ASSESSMENT OF SELECTED PROPERTIES OF MINE TAILINGS AT THE FORMER KABWE MINE AND THEIR POTENTIAL TO SUPPORT PLANT GROWTH

By

Mercy Mulenga

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DECLARATION

I, **Mercy Mulenga**, hereby do declare that this dissertation which I hereby submit for award of Master of Science Degree in Integrated Soil Fertility Management at the University of Zambia was compiled and written by myself and the work presented is from my own research and that no part of this report has been submitted by me or any other person for award of any degree in any institution.

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APPROVAL

This dissertation by Mercy Mulenga has been approved as partial fulfilment of the requirements for the award of the degree of Master of Science in Integrated Soil Fertility Management by the University of Zambia.

Examiner 1__________________ Signature _____________ Date__________

Examiner 2__________________ Signature ____________ Date___________

Examiner 3_________________ Signature ____________ Date___________

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ABSTRACT

Lead (Pb) and Zinc (Zn) were mined in Kabwe from 1904 to 1994, generating large quantities of solid mine waste. Among the solid wastes, were tailings from the leach plant which are now an environmental concern because of their high contents of Pb, Zn and other potentially toxic metals. To prevent contamination of the environment surrounding the tailings, there is need to grow plants on the tailing to stabilize them. Efforts to establish plants on the tailings in the past have proved to be difficult. A study was conducted to: (i) determine selected physical and chemical properties of the tailings (ii) to assess the suitability of the tailings for growing plants and (iii) to determine if the tailings qualify to be classified as hazardous materials due to their contents of Pb, Zn, Cu and Cd. Eighty-one (81) tailing samples from the top 0 - 60 cm depth were collected and characterized for their particle size distribution, bulk density, pH, Electrical conductivity (EC), organic matter, plant available P, exchangeable Ca, Mg, Na, and K; DPTA and Aqua regia extractable Cu, Zn, Fe, Mn, Pb and Cd. The tailings were red to dark reddish brown, with a fine earth fraction dominated by sand and silt sized particles with very low clay. They had a sandy loam texture, a low bulk density (1.00 ± 0.03 $g.cm^{-3}$), and a mean total porosity of 57 %, indicating that they were fine, loose and porous materials. The tailings were very strongly acid to neutral (pH: 4.19- 6.81), and had low salinity (EC: 0.08-3.69 mS/cm).They had low organic matter (1.53 %) and plant available P (10.87 $mg.kg^{-1}$), but high levels of exchangeable Ca, Mg, K and Na. They also had high to very high concentrations of DPTA and Aqua regia extractable Cu, Zn, Mn Fe, Pb and Cd. Mean concentrations of DPTA extractable metals were: 51.52 ± 3.97 mg $Cu.kg^{-1}$; 1058.20 ± 96.34 mg $Zn.kg^{-1}$, 2,999.17 ± 154.65 mg $Pb.kg^{-1}$ and 4.61 ± 0.39 mg $Cd.kg^{-1}$. The mean Aqua regia extractable concentrations were: 272,773 ± 860 mg $Fe.kg^{-1}$, 20,781 ± 455 mg $Mn.kg^{-1}$, 1,462 ± 55 $mgCu.kg^{-1}$, 244 ± 13 mg $Zn.kg^{-1}$, 18,945 ± 550 mg $Pb.kg^{-1}$, and 535 ± 74 mg $Cd.kg^{-1}$. The Kabwe mine tailings were found to be unsuitable for plant growth, because of their low organic matter content, and high concentrations of bio-available Zn, Cu, Pb and Cd, which were likely to be toxic to plants. A comparison of mean total concentrations of Pb, Cu, Zn, and Cd in the tailings with the US EPA Total Threshold Limit Concentrations (TTLC) for these metals showed that the Kabwe tailings qualified to be classified as toxic materials with respect to Pb and Cd. Concentrations of plant extractable Pb and Cd were found to be inversely related to the pH of the tailings. The Kabwe mine tailings should be treated as toxic materials because of their high Pb and Cd contents. Access to the tailings should be restricted. Efforts to establish vegetation on the tailings should include means of increasing the organic matter content and measures to reduce the bioavailability of Pb, Cd, Zn and Cu.

Key words: *Kabwe mine, Tailings, Lead, Zinc, Copper, Cadmium, toxicity, plant growth***.**

DEDICATION

This dissertation is dedicated to my beloved daughter Thelisa Mutasha, the reason for my hard work.

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ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectroscopy
ATP	Adenosine Triphosphate
CWT	Clean Water Team
DPTA	Diethylene Triamine Penta Acetic Acid
EC	Electrical Conductivity
ECZ	Environmental Council of Zambia
SAS	Statistical Analysis Software
TTLC	Total Threshold Limit Concentration
UNZA	University of Zambia
US EPA	United States Environmental Protection Agency
USDA	United States Department of Agriculture

CHAPTER ONE: INTRODUCTION

Mining has been in existence for a very long time in Zambia and has contributed greatly to the economic development of the country. Despite its many benefits to the economic growth of the country, mining has had its negative impacts on the environment. For a long time, mining activities were carried out with little regard for their adverse effects on their surrounding environment.

In Kabwe, the commercial mining of lead (Pb) and zinc (Zn) commenced in 1904 and ended in 1994 (Musonda and Tembo, 2004) The town thus had a period of 90 years of mining Pb and Zn without much regard for the potential impacts of the spread of the waste from the mining activities on one location surrounding the mining site. The mineral ores at Kabwe mine consisted of sulphide ores with galena (PbS) and sphalerite (ZnFe)S) as the main minerals and pyrite (FeS_2) as the minor mineral. The ores also contained mainly silicates, oxides and carbonates of Pb, Zn and iron (Fe) with subsidiary amounts of vanadium (V) and copper (Cu). During the active mining period, about 25 minerals were extracted from the ores at Kabwe mine (Leteinturier, *et al,* 2001). The minerals extracted were mainly Pb and Zn with lesser quantities of silver (Ag) and cadmium (Cd). The mining activities officially ceased in 1994. Since then the authorities have been involved in the rehabilitation of the environment at the mining site and surrounding areas.

Mining activities usually generate large amounts of solid waste (Fernandez *et al*., 2008). These often have negative impacts on the quality of soils and other natural bodies on which they accumulate. The common mine solid wastes from mining sites include overburden, waste rock, slag and tailings. Overburden refers to soils and rocks that overly an ore of interest, that have to be removed in order to access the ore. They are a common waste especially where open cast or open pit mining is carried out. Waste rocks on the other hand, are rock materials produced during the mining of ore that do not contain minerals of economic value. These two are common waste products of both open pit and underground mines. Slag refers to solid wastes generated during the processes of smelting ores, carried and deposited as molten material which eventually solidifies upon cooling. Tailings on the other hand are fine solid wastes produced during mineral processing operations. They are transported and disposed of as slurry, (Environmental Council of Zambia, 2004). Because of their fine size, tailings are very prone to wind erosion and can be easily blown to surrounding areas by the wind. They can also be easily washed away through runoff from the points where they have been deposited. Many of the solid mine wastes are generally considered to have no economic benefit for the mining companies whose main interest is the processing and marketing of the minerals of interest from the ore.

At Kabwe mine, large quantities of solid wastes were generated. According to Leteinturier, *et al*. (2001), the solid wastes at Kabwe mine amounted to about 8 million metric tons and covered an area of over 75 ha. Among the main solid wastes were the tailings from the leach plant. These wastes are now a source of concern due to their reported high contents of potentially toxic metals such as Pb and Cd. The wastes at Kabwe mine pose a number of health and environmental problems in areas associated with the presence of high levels of Pb in the environment. According to Yabe *et al* (2015), high levels of Pb have been found in soils and plants in residential areas close to the former mine. Most of the Pb found in the environment are suspected to have been introduced by dust particles from the tailings containing high concentration of Pb and other heavy metals. There is great concern about the potential health risk to the population that lives in areas with high levels of Pb in the environment close to the former Pb and Zn mine. Yabe *et al.* (2015) further report that between 1973 to 1974 soil Pb concentrations in Kasanda township, approximately 2 km north west of the former Kabwe mine Pb and Zn mine had reached levels of 2400 mg Pb kg^{-1}.

Mbewe, *et al,* (2015) recently reported blood levels of Pb in some children in Kabwe ranging from 60 to 120 µg/dL and sometimes reaching 300 µg/dL (micrograms per deciliter), compared to reported normal levels of Pb in blood of less than 10 µg/dL according to the United States Environmental Protection Agency (US. EPA. 1998). Results such as these have raised concern about the extent of environmental pollution in Kabwe due to Pb especially in residential areas close to the former Pb and Zn mine. Efforts to assess the health risks to the local population and the environmental degradation associated with Pb pollution have become one of the major issues in Kabwe since the closure of the former mine.

In view of the above, there is need to find sustainable ways of managing areas contaminated with Pb and other potentially toxic metals in Kabwe to make them safe for human habitation. There is also need to prevent further contamination of areas surrounding the mine site from Pb and other metals contained in mine wastes. One possible approach is to grow plants on the tailings to prevent their spread to surrounding areas.

Before embarking on such a programme it is necessary to assess the potential of the tailings to support plant growth. This is an aspect that has not been addressed by other researchers that have worked on the problem of rehabilitating the mine wastes at Kabwe Mine. Knowledge of the potential of the tailings to support plants, would help in the development of appropriate methods of managing the tailings. The successful establishment of vegetation on the tailings could significantly contribute to the control of the dispersal of heavy metals contained in the tailings to the surrounding environment. The assessment of the suitability of the tailings for plant growth, requires characterizing physical and chemical properties of the tailings known to be important for plant growth and a comparing these with requirements for plant growth.

1.1 Statement of the Problem

The mining of Zn and Pb in Kabwe generated large quantities of solid mine wastes which have become a major source of concern to human health and the environment because of their reported high contents of Pb, Zn and other potentially toxic heavy metals. The solid mine wastes at the former Kabwe mine are believed to be responsible for aerial emissions of dust particles with high levels of Pb and other metals to neighboring residential areas where Pb pollution is now considered to be a great risk to the inhabitants. Efforts to grow plants on the tailings at Kabwe mine have not been very successful. If the movement of the tailings is not restricted, there is a risk of further contamination of the environment around the tailings through transportation by wind and water. The tailings also pose a risk of contaminating surface and ground water with heavy metals and other contaminants through leaching and erosion. The management of the tailings and other solid mine wastes is likely to be more effective if the characteristics of these mine wastes are understood.

1.2 Justification

A number of environmental studies have been conducted in Kabwe, in relation to the contamination of the environment near the former Kabwe mine by Pb and other heavy metals. Most of the studies conducted in Kabwe have focused on assessing the levels of Pb and other metals near the former mining area, particularly in soils, water, plants and in the blood of children from residential areas believed to be highly contaminated with Pb. There is, however, still need to assess and understand the characteristics of the tailings and other mine solid wastes at the former Kabwe mine, which are the potential sources of Pb contaminating the environment. It is particularly important to study the characteristics of the tailings because they are relatively small particles that are highly susceptible to transportation by wind and water and thus likely to be the major source of Pb contamination. While a lot has been done to try and remediate the contaminated environment surrounding the mine area, not much effort has been directed at trying to understand the characteristic properties of the tailings and their potential to further contaminate the surrounding environment. It is therefore necessary to know the characteristics of the tailings if appropriate measures are to be developed to manage the tailings effectively. Sound knowledge of physical and chemical properties of the tailings is therefore a pre-requisite to the development of effective means of managing the tailings at the former Kabwe mine.

1.3 Main Objective

The main objective of this study was to assess the physical and chemical properties of the tailings at the former Kabwe mine and their potential to support plant growth.

1.4 Specific Objectives

The specific objectives of this study were:

1. To establish the values of selected physical and chemical properties of tailing important for plant growth.
2. To assess the potential of the tailings at Kabwe former mine to support plant growth.

3. To establish whether the tailings at Kabwe mine are a potential source of environmental contamination of Pb, Zn, Cu and Cd.

1.5 Hypotheses

The following research and null hypotheses were tested in the study:

1. Ha_1: The tailings at Kabwe mine are suitable for growing plants
   Ho_1: The tailings at Kabwe mine are not suitable for growing plants

2. Ha_2: The Kabwe mine tailings contain hazardous levels of Pb, Zn, Cu and Cd.
   Ho_2: The Kabwe mine tailings do not contain hazardous levels of Pb, Zn, Cu and Cd.

1.6 Organization of the Dissertation

This thesis comprises of five chapters. Chapter two comprises of an examination of the literature that was done to assess selected properties of mine tailings at the former Kabwe mine and their suitability for plant growth. In chapter three, an explanation of how the materials and methods that were used in the study was done. The detailed methods and formulas for each of the experiments in the study were also presented. Chapter four presents the results and the discussion on the physical and chemical properties of the tailings, the suitability of the tailings for plant growth and the classification of the tailings as toxic material with respect to Pb, Zn, Cu and Cd. Chapter five presents the conclusions and recommendations.

CHAPTER TWO: LITERATURE REVIEW

Kabwe, formerly known as Broken Hill, is the provincial headquarters of Central Province of Zambia. According to Yabe *et al*, (2015), Kabwe which has a population of about 300,000 was once Zambia's thriving industrial base. In 1902, rich deposits of lead were discovered in Kabwe and led to the establishment of a mine and smelter near the center of the town. In 1904, mining and smelting operations for Pb and Zn started and continued until 1994 when the mining activities ceased. During the period of mining of Pb and Zn in Kabwe, little attention was paid to the potential dangers to human health and the environment posed by Pb and Zn mining and processing operations.

Musonda and Tembo (2004) report that the mining activities at Kabwe mine generated large quantities of solid wastes which are now a source of concern due to their reported high contents of Pb and other potentially toxic metals. They further estimated the solid wastes at Kabwe to be at 8 million metric tonnes, covering an area of over 75 ha (Leteinturier, *et al*, 2001).

2.1 Characteristics of Solid Wastes from Mining Activities.

According to Dennis *et al*, (1997), solid wastes from mining activities are usually unsuitable for the growth of fauna and flora commonly found in natural soils. They usually have no or very poor aggregation and contain low levels of nutrients and organic matter (Sheoran *et al*, 2010). Singh and Singh (2006) report that solid wastes from mining activities commonly tend to disturb the biological functioning and nutrient cycling of natural soils and consequently lead to the development of non-functional soil systems. Due to their low organic matter content and sometimes very low or very high pH, solid wastes from mining activities do not support plant and microbial growth (Agrawal *et al*, 1993).

Areas associated with mine wastes typically have elevated levels of trace elements that remain in the soil. According to Mendez *et al*, (2007) and Mendez and Maier, (2008), heavy metals such as Pb, Zn, Cu and Cd usually occur in very high concentrations in mine tailings generated from sulphide ores. These metals usually pose a danger to organisms in the environment depending on their levels of mobility and bioavailability.

Most mine tailings are reported to contain low levels of organic matter. According to Ye *et, al*, (2002), Organic matter is the natural reservoir of plant nutrients and is also the main source of energy and nutrients for microorganisms responsible for mineralization of nutrients in terrestrial environments.

According to Sheoran *et al*, (2010), mine tailings are reported to have lower bulk densities compared to natural mineral soils. The bulk density of natural soils depends on the texture, density of the minerals and organic matter particles and on the packing of soil particles within the soil. High bulk densities limit aeration, water flow and the growth of plant roots in the soil and other related media. According to Brady, (1990) as the bulk density increases, pore spaces decrease resulting in compaction. Consequently, the volume of air and water that a soil can hold decreases with increasing bulk density. On the other hand, decreasing bulk density results in increased water infiltration rates which reduces runoff but increases the degree of aeration and potential for leaching of dissolved nutrients in the soil or sediment solution.

Sheoran *et al*., (2010), report that most mine tailings are generally deficient in the three primary plant nutrients nitrogen (N), phosphorus (P) and potassium (K). This is consistent with the reported low content of organic matter in most mine tailings. According to Donahue *et al*., (1990), soils with low amounts of organic matter generally tend to contain low levels of N, P and K.

2.2 Effects of Mine Tailings on the Environment.

According to Wong (2003), the effects of mine tailings on the environment can be multiple. They can among others adversely affect the quality of air, water and surrounding soils. The introduction of high concentrations of contaminants through the tailings can lead to the development of toxicities of various elements in the environment that may lead to the loss of biodiversity of the affected environment, and ultimately loss of economic potential.

2.2.1 Effects of Mine Tailings on Air Quality.

Air pollution occurs when harmful or excessive quantities of substances including gases, solid particles of potentially hazardous chemicals and biological molecules are introduced into the earth's atmosphere. The tailings at Kabwe mine have small solid particles that contain heavy metals that can spread to the surrounding environment when the tailing particles are picked up and transported and deposited by the wind. Since some of the heavy metals associated with the tailings at Kabwe mine are potentially toxic, the disposal of the tailings from their original location is a source of health concern especially for residents in areas affected by the tailings.

In Kabwe, it has been established that atmospheric transfer of Pb and other metals from mine site to surrounding areas is one of the mechanisms responsible for pollution of areas surrounding the mine. Musonda and Tembo (2004) in Kabwe, have shown that areas on the upwind or leeward eastern side of the mine, has lower concentrations of Pb and other metals in soils compared to locations on the down wind or wind ward western side of the mine. Their findings indicate that atmospheric transfers of Pb and other metals from the mine sites to locations near the mine is one of the main mechanisms responsible for pollution of areas surrounding the mine in Kabwe.

2.2.2 Effects of Mine Tailings on Water Quality

Water pollution occurs when there is a change in the chemical, physical or biological properties of the water lowering the quality of the water for some intended use. Pollution makes the water less suitable or more harmful to organisms that depend on water for their survival. Mine tailings containing potentially toxic substances are common point sources of pollution for those substances. Water pollution from tailings can result from the leaching of potentially toxic substances, from the tailings into surrounding ground or surface water bodies. The potential risk of water pollution from mine tailings depends on the amounts, solubility and mobility of contaminants in the tailings. The pH of the tailing is one parameter that has a significant influence on the solubility and potential mobility of metallic contaminants in tailings.

The leaching from mine tailings can carry potentially toxic heavy metals such as Pb, Cu, Zn and Cd into surface and ground water bodies and consequently pose significant risks to the health of humans, animals and vegetation which depend on these water bodies for their survival. According to Johansen *et al.* (2008), heavy metals such as Pb, Cu, Zn and Cd often leach from mine tailings to contaminate the water bodies around the mining area. Ekeleme *et al.* (2013) reports that the Lead – Zinc mining activities in upper Benue region of Nigeria are responsible for the pollution of the water sources in the area with Cd. In Kabwe, a number of residents near the former mine use water from shallow wells and ponds for their domestic requirements. There is a greater likelihood that some of this water is contaminated with potentially toxic elements from the mine site

2.2.3 Effects of Mine Tailings on Biodiversity

The presence of potentially toxic contaminants in mine tailings poses a risk to the biodiversity of the surrounding environment if the contaminants from the tailings spread to the surrounding environment. The accumulation of contaminants beyond critical thresholds for the survival of organisms degrades the natural habitat and may result in the disappearance of species that are sensitive to the contaminants that accumulate in the environment. Drastic changes in the habitat such as those caused by changes in the pH and temperature, can significantly disturb the natural ecological communities in an area. According to Tiwari *et al*. (2013), the most noticeable effect of environmental pollution related to mining activities on biological diversity is the elimination of vegetation, which in turn changes the availability of food and shelter for wildlife. Such changes eventually lead to changes in species composition and structure in a given location.

Areas adjacent to mine waste disposal sites often contain elevated concentrations of metals compared to natural soils, Branson and Ammons (2004). Sheoran *et al*. (2011), reported elevated levels of Cu in soils surrounding a Copper mining site in India compared to levels in normal soils. The vegetation near the mining site also had higher concentration of Cu compared to plants from areas with normal soils. In Ghana, Boateng *et al.* (2012) reported high levels of As, Cu and other heavy metal in soils near the Ashanti mine area that constantly received gaseous effluents from the mine compared to soils from areas not affected by the effluents from the mine.

High concentrations of metals such as Pb in soils are known to be toxic to plants. According to Pahlsson (1989), Pb inhibits plant growth, it is believed to interfere with the activity of enzymes required for photosynthesis and interferes with cell division and respiration. It also reduces water absorption and transpiration and reduces the synthesis of chlorophyll, carotenoid and adenosine triphosphate (ATP). Fargasova (2001) reports that although Zn is a micronutrient for plants, it reduces the activities of enzymes involved in photosynthesis and hydrolysis at solution concentrations of 650 µg Zn /L.

2.3 Heavy Metals as Environmental Contaminants

Most of the potentially toxic metals associated with mining activities are heavy metals. According to Tchounwou *et al.* (2012), the term heavy metal has several definitions. One definition is that they are naturally occurring elements with a high atomic mass and a density 5 times or more than that of water. Another definition is, any metallic element with a relatively high density that is toxic or poisonous at low concentration. According to Gautum *et al.* (2011) and Johansen *et al* (2008), some of the common heavy metals associated with mine tailings include Cu, Pb, cobalt (Co), Cd, As, Mn and Zn. Although elements such as Cu, Mn, Zn and molybdenum (Mo) are required by both plants and animals, they can be toxic when present in high concentrations in the environment.

2.4 Heavy Metal Mobility and Bioavailability

The potential risk of heavy metals to living organisms depends on their ability to move from their original site to another location or their mobility. The potential of an element to cause harm to living organisms also depends on the chemical form in which it occurs. For a substance to cause harm to an organism, the substance has to be present in chemical form that can be absorbed by a living organism or their bioavailability. This chemical form is termed the bioavailable form. Not all chemical forms of elements are harmful to living organisms. It is the bioavailable form that is able to cause harm.

According to D'Amore *et al* (2005), an understanding of the mobility, bioavailability and potential fate of contaminants in mine tailings is necessary for their effective management in the mine wastes. For most metals, the free ionic chemical form is usually the bioavailable form. The ionic forms can be removed from solid particles on which they are adsorbed by ion exchange with the hydrogen ions and other cations that may be present in solutions in the mine tailings.

Finžgar *et al* (2007), showed that the fractionation, bioavailability, mobility and leachability of Pb and Zn in soils in Czech Republic was partly controlled by the pH and organic matter content of the soils. They also observed that more than 95% of the variability in Pb and Zn in the exchangeable fraction of the soil was attributed to the variability in the pH of the soil. These results suggested that the control of properties such as pH could be employed to regulate the mobility and bioavailability of metals in mine tailings.

Gimmler *et al* (2002), report that results of environmental impact assessments on mine sites and areas around the mines usually show high exposure of plants and animals to heavy metals. Most of the heavy metals are also reported to accumulate in living organisms. The accumulation of substances in living organisms is called bioaccumulation. Bioaccumulation is believed to be partly responsible for the poisoning of plants or phyto-toxicity which results in the observed changes in plant communities Gimmler *et al* (2002).

2.5 Use of Vegetation to Stabilize Mine Tailings

The use of vegetation as a means of stabilizing mine tailings has been attempted in a number of countries, (Vassilev *et al*, 2004), (Branson and Ammons, 2004), (Sheoran *et al*, 2010), including Zambia (Kambing'a and Syampungani, 2012), (Leteinturier *et al*, 2001). According to Pichtel and Salt, (1998), efforts to rehabilitate mine tailing sites by re-vegetation have not been very successful.

This could probably be because mine tailings are new ecological environments that have to be colonized before other vegetation can become established on them. Recent studies on selected tailings in Zambia by Kambing'a and Syampungani, (2012) show that a selection of pioneer species dominated by *Acacia polyacantha*, *Acacia sieberana*, *Bauhinia thonningii* and *Peltophorum africanum* tend to grow well on mine tailings. According to Kambing'a and Syampungani, (2012), these pioneer species have very low nutrient requirements and have evolved characteristics that enable them to survive in such environments. Such pioneer species can improve the nutrient conditions of the tailing over time, making them more suitable for habitation by other plants species.

Preventing heavy metal pollution is important because cleaning up contaminated soils is usually quite expensive. The limited success in attempts to re-vegetate tailings can be attributed to many factors among which high concentrations of metals, (Mendez *et al,* 2007), (Mendez and Maier, 2008), absence or low levels of organic matter, nitrogen, phosphorus and potassium are commonly cited,(Ye *et al*, 2002), and (Dennis *et al*, 1997). Other factors include very low or high pH levels, (Agrawal *et al*, 1993), low moisture retention capacity, (Sheoran *et al*, 2010) and other adverse physical, chemical and biological characteristics of tailings which suppresses re-vegetation (Singh and Singh, 2006).

It is therefore important to assess the physical and chemical characteristics of mine tailings before embarking on measures to abate pollution of the surrounding environment from the mine tailings. A sound knowledge of the characteristics of the contaminated materials and their behavior should form the basis for the development of soil environmental management practices.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Location and Ecological Condition of the Study Site

The samples that were used in this study were obtained from mine tailings at the former lead and zinc mine in Kabwe district of the Central Province of Zambia as shown in Figure 1. The site is situated at latitude 14°28′00″ South and longitude 28°25′51″ East at an average altitude of 1190 m above sea level. Kabwe town is in Agro - ecological Region IIa of Zambia which receives an annual rainfall of between 800 and 1000 mm as shown in Figure 1. The climate of Kabwe is like much of the plateau region of Zambia and has been described as a Tropical Continental Climate with three distinct seasons. Kabwe has an average annual rainfall of about 945 mm and mean monthly air temperatures ranging between 14.7° C to 27° C (Leteinturier, *et al*, 2001). The study site is along the Lusaka – Kabwe road or Great North road on the right side when approaching Kabwe from Lusaka.

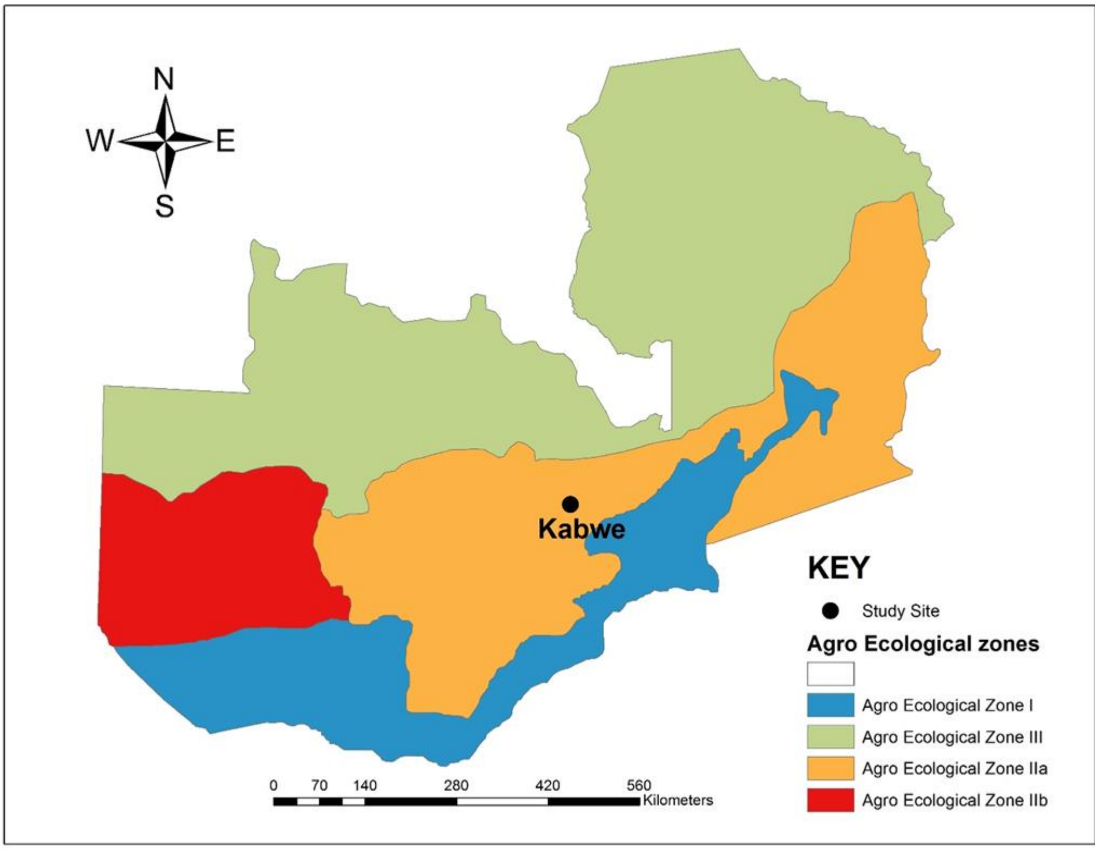

Figure 1. Agro-ecological zones map of Zambia showing location of study site

The tailings appear as large black heaps of earthly materials adjacent to the main road as shown in Figure 2. The black materials that is seen, are not the actual tailings, but is the slag that was applied on top of the tailings, to prevent them from being dispersed from the site by wind and water.

Figure 2. Tailings covered with black slag near the Kabwe - Lusaka road

The actual tailings are light very fine solid materials that are porous and reddish in colour, and can be seen on the summit of the tailings heaps seen adjacent to the Lusaka-Kabwe road as can be seen in Figure 4, vegetation on the soils near the tailings is scanty, probably due to the reported high concentrations of metallic elements which could be toxic to plants.   Figure 4 shows the appearance of tailings exposed to the surface on the summit of the tailing's heaps. The absence of vegetation on the tailings is evident on Figure 3, indicating that there is a probably a problem that limits the growth of plants on the tailings and on soils in the neighborhood of the tailings.

Figure 3. Sparse vegetation cover on soils near the tailings at Kabwe Mine

Figure 4. Reddish to reddish brown surface of the mine tailings

3.2 Sample Collection and Preparation

Samples were obtained from areas covered with tailings from the leach plant only. The samples were collected from three randomly selected sites. A stratified random sampling approach was used to obtain the samples. At each sampling site, a total of 27 tailing samples were collected. They were obtained from 3 topographic positions, at 3 different soil depths in triplicates as summarized in Table 1. The samples were collected in polythene bags, labelled and transported to the University of Zambia, agricultural science laboratories for analysis.

Table 1. Summary of sampling scheme used to collect samples of tailings

Topographical positions	Sampling depth (cm)	Replication	Total
Summit	0 – 20	3	9
Summit	20 – 40	3	9
Summit	40 – 60	3	9
Backslope	0 – 20	3	9
Backslope	20 – 40	3	9
Backslope	40 – 60	3	9
Depression	0 – 20	3	9
Depression	20 – 40	3	9
Depression	40 – 60	3	9

3.3.0 Methods of Soil Analysis

In the laboratory, the tailing samples were first air dried and then passed through a 2 mm sieve. Portions of the tailing samples passing through the 2 mm sieve were kept for laboratory analyses.

3.3.1 Determination of Particle Size Distribution

The particle size distribution of the tailings was determined using the hydrometer method, (Bouyoucos, 1962). Fifty grams of air-dried sample was weighed into a dispersing cup. The cup was filled to half its volume with distilled water. Then 50 mL solution of the dispersing agent, sodium hexametaphosphate ($Na_6(PO_3)_6$) or Calgon solution was added. The dispersing cup was placed on a stirrer and the suspension was stirred continually for 5 minutes.

The suspension was transferred to a 1000 mL sedimentation cylinder using a stream of distilled water and the cylinder was filled to the 1000 mL mark with distilled water. The temperature of the suspension was measured. A plunger was then inserted into the cylinder and was moved up and down continually to mix the suspension. Twenty seconds after removing the plunger from the cylinder, a hydrometer was carefully inserted into the suspension to measure the density of the suspension 40 seconds after agitating the suspension, the temperature and the hygrometer reading of the suspension were taken and used to calculate the mass of the clay sized particles present in the samples. The percentages of the sand, silt and clay sized particles in the tailings were then calculated. Results of the contents of sand, silt and clay sized particles were then plotted on the USDA textural triangle to determine the textural class of the tailing samples.

3.3.2 Determination of Bulk Density.

The dry bulk densities of the tailing samples were determined using clod method (Blake, 1965). According to Grossman and Reinsch (2002), Bulk density is the measure of soil mass per unit volume of soil. It is used as a measure of soil wetness, volumetric water content and porosity.

3.3.3 Determination of Soil Organic Matter

To determine the organic carbon content of the tailing samples, the Walkley and Black Method, (Nelson and Sommers (1982) was used. A 10 mL solution of 1 N $K_2Cr_2O_7$ and a 20 mL solution of concentrated H_2SO_4 were placed in 250 mL conical flask to which a 1 g of air-dried tailing sample was added. The mixture was swirled and left to digest under a fume hood for 30 minutes. Then 150 mL of distilled water was added to the flask, to which 10 mL of concentrated H_2PO_4 was further added.

Then 10 drops of diphenylamine indicator were added to the flasks which was then titrated with a solution 1 N $FeSO_4$ to a green color end point. A blank sample to which no tailing samples were added was subjected to the sample procedure as the tailing samples. The amount of organic carbon present in the tailings was then calculated from the difference between the total volume of the $FeSO_4$ used to titrate the solution with the sample and the solution with the blank. To calculate the organic carbon content in the tailings, equation 1.0 was used:

$$\%Org\ C = \frac{4*N*(Vb-Vs)}{mass\ of soil(g)} * 100 \qquad [1.0]$$

where: N = normality of $FeSO_4$, Vb = volume of $FeSO_4$ used to titrate blank.

Vs= volume of $FeSO_4$ used to titrate samples.

To calculate the organic matter content of the tailings from values of organic carbon contents, equation 2.0 was used:

$$\% \text{ OM} = 2 \text{ x } \% \text{ Org C} \qquad [2.0]$$

3.3.4 Determination of Soil pH

The pH of the tailings was measured in solutions of 0.01 M $CaCl_2$ using a solution ratio of 1:2.5 (McLean, 1982). Twenty grams of the tailing samples were weighed and placed in 50 mL plastic bottles to which 25 mL of 0.01 M $CaCl_2$ was added. The suspension was shaken for 30 minutes and allowed to settle for 5 minutes after which the pH of the supernatant was measured using a digital pH meter.

3.3.5 Determination of the Electrical Conductivity (EC)

The electrical conductivity (EC) of aqueous solution of the tailings were also measured as described by McLean, (1982). Ten grams of the tailing samples were weighed into 100 mL plastic bottles to which 50 mL of distilled water was added. The suspension was placed on a mechanical shaker for 1 hour and allowed to settle for 5 minutes. Then, Electrical Conductivity of the solution was measured using a digital EC meter.

3.3.6 Determination of Available Phosphorus

To determine the amount of plant available phosphorus (P), the Bray 1 method was used, (Bray and Kurtz, 1945). Three grams of air-dried tailing samples were weighed into 50 mL plastic bottles to which 21 mL of Bray-1 extraction solution (0.03 M NH_4F and 0.25 M HCl) was added. The suspension was shaken for 1 minute on a mechanical shaker and then filtered.

Two reagents for developing the molybdenum blue color was prepared. The first solution, Reagent A was prepared by dissolving: 12 g of ammonium molybdate in 250 mL of distilled water, 0.2908 g of potassium antimony tartrate in 100 mL of distilled water. These were placed in a 2 L volumetric flask to which 1 L of 2.5 M H_2SO_4 was added and the flask was filled to the mark with distilled water. The second solution, Reagent B was prepared by dissolving 1.056 g of ascorbic acid in 200 mL of reagent A.

One milliliter of the filtrate was pipetted into a 25 mL volumetric flask to which 4 mL of fleshly prepared reagent B was added and made to the mark with distilled water. The mixture was shaken and the molybdate blue color was allowed to develop. The concentration of P in the extracts were determined from the absorbance of the solution determined at wavelength of 882 nm using a U-V Visible JENWAY 6305 spectrophotometer. The concentration of plant available P were calculated using equation 3.0:

$$Available\ P\ \left(\frac{mgP}{kg\ soil}\right) = conc\ P\ \left(\frac{mgP}{L}\right) x\ DF\ x\ Vol\ of\ Extract\ Vol(L)\ x \frac{1000g/kg}{g\ soil} \qquad [3.0]$$

3.3.7 Determination of Exchangeable Bases

The exchangeable cations, Ca, Mg, K and Na in the tailings were extracted using 1 N NH_4 AOC buffered at pH 7.0 as described by Jackson, (1973). Five grams of the tailing samples were weighed into 100 mL plastic bottles to which 25 mL of 1 N NH_4 AOC buffered at pH 7.0 was added. The suspensions were then shaken for 30 minutes and filtered.

Concentrations of Na and K were read by Atomic Absorption Spectroscopy (AAS) directly from the filtrate using the Flame Emission mode. To determine concentrations of Ca and Mg, a 1 mL aliquot of the filtrate was transferred into a 25 mL volumetric flask to which 5 mL of a 5000-ppm solution of $SrCl_2$ was added. The volumetric flask was then filled to the mark with 1 N NH_4 AOC buffered at pH 7.0. Then the concentrations of Ca and Mg in the extracts were read by Atomic Absorption Spectroscopy (AAS). The concentrations of the exchangeable cations in the tailings were then calculated using equation 4.0:

$$Exch\ cation\ \left(\frac{meq}{100g}\right) = cation\ conc \left(\frac{mg}{L}\right) x\ DF\ \ x\ vol\ of\ extractant\ (l)\ x\ \left(\frac{1}{g\ soil}\right) x\ 100 \qquad [4.0]$$

where: cation conc= cation concentration in extract, DF= Dilution factor

3.3.9 Determination of Plant Available Trace Elements

To estimate potentially Plant available concentrations of the metals Cu, Zn, Fe, Mn, Cd and Pb, the extractant diethylene triamine penta acetic acid buffered at pH 7.3 (DTPA- TEA, PH 7.3) was used to extract the metals from the tailing samples described by Jackson, (1973). Twenty grams of air-dried samples were mixed with 40 mL of DPTA-TEA extraction solution. The suspensions were shaken for 2 hours and then filtered using a Whatman No 42-filter paper. Concentrations of the metals in the extract were determined by AAS. The concentrations of the plant available trace metals in the tailings were calculated using equation 5.0:

$$metal \left(\frac{mg}{kg}\right) = metal\ conc\ \left(\frac{mg}{L}\right) * DF\ x\ vol\ of\ extractant\ (L) * \frac{1}{g\ soil} * \ \frac{1000g}{kg} \qquad [5.0]$$

where: metal conc = metal concentration in extract, DF: Dilution factor.

3.3.10 Determination of Concentration of Aqua Regia Extractable Metals

To determine the total concentrations of Cu, Zn, Fe, Mn, Cd and Pb in the mine tailings, the aqua regia metal digestion method was used. The aqua regia extraction solution was prepared by mixing concentrated HCl and concentrated HNO_3 in the ratio 3:1. One gram of air-dried tailing samples were placed into 250 mL conical flasks and then moistened with little distilled water. Then 18 mL of concentrated HCl and 6 mL of HNO_3 was added to the flasks. The mixtures were boiled on a hot plate until about 5 to 10 mL of the extract remained in the flask. The flasks were then removed from the hot plate and allowed to cool for about 15 minutes. Another 18 mL of HCl and 6 mL of HNO_3 was added to each of the flasks and the heating process was repeated until about 5 to 10 mL of the extracts remained in the flasks. The flasks were then removed from the hot plate and allowed to cool to room temperature. Then, 10 mL of distilled water was added carefully to the flasks and filtered the extract into 50 mL volumetric flasks. The volumetric flasks were filled to the mark with distilled water. Concentrations of the metals in the extracts were determined by AAS. Concentrations of the metals in the tailings were then calculated using equation 6.0:

$$metal\ \left(\frac{mg}{kg}\right) = metal\ conc\ (\frac{mg}{L})\ x\ vol\ of\ extractant\ (l) x\ DF\ x \frac{1}{g\ soil} x\ 1000 g/kg: \qquad [6.0]$$

where: metal conc= concentration of metal in extract. DF: Dilution factor.

3.4 Data Analysis

Data obtained from the laboratory analyses were subjected to statistical analyses. Descriptive statistics were calculated for the parameters of interest. A t–test was used to establish whether the total levels of Pb, Cd, Zn, Fe, Mn and Cu in the tailings were high enough to warrant classifying the tailings as toxic with respect to these metals. The t– test was further used to compare mean concentrations of selected metals in the tailings with Total Threshold Limit Concentrations (TTLC) established by US Environmental Protection Agency. The critical level of significance used for all the statistical tests was 0.05. All statistical Analyses conducted using the SAS Software version 9.1 for windows.

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Selected Properties of Kabwe Mine tailings

Several physical and chemical properties of the tailings at Kabwe mine were determined. A summary of the characteristics of the tailings is presented in Table 2.

Table 2. Summary of selected physical and chemical properties of tailings

Property	Units	Sample size	Range	Mean ± standard error
Colour	NA	81	Red, - very dark Reddish brown	Red
Sand	%	81	52.0 - 97.0	73.23 ± 12.64
Silt	%	81	3.80 -54.20	23.39 ± 12.25
Clay	%	81	0.0 -25.20	3.66 ± 5.12
Textural class	NA	81	Loamy sand-Sandy loam	Sandy loam
Bulk density	$g.cm^{-3}$	56	0.46 - 1.53	1.00 ± 0.03
Particle density	$g.cm^{-3}$	75	0.85 -7.55	2.58 ± 0.14
Porosity**	%	NA	NA	57.0 ± 0.02
Organic matter	%	80	0.48 - 2.32	1.54 ± 0.05
Phosphorus	mg/kg	81	0.50 - 33.10	10.87 ± 0.74
pH (0.01M$CaCl_2$)	NA	81	4.19 - 6.36	5.44 ± 0.06
EC	mS/cm	81	0.08 - 3.69	1.42 ± 0.12
Ca	meq/100g	81	0.70 - 50.75	14.69 ± 1.57
Mg	meq/100g	81	0.14 - 3.04	1.01 ± 0.08
K	meq/100g	81	1.29 - 9.16	4.72 ± 0.22
Na	meq/100g	81	1.78 - 17.28	7.18 ± 0.45

4.1.1 Colour

The most prominent observable property of the tailings is their colour. The tailings at Kabwe mine are covered with dark coloured slag to prevent the fine tailing particles from being blown away. Because of the dark colour of the slag, most people who observe the tailings heaps from a distance see the dark coloured slag on the surface of the tailing and assume this to be the actual colour of the tailings. The actual tailings are reddish in colours with a Hue of 10 R on Munsell and Standard colour charts (Oyama and Takehara, 1970). The actual colours of the dry tailings range from red (10 R 5/8) to very dark reddish brown or dusky red (10 R 3/3).

4.1.2 Particle size distribution

The fine earth fraction (< 2 mm) of the mine tailings was found to be dominated by sand sized (0.05 -2.0 mm) particles which ranged from 52 to 97 %, followed by silt (0.002-0.05 mm) particles that ranged from 3.80 - 54.2 %. The tailings contained very little clay sized particles (< 0.002 mm) which ranged from 0 - 25.2 %. This observation is similar to that of Sheoran *et al*, (2010) who report that tailings are generally deficient in clay-sized particles and are prone to moisture and nutrient deficiencies. The textural classes of the Kabwe tailings based on the USDA textural triangle, were loamy sand and sandy loam, with sandy loam being the modal class. This textural class is similar to that of most upland Zambian soils, which have sandy loam textures (Shitumbanuma, *et al*. 2018). Since clay particles have a great bearing on important properties such as moisture and nutrient retention, the low clay content of the tailings may limit their ability to retain moisture and nutrients.

4.1.2 Bulk Density and Porosity

The bulk density of the tailings was generally low with a mean value of 1.0 $g.cm^{-3}$. This is much lower than the reported mean value in Zambian mineral soils with similar texture of 1.41$g.cm^{-3}$ (Shitumbanuma, *et al*. 2018). The mean bulk density of the tailings at Kabwe is also lower than reported range for ordinary aggregated loams and clays and sandy soils of 1.2 to 1.6 $g.cm^{-3}$ (Hillel, 2004). This indicates that the tailing at Kabwe mine are looser or less compacted than ordinary mineral soils. They are thus, likely to be more permeable to water and air than ordinary mineral soils.

The total porosity of the tailings calculated from the mean values of the particle density and bulk density of the tailing was 57 %. This porosity falls within the range observed in soils of 30 - 60 % (Hillel, 2004). It is however higher than the reported average porosity for cultivated mineral soils in Zambia of about 47 % (Shitumbanuma, *et al*. 2018). The tailings at Kabwe mine thus probably have a higher potential to leach substances dissolved in their solutions to underlying layers compared to ordinary soils because of their higher porosity and very low clay content.

4.1.3 Organic Matter

The average organic matter content of the tailings at Kabwe mine of 1.54 % was low. This is consistent with the reports of Agboola (1982) that the levels of organic matter at former mining locations were low and that the restoration of such sites required building up the levels of soil organic matter, plant nutrients and vegetation cover to accelerate the natural recovery processes. Since organic matter is the main source of nitrogen in soils and sediments, the low organic matter contents also is an indicator of the likely low content on N in the tailings.

According to Cooperband, (2002), properties such as the structure of the soil, water retention, nutrient retention and the nutrient content are influenced by organic matter contents. Soils with low organic matter contents tend to be less fertile and generally have low cation exchange capacities. The low levels of organic matter in the tailings at Kabwe former mine are thus a likely to be limitation to the revegetation of the tailings.

4.1.4 pH

The pH of the tailings at Kabwe mine ranged from 4.19 to 6.36 with a mean of 5.44. The reaction of the tailings thus ranges from very strongly acid to neutral, with a mean reaction of moderately acid. The mean range of the Kabwe tailings is similar to that of cultivated mineral soils in Zambia (Shitumbanuma, *et al*. 2018).

The pH of soils or sediments is an important factor that affects the mobility of metallic elements. According to Peterson *et al*., (1984), the toxicity and availability of heavy metals in mine wastes is dependent on the pH Maiti, (2008) reports a strong negative correlation pH and the concentration of dissolved metals in solutions.

4.1.5 Electrical Conductivity

The EC of soils and sediments is a measure of the presence of dissolved ions in the solutions of these materials. High EC values indicate the presence of high amounts of dissolved ions, while low EC values indicate the presence of low levels of dissolved ions in the solution. The EC of the tailings at Kabwe mine was generally low with a mean value of 1.42 $mS.cm^{-1}$. The EC values indicate that the portion of the tailings that was sample has low concentrations of soluble salts. Boateng *et al*, (2012) also reported low EC values in all the mine waste samples from the abandoned Obuasi mine in Ghana of less than 2 $mS.cm^{-1}$. Since the Kabwe tailings are porous and have low clay contents, it is possible that most of the dissolved salts have been leached of soluble salts

4.1.6 Available Phosphorus

The mean levels of plant available phosphorus (P) in the Kabwe mine tailings were low with a mean value of 10.87 ± 0.74 $mg\ P.kg^{-1}$ which is quite similar to that of Zambian agricultural soils reported to be about 10.78 mg P/kg soil (Shitumbanuma, *et al*. 2018). The P content of the tailings though low may not limit the growing of plants on the tailings, because soils with similar P contents are able to support a diversity of plants.

4.1.7 Plant available Cations

The mean values of plant available cations Ca, Mg, K and Na in the tailings Kabwe mine were generally higher than concentrations of the same in upland cultivated Zambian agricultural soils. The elevated levels of Ca, Mg and K in the Kabwe mine tailings could be attributed to the mineral ores that were mined at Kabwe which consisted of mainly silicates, oxides and carbonates of Pb, Zn and Fe (Leteinturier, *et al*, 2001). Silicate minerals often contain elements, such as Ca, Fe, and Mg. According to Ye *et al*, (2002), limestone and other alkaline mineral products which are usually added to the mine tailings before they are discharged into the environment could have contributed to the elevated levels of Ca and Mg in the mine tailings.

4.2 Concentration DPTA Extractable Metals in Kabwe Mine Tailings

The concentrations of DPTA extractable metals in soils or sediments indicates of the concentrations of metals that can readily be taken up by plants. The plant available levels of selected metals in the Kabwe mine tailings are presented in Table 3.

Table 3. Concentrations of DPTA extractable metals in the tailings

Metal	Sample size	Range (mg/kg)	Mean ± standard error (mg/kg)
Cu	81	14.20 -174.30	51.52 ± 3.97
Zn	80	206.00 - 3,345.00	1,058.20 ± 96.34
Fe	80	0.21 - 27.20	4.86 ± 0.60
Mn	79	0.20 - 138.00	15.99 ± 3.01
Pb	81	22.00 -10,735.00	2,999.17 ± 154.65
Cd	80	0.90 - 14.70	4.61 ± 0.39

The results in Table 3 show that the tailings have very elevated levels of plant available Pb, Zn, and Cu and high levels of Cd, Mn and Fe. The observed concentration of DPTA extractable Cu and Zn in the tailings at Kabwe mine were significantly higher than reported levels in cultivated Zambian agricultural (Shitumbanuma, *et al*. 2018). The mean levels of plant extractable Fe and Mn in the tailings were similar to those of in cultivated agricultural soils. The elevated concentrations of metallic elements in the Kabwe mine tailings can be attributed to the mineral ores at Kabwe mine which consisted of mainly silicates, oxides and carbonates of Pb, Zn and Fe with subsidiary amounts of V and Cu, (Leteinturier, *et al*, 2001).

4.3 Total Concentration of Selected Metals in Kabwe Mine Tailings

The Aqua Regia extractable or total concentrations of selected metals in the tailings at Kabwe mine are presented in Table 4.

Table 4. Concentrations of Aqua Regia Extractable metals in the tailings

Metal	Sample size	Range (mg/kg)	Mean ± standard error (mg/kg)
Cu	81	580.00 - 2870.00	1,462.35 ± 54.12
Zn	81	84.40 - 709.00	244.53 ± 13.22
Fe	81	158,500.00 - 365,800.00	272, 772.84 ± 859.68
Mn	81	7,512.50 - 37,670.00	22, 643.64 ± 454.68
Pb	81	1,395.00 - 29, 165.00	18,945.31 ± 551.68
Cd	81	10.00 -3100.00	535.55 ± 73.85

The mean total concentrations of Pb, Zn, Cd, Fe, Mn and Cu in the Kabwe mine were very high. Nikolaidis *et al* (2010), observed similar concentrations of heavy metals in the abandoned Lead and Zinc mine tailings in the Kirki region of Greece with mean concentrations of 12,567 mg $Pb.kg^{-1}$, 22,292 mg $Zn.kg^{-1}$, 174 mg $Cd.kg^{-1}$ and 241 mg As $.kg^{-1}$. The high total concentration of heavy metals in the Kabwe mine tailings indicate high levels of heavy metal contaminants in the tailings and that the tailings may be potential sources of contamination of these metals to surrounding areas.

4.4 Assessment of the suitability of Tailings for Plant Growth

Mine tailings are new environments introduced on pre-existing soil environments. According to Bengao and Cababat, (2014), the bare surfaces of tailing materials are open to erosion by water and wind in the absence of a protective vegetation cover. If the movement of the tailings is not restricted, there is a risk of further contaminating the surrounding environment with the tailings and their contaminants when the tailing particles are carried by water and or wind and when solutions from the tailings leach into ground water or surrounding surface water bodies. The management of tailings among other things should aim at diminishing the adverse environmental impact the tailings may pose to the surrounding environment. Establishing plants on the tailings is one way of arresting the spread of tailing particles to the surrounding environment, by erosion.

Bansah and Addo, (2016) report that the possibilities of growing plants on mine tailings depend on the ability of colonizing plants to adapt to the physical and the chemical environment of the tailings. If the physical and chemical conditions of the tailings are suitable, plants are likely to easily establish on the tailings. When physical and chemical conditions on the tailings are unsuitable, establishing plant cover on the tailings will be difficult. It is therefore necessary to assess the physical and chemical properties of tailings in relation to the requirements for plant growth. Such assessments can indicate potential limitations and also help identify remedial measures to improve the suitability of tailings as media for plant habitation.

To assess the suitability of the tailings at Kabwe mine for plant growth, a number of important physical and chemical properties of the tailings were compared with general requirements for the growth of flowering plants. Based on values results of these comparisons, suitability ratings were made for each of the key properties identified to be critical for plant growth. Table 5 provides mean values of selected properties of the Kabwe mine tailings critical for plant growth and their suitability ratings for plant growth.

Table 5. Properties, requirements and suitability rating of tailings for plant growth

Soil property	Units	Mean in tailings	Critical value	Interpretation	Suitability Rating
Soil textural class	NA	Sandy loam	NA	Suitable	Suitable
Bulk density	$g.cm^{-3}$	1.00		Low	Suitable
Particle density	$g.cm^{-3}$	2.58	NA	NA	NA
Porosity	%	0.57		High	Suitable
Organic matter	%	1.54	3.0[a]	Low	Marginal
Phosphorus (Bray-1)	mg/kg	10.87	12[a]	Low	Suitable
pH (0.01 $CaCl_2$	NA	5.44	14 -7.5[b]	Moderately acid	Suitable
EC	mS/cm	1.42			Suitable
Ca^{2+}	meq/100g	14.69	0.20	High/Adequate	Suitable
Mg^{2+}	meq/100g	1.01	0.50[c]	High/Adequate	Suitable
K^{+}	meq/100g	4.72	0.40[b]	High/Adequate	Suitable
Cu	mg/kg	51.52	0.20[d]	Very high	Unsuitable
Zn	mg/kg	1058.20	1.0[d]	Very high	Unsuitable
Fe	mg/kg	4.86	4.50[d]	High	Suitable
Mn	mg/kg	15.99	1.0[d]	Very high	Suitable
Pb	mg/kg	2999.17	NA	Very high	Unsuitable
Cd	mg/kg	4.61	NA	Very high	Unsuitable
Overall					**Unsuitable**

Sources of critical values: a. Mutsaers *et al*, (1997), b. Mc Phillips (1987), c. Landon (1991), d. Viets and Lindsay (1973)

Texture and Bulk Density

Results in Table 5 show that the textural class of the tailing was sandy loam. Therefore, the tailings have a loamy texture. Loamy textures are considered to be the ideal textures for plant growth, as they give soils a combination of physical characteristics that are favourable for plant growth. Sandy loam textures are very common in ordinary soil. Soils with such textures are generally suitable for plant growth if not compacted. The texture of the Kabwe mine tailings is therefore suitable to support plant growth and is not likely to limit plant establishment.

The mean bulk density of the tailings of 1.0 $g.cm^{-3}$ is relatively low compared to that of mineral soils with similar texture, which in Zambia average about 1.4 $g.cm^{-3}$ (Shitumbanuma *et al*, 2018). According to Aubertine and Kardos (1965), the normal range for bulk densities for plant growth is 1.1 $g.cm^{-3}$ to 1.6 $g.cm^{-3}$. Therefore, the low bulk density of the tailings at Kabwe mine is not likely to pose a physical limitation to plant growth. The low bulk density, however, indicates that the tailings are highly porous and therefore likely to be highly permeable to water and consequently likely to have a high potential for leaching of nutrients and contaminants present in tailing solutions.

pH and Electrical Conductivity

One of the key indicators of the general chemical condition of soils and other planting media is the pH. There is a strongly relationship between the availability of nutrients and non-nutrient elements for uptake and the pH of the solution. According to Brady and Weil (1999) plants vary greatly in their tolerance to the acidity or alkalinity of the growing medium. Ye *et al*. (2002), report that most plants grow well in the pH range of 5–7, but at pH values below 3 and above 9, adverse chemical conditions limit plant growth and establishment. The pH of the tailings measured in 0.01M $CaCl_2$, ranged from 4.19 to 6.36. This pH range is similar to that of ordinary soils in Zambia that support a diversity of plants. Therefore, the pH of the tailings was not likely to be a limitation for plant growth.

The Electrical conductivity (EC) of a solution is an indicator of the level of dissolved ions present in the solution. The presence of high concentrations of dissolved ions can hinder water uptake and can also inhibit plant growth if the ions are potentially toxic to plants. High EC values indicate the presence of high salt concentrations in the solution. Plant species differ considerably in their ability to tolerate salts in their root zone. Ye *et al*. (2002) report that all plant species are able to survive in solutions with EC values of 0 – 2 dS/m, while sensitive species are affected by EC values of 4 – 8 dS/m, and that only tolerant species are able to achieve satisfactory growth when EC values exceed 8 dS/m. The EC values of the Kabwe tailings ranged from 0.08 to 3.69 mS/cm with a value of 1.42 mS/cm. This was low, indicating that the salt content of the tailings was not likely to limit plant establishment. The EC values were much lower than those reported for tailings from Lechang Pb/Zn mine in China that ranged from 3.55-13.85 mS/cm (Ye *et al.* 2002).

Organic matter and Nitrogen

According to Stevenson, (1986) organic matter serves as a reservoir for N, P and S for plant growth. The organic matter content of the tailings was found to be low. Therefore, the supply of critical nutrients such as N, which is mostly derived from organic matter in the tailing was also expected to be low. Low N contents are likely to result in deficiencies of N for plant growth, which would limit plant establishment on the tailings. The tailings are therefore most probably deficient in N, although it was not measured. Since N, is the most limiting nutrient to plant growth in most natural upland environments, N deficiency may probably be a major limiting factor to the establishment of plants on the tailings.

According to Hossner and Hons (1992), tailings are almost universally deficient in N. Introducing nitrogenous organic amendments on the tailings may therefore be necessary in efforts aimed at establishing plants on the tailings. Growing nitrogen fixing leguminous plants on the tailings may be another way of naturally increasing the levels of N and organic matter on the tailings. The use of legumes in the revegetation of tailings has been reported to help improve the conditions of tailings for plant growth (Domingo and David, 2014).

Phosphorus and Potassium

Phosphorus is the other nutrient after N that limits plant growth on tailings (Hossner and Hons, 1992). The levels of P in the mine tailings at Kabwe were below the critical values for high P requiring plants. However, the mean levels may not be limiting for the establishment of plants with low P requirements. Plants with mycorrhizal associations are able to grow well on low P containing soils (Mohammadi *et al,* 2011). Therefore, although the levels of P in the tailings were generally low, P was not likely to be a major limiting factor to plant growth.

A number of researchers report that K is usually deficient in tailings (Sheoran *et al*. 2010 and Hossner and Hons 1992). The levels of K in the tailings at Kabwe were high and above the critical level for most plants. Potassium, was therefore, not expected to be a limiting nutrient to the establishments of plants on the tailings.

Calcium and Magnesium

Calcium and magnesium are secondary nutrients required in lesser quantities than N, P and K by plants. They are not usually deficient in fresh rock materials containing Ca and Mg bearing minerals. The levels of Ca and Mg in the tailings at Kabwe mine, were higher than the critical levels in soils of 0.2 cmol (+).kg $soil^{-1}$ (Landon, 1991) indicating that these nutrients were present in adequate amounts for plants. Therefore, Ca and Mg were not expected to limit plant growth on the tailings.

Iron, Manganese, Zinc and Copper

The elements Fe, Mn, Zn and Cu are micronutrients. When deficient in soils or other media, they can limit plant growth, and when present in excess amounts, they can be toxic to plants and inhibit plant growth. The phyto-toxicity or potential toxicity of these elements to plants nutrients vary. According to McBride (1994), the phyto-toxicity of Fe is low, that of Mn and Zn is low to moderate while that of Cu is moderate to high, indicating that Cu has a greater potential toxicity to plants than the other metallic micronutrients when present in large bio-available concentrations. Results in Table 4 show that concentrations of plant available Fe, Mn, Zn, and Cu in the tailings were high to very high. With such high concentrations, it is probable that Zn, and Cu were likely to inhibit plant growth due to their toxic effects when present in high concentrations. Iron and Mn were not likely to limit plant growth because their concentrations were not very high. The high concentrations of Zn and Cu were likely be limiting factors to plant establishment on the tailings. The mean DPTA extractable concentrations of 1058.20 mg $Zn.kg^{-1}$ and 51.52 mg $Cu.kg^{-1}$, in the tailings at Kabwe mine were much higher than those reported by Ye *et al*. (2002) of 21-200 mg $Zn.kg^{-1}$

and 4.3-12 mg $Cu.kg^{-1}$, in tailings from Lechang Pb/Zn mine north of Guangdong Province in southern China

Lead and Cadmium

Lead and Cd are not plant nutrients, they are however both potentially toxic to plants when present in high concentrations in their plant available form. According to Sposito (1989) both Pb and Cd phyto-toxic to flowering plants, with Pb being more potentially toxic than Cd. McBride (1994) reports that the phyto-toxicity of Pb is moderate while that of Cd is moderate to high. The concentrations of plant available Pb and Cd in the tailings at Kabwe mine were very high. It is therefore most probable that Pb and Cd in the mine tailings are likely to cause toxicity to plants and thus limit plant establishment and growth.

Mean DPTA extractable concentrations of 2999.17 Pb $mg.kg^{-1}$ and 4.61 mg $Cd.kg^{-1}$ in tailings at Kabwe mine of were also much higher than values reported for tailings from Lechang Pb/Zn mine in China of 21-200 mg $Pb.kg^{-1}$ and 0.3 -1.5 mg $Cd.kg^{-1}$ (Ye *et al*. 2002). Since plant growth was reported to have been adversely affected by the reported levels of Pb and Cd in tailings in China, it is expected that the much higher levels of these two metals in the Kabwe tailings would have an inhibitory effect on plant growth.

Based on the foregoing results and discussion it is evident that the tailings at Kabwe are unsuitable for growth of plants. This is on account of their low levels of organic matter content which are also indicative low levels of N and also due to high concentrations of bioavailable Zn, Cu, Pb and Cd which are known to inhibit plant growth.

4.4 Assessment of Potential Toxicity of Tailings as sources of selected Metals

A comparison of the mean concentrations of Cu, Zn, Fe, Mn, Pb and Cd in the Kabwe mine tailings with the Total Threshold Limit Concentrations (TTLC) of the US Environmental Protection Agency (U.S EPA, 1996), are presented in Table 6. The TTLC defines the critical concentration above which a material containing contaminants qualifies to be classified as a toxic material with respect to the contaminant in question.

Table 6. Means and Total Threshold Limit Concentrations of metals in the tailings

Metal	Mean conc (mg/kg)	Total Threshold Limit conc (TTLC) (mg/kg)	T –test p -value	Classification of material
Cu	1462.35	2500	< 0.0001	Non- Toxic
Zn	244.54	5000	< 0.0001	Non- Toxic
Fe	272, 772.84	NA	ND	Non- Toxic
Mn	20, 780.59	NA	ND	Non- Toxic
Pb	18,945 .31	1000	< 0.0001	Toxic
Cd	535.55	100	< 0.0001	Toxic

Results in Table 6 show that the tailings at Kabwe mine qualify to be classified as toxic materials with regard of the latter metals. Despite the relatively high concentrations in soils and sediments, there are no TTLC values for Fe and Mn because the two elements are considered to be generally non-toxic.

The tailings at Kabwe mine therefore contain toxic levels of Pb and Cd and should be considered as toxic materials with respect to the two metals. The classification of the tailings as toxic material with respect to Pb and Cd, means that they pose a risk as a source of these two elements to areas surrounding the tailings. The tailings at Kabwe mine are windward side of Kasanda, Makululu and Chowa townships, which are highly populated residential areas. The tailings are thus a potential source of windblown particles containing Pb and Cd to these residential areas.

Besides being a source of windblown contaminants, the tailings are also a potential source of contamination of ground water to surrounding areas. The high porosity and low clay content in the tailings make them to be a potential source of leaching of heavy metals to the ground water. Since some residents in areas near the mine use ground water pumped from local bore holes for their daily activities, there is a risk of consuming water contaminated with heavy metals which could adversely affect their health. According to Zeshan *et al* (2015), high rainfall or flooding of areas near the mine tailings, can lead to a mobilization of heavy metals and their transfer to agricultural land, enabling their further spread to plants, animals, and finally humans.

To reduce the chances of the spread of the contaminants present in the tailings at Kabwe mine from spreading to surrounding areas, there is need to establish means of preventing the tailing particles from being transported to surrounding areas and the metallic elements in the tailings from being leached from the tailings into surface and ground water. Any form of vegetation cover that would inhibit soil erosion would help in reducing pollution of the adjoining water and their environment with particulate matter. Furthermore, methods that reduce the solubility of potentially toxic metals in the tailings would also help in arresting the potential spread of the contaminants through leaching.

4.5 Relationship Between pH and the EC of the Tailings

The solubility of ions in solution is known to be influenced by a number of factors, among which the pH of the solution is an important factor. The amounts of dissolved ions in an aqueous solution is directly related to the electrical conductivity of the solution. The ability of tailings to pollute ground or surface water by the leaching of dissolved ions in the solution from tailings is dependent on the quantity of dissolved ions or salts in the solution. It is therefore important to establish the relationship between the pH of the solution and the EC of the solution. The relationship between pH and EC of aqueous solutions of the Kabwe mine tailings is presented in Figure 5 below.

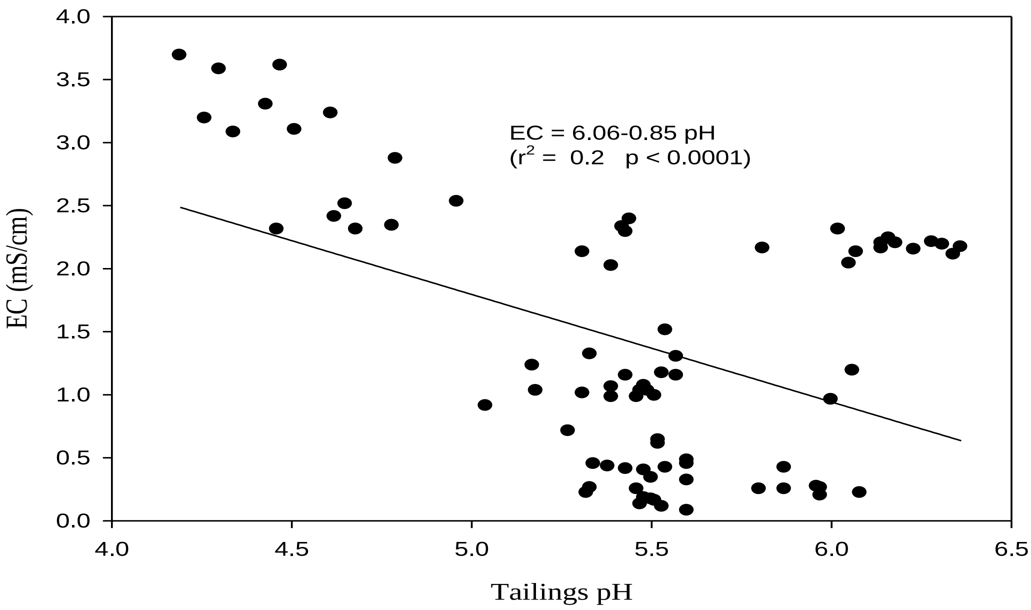

Figure 5. Relationship between pH and EC of tailings solutions

The relationship in Figure 5 shows that there is a general decrease in the EC with increasing pH from of 4.5 to about 6.0 indicating that the amounts of dissolved ions decrease as the pH increases up to about pH 5.5. Under very strongly acidic conditions there are more dissolved ions than at slight acidic to near neutral pH, implying that most ions dissolve under strongly acid conditions, but their concentrations reduce significantly under moderately acidic to slightly acidic conditions. The general indication is that raising the pH of the tailings to moderately acid to slightly acid conditions can significantly reduce the solubility of dissolved ions and reduce the risks of water pollution associated with leaching of ions from the tailings into surface and sub-surface water bodies.

According to the Clean Water Team (CWT) (2004), the presence of salts in water affects the quality of the soil irrigated with such water as well as the general suitability of the water for irrigation and drinking. Results in Figure 5 show that the pH of the solutions from the tailings was inversely related with the EC of the solutions.

4.6 Relationship between pH and DPTA Extractable metals in the Tailings

Since the results of the TTLC revealed that the tailings at Kabwe mine qualify to be classified as toxic with respect to Pb and Cd, it is important to know how the behavior of these two potentially toxic elements in the tailing are influenced by the pH of the tailings. A knowledge of the influence of pH, which is one of the master variables that controls the behavior of most metallic elements in soils and sediments is important for the proper management of elements present in the tailings. The pH of sediments and soils is generally acknowledged to be an important regulating factor for metal partitioning.

Results in Figure 5 showed that the concentration of dissolved ions in the tailing solutions increased with increasing acidity or reducing pH. Since it has been established that the tailings at Kabwe mine qualify to be classified as toxic materials with respect to Pb and Cd. It is necessary to establish how the concentrations of these two elements vary with the pH of the tailings.

4.6.1 Relationship Between pH and DPTA Extractable Lead

The relationship between concentrations of plant extractable Pb and the pH of the Kabwe mine tailings is shown in Figure 6. The concentration Pb in tailing solutions is high below pH 5.7 but drastically drops above this pH. The results show that at low pH, Pb concentrations in the tailings solutions were high and that Pb was likely to be mobile. This implies that under acidic conditions, the harmful effects of Pb are more likely to be exhibited or to be observed. However, Pb concentrations drop significantly above pH 5.7. This could likely be due to the precipitation and complexation of dissolved Pb by various reactions that are more likely to occur at higher pH. Lead forms many minerals that precipitate at high pH. Such minerals dissolve with increasing acidity as illustrated in the reaction below given by Appello and Postma (1994).

$$Pb\,(OH)_{2cr} + 2H^{+}_{aq} \leftrightarrow Pb^{2+}\,aq + 2H_2O_{aq}$$

From the above reaction it is evident that the solubility of the Pb^{2+} increases with increasing acidity or reducing pH and decreases as the pH increases. It can therefore be expected that concentrations of Pb in tailing will increase with increasing acidity and decrease with increasing alkalinity. Leteinturier *et al*, (2001) report that oxidation of pyrite in the Kabwe mine tailings resulted in acidity and salinity and the increase of soluble heavy metals. The increased Pb concentrations in the tailings may be responsible for the observed poor growth of vegetation on the tailing.

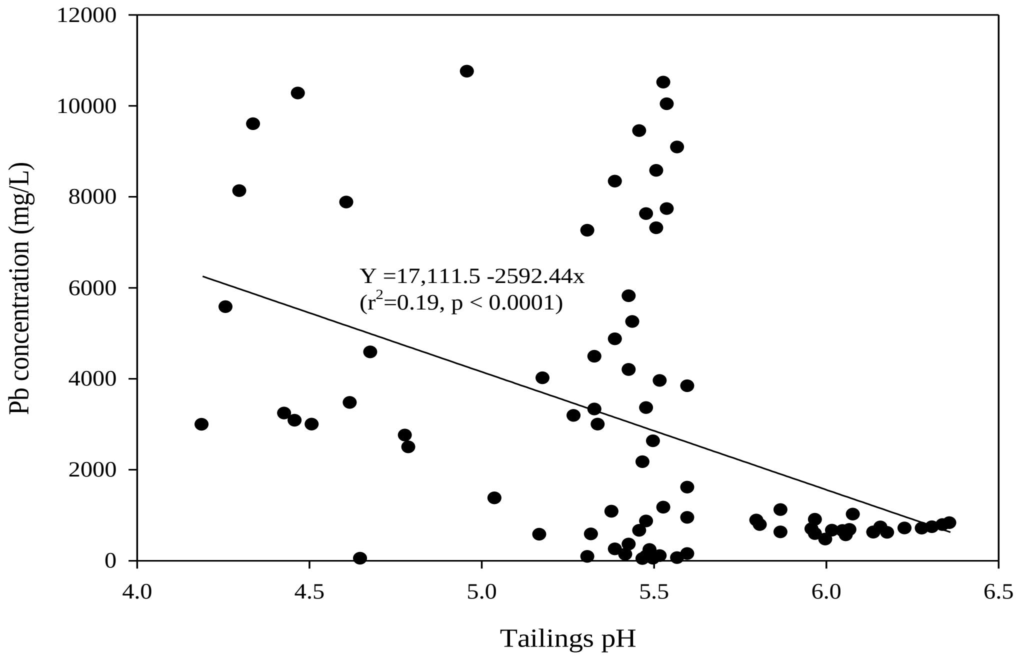

Figure 6. Relationship between pH and plant extractable Pb in tailings

Controlling the pH of the tailings may therefore be one means of controlling the solubility of Pb in the tailings. Keeping the pH in the near neutral range is likely to lower the solubility of Pb and reduce the leaching of Pb from the tailings into surrounding surface and groundwater bodies.

4.6.2 Relationship between pH and DPTA Extractable Cadmium

Cadmium is one of the metallic elements known to be toxic to humans. In severe cases, high levels of Cd replace Ca in the bones to cause a degenerative disease called *itai-itai* (Baird, 1995). Results of the total concentrations of Cd presented earlier showed that the tailings at Kabwe mine have high concentrations of Cd that exceed the Total Threshold Limit Concentrations for materials considered toxic. Figure 7 shows the relationship between concentrations of plant available Cd and the pH of the tailings.

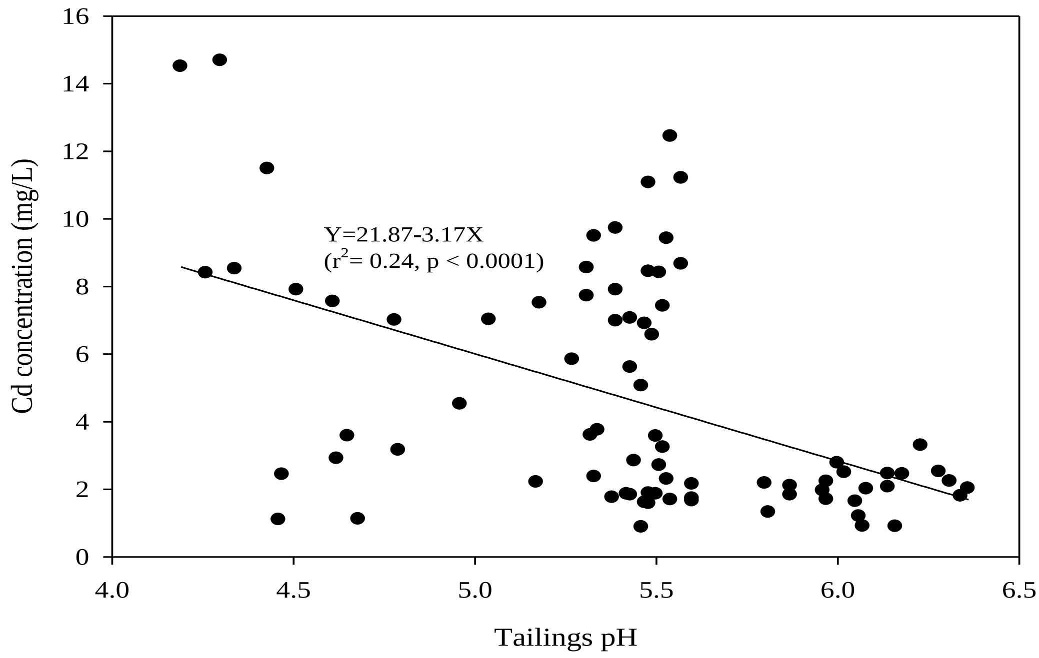

Figure 7. Relationship between pH and plant extractable Cd in tailings

The trend in the concentration of DPTA extractable Cd with the pH was similar to that of Pb. Concentrations of extractable Cd decreased with increasing pH of the tailings. The concentrations of Cd were high below pH 5.7 and dropped significantly above this pH. It is evident that concentrations of DPTA extractable Cd increased with increasing acidity. This observation is consistent with the behavior of many metallic elements which tend to precipitate as hydroxides when the soils or sediments in which they occur become alkaline. Baird (1995), shows the reaction of Cd in aqueous solutions below.

$$Cd\,(OH)_{2c} + 2H^+ \leftrightarrow Cd^{2+} + H_2O$$

The reaction, shows that increasing acidity leads to increased concentration of dissolved Cd^{2+} in solution. It is evident that lowering the pH of the tailings is likely to lead to increase concentration of dissolved Cd, and that the harmful effects of Cd are more likely to occur when tailings are acidic than when they are alkaline. Therefore, maintaining the pH of the tailings in the near neutral range may be an effective way of reducing the solubility of Cd and its potential to spread through water to the surrounding environment. Thus, the potential toxicity of Cd could be reduced by maintaining the pH of the tailings at pH values close to 6.0. This could be achieved by applying lime to the tailings and monitoring the pH to ensure that it stays near pH 6.0.

From the foregoing discussion it is clear that plant available Pb and Cd in the tailings are influenced by the pH of the tailings. Acidification of the tailings is likely to enhance the availability and mobility of metals. This is consistent with the findings of Wong *et al*., (1998) and Ye *et al*., (2000) who report that under highly acidic conditions, ions of metals such as Pb, Zn, Cu, Cd and Al are released from tailings and may reach toxic levels for plants. Ecological surveys and greenhouse experiments have demonstrated that acidification of pyrite in lead and zinc mine tailings in southern China is the most important constraint to plant establishment (Ye *et al*, (2002). It is thus probable that the poor vegetative cover on the tailings at Kabwe mine could among other factors be due to the concentrations of metals such as Pb and Cd that may have reached toxic levels for plants.

CHAPTER FIVE: CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The tailings at Kabwe mine are red to dark reddish brown fine materials with a dominance of sand and silt sized particles and very low clay content. They have a sandy loam texture, a low bulk density and high porosity. They are very strongly acid to neutral, and have low concentrations of dissolved salts. They have low organic matter and plant available P, but have high levels of exchangeable K, Ca, Mg and Na. The tailings however have high concentrations of plant available and total Fe, Mn, Cu, Zn, Pb and Cd.

Because of their low organic matter content, and high concentrations of plant available, Zn, Cu, Pb and Cd, which are likely to be toxic to plants, the tailings are unsuitable for plant growth. The Kabwe tailings qualify to be classified as toxic materials because of their high Pb and Cd content. Concentrations of plant available Pb and Cd are inversely related to the pH of the tailings.

5.2 Recommendations

Based on the results of this study, it is recommended that:

i. The tailings be closed off from public use because of their hazardous contents of Pb and Cd.
ii. Efforts to establish vegetation on the tailings should include addition of organic materials to increase the organic matter content of the tailings and also employ measures to reduce the bioavailability of metals Pb, Cd, Zn and Cu, which are potentially toxic to plants.
iii. The potential plants that could be considered in establishing vegetation on the tailings should include leguminous plants with mycorrhizal associations which have low N requirements.

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APPENDICES

Appendix 1: T-test for comparing Cu concentrations with Total Threshold Limit

Statistics

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
Cu	81	1353.8	1462.3	1570.8	425.01	490.67	580.51	54.519

T-Tests

Variable	DF	t Value	Pr > |t|
Cu	80	-19.03	<.0001

Appendix 2: T-test for comparing Zn concentrations with EPA Total Threshold Limit

Statistics

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
Zn	80	218.21	244.54	270.86	102.37	118.28	140.1	13.224

T-Tests

Variable	DF	t Value	Pr > |t|
Zn	79	-359.60	<.0001

Appendix 3: T-test for comparing Pb concentrations with EPA Total Threshold Limit

Statistics

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
Pb	81	17847	18945	20043	4300.7	4965.1	5874.2	551.68

T-Tests

Variable	DF	t Value	Pr > |t|
Pb	80	32.53	<.0001

Appendix 4: T-test for comparing Cd concentrations with EPA Total Threshold Limit

Statistics

Variable	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
Cd	81	388.59	535.56	682.52	575.72	664.66	786.37	73.851

T-Tests

Variable	DF	t Value	Pr > |t|
Cd	80	5.90	<.0001