductivity may be attributed to the contraction of the diffuse double layer surrounding the clay particles.

The variation in the hydraulic conductivity of Sample HW with pore volume is presented in Figure 1b. On permeation with 0.01N $CaSO_4$ the hydraulic conductivity of Sample HW was 2.8 x 10^{-9} m/s but increased steadily to 3.3 x 10^{-9} m/s after the passage of approximately 6 pore volumes of ARD. On further permeation with ARD, the hydraulic conductivity was stabilized between 3.2 x 10^{-9} m/s and 3.3 x 10^{-9} m/s with an average value of 3.24 x 10^{-9} m/s, after 19 pore volumes had been passed. These results indicate an increase of less than one quarter of an order of magnitude over the baseline hydraulic conductivity of 2.8 x 10^{-9} m/s.



(a) Sample KWB



(b) Sample HW

Figure 6:Variation of hydraulic conductivity of soils.

3.3.2 Effluent Chemistry

3.3.2.1 pH And Electrical Conductivity

The variation in the pH and electrical conductivity of the effluent produced from the permeation of Sample KWB with 0.01N $CaSO_4$ and ARD is presented in Figure 2. After passing only 2.79 pore volumes of ARD, the pH of the effluent decreased from 6.5 to 2.6 initially and then increased to 18.9 pore volumes of the permeant had been passed. The slight increase in the pH of the effluent could be attributed to the dissolution of carbonate minerals in Sample KWB by the ARD. Generally the decrease in pH of the effluent was matched by a corresponding increase in its electrical conductivity. However, during the period when 14.2 and 18.9 pore volumes of ARD were passed, both the pH and the electrical conductivity of the effluent increased (Figure 2). During this same period a corresponding increase in the hydraulic conductivity of the soil was also observed (Figure 1a). As will be shown later (Figure 4), significant increases in the concentration of aluminium and iron in the effluents also occurred during the same period. These observations suggest that aluminum and iron hydroxides and aluminosilicates in Sample KWB likely dissolved leading to the creation of preferential flow paths and consequently, the observed increase in hydraulic conductivity.

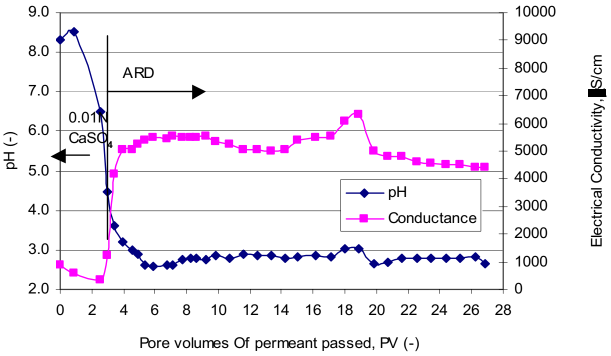


Figure 2: Variation of effluent pH and electrical conductivity - Sample KWB

Figure 3 shows the variation of pH and electrical conductivity of the effluent with pore volume during hydraulic conductivity testing of Sample HW. There was a significant pH increase (from 6.9 to 8.2) in the effluent from the soil on permeation with 0.01N $CaSO_4$ before it decreased to 7.7 after 2.7 pore volumes had been passed. On further permeation with ARD the pH of the effluent dropped considerably to 3.2 after only 1.3 pore volumes had been passed. The rate of decrease diminished after 5.8 pore volumes until the pH became fairly constant (approximately 2.6) after 13.4 pore volumes had been passed. The high buffering capacity of the soil occurs at pH<2.8. Similarly, there was an initial decrease in the electrical conductivity of the effluent when the soil was permeated with 0.01N $CaSO_4$. This was however, increased upon sequential permeation with ARD with the significant increases occurring up to the infusion of 3.6 pore volumes of the permeant. The conductance of the effluent was fairly equilibrated around 2800 µS/cm after 10.8 pore volumes of ARD had been passed.

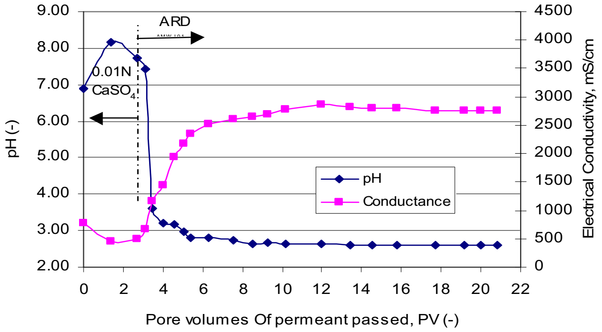
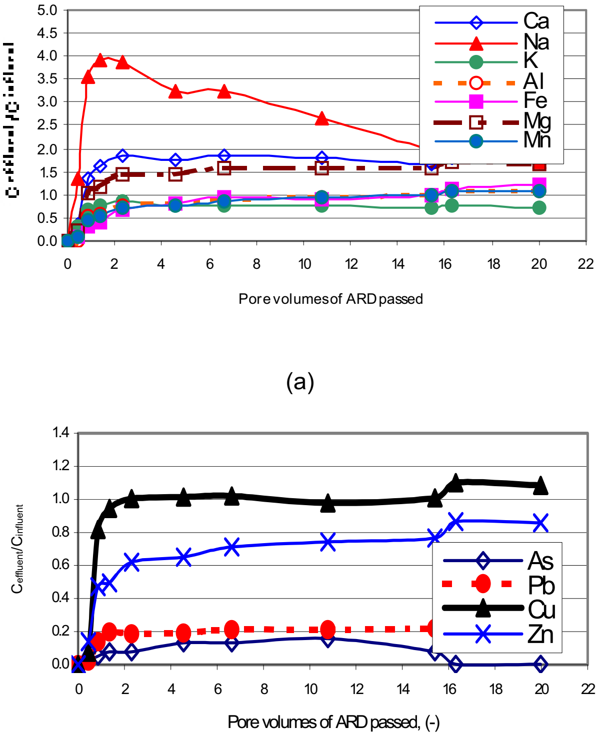


Figure 3: Variation of effluent pH and electrical conductivity - Sample HW

3.3.2.2 Breakthrough Curves

The effluent breakthrough curves for Sample KWB are shown in Figure 4. Almost all the species showed early arrival with the breakthrough curves shifted to the left. This is probably due to either channel flow caused by the occurrence of large pores due to soil aggregation or the high solute concentration in the ARD, which could have caused incomplete mixing of the solute with the soil porewater initially. The increases in the effluent concentrations of almost all the major species were so remarkable that before permeation of the soil with 2 pore volumes of ARD the influent concentrations had been exceeded. K was strongly retarded probably due to cation exchange reactions. Na showed high desorption peak and this would suggest that it was a major species in cation exchange reactions (Figure 4a). Iron and aluminum were retarded for a considerable period but their concentrations in the effluent exceeded the influent concentrations after 16 pore volumes. This could be due to desorption from the soil after its cation exchange capacity had been exceeded. The breakthrough curve for the trace metal Pb showed early arrival and tailing (Figure 4b). After permeation with 20 pore volumes of ARD the effluent concentrations of the trace metals As, Cu and Zn did not reach the influent concentrations. This suggests that Sample KWB could be an effective barrier material in controlling the migration of these harmful elements from mine tailings impoundments and acid water ponds into water resources.

Figure 5 shows the effluent breakthrough curves for Sample HW. It is observed that even after passing 15 pore volumes of ARD through the soil the concentration of Fe, Al and Pb in the effluent continued to exhibit steady increases over the influent concentration (Figures 5a and 5b). Pb was retarded and slowly approached equilibrium at nearly 4 pore volumes. The Al and Fe in the ARD might have displaced Ca, Mg and K in the soil. As Ca shows a desorption peak it appears to be a significant exchange cation in the soil. The breakthrough curves show early arrival and desorption of Ca, Mg and K (Figure 5c). The high effluent/influent concentration ratios of most of the species even after passing more than 10 pore volumes of ARD through the sample, suggests the displacement of these species from the soil by the permeant. It is apparent that these species were adsorbed onto the soil and later only desorbed when the cation exchange capacity of the soil was attained.

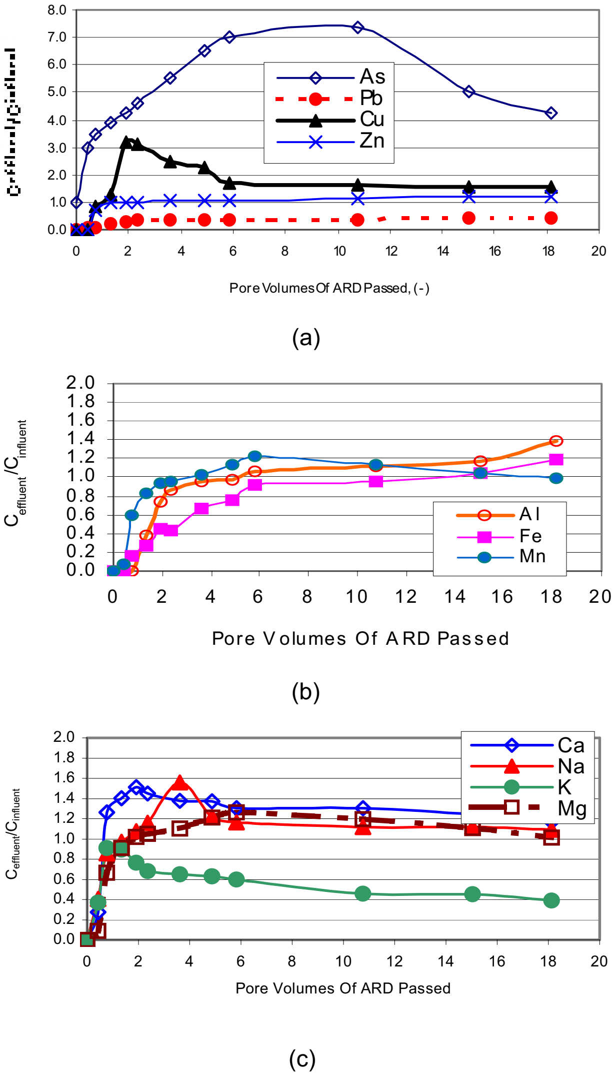


(a)

(b)

Figure 4: Effluent composition vrs pore volume of ARD passed through Sample KWB

Further testing has shown that within the pH ranges of $2.8<pH<8$ and $4.2< pH< 9$ the buffer capacities of Samples HW and KWB respectively are independent of pH. The buffer capacity of noncalcareous soils at $5<pH<8$ has been shown to be primarily caused by cation exchange reactions where functional groups associated with clays and organic matter serve as sinks for H^+ and OH^- (Nielsen et al., 1995; Curtin et al., 1996 and Curtin and Rostad, 1997). Since the pH of the undisturbed specimen of Sample HW and KWB are within the above range of values their buffer capacities may essentially have resulted from cation exchange reactions.



(a)

(b)

(c)

Figure 5: Effluent volume vrs pore volume of ARD passed through Sample HW

Harter (2002) also postulates that at pH≥5.5 the amount of available calcium within a soil influences the ability of calcium to change the pH. However, at pH<5.5 the amount of calcium in most acidic soils would have generally been so diminished that their capacity to buffer the pH change is usually taken over by aluminum. This process, which involves several intermediate reactions, can be represented by the ultimate reaction (Equation 1):

$$Al(OH)_3 + 3H^+ = Al^{3+} + 3H_2O \quad \ldots \quad [1]$$

Consequently, soil pH will be changed at a very slow rate in comparison with the acidification reactions since, for each aluminum ion released, during the reaction, three hydrogen ions have to be absorbed. Sample HW with pH<5.5, contains very small amounts of CaO (<0.12%)

while the Al_2O_3 concentration was 21.4%. It is therefore possible that, for this soil, the slow rate of change in pH with the addition of acid at pH<5.5 was probably due to its high aluminum content. However, for Sample KWB, which had a pH>5.5 and a relatively higher CaO content (2.23%) as well as a lower Al_2O_3 content (13.9%) the change in pH due to the addition of acid appeared to have been dominated by the calcium content.

4. CONCLUSIONS

The geotechnical and geoenvironmental properties of two tropical clayey soils have been determined. One of the soils was lateritic and strongly acidic while the other was non-lateritic and weakly alkaline. The effectiveness of these soils as liners particularly, in the retention of heavy metals from ARD, has been assessed. After passing 2 pore volumes of ARD the hydraulicconductivity of the non-lateritic soil, which also contained a relatively high proportion of active clay mineral, increased by nearly half an order of magnitude (8.5×10^{-10} m/s to 1.7×10^{-9} m/s). There was however, a slight increase in that of the lateritic soil (2.8×10^{-9} m/s to 3.2×10^{-9} m/s) after permeation with 21 pore volumes of ARD. The soils may not be considered for use alone in liner construction as their hydraulic conductivities at the end of permeation exceeded the threshold of 1×10^{-9} m/s. Sample KWB may not be used as a liner as, with a volumetric shrinkage exceeding 11%, its hydraulic conductivity has the potential to excessively increase when desiccated.

After passing 20-25 pore volumes the concentrations of Fe and Al in the effluent continued to increase steadily above the influent concentrations suggesting the dissolution of aluminum and iron hydroxides and aluminosilicates in the soils. The effluent concentration-pore volume curves showed early arrival and desorption of Ca, Mg, Mn and K for the lateritic soil and Na, K and Ca for the non-lateritic soil. It is apparent that these species were desorbed as a result of ion exchange with cations originally present in the ARD permeant. At the end of permeation the effluent concentrations of only K and Pb in both soils and those of As, Zn and Cd in the non-lateritic soil were found to be much lower than the influent concentrations. This shows that the non-lateritic soil was relatively more effective in controlling the migration of heavy metals present in ARD. The results of this study would enhance awareness so that ARD-clay barrier compatibility studies could be incorporated into the environmental impact assessment and mitigation strategies in mine environments within the tropics.

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