Petrographic and Physico-Chemical Characterisation of Tailings Dump and Soils Around a Nickel-Copper Mining and Smelting Environment

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ABSTRACT

Recent concerns of mining and smelting of nickel-copper (Ni-Cu) in Selebi Phikwe, Botswana possibly affecting the environmental physico-chemistry motivated this study. Physico-chemical analyses which included particle size distribution (PSD), pH, electrical conductivity (EC), cation exchange capacity (CEC), color and descriptive petrography on samples of tailings dump and soils were performed in order to understand the significance of these properties on the surrounding physical environment. The PSD of soil samples revealed the average wt % of the < 2 μm fraction (clay fraction) was between 3 and 9 wt %, the > 2 μm to < 50 μm fraction (silt fraction) was between 34 and 44 wt %, and the > 50 μm to < 250 μm fraction (sand fraction) was between 47 and 63 wt %. Soil pH ranged from 3.5 to 6.0. Electrical conductivity values were significantly low, and the range was from 50 μS/cm to 250 μS/cm. Soils with low pH correspondingly had low EC and were close to the mine. The CEC values occurred between 2 meq/100g and 20 meq/100 g. Hand specimens of tailings dump viewed with a microscope and physical tests performed on the samples for hardness, cleavage, fracture, color, streak, lustre, and crystal appearance depict albite, quartz, biotite, chlorite, pyrite, pyrrhotite, tremolite, and pentalite to be contained in them. Soil colour varied from pale yellow, reddish-yellow to dark reddish brown. Grains were poorly sorted, with subangular grains located further from the plant, which is indicative of windblown particles transported at a short distance. Reddish brown soils were closer to the tailings dump, mining areas and the smelting/concentrator plant. The observation is indicative of both Fe and Cu containing minerals enriching the soils of the study area. The findings of this study are indicative of increase in soil acidity due to mining and smelting of Ni-Cu at Selebi Phikwe area. High acidity favoured the leaching of heavy ions from tailings dump and related mining waste to the soils. Fewer exchange sites have resulted in a low CEC for ions adsorbed on the sediment surfaces, consequently they remain in solution and are bioavailable for plant uptake.

KEYWORDS: tailings dump; soils; physico-chemistry; particle size distribution; petrography; environment

INTRODUCTION

Nickel-copper, (Ni-Cu) has been mined in Selebi Phikwe, Botswana since 1966, and it is suspected that the mining and smelting activities are having an effect on the immediate physical environment.

Previous studies of Ni-Cu orebodies (Nkoma and EKOSSE, 1999; 2000) and soils (EKOSSE et al., 2003), and particulate air matter (EKOSSE et al., 2004) conducted on different samples obtained within the Selebi Phikwe area indicated mineral constituents that reflected the presence of heavy metals emanating mainly from mining and smelting activities. Furthermore, studies on environmental chemistry of the Selebi Phikwe area depicted trends in heavy metals concentrations in soils and Cotophyllum mopane (EKOSSE et al., 2004a) to be similar to those obtained for Imbrosia balina in the same study area (EKOSSE et al., 2004b) which were all related to the mining activities there.

However, no work has so far been reported on in literature regarding the petrographic and physico-chemical aspects of the tailings dump and soils surrounding the Selebi Phikwe Ni-Cu mining and smelting environment. In this study, an attempt was made to link information on mineralogy of the transition sulphide minerals from the ore bodies (Nkoma and EKOSSE, 2000), to the physico-chemical characteristics of the tailings dump and soils around the Selebi Phikwe Ni-Cu mine area, Botswana. The primary objective of this study; was to petrographically and physico-chemically characterise the tailings dump and soils in order to understand how mining and smelting activities affect the physico-chemistry of the environment.

MATERIALS AND METHODS

Study Area

Selebi Phikwe is one of the urbanized townships of Botswana.

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Phikwe is located

Table 1: Location/Characteristics of sampling sites at the Selebi Phikwe township area

<table>
<thead>
<tr>
<th>Sampling site</th>
<th>Location/Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Industrial area (150 m after the railway crossing)</td>
</tr>
<tr>
<td>2</td>
<td>Seosele Hotel (Commercial area) and new township</td>
</tr>
<tr>
<td>3</td>
<td>Between the township stadium and the mine (behind the Botswana Power Corporation, BPC)</td>
</tr>
<tr>
<td>4</td>
<td>Between the Township boundary and the railway line (directly behind a Community Junior Secondary School, CJSJ)</td>
</tr>
<tr>
<td>5</td>
<td>Opposite the Mine hospital, close to old township</td>
</tr>
<tr>
<td>6</td>
<td>Between the mine and explosive storage facilities (close to old township)</td>
</tr>
<tr>
<td>7</td>
<td>Towards the airport (about 250 m from the Airport-Seosele-Selebi Phikwe Road junction)</td>
</tr>
<tr>
<td>8</td>
<td>Off untarred road leading to the Selebi North mine (100 m out of township boundary, adjacent to the new township)</td>
</tr>
<tr>
<td>9</td>
<td>Off last but one bridge before entering into the Selebi Phikwe township</td>
</tr>
<tr>
<td>10</td>
<td>Control site located close to the road juncture leading to Selebi Phikwe from the Gaborone-Francistown main road</td>
</tr>
</tbody>
</table>

The mechanics/electrical shaker was set at 60 strokes per minute (spm), and the nest of sieves consisted of the following particle size ranges in μm: 500, 425, 355, 300, 250, 180, 150, 125, 106, and 53. The < 53 μm size fraction of surface sediments samples were analyzed using the 1993 model Shimadzu SA-CP4 automatic particle size analyzer (PSA). The analyzer was set at 240 revolutions per minute (rpm). The particle sizes were automatically measured by the PSA.

Descriptive Petrography and Color Determination
Tailings dump and soil samples for descriptive petrography and color determination were aerated for 24 hours. Clayey aggregates were separated using a mortar and pestle to single particles. With a spatula, the samples were mounted on white cardboard sheets provided by the Munseil Soil Color Company Inc., MD 21218, USA. The color descriptions, which comprise the hue, value/chroma and color of the mounted samples, were obtained by visually comparing them to those of standard surface sediments recorded in the Munseil Soil Color book (1992). Optical microscopy technique was used for descriptive analyses of the tailings dump and the non-clay fraction of the surface sediments. A Leitz Ortholux II Pol-BK petrographic microscope was used for the analyses.

The pH and Electrical Conductivity
Van Reeuwijk (1993), Okalebo et al. (1993) and Barnard et al. (1999) described the methods for pH and EC analysis of soils. Finely ground/pulverized soil samples were used for pH and EC determination. Aliquots of 2.5 g of sample were placed in three centrifuge tubes and suspended in 25 ml of distilled H2O. After shaking on a horizontal shaker for about 30 minutes, the tubes were centrifuged for five minutes. Average values were calculated and recorded for each sample analyzed. The pH and EC of the supernatant of the samples were analyzed with a Jenway 3020 pH meter and a Jenway 4020 EC meter. The temperature of the samples at the time of analyses was recorded.

\[
V = \frac{2\pi r (d_p - d_w) g \eta}{9} \quad (1)
\]

where \(V\) = rate of settling of particles (cm²/s), \(r\) = radius of particles (cm), \(d_p\) = density of liquid medium (g/cm³), \(d_w\) = density of water (g/cm³), \(\eta\) = coefficient of viscosity (poise) (g/cm·s²), and \(g\) = acceleration due to gravity (981sec²).
Analysis of Exchangeable Cations

The CEC of the surface sediments was determined using the barium chloride-nitromethane \((\text{BaCl}_2-\text{CH}_3\text{CH}_2\text{OH})_N\) method which is described in Inglethorpe et al., (1993), and also described in Ma and Eggleton (1999). Five grams of soil sample were put in 100 ml centrifuge and buffered with BaCl\(_2\) for an hour with four or five stirrings periodically. The centrifuge tube was set to make 30,000 rounds at 2000 rpm. After centrifuging, the supernatant was decanted and an additional 100 ml of BaCl\(_2\) added. All the unabsorbed ions of Ba were washed off using deionized water. 100 ml of 0.05 M MgSO\(_4\)-7H\(_2\)O was added to each of the weighed contents in the tube and the mixture was allowed to react for at least two hours. Centrifuging of the mixture was done for another hour, and 10 ml of the supernatant was collected into a 100 ml conical flask. Twelve drops of 1M \(\text{NH}_4\) of SG 0.91 and six drops of catechol violet indicator were added to the suspension, which was titrated with 0.02 M Di-Na EDTA. The CEC was calculated from the titrant values.

RESULTS

Granulometric Analyses

Based on the classification scheme of particle sizes for the Association Internationale Pour Les Etudes d’Argiles (AIEA) (International Association for Study of Clay Minerals), particles that are \(\leq 2 \mu m\) in euhedral spherical diameter (esd) are classified as clay, particles that are \(2 \mu m < 50 \mu m\) are taken to be silt, and particles \(> 50 \mu m \leq 250 \mu m\) are considered to be sand. Particles > 250 \(\mu m\) were discarded because their mineralogy is mainly grain quartz which does not affect the chemistry of the surface environment (Krakl, 1999).

The distribution pattern of soil particles showed an apparent homogeneity within the study area, although slight variations were detected. The mean wt % for the soil samples occurred at between 100 \(\mu m\) and 120 \(\mu m\). Average trend of distribution of particles revealed clay fraction to be between 3 and 9 wt %
Table 2: Descriptive petrography of minerals contained in tailings dump from the Selebi Phikwe Ni-Cu orebodies.

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Hardness (Mohr scale)</th>
<th>Cleavage</th>
<th>Fracture</th>
<th>Color</th>
<th>Streak</th>
<th>Lustre</th>
<th>Crystal appearance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Actinolite</td>
<td>5 - 6</td>
<td>Good</td>
<td>Uneven to subconchoidal</td>
<td>Light to blackish green</td>
<td>White</td>
<td>Vitreous</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Albite</td>
<td>6 - 6.5</td>
<td>Distinct</td>
<td>Uneven</td>
<td>White to colorless</td>
<td>White</td>
<td>Vitreous to pearly</td>
<td>Triclinic</td>
</tr>
<tr>
<td>Cristobalite</td>
<td>7</td>
<td>None</td>
<td>Conchoidal</td>
<td>Colorless to gray</td>
<td>White</td>
<td>Vitreous</td>
<td>Tetragonal</td>
</tr>
<tr>
<td>Chalcopyrite</td>
<td>3.5 - 4</td>
<td>Poor</td>
<td>Uneven to conchoidal</td>
<td>Brass yellow</td>
<td>Green to black</td>
<td>Metallic</td>
<td>Tetragonal</td>
</tr>
<tr>
<td>Malachite</td>
<td>3.5 - 4</td>
<td>Good</td>
<td>Uneven to conchoidal</td>
<td>Emerald green</td>
<td>Light green</td>
<td>Vitreous to silty</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Pyrite</td>
<td>6 - 6.5</td>
<td>None</td>
<td>Conchoidal to uneven</td>
<td>Pale yellow</td>
<td>Green to black</td>
<td>Metallic</td>
<td>Cubic</td>
</tr>
<tr>
<td>Pyrhotte</td>
<td>3.5 - 4.5</td>
<td>None</td>
<td>Uneven to subconchoidal</td>
<td>Bronze yellow</td>
<td>Dark gray to black</td>
<td>Metallic</td>
<td>Hexagonal</td>
</tr>
<tr>
<td>Tremolite</td>
<td>5 - 6</td>
<td>Good</td>
<td>Uneven to subconchoidal</td>
<td>Colorless white</td>
<td>White</td>
<td>Vitreous</td>
<td>Monoclinic</td>
</tr>
<tr>
<td>Pentlandite</td>
<td>3.5 - 4</td>
<td>None</td>
<td>Uneven to conchoidal</td>
<td>Light bronze yellow</td>
<td>Bronze to brown</td>
<td>Metallic</td>
<td>Isometric</td>
</tr>
</tbody>
</table>

with a mean of 7 wt%, silt portion to be between 34 and 44 wt% with a mean of 39 wt%, and sand portion between 47 and 63 wt% with a mean of 51 wt%. The wt% of clay size fraction along study sites was almost uniformly distributed as revealed in Figure 3. The mean PSD curves of soils from the ten sites are given in Figure 4. Sites two, four and nine were the most clayey sites with mean average of 9 wt%. These sites were close to water runways and a stream (site nine) where leaching of ions for clay mineral formation was prevalent. Clay contents in sites six, seven, and eight were less than the mean wt% of clay at the study area. The 7 wt% of clay in soil samples from sites three, five and ten corresponded to the mean wt% of clay fraction at the study area.

The siltiest samples were from sites two, seven and eight with values which approached 44 wt%, whereas the least silt samples were from site five with 35 wt% as indicated in Figure 3. The sites where the siltiest samples were found were located near gravelled motorways where particle reworking had been promoted by traffic as well as other factors, such as wind, rain and topography. The silt fraction obtained from soil samples at sites one, four, nine and ten were consistent and approximated at 40 wt%. The values for silt fraction from sites three and six exceeded 35 wt% but were below 40 wt%. Sites five and six shown in Figure 4, were the most sandy and site two was the least sandy, with a value of 47 wt%. All other sites had mean values of their sand fraction to between 48 wt% and 58 wt%. Trends in sandiness of surface sediments samples deviated slightly from trends for silt and clay fractions of the samples.

Descriptive Petrography and Color Determination

Hand specimens viewed with a microscope and physical tests performed on the samples for hardness, cleavage, fracture, color, streak, lustre, and crystal appearance depicted albite, actinolite, chalcopyrite, pyrhotite, tremolite, and pentlandite in the samples. Small, dark and brassy yellow pseudotetragonal crystals of chalcopyrite and acicular green films of malachite could visibly be detected as mineral constituents of the tailings dump.

<table>
<thead>
<tr>
<th>Site Number</th>
<th>Hue</th>
<th>Value/Chroma</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5 YR</td>
<td>5/6</td>
<td>Strong brown</td>
</tr>
<tr>
<td>2</td>
<td>5 YR</td>
<td>4/3</td>
<td>Dark reddish brown</td>
</tr>
<tr>
<td>3</td>
<td>10 R</td>
<td>7/6</td>
<td>Pale red</td>
</tr>
<tr>
<td>4</td>
<td>7.5 YR</td>
<td>7/6</td>
<td>Reddish yellow</td>
</tr>
<tr>
<td>5</td>
<td>10 YR</td>
<td>7/6</td>
<td>Yellow</td>
</tr>
<tr>
<td>6</td>
<td>10 YR</td>
<td>8/3</td>
<td>Very pale brown</td>
</tr>
<tr>
<td>7</td>
<td>7 YR</td>
<td>7/6</td>
<td>Reddish yellow</td>
</tr>
<tr>
<td>8</td>
<td>10 YR</td>
<td>8/4</td>
<td>Very pale brown</td>
</tr>
<tr>
<td>9</td>
<td>10 YR</td>
<td>4/3</td>
<td>Dark reddish brown</td>
</tr>
<tr>
<td>10</td>
<td>10 YR</td>
<td>3/1</td>
<td>Very dark gray</td>
</tr>
</tbody>
</table>
precipitates were found on soils close to the smelter/concentrator plant. In areas where surface sediments were tinted with whitish gray precipitates, the strong smell of sulphur was detected, and there was no vegetation cover. At sites nine and ten, the surface sediments were dark reddish brown and very dark gray; dark color being influenced from organic matter deposition resulting from decayed plants and fluvial activities. Cement, sand and concrete formed an integral part of the surface sediments at the control site.

The pH and Electrical Conductivity
The average pH values at ambient temperature, for the soil obtained from all the sampling sites are given in Figure 5. The pH values ranged from 3.5 to 9.0. Slightly basic to basic pH values were obtained from surface sediments from sites seven, eight, nine and ten. The pH values obtained for samples from sites three, four, five and six were prominently lower than those for samples from other sites of the study area.

The samples obtained from the ten sites of the study area were grouped into three based on their EC values. Samples from sites four and five had EC values, which were < 50 \( \mu \text{Scm}^{-1} \). Samples obtained from sites one, two, seven, eight and nine had EC values \( \geq 50 \mu \text{Scm}^{-1} \leq 150 \mu \text{Scm}^{-1} \). The third group of samples was obtained from sites three, six and ten and had EC values \( \geq 100 \mu \text{Scm}^{-1} \leq 250 \mu \text{Scm}^{-1} \).

Figure 4: Mean cumulative frequency distribution of representative soil samples from the study sites.
Cation Exchange Capacitance

The CEC values of the soil samples were between 2 meg/100 g and 20 meg/100 g (Figure 5), which is typical of 1:1 clay minerals that are found dominantly in kaolinitic surface sediments. The mineral content of the soils could have included minor trace quantities of 2.1 clay minerals such as smectite and illite. It should be pointed out that the soils from site eight had a remarkably low CEC; with an average value of ≤ 2 meg/100 g. The soils from sites one, three and six had CEC values slightly higher than 15 meg/100 g.

The average CEC value for site one was 20 meg/100 g, site three was 16 meg/100 g and site six was 17 meg/100g. With low pH values and high CEC values for soils from site six, it is likely that acidification could have taken place significantly more compared to other sites of the study area.

DISCUSSION

Grain diameter Influence on the Environment

The PSD of soil samples revealed the < 2 µm fraction (clay fraction) to be in the range of 3 and 9 wt %, the > 2 µm to < 50 µm fraction (silt fraction) was between 54 and 44 wt %, and the > 50 µm to < 250 µm fraction (sand fraction) was between 47 and 63 wt %. This observed uniformity of PSD created equal opportunity for ions of heavy metals to migrate and to adhere to the clay fraction; thereby promoting similar soil contamination trends. Distance of source of contaminants may have played a major role in determining the quantitative aspects of the contaminants in the soils. Grains were poorly sorted, with subangular grains located further from the plant, which is indicative of windblown particles transported at a short distance (Ringrose et al., 1995). Finer particles from the tailings dump could be windblown to distant environments, and eventually affect the ecosystem.

Environmental Aspects of Descriptive Petrology and Color

The grains of tailings dump observed at Selebi Phikwe were subangular, depicting limited transportation from source (Bain et al., 1995), and also indicative of less aggressive leaching activities taking place (Singh et al., 1999). Mineral ore bodies and tailings dump release particles to the atmosphere through convectional forces with wind energy as vector agent (Buseck and Posfai, 1999). Smelting processes release gases. Most significant are wastes released from tailings dump into the surface sediments, which eventually influence the concentrations of heavy metals contained in living organisms (Kozákov et al., 1995). Due to the fact that tailings dump are main sources of acid mine drainage (AMD) (Galan et al., 1999), adequate control measures are necessary in limiting the spread of contaminants in the surrounding environments.

The steps obviously taken by the mining authorities in containing their tailings dump are in conformity to basic principles of environmental management of tailings dump as described to by Galan et al. (1999), and Jambor and Bowles (1998).

The color of soils reflects Fe content (Dixon, 1989), which is contained in pyrite and pyrrhotite (Nkoma and Ekoese, 1999; 2000). Color changes influence in mineral and chemical compositions of the soils (Tan, 1996). Whitic gray sediments in some soil samples were due to precipitation from saturated ions of dissolved salts in heavy metals (Robertson et al., 1997; Shaw et al., 1998). In these environments, the surface sediments were deprived of vegetation cover and dead zones formed. Remaining aggregates used during road construction, which were not removed from the area, have weathered, and might also have influenced surface sediments color at the control site.

Influence of pH and Electrical Conductivity on the Environment

The pH of soils ranged from 3.5 to 9.0 with very acidic soils located close to the smelter/concentrator plant. The low pH values at these sites (three, four, five and six), could be attributed to their closeness to the smelter/concentrator plant, the tailings pond and the tailings dump where very high concentrations of SO$_4^{2-}$, Cd, Co, Cr, Cu, Fe$^{2+}$, Ni, Se, and Zn as described by Bowles et al. (1998), occur. Very high concentrations of Fe$^{2+}$ and SO$_4^{2-}$ increase acidity in the environment, and there is the tendency of acid expansion due to probable depletion of the acid-neutralizing capacity of the soils (Shaw et al., 1998). Eventually, the pH values at sites seven, eight, nine and ten could drop as the surrounding soils are contaminated with heavy metals.

High acidity could favor the leaching of heavy ions from the tailings dump and related mining waste to the soils. High acidity of soils is reflected by on-going acid mine drainage (AMD) activity which is depicted by areas of poor or no vegetation cover and are referred to as dead zones (Hantong-Fong et al., 1997). A similar phenomenon occurred at the Ni mine area, near Sudbury, Ontario, Canada (Hantong-Fong et al., 1997). Low pH of soils, furthermore, could promote the leaching and precipitation of ions including those of heavy metals namely Cd, Co, Cr, Cu, Fe$^{2+}$, Ni, Se and Zn. The pyrrhotite (Fe$^{2+}$S, FeS) and pyrite (FeS$_2$) in the tailings dump as explained by Holmström and Öhlender (1999) and Holmström et al. (1999), are oxidised on exposure to water to form sulphate and sulphuric acid.

Electrical conductivity values obtained for the soil samples from the different sampling sites at the Selebi Phikwe area. (Note numbers in graph depict sampling sites).
were significantly low, and ranged from 50 μ s cm⁻¹ to 250 μ s cm⁻¹. The amount of total dissolved solids (TDS) in soils can be estimated from their EC values (Murray, 1986). The EC is used to estimate the presence of dissolved salts such as sulfates, carbonates, phosphates and chlorides. The TDS of given sample may not be reflected by its pH because the salts are generally neutral. Soils with low pH correspondingly had low EC.

The rocks become acidic in a low pH environment, leading to precipitation of ions including those of heavy metals. Pyrrhotite (Fe₅S₈-FeS) and pyrite (FeS₂) in tailings dump are oxidized on exposure to water to form sulphate and sulphuric acid as indicated in equations 2 and 3 (Al et al., 1994, 1994a; Benner et al., 1997; Bowles et al., 1995).

\[ 2\text{FeS}_2 + 16\text{H}_2\text{O} \rightarrow 2\text{FeSO}_4 + 2\text{H}_2\text{SO}_4 + 14\text{H}^+ \] (2)

\[ 4\text{FeSO}_4 + 10\text{H}_2\text{O} + \text{O}_2 \rightarrow 4\text{Fe}^{3+} \text{OH}^+ + 4\text{H}_2\text{SO}_4 \] (3)

The acidification reactions could be accelerated by the bacterium Thiobacillus ferroxidans, the absence of neutralizing minerals such as calcite (CaCO₃), and release of heavy metals into their ionic state (Bowles et al., 1998). Piles of tailings dump stay for years probably without proper disposal. During stockpiling, ions of heavy metals leached into the soils and water bodies, and could eventually be absorbed by plants.

**Influence of Cation Exchange Capacity on the Environment.**

The CEC values for soil samples obtained were between 2 meq 100g⁻¹ and 20 meq 100 g⁻¹. These values are typical for kaolin minerals intercalated with smectite in soils (Dixon, 1999). Samples with high EC also contained illite. Finer clayey particles tend to adsorb heavy ions of elements on their surfaces as demonstrated by Song et al. (1999). In the soil samples, fewer exchange sites resulted in a low CEC for ions adsorbed on the surfaces of the soil particles, consequently they remained in solution and are bioavailable for plant uptake.

Values obtained for CEC at the study area reflected cation exchange sites for ions of heavy metals to either have been adsorbed on the surface of clay mineral structure, or absorbed by isomorphous substitution. Whereby heavy metal ions are either adhered on or absorbed into the clay mineral structure, the surface sediments were contaminated with the corresponding heavy metals, and eventually got polluted.

**CONCLUSIONS**

This study has attempted to petrographically and physicochemically characterise the tailings dump and soils surrounding a Ni-Cu mining and smelting environment in Botswana. The primary objective was to establish any influence on the environmental physico-chemistry as a result of mining/smelting activities. Physico-chemical analyses which included particle size distribution (PSD), pH, electrical conductivity (EC), cation exchange capacity (CEC), color and descriptive petrography on samples of tailings dump and soils were performed in order to understand the significance of these properties on the surrounding physical environment.

Results depicted in-put of contaminants from tailings dump and mining/smelting activities to the soils. High acidity of soils is reflected by on-going acid mine drainage (AMD) activity which is depicted by the formation of dead zones. Pyrrhotite (Fe₅S₈-FeS) and pyrite (FeS₂) in tailings dump are oxidized on exposure to most environments forming sulphate and sulphuric acid. Fewer exchange sites have resulted in a low CEC for ions adsorbed on the surfaces of soil particles; consequently they remain in solution and are bioavailable for plant uptake.

**REFERENCES**


