# USE OF CEMENT TO REDUCE EROSION OF THE SLOPES OF MINE TAILINGS DAMS

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**DECLARATION**

I declare that this dissertation is my own unaided work. It is being submitted for the degree of Master of Science in Engineering to the University of Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination to any other University.

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**ABSTRACT**

Erosion on the slopes of mine tailings represents one of the most important environmental problems arising from the disposal of mine tailings. Tailings dam erosion is the main source of pollution that contaminates agricultural land and streams around mining areas. There is an urgent need to reduce erosion of the slopes of mine tailings in-order to limit further devastation of natural ecology. The present study investigates the possible use of cement to reduce erosion of the slopes of mine tailings dams. The pinhole erosion test was used to measure erodibility of tailings stabilized with cement. The strength properties of cement-stabilized tailings have been evaluated by the unconfined compression test. Conbex and ordinary Portland cement have been used for tailings stabilization, with contents of 0, 3, 5, 7, and 10% by mass.

It has been established that cement can be used to reduce erosion of the slopes of mine tailings dams. At least 3% by mass cement is required to produce zero erosion loss. The resistance of tailings to erosion can be enhanced by increasing compaction density, curing period and cement content. Ordinary Portland cement produced higher strengths and erosion resistance than Conbex, although Conbex may be useful for stabilizing fine tailings. Cement-stabilized tailings could be used to make bricks and rubble for use in reducing erosion of the slopes of mine tailings dams. As little as 10% of cement is necessary to produce unconfined compressive strengths of 1600-2600 kPa.

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Dedicated to my family

who supported me in hard and trying situations

Takalani, Florah, Fulufhelo, Mulalo, Elelwani, Lutendo, Walter and Nnditshe

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## LIST OF SYMBOLS

**Symbols**………………………………………………………...**Quantity**

A………………………………………………………………...Area

Au…………………………………………………………………Gold tailings

Ca…………………………………………………………………..Calcium

$Ca(OH)_2$………………………………………………………...Slaked lime

Cm………………………………………………………….....Centimeters

Co…………………………………………………………......Cobalt

Cu…………………………………………………………......Copper

EC…………………………………………………………......Electrical conductivity

F………………………………………………………………….Maximum failure load

Fe………………………………………………………………...Iron

$Fe_2S$…………………………………………………………Iron Sulphate

g…………………………………………………………………..Acceleration of gravity

$G_s$……………………………………………………….………...Specific Gravity

Kg…………………………………………………………………Kilograms

kPa………………………………………………………………...Kilopascal

M…………………………………………………………………Mass

m…………………………………………………………………..Meters

Mg…………………………………………………………………Magnesium

Mg/kg……………………………………………….…………..Milligram per Kilogram

mm…………………………………………………………………Milimeters

ms/m………………………………………………………………Millisiemens per meter

Ni…………………………………………………………………..Nickel

P…………………………………………………………………Force

Pb…………………………………………………………………..Lead

pH…………………………………………………………………..Potential for hydrogen

PI……………………………………………………………….…..Plasticity index

Pt………………………………………………….…………Platinum tailings

$SO_4$………………………………………………..………...Sulphates

T/ha/yr………………………………………………………….....Tons /hectare/year

TDS……………………………………………………………....Total dissolved salts

UCS……………………………………………………………Unconfined compressive

W………………………………………………………………Water content

$W_{opt}$………………………………………………………………….....Optimum water content

Zn………………………………………………………………Zinc

$\gamma_{d\ opt}$ (kg/$m^3$)…………………………………………………..Optimum Dry density

**ABBREVATIONS**

APPA……………………………………………….Atmospheric Pollution Prevention Act

ASCE……………………………………………..American Society of Civil Engineers

COM……………………………………………...Chamber of Mines

DME……………………………………………...Department of Mineral and Energy

DEAT……………………………………………Department of Environmental Affairs and Tourism

EPA………………………………………………Environmental Protection Agency

NEMA……………………………………………National Environmental Management Act

USA………………………………………………United States of America

USDA……………………………………………..United State Department of Agriculture

USLE……………………………………………...Universal Soil Loss Equation

# CHAPTER 1: INTRODUCTION TO THE STUDY

## 1.1 Background Information

The mining sector is a well-established and resourceful sector of the South African economy. For more than a century, South African's mining sector, mainly supported by diamond, gold, coal and platinum mining have made an immense contribution to the national economy. It has provided the momentum for the growth of an extensive and efficient physical infrastructure and has contributed significantly to the establishment of the country's secondary industry. Mineral extraction usually involves crushing mined rock down to smaller sizes to liberate metal contents; the result is generation of large amount of solid waste. Mine waste is either dumped to form overburden or waste rock dumps or deposited in tailings disposal dams. Tailings disposal began by dumping tailings in the nearby streams, and progressed to empirical design of impoundments, based on principles of trial and error (Sarsby, 2000). Up to now, a great number of abandoned tailings deposits exist within the Witwatersrand metropolitan and in the region of Barberton, in South Africa. Large numbers of tailings deposits also exist in diamond, copper and platinum mining areas.

Tailings are defined as a fine-grained waste product of the mining industry (Klohn, 1981). They consist of the ground-up rock that remains after the valuable minerals have been removed from the ore. Disposal in hydraulic fill dams is the most common method for storing tailings. More often than not, the mining companies accountable for rehabilitation of early tailings dams are now defunct. It is now the responsibility of the State to make sure that these tailings deposits conform with the legal requirements of the Departments of Minerals and Energy (DME), Water Affairs and Forestry (DWAF), and Environmental Affairs and Tourism (DEAT), as well as the guiding principles of the South African Chamber of Mines (Blight, 1996).

In the early years of the South African Mining industry the design, construction, and operation of tailings dams were not a matter of concern either for public health and safety or for the environment. In the past few years this issue has turned to one great concern and requires design and mitigation measures that are based on sound engineering principles and practices to be researched and developed. Slopes of older tailings dams are often steeper than $35^0$ (Blight, 1984). Protection of these steep slopes against erosion loss is very difficult. Generally, slopes of tailings dams are protected against erosion loss by covering them with a layer of waste rock or by establishing plants.

Vegetation stabilization is certainly the most widely used stabilization option. However, plants have numerous shortcomings when used for this purpose, the main one being the unstable character of the surface material that enables wind action and water to undermine the root system of plants (Blight et al, 1984). Metals such as Co, Ni and Zn are phytotoxic and are common in mine tailings; therefore, they inhibit plant growth on tailings. The pH of the surface material is also often low; for this reason, the pH should be elevated, or the growth of plants will be restricted to certain species that can thrive in acidic soils. The majority of the species that flourish in acidic soils are alien rather than endemic, and it is to be expected that they will cause problems by invading areas of indigenous plants. For the period of the dry winter months, fire is another hazard that threatens the plant cover of tailings dams. Tailings also have poor moisture-retention characteristics and aeration; they become dense on drying, thus inhibiting root penetration and plant development.

In 1978 the Chamber of Mines of South Africa estimated that the cost of vegetation and its associated maintenance was R10 000 per hectare (in 2005, this had escalated to R250 000 per hectare), while the cost of importing soil or waste rock was prohibitive, unless these materials were readily obtainable on the site. In view of the above issues, the Chamber of Mines decided to look into the possible use of cement for stabilization of the surfaces of tailings dams to reduce water and wind erosion. The study was abandoned in the early 1980s when the State accepted liability for rehabilitating neglected mine waste deposits, relieving the Chamber of Mines of that responsibility.

## 1.2 Legislative Requirements

Ore quality has deteriorated during the years as the high quality deposits have been exhausted, and this has caused a corresponding rise in the quantity of tailings left subsequent to the extraction of each tonne of metal (Sarsby, 2000). The disposal of mine tailings has assumed an importance in numerous countries, and this importance is shown the by formulation of laws and guiding principles to standardize tailings disposal. In the early years of the South African mining industry there was no legislations that dealt explicitly with protection of the environment (Blight et al, 1978). However, the impacts experienced from derelict mine tailings dams eventually led to upgrading of the environmental regulations and the guiding principles for tailings disposal.

The legal requirements have been incorporated in the following legislations and bills: Minerals Act 50 of 1991: This act regards rehabilitation of tailings dams as significant for both safety and health, and states that it ought to become an integral element of the mine planning (DME, 1991). National Environmental Management Act (NEMA) 107 0f 1998: Section 28 of this act makes provision for care and remediation of environmental damage. Atmospheric Pollution Prevention Act (APPA) of 1965: This states that anyone who carries on whatever industrial activity or has deposited substances on land, which may cause nuisance because of dust, must take agreed steps or make use of the best feasible ways to avoid dust from being dispersed or causing irritation (DEAT, 1965). Minerals and Petroleum Resources Development Bill, Section 43: This states legal requirements to the rehabilitation of abandoned mine tailings by the State and mining companies (DME, 2002).

## 1.3 Problem Statement

Tailings are far from being ideal dam-constructing materials, although in the mining industry they are used for this function since they are the cheapest readily obtainable material and mine operators are reluctant to bring in more appropriate material. The utilization of tailings for dam building has the following problems:

Tailings are highly susceptible to wind and water erosion, particularly the silt size particles. Loose and saturated tailings may be subjected to liquefaction under earthquake and other shock loading, and this may lead to loss of life and damage to property. Material eroded from the slopes of tailings dams is the main source of contamination of agricultural land. Possible contamination of natural resources such as streams and lakes is also a foremost concern linked to erosion of material from the slopes of tailings dams. Material eroded from the slopes of tailings dams can also lead to sedimentation in streams, thus destroying the natural ecology.

Windy weather may carry fine particles of tailings in suspension for long distances; this can result in reduced visibility, spoil growing crops and cause health problems such as lung cancer and silicosis when the dust-laden air is inhaled. The problem of tailings erosion is growing corresponding to the increasing mass of tailings and as tailings deposits become surrounded by built-up areas.

## 1.4 Significance of the Study

The dry climatic conditions of South Africa do not favour the utilization of plants for lessening erosion on the slopes of mine tailings. The plants are susceptible to fires in the dry season, as stated previously, and require continuous irrigation during drought. In addition, plants do not thrive well in the acidic condition of tailings. Utilization of plants also requires a high level of technical know-how and the maintenance costs are high.

In recent times, the cost of establishing plants on tailings dams has escalated to a point where the mining industry is willing to consider alternative cheaper and more efficient methods (Blight & Smith, 1996). For these reasons, the present study is justified in view of the fact that it is intended to develop cheaper and more efficient methods for reducing erosion of the slopes of tailings dams.

### 1.5 Identified Gap of Knowledge

The gap of knowledge arises from the abandonment of the earlier study in the 1980s. This should now be continued and developed to a stage where it can be applied in practice. Muasi (2005) noted that cured cement-stabilized platinum and gold tailings suffered as high on erosion loss as the uncured specimens and specimens without cement made a start in this direction. He also noted that his results were unexpected, and could not be explained at the time. These questions call for answers and the research should extended.

### 1.6 Objectives of the Study

The main objective of this dissertation is to investigate the use of cement to reduce erosion of the slopes of mine tailings dams.

The specific objectives are to:

- investigate the consequence of curing and hardening mine tailings by the addition of cement on the resistance of the tailings to erosion forces, both by wind and water,
- investigate the quantity of cement that is required to provide adequate resistance of modified tailings to erosion,
- investigate the types of stabilizer required for tailings of particular characteristics,
- understand the function of the physical and chemical properties of tailings on erosion, and the utilization of cement for stabilization of tailings against erosion.

## 1.7 Hypothesis

Curing and hardening of tailings by cement helps to lessen erosion loss. Physical and chemical properties of tailings have an influence on erosion; they also have an effect on the effectiveness of cement for stabilisation of tailings to reduce erosion, both in the short and long terms.

## 1.8 Delimitation of the Study

When considering the problem of tailings erosion, it is necessary to consider both water and wind erosion (Blight & Amponsah-Dacosta, 2004). Blight (1989) demonstrated that material is eroded from the slopes of tailings dams due to the effects of both water and wind. Wind tunnel experiments conducted by Amponsah-Dacosta (2001) confirmed that the area of tailings dams that is mainly susceptible to wind erosion is the vicinity of the slope crests or crest walls. The present study will give attention to the surface stability of tailings slopes due to the effects of water erosion, but the effect of wind erosion will not be forgotten.

# CHAPTER 2: MECHANISMS AND CONTROL OF WATER EROSION

## 2.1 Introduction

Substantial studies have been conducted on tailings erosion in the past 25 years. However, in spite of this work, engineers' understanding of this unconventional subject in civil engineering is far from adequate. In many cases, understanding has not reached such a stage that the pertinent knowledge can be integrated into a rational and amalgamated theory. The uncertainty surrounding the mechanisms of erosion on the tailings dams often call for knowledge transfer from the other branches of engineering such as agricultural engineering. Agricultural engineers have made considerable progress in terms of erosion studies, applied to agricultural fields. Prevention and control of erosion depends on the understanding of the mechanisms of erosion. The present chapter will present a literature review of the mechanisms and processes of erosion. Properties of individual soil particles such as size, shape and mineral composition, which are significant when dealing with soil erosion and their function on erosion are also reviewed. The factors that have an effect on erosion and methods of finding indices of erodibility on natural slopes, and on agricultural land are also envisaged.

## 2.2 Nature and Mechanisms of Water Erosion

Erosion is an inclusive term for the detachment and removal of soil and rock by the action of running water, wind, waves, flowing ice, and mass movement (Gray and Sotir, 1996). Raindrop impact on the ground is a primary cause of water erosion. Selby (1993) recognized raindrops as being responsible for detachment of soil aggregates because of their impact. The raindrop impact causes minor lateral displacement of soil particles (creep), splashing of soil particles into the air (saltation), and selection or sorting of soil particles by raindrop impact. These may occur because of the forcing of fine-grained particles into voids, causing the infiltration rate to reduce and selective splashing of detached grains (Gray & Sotir, 1996).

2.2.1 Detachment of Soil Particles

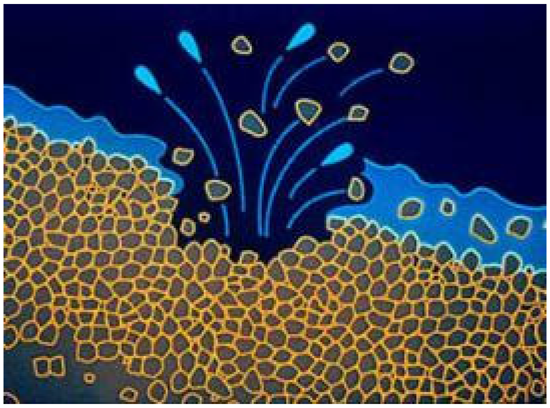


Figure 2.1 Impact of raindrop on bare soil
(http://www.partnershipsforchange.cc)

Raindrop erosion is the first effect of a rainstorm on the soil (Selby, 1993). The impact of raindrop action on bare soil disrupts aggregates and dislodges soil particles in a process called detachment as shown in Figure 2.1. The detached soil particles are susceptible to sheet erosion. The nature and effect of erosion depend on the rainfall characteristics, nature of the soil and ground surface characteristics (Gerrard, 1981).

A certain amount of kinetic energy is required to start the detachment process. Studies of the kinetic energy necessary to detach one kilogram of sediment by raindrop impact have shown that the minimum energy is required for particles of 0.125 mm size while particles of between 0.063 to 0.250 mm are only slightly less susceptible to detachment. This means that soils with a high content of particles in susceptible range, for example silty loam, loamy, fine sandy and sandy loam are most susceptible to particle detachment (Lujan, 2003).

### 2.2.2 Transport of Soil Particles

With continuous rainfall, displaced particles reorientate on the surface, filling in larger soil pores, so restricting water infiltration into the soil profile. When rainfall exceeds the infiltration capacity of soil, the flow of water over a soil surface will exert a drag or a tractive force on the soil. If this drag force is sufficiently large, soil particles are dislodged and transported along with the water. The movement of soil particles can also occur because of the flow of high velocity winds over a soil surface (Garde and Granga-Raju, 1977). Further rainfall causes ponding and the water will eventually begin to move downhill as run-off. In the beginning, run-off will be muddy with the soil particles displaced by rainfall, and as it continues to move, it will further erode the soil surface.

Erosion is a function of the eroding power (i.e. erosivity) of raindrops, running water, and sliding or flowing earth masses, and the erodibility of the soil (Gerrard, 1981). Fine soil particles are more susceptible to erosion than coarse particles. The process of soil transportation by wind and water is retarded by the presence of large particles, grass, weeds, trees and other vegetation on the ground (Garde & Ranga-Raju, 1977).

### 2.2.3 The Influence of the individual Soil Particles on Erosion

When dealing with the problem of soil erosion, one is concerned with soil not only as a collection of several individual particles (i.e. as aggregates), but also with each particle considered as a separate entity. Both individual and bulk properties of sediment should be considered (Garde & Ranga-Raju, 1977).

The significant individual properties of the soil particles to be considered when dealing with soil erosion are size, shape, and mineral composition. Of all the properties of soil particles, grain size is the most important and a commonly considered soil property. Particle size also provides a measure of evaluating the susceptibly of soil to erosion as discussed in the last section. Clay size particles play an important role of binding the soil particles together, therefore reducing erosion.

Engineers dealing with soil erosion should also pay attention to defining the shape of a particle, since it has an influence on the mean velocity of the flow at which a particle on the bed moves, on the fall velocity, and on bed load transport. Particle shape is also significant when determining porosity, permeability, and cohesivity of soils (Das, 1994).

Mineral composition is a significant individual property, since properties such as shape; density and fall velocity are considerably influenced by the mineral composition. There is a close relation between mineral composition and the particle size. Soils that resulted from weathering of rocks composed of low temperature minerals such as quartz usually have coarser particles than soils that resulted from weathering of rocks composed high temperature minerals, which are less resistant to weathering. Furthermore, the specific gravity of a soil particle also depends on the mineral composition of the soil (Garde & Ranga-Raju, 1977).

## 2.3 Types of Water Erosion

Running water removes soil from slopes by a variety of processes. It has been noted that raindrop is the initial process that start water erosion. Sheet wash, rilling, gulling and piping are some of the modes in which soil is removed from slopes of landforms. This section provides a discussion of sheet, rill and gully processes, as well as agents causing these types of erosion.

### 2.3.1 Sheet Erosion

Sheet erosion involves the removal of a uniform thin layer of soil by raindrop splashes or run-off water. The thin layer of topsoil often disappears gradually; it is difficult to monitor this process because the damage is not immediately perceptible and the insidious process is often overlooked until the subsoil is exposed (Wischmeier & Smith, 1978). Sheet erosion prevails on soils of high silt content, fragile sandy soils, stiff clays, and mine tailings and fly ash that are uncemented and deficient in organic matter. Sheet erosion commonly occurs on recently ploughed fields or on sites with poorly consolidated soil material having little vegetation cover.

There are two stages of sheet erosion: the first is rain splash, in which soil particles are knocked into the air by raindrop impact. A hundred tons of particles per hectare may be dislodged during a single rainstorm. In the second stage, the loose particles are moved downslope, commonly by sheet flooding. Broad sheets of rapidly flowing water filled with sediment present a potentially high erosive force (Dunne & Aubry, 1986). On relatively rough surfaces, sheet flooding may give way to rill wash, in which the water moves in a system of enmeshed micro-channels, which eventually become larger and develop into gullies (Selby, 1984).

### 2.3.2 Rill and Interrill Erosion

Selby (1993) defined rills as small grooves spaced uniformly along slope channels with cross-sectional dimensions of a few centimetres to a few tens of centimetres. Interrills are areas in which erosion is dominated by raindrop impact, and transport is by very shallow sheet flows (Nearing et al, 1994). Rills are usually discontinuous, and may have no connection to the system of a stream channel. They are often obliterated between one storm and the next, even during a storm by the supply of sediments from splash on inter-rill areas or collapse of rill walls, and liquefaction of the bed and walls. Rills usually take place on slopes steeper than 2-3$^{o}$ (De Ploey, 1983).

Rill erosion is a process that results from a concentration of surface water (sheet erosion) into deeper, faster-flowing channels or rivulets. As the flow becomes deeper the velocity increase, detaching soil particles and scouring channels called rills, these channels may be 30 cm deep (Goldman et al; 1986). Rill erosion represents the intermediate process between sheet and gully erosion. Horton (1945) noted that parallel rills on a fresh surface become integrated into a drainage net by breaking down of divides between rills with diversion of water into the deeper rills, and the overtopping of rills and diversion of the water towards the lowest elevation. These two processes are called micropiracy and cross grading, their effect is to cause wider spacing of rills downslope (Selby, 1984). Mostly, flows in rills act as a transporting agent to carry sediment from rill and interill sources downslope, but if shear stress in the rill is high enough, rill flow may also detach significant amounts of soil (Nearing et al, 1994).

### 2.3.3 Gully Erosion

Over the last decade, studies of water erosion have mainly focused on interrill and rill erosion. Gully erosion has only recently been considered as a distinct erosion class (Nachtergaele et al, 2001). A gully is defined as the erosion feature in which runoff water accumulates and often occurs in narrow channels and, over short periods, removes the soil from this narrow area to considerable depths (Poesen, 2002). Once rills are large enough to restrict vehicular access they are referred to as gullies.

Gullies may also form at any break of slope or break in vegetation cover when the underlying material is mechanically weak or unconsolidated (Selby, 1993). Gully erosion nearly always starts for one of two reasons: either there is an increase in the amount of flood runoff, or the flood runoff remains the same but the capacity of watercourses to carry the floodwaters is reduced.

Major concentrations of high velocity run-off water in larger rills remove a large amount of soil. This high velocity water removes the soil, and leads to deep and wider gullies. The gullies formed may be scour gullies or headward erosion. The former are often associated with gently undulating landscapes, while the latter are related to steeper landscapes.

In scour gullies, run-off water concentrated in rills or depressions removes soil particles in the course of sluicing (the washing effect of running water on loose grains). Material eroded is usually fine to medium sand or may be derived from slaking, when large aggregates disintegrate upon wetting. In headward erosion, the gully extends upstream because of waterfall undercutting and gravitational slumping of the gully head. In both cases, gullies may widen through lateral erosion, where water undercutting causes subsequent slumping of the sides. Sides of the gully may also be subject to splash, sheet or rill erosion.

2.3.4 Piping Erosion

Subsurface natural pipes resulting from erosion exist in numerous environments ranging from arid, through semiarid to humid temperate and humid tropical. These natural pipes develop in various soil types and at a range of depths, and have diameters ranging from 0.02 m to greater than 1m, and lengths of a few meters to greater than 1km. The prerequisite for the existence of natural pipes is a soil body that is strong enough to support the walls and roof of a pipe but not so strong, that it inhibits pipe erosion by flows, which, at least initially, are of low volume and velocity. Seasonal or highly variable rainfall, a soil subject to cracking in dry periods, a relatively impermeable layer in the soil profile, existence of a hydraulic gradient in the soil, and a dispersible soil layer are a few of the factors which makes soil amenable to piping (Selby, 1993).

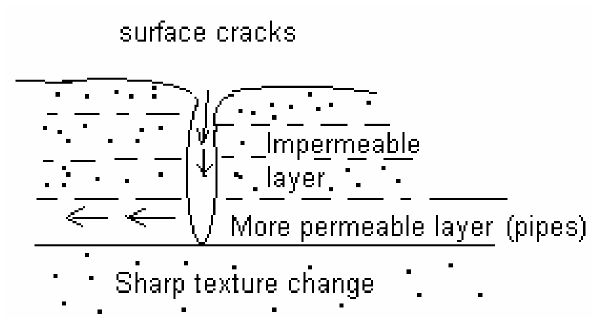



Figure 2.2 Condition favouring the development of pipes (after Selby, 1993)

Piping erosion is the process where fine soil particles in the embankments of earth dams or natural slopes are carried into suspension, and eroded to create a pipe that serves as conduits for water. Some natural clay soils disperse (or deflocculate) in the presence of relatively pure water and are, therefore, highly susceptible to erosion and piping. The tendency for dispersive erosion in a given soil depends upon such variables as the mineralogy and chemistry of clay and dissolved salts in the soil pore water and in the eroding water. Standard tests for classifying soils for engineering purposes do not identify the properties of a fine-grained soil. Dispersive clays that cannot be differentiated from ordinary erosion-resistant clays by routine civil engineering tests may erode rapidly in slow moving (or even still) water by individual colloidal clay particles going into suspension (Sherard et al, 1977).

### 2.4 Factors that affect Water Erosion

Climate, soil, ground cover and topographic characteristics are the main factors that determine the occurrence of erosion in a given area (Selby, 1984). The dominant factors causing erosion on hillslopes in most parts of the world include the action of raindrops, running water, subsurface water, and mass wasting. The action of waves, ice or wind may be regarded as exceptional cases restricted to particular environments. It is noted that climate and geology are the most significant factors that influence erosion as shown in Figure 2.3. Vegetation and soil characteristics depend upon the climate and geological conditions, and are interconnected with each other (Selby, 1993). The degree of soil erosion in a particular climatic region, with particular soils and topography will normally result from a combination of factors listed in Table 2.1. It is not easy to isolate a single factor.

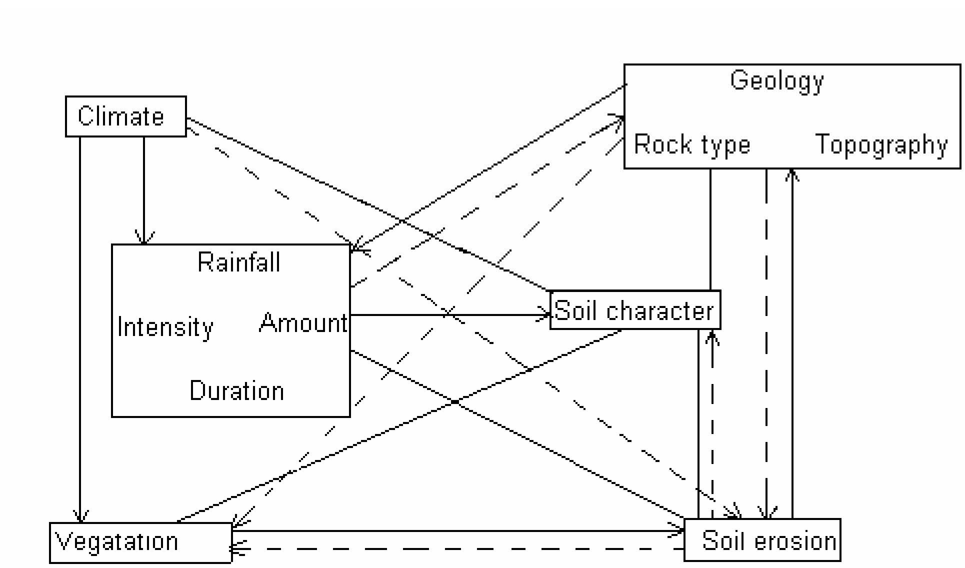



Figure 2.3 Interrelationship between the main factors influencing soil erosion (after Morisawa, 1968).

Table 2.1 The major factors causing soil erosion (Lujan, 2003).

| *Energy factors* | *Protection factors* | *Resistance factors* |
|---|---|---|
| Rainfall erosivity | Plant density | Soil erodibility |
| Runoff volume | Plant cover | Infiltration capacity |
| Wind strength | Amenity value (pressure for use) | Soil management |
| Slope angle | Land management | |
| Slope length | | |

2.4.1 Physical Properties of Soil

Physical properties of soil that control erosion include texture, structure and cohesion. Soil texture refers to the percent by weight of individual particles of sand, silt, and clay in the soil. Structure refers to the degree to which soil particles are bound together forming larger clumps and pore spaces. The individual soil particles are usually bound together into soil aggregates by clay and decomposing organic matter. Coarse textured soils such as sandy loams and sands are the least likely to form stable aggregates and are, therefore, very susceptible to wind erosion (Goldman et al, 1986). These soils only form stable aggregates if they are wet; weathering readily breaks down these aggregates. Fine textured soils such as clay and silt usually form aggregates that are more resistant to breakdown and are, therefore, less erodible.

The capability of soil to oppose erosion is related to the distribution of particle sizes, as well as the capability to cling together to form stable aggregates (Bouyoucos, 1935). When an unprotected soil surface is exposed to a direct impact of a raindrop, it can produce various responses depending on strength of the aggregates. The response may be in the form of production of smaller aggregates, dispersed particles, particles in suspension and translocation and deposition of particles. When this has occurred, the material is reorganized at the location into a surface seal. Many aspects of the soil performance in the field such as hydraulic conductivity, water retention, soil crusting, soil compaction, and workability also have a greater influence on soil stability against water erosion (Lujan, 2003).

### 2.4.2 Climatic Factors

The major climatic factors that influence run-off and erosion are precipitation, temperature, and wind. Climate may change the absorptive properties of soil by causing the soil to freeze or desiccate. Effects of wind include the power to pick up and carry fine soil particles, and more rarely its effect on vegetation (Selby, 1983).

Rainfall determines the amount of erosion, i.e. how much it rains and how hard it rains (rainfall frequency and intensity). Erosion is also related to raindrop size, velocity and shape (Evans, 1980). Another important climatic variable is temperature. Temperature affects runoff by contributing to changes in soil moisture between rains; also it determines whether precipitation will be in the form of rain or snow. Temperature also determines the longevity of biological materials like crop residue and applied mulch used to control erosion. Air temperature influences the potential for wind erosion, thus high temperatures dry the soil, leaving it more susceptible to wind erosion.

### 2.4.3 Topographic Factors

Slope length, steepness, and shape are the main topographic factors that have an effect on the process of erosion (Lujan, 2003 and USDA, 1987). The erosive energy of water tends to conform to the ground surface but may be funnelled along channels parallel to its path thereby increasing its energy (Selby, 1993). A rough surface is more effective in reducing water and wind velocity than a smooth one and is thus less susceptible to erosion, provided the material contains non-erodible particles (Cooke & Doornkamp, 1990). Holy (1980) and Selby (1993) noted that the rough surfaces have a disadvantage of increasing turbulence of the wind; rough surfaces also funnel water along channels parallel to its path thereby increasing susceptibility to erosion. Wind erosion has a greater influence on the windward faces of ridges and knolls in areas of complex topography.

The magnitude of erosion is not just proportional to the steepness of slope, but also, within limits, increases with the rising slope angle. The length of slope has a similar effect upon erosion, because on a long slope, there can be a greater depth and velocity of overland flow, and rills can develop more rapidly than on short slopes (Selby, 1993).

### 2.4.4 Vegetation Cover

Exposed soil is more susceptible to erosion than soil covered with living or dead vegetation such as foliage, crop residues and weeds. These protect the soil against wind erosion by reducing the wind velocity at the ground surface (Craig, 2000). Vegetation can also reduce erosion by trapping soil particles, and thus preventing soil movement downslope. In the case of water erosion, vegetation cover not only reduces runoff velocity, but may also prevent the runoff water from becoming channelled, which can result in more erosion. Slowing down runoff increases the time for infiltration, and thus less erosion occurs.

Accumulation of litter from a plant canopy may form a layer to prevent raindrops from hitting the bare soil. Maintenance of a good vegetative cover on the ground is the most helpful approach to control wind erosion. The significance of this feedback is most understandable when the vegetation cover is inadequate to protect the soil (Selby, 1993). Furthermore, vegetation also influences the soil through the action of roots; take-up of nutrients, and provision of organic matter and protects it from erosion by binding the soil particles together.

## 2.5 Models of Water Erosion

Many recent research efforts have focussed on improved understanding of erosion processes. These efforts have resulted in the invention of models to predict the rate of erosion. Modelling soil erosion is the process of mathematically describing soil particles' detachment, transport, and deposition on land surfaces (Nearing et al, 1994). Erosion models have most often been presented as computer programs designed to handle the tedious task of repetitive or complicated calculations. Some of the reasons for modelling erosion are to:

- find a predictive tool for assessing soil loss for conservation planning, soil erosion inventories, and for regulation.
- understand erosion processes and their interactions, and for setting research priorities (Nearing et al, 1994).

The three models of soil erosion have been experimental, theoretical, and physical-based models. The experimental models of erosion are based primarily on surveillance and are usually statistical in nature. Universal Soil Loss Equation (USLE) is a classic example of the empirical models of erosion. Physically based models are intended to represent the essential mechanisms controlling erosion. They represent a synthesis of the individual components, which affect erosion, including the complex interactions between various factors and their spatial and temporal variabilities (Nearing et al, 1994).

### 2.5.1 Universal Soil Loss Equation (USLE)

In this equation, erosion is seen as a multiplier of rainfall erosivity (the R factor, which equals the potential energy); this multiplies the resistance of the environment, which comprises K (soil erodibility), SL (the topographical factor), C (plant cover and farming techniques) and P (erosion control practices). Since it is a multiplier, if one factor tends toward zero, erosion will tend toward zero.

This erosion prediction equation is composed of five factors, R, K, SL, C and P

$$E = R \times K \times SL \times C \times P$$

R, the rainfall erosivity index, equals E, the kinetic energy of rainfall, multiplied by 30 (maximum intensity of rain in 30 minutes expressed in centimetres per hour). This index corresponds to the potential erosion risk in a given region where sheet erosion appears on a bare plot with a 9% slope. Soil erodibility, K, depends on the organic matter and texture of the soil, its permeability and profile structure. It varies from 70/100 for the most fragile soil to 1/100 for the most stable soil. It is measured on bare reference plots 22.2 m long on 9% slopes, tilled in the direction of the slope and having received no organic matter for three years.

SL, the topographical factor, depends on both the length and gradient of the slope. For example, it varies from 0.1 to 5 in the most frequent farming contexts in West Africa, and may reach 20 in mountainous areas.

C, the plant cover factor, is a simple relation between erosion on bare soil and erosion observed under a cropping system. The C factor combines plant cover, its production level and the associated cropping techniques. It varies from 1 on bare soil to 1/1000 under forest, 1/100 under grasslands and cover plants, and 1 to 9/10 under root and tuber crops.

Finally, P is a factor that takes account of the exact erosion control practices such as contour tilling, mounding, or ridging. It varies from 1 on bare soil with no erosion control to about 1/10 with tied ridging on a gentle slope.

In reality, in order to work out the erosion control measures to be set up in a given region the first step is to establish the risk of erosion from rainfall, then the degree of erodibility. A series of trials then follow to determine a factor C based on desired rotations, farming techniques and erosion control practices; finally, the length and gradient are calculated for the slope to be obtained through erosion control structures in order to reduce land loss to a tolerable level (1-12 t/ha/yr). It is thus a practical model for an engineer with few data to use as a less empirical basis for finding rational solutions to practical problems (United States Department of Agriculture, 2005). The Problem with USLE, however, is that it has only been applied to agricultural land where slopes seldom exceed $12^0$ (I on 4.7) whereas tailing slopes may be as steep as $33^0$ (I on 1.5).

This model only applies to sheet erosion since the source of energy is rain, so it does not apply to linear or mass erosion. The type of countryside: the model has been tested and verified in peneplain and hilly country with 1-20% slopes ($0.6^0$-$11.3^0$), and excludes young mountains, especially slopes steeper than 40% ($22^0$), where runoff is a greater source of energy than rain and where there are significant mass movements of earth. The type of rainfall: the relations between kinetic energy and rainfall intensity generally used in this model apply only to the American Great Plains, and not to mountainous regions although different sub-models can be developed for the index of rainfall erosivity, R. The model applies only for average data over 20 years and is not valid for individual storms. This model also has a limitation of neglecting certain interactions between factors in order to distinguish more easily the individual effect of each. For example, it does not take into account the effect on erosion of slope combined with plant cover, or the effect of soil type on the effect of slope (Gray & Sotir, 1996).

### 2.5.2 Universal Soil Loss Equation Two (RUSLE2)

RUSLE2 include several components. One major component is the computer program that solves many mathematical equations used by RUSLE2. A very essential part of the computer program is its interface that connects the user to RUSLE2. An additional chief component is its database, which is a large collection of input data values. The user selects entries from the database to describe site-specific field conditions. It also has the mathematical equations, scientific knowledge, and technical judgment.

RUSLE2 estimates rates of rill and interrill soil erosion caused by rainfall and its associated overland flow. Detachment (separation of soil particles from the soil mass) by surface runoff erodes small channels (rills) across the hillslope (Goldman et al; 1986). Erosion that occurs in these channels is known as rill erosion. Erosion on the areas between the rills, the interrill areas, is called interrill erosion. Detachment on interrill areas is by the impact of raindrops and waterdrops falling from vegetation (Charman & Murphy, 1991). The detached particles produced on interrill areas are transported laterally by thin flow to the rill areas where surface runoff transports the sediment downslope to concentrated flow areas (channels). Climate, soil, topography, and land use determine the rates of rill and interrill erosion. A RUSLE2 user applies RUSLE2 to a specific site by describing field conditions at the site for these four factors. RUSLE2 uses this field description to compute erosion estimates (USDA, 1987).

# CHAPTER 3: EROSION ON THE SLOPES OF TAILINGS DAMS

## 3.1 Introduction

A study of erosion on tailings dams is a relatively new development, and little information is at hand pertaining to the factors that control erosion processes of this nature. (Blight, 1989, Amponsah-Dacosta, 2001) identified some of the factors That influence slope erosion. These factors include: slope length and angle. Slope length and angle also control the velocity with which water runs down the slope. Plant cover and rain intensity also play a major role on the occurrence of erosion on tailings dams. Erosion of tailings dams may be exacerbated by techniques implemented through deposition, closure and rehabilitation of dams. Any efforts intended to reduce erosion of the slopes of tailings dams will require incorporation of existing literature information about the mechanisms of erosion on the slopes of tailings dams. The mechanisms of water erosion on natural slopes and sloping agricultural land were reviewed in the previous chapter. This chapter will present a review of previous studies on factors associated with erosion of tailings dams and the existing remedial measures. An evaluation of the methods for controlling tailings erosion is also discussed.

## 3.2 Nature of Tailings Dams Erosion

Losses of residue from the slopes of gold tailings dams of as much as 500 t/ha/yr have been measured in South Africa; hence, erosion can pose a very significant maintenance and environmental problem (Blight, 1996). The loss of material from unprotected tailings is attributed to factors of wind and water (Blight, 1989, 1991). Erosion varies seasonally and depends on the physical characteristics of material forming the slope surface, as well as the local climatic conditions. In South Africa, the magnitude of both the wind and water erosion on the tailings dams is roughly equal.

Amponsah-Dacosta (2001) pointed out that the vicinity of the slope crest or crest walls is the most susceptible to wind erosion, and relatively little erosion occurs from the top surfaces of tailings dams. Erosion losses are roughly proportional to slope length as shown on Figure 3.1. Relatively little erosion occurs from slopes flatter than $20^0$ or steeper than $40^0$ (Blight, 1996). Erosion of the slopes of tailings dams can reach a maximum for slope angles between $20^0$ and $35^0$ this is shown on Figure 3.2.

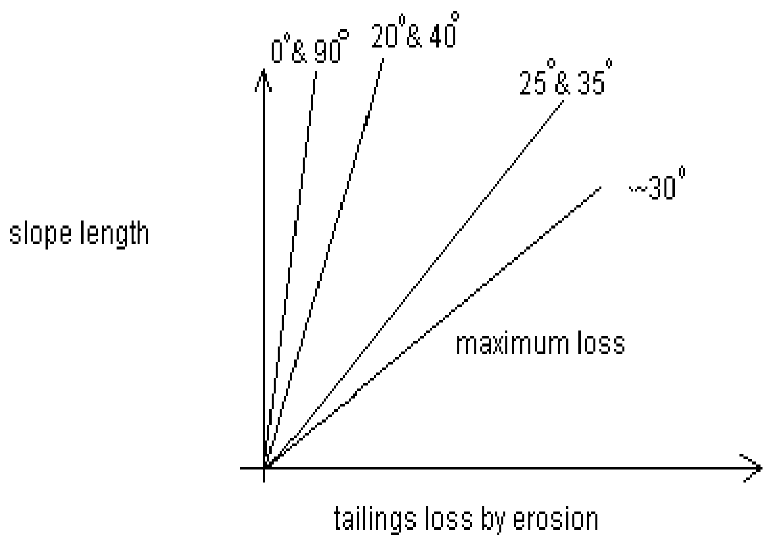



Figure 3.1 Effect of slope length on erosion of the outer slopes of tailings dams (Blight, 1996).

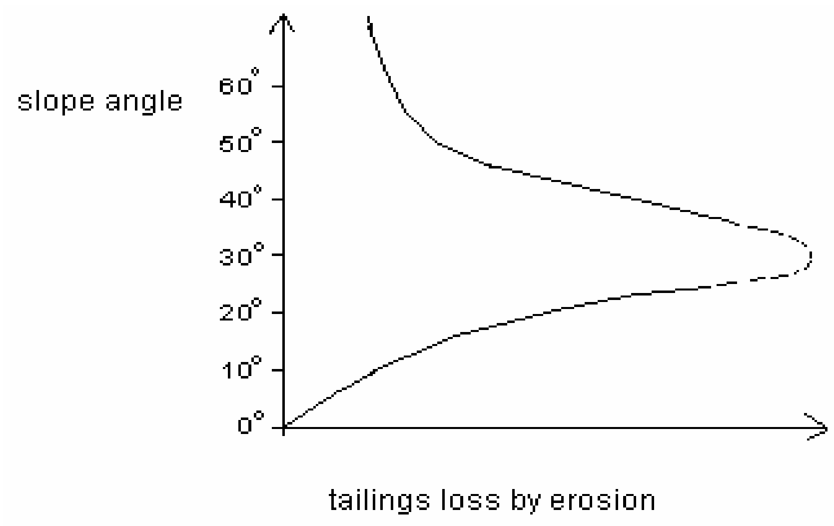



Figure 3.2 Effect of slope angle on erosion of the outer slopes of tailings dams (Blight, 1996).

### 3.3 Tailings Dams Design

Erosion studies conducted through observations and measurements indicated that the strength of the slope surface, slope length, and slope angle of mine tailings are key parameters affecting erosion of the gold tailings dams in South Africa (Blight, 1989, 1991). It is believed that the above-mentioned parameters may be associated with the methods of raising dam embankments, as well as techniques that were used for disposal of tailings. As a result, it is appropriate to review some of the methods for raising tailings embankments, and the techniques used for tailings disposal.

#### 3.3.1 Methods of Raising Dam Embankments

The methods of raising tailing dam embankments are related to the direction in which the crest of embankment moves in relation to the starter wall (Klohn, 1980, Blight, 1996, Papageorgiou, 2004).

The three main methods for incremental rising embankments of tailings dams are:

- Upstream method
- Downstream method
- Centreline method (Klohn, 1980 & Blight, 1996).

*Upstream Method*

The upstream technique is the oldest of the methods commonly used for raising embankments of tailings dams. The upstream method is no longer used in many parts of the world, although it is still used in South Africa (Blight, 1996). Tailings dams are constructed by depositing tailings in an upstream direction from a low starter dyke. The most common method of upstream construction is to raise the dyke by dragging up material from the previously deposited tailings (Klohn, 1980, Sarsby 2000). In this method, the starter dam is formed, slurried tailings is deposited behind the dam to form the lagoon, and sands settle out near to the dams. Sand is raked forward to raise the front of the tailings dam over the starter dam and settled tailings. When the lagoon is full more sand is raked forward to raise the dam.

The drawback of the upstream method is that the long-term stability of the dam is uncertain since the dam is built on the formerly deposited unconsolidated tailings (Amponsah-Dacosta, 2001). The major rewards are small expenditure required during the construction phase, and the rapidity with which the dam can be raised by each successive increase of dyke.

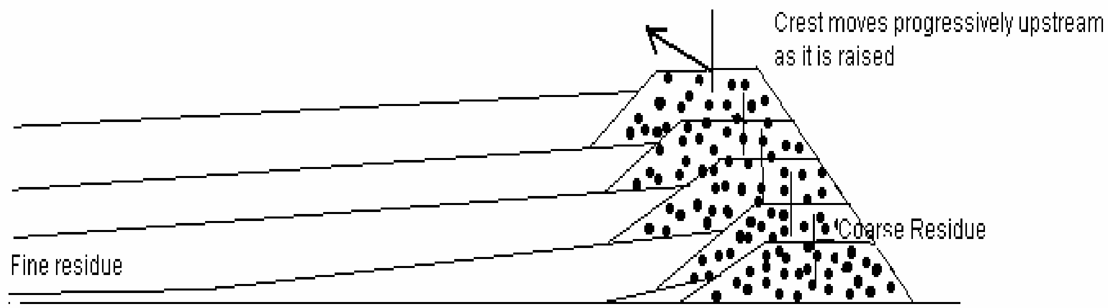



Figure 3.3 Upstream tailings dam construction (Klohn, 1980 and Blight, 1996).

*Downstream Method*

Methods of downstream of construction have one feature in common; the dam is raised in a downstream direction and is not underlain by formerly deposited tailings as shown in Figure 3.4. The volume of fill necessary often increases exponentially with height, so there is corresponding high cost (Sarsby, 2000). This method is more suited to conditions where significant storage of water along with the tailings is necessary, since the system has superior liquefaction resistance with little limitation placed on rates of raising the dam (Vick, 1983, McPhail, 1994, and Sarsby, 2000). Downstream methods are structurally sound and are equivalent to water-retaining dams (Sarsby 2000).

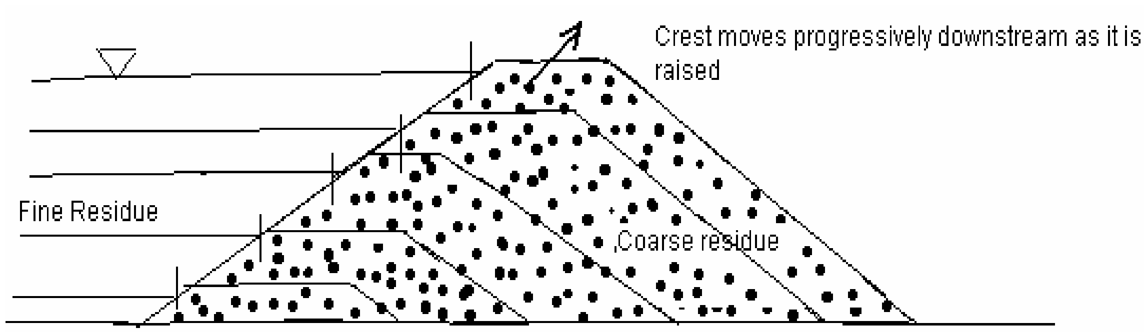



Figure 3.4 Downstream tailings dam construction (Klohn, 1980 and Blight, 1996).

*Centreline Method*

Centreline method is a variation of the downstream method. The only distinction being that, instead of the crest moving downstream as the dam is build, the crest in fact is raised vertically. This procedure allows the dam to be raised faster, as less sand is required (Klohn, 1980). The centreline of the impoundment remains in the same position throughout the construction period (Blight, 1996).

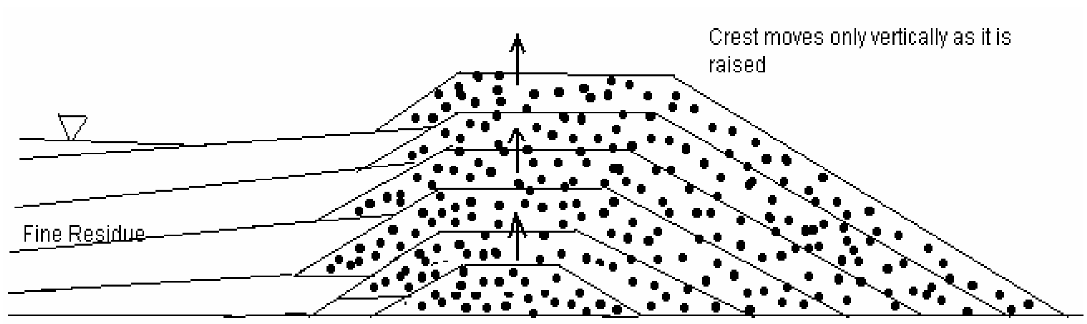



Figure 3.5 Centreline tailings dam construction (Klohn, 1980 and Blight 1996).

3.3.2 Tailings Disposal

The basic techniques for disposal of mine tailings are to be discussed in this segment. These techniques are related to the particle distribution of the particular tailings. Techniques for disposal of tailings can be applied with any one of the tailings construction methods (Blight, 1996 and Papageorgiou, 2004). It is imperative to choose the correct depositional procedures, because the depositional techniques provide good results if used with the suitable kind of tailings (Papageorgiou, 2004). The three main methods of tailings disposal are:

- Paddock method
- Spigot method
- Cycloning method

*Paddock Method*

The paddock method is suitable for tailings of uniform grain size or fine material that does not segregate readily, particles falling in a relatively narrow range (e.g. gold tailings (Blight, 1996 and Papageorgiou, 2004). If the paddock method is used with graded tailings, gravitational sorting of the particles sizes result in the formation of a series of fine horizontal impervious layers which have the effect of increasing the ratio of horizontal permeability to vertical permeability which might result in a deposit with highly anisotropic properties, a high seepage surface and slope stability problems.

The material is deposited to form a day wall in a series of paddocks constructed by raising low walls of previously deposited tailings. 100 to 150 mm of tailings slurry is deposited in the paddock, and after settling, the supernatant water is drained off towards the pool. When the first layer of tailings is dried the new cycle begins (Blight, 1996). The paddocks form the embankments that retain the bulk of the tailings, pool and storm water (Papageorgiou, 2004).

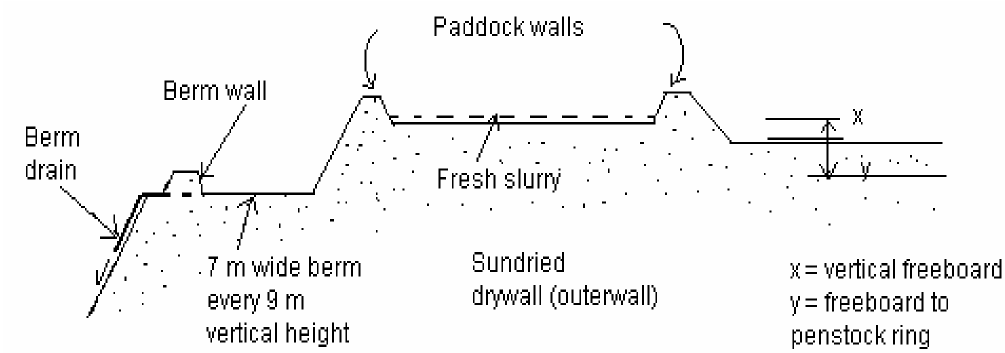



Figure 3.6 Section of the Paddock Deposition (Papageorgiou, 2004).

*Spigot Method*

Spigot deposition is suitable for tailings that are less fine and those that cover a wider range of grain sizes (e.g. platinum tailings). Spigots are multiple outlets along a delivery line and are used when it is possible to cause a grading split between the coarse and fine fractions of tailings. In the spigot, the particle size decreases with distance from the spigot, the finer fraction reaching the pond area as shown in Figure 3.7 (Blight, 1996).

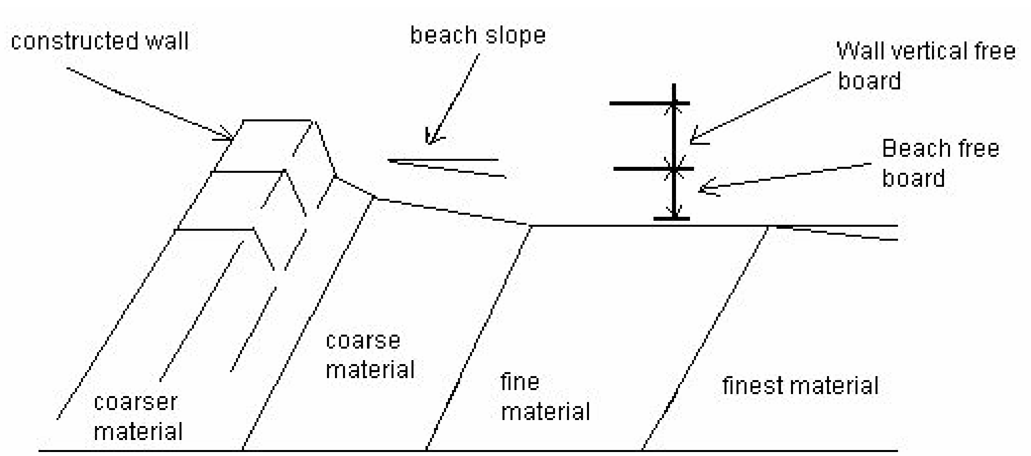



Figure 3.7 Principles of Spigot Deposition (Chamber of Mines, 1996)

*Cycloning Method*

When using the cyclone method of tailings deposition the material is segregated by the use of centrifugal force (Papageorgiou, 2004 and Blight, 1996). The tailings are fed under pressure into a conical cyclone that separates the coarser and the finer material. The coarser particles spiral downwards (underflow), while the finer particles spiral to the larger end of the cone (overflow). The coarse cyclone underflow is relatively free draining and will form a cone discharge from the cyclone. The overflow is the high water content slurry that is finer and has a low permeability than the underflow (Blight, 1994).

## 3.4 Control of Tailings Dams Erosion

All slopes are subject to erosion and mass wasting. Various approaches can be used to slow down, if not completely prevent this degradation. Installing erosion control measures as early as possible can minimize erosion losses, and where feasible by adoption of landform grading practices that mimic natural slopes (Gray & Sotir, 1996 and Amponsah-Dacosta, 2001). In the case of mine tailings stabilization is still not easy, for the reason that the nature of the material is complex. (Blight, 1996) stressed that, at closure tailings dams should be in such a state that minimize as far as feasible, erosion of slopes. More often than not, tailings contain toxic metals that can be eroded to adjacent agricultural land. Moreover, tailings dams also represent a potential threat to human safety especially where piping erosion occurs, as it may lead to dam failure, hence, it is becoming increasingly compulsory to prevent degradation of tailings dams by erosion.

The primary protection against wind and water erosion is usually vegetation, although armouring, by means of gravel or broken rock layers, has also proved promising in numerous cases (Blight, 1996 and Amponsah-Dacosta, 2001). This section describes some common strategies for controlling erosion on the slopes of tailings dams, which are frequently used in the South African mining industry.

### 3.4.1 Stabilisation by Vegetation

Vegetation stabilisation entails the utilization of plant parts, that is, roots and stems, which supply the main structural and mechanical elements in a slope protection system. Live cuttings and rooted plants are imbedded in the ground in various arrangements and geometric arrays to serve as soil reinforcements, hydraulic wicks (or drains), and barriers to earth movement. The correct choice of plant materials is key to the success of the strategy. A tight, dense cover of grass or herbaceous vegetation provides one of the best protections against surficial rainfall and wind erosion. Conversely, deep-rooted, woody vegetation is more effective for mitigating or preventing shallow, mass stability failures.

The beneficial effects of vegetation in preventing erosion are summarised as follows:

- Interception: Foliage and plants residues absorb rainfall energy and prevent soil detachment by raindrop splash.
- Restraint: Root systems physically bind or restrain soil particles while aboveground portions filter sediment out of runoff.
- Retardation: Stems and Foliage increase surface roughness, retard the wind and slow the velocity of water runoff.
- Infiltration: Plants and their residues help to maintain soil porosity and permeability, thereby promoting infiltration and delaying the onset of runoff (Gray & Sotir, 1996).

Vegetation has been extensively utilized for reducing erosion of tailings dams in many countries such as South Africa, Australia and the United States of America. In South Africa, vegetation is seeded and established under irrigation, and at first flourishes. But because of the semiarid climate conditions in the gold mining region and steep slopes on which it is growing, vegetation declines in vigor once irrigation is stopped (Blight & Amponsah-Dacosta, 2004). It is also difficult to continue irrigation for a long time since South Africa has inadequate water resources.

Salinity and waterlogging are major constraints to plant establishment and growth when directly revegetating tailings dams. During wet seasons, tailings dams may become waterlogged with moderate salinity and the combined effects of salt and waterlogging can have a detrimental impact on plant establishment, growth and survival. High rates of evaporation and drying may result in shrinkage cracking as well as the formation of a salt crust at the surface of saline tailings. The salt crust may be subject to wind erosion. Dried residue has a fine texture, no structure, and is lacking macropores needed for water and air movement. Voids created by shrinkage cracks provide channels through which drainage water and air can move through the surface of the residue, as well as being potential channels for the formation of voids by piping erosion.

### 3.4.2 Stabilisation by Physical Barriers

Physical stabilization entails the use of the physical barriers to prevent wind and water from eroding the slopes of tailings dams. The physical barriers may include soil, sand and broken waste rock or other restraining material. The use of the crushed rock and gravel has several advantages over the other methods. They have larger particle sizes that are resistive to water erosion, and have a higher shear strength compared with the finer particles. In some cases riprap, bark and straw have been used successfully for this purpose (Amponsah-Dacosta, 2001). Obstructions that roughen a slope surface, such as a discontinuous layer of stone chips or rock fragments have also proved to be effective.

The use of a layer of natural soil is one of the physical barriers that have received wide application. However it should be noted that this is not a good alternative considering the cost associated with importing the soil from other areas to the site where the tailings dam is located (Blight & Caldwell, 1984). The removal of the soil also has a negative impact on the environment causing land degradation, and destruction of the soil structure in the borrow area.

Slopes of tailings dams built in South Africa are often steep (about $35^0$). The protection of the steep slopes against erosion is very difficult to accomplish. Provision of crest walls helps by preventing water from cascading off the top and down the slopes of the tailings dams, and thus reducing the sheet erosion, and gully erosion is virtually eliminated (Blight, 1978). Water erosion on top surfaces as well as the requirement that all precipitation be held on the dam is cared for by a system of crest walls and erosion catchments berms that sub-divide the surface of the dam into a series of paddocks as shown in Figure 3.8-9 (Blight & Caldwell, 1984 and Blight, 1996).

Cladding of the slopes of tailings dams with a layer of rockfill is one of the alternatives for reducing erosion of the slopes of tailings dams (Amponsah-Dacosta, 2001). Blight (1996) pointed out that the nature of the rock to be used for cladding is not important provided that it is not erodable and will not weather in-situ, and should fulfil the guidelines such as those of the Chamber of Mines of South Africa as well as other legislative requirements.

Amponsah-Dacosata (2001) noted that stone protective systems have potential field application to mitigate erosion on tailings dams for longer-term period. However, the use of rock layer for reducing erosion on the slopes of tailings dams may cause slope instability (Blight and Caldwell, 1984). The methods to be used for reducing erosion of tailings dams should not compromise the structural stability of the dam. They must be properly engineered before they can be implemented and should produce reasonable side effects. Recently the methods of physical stabilization of tailings are moving towards a cover comprising of a combination of soil, gravels, rocks and vegetation, and Amponsah-Dacosta (2001) noted that these methods hold more promise of success. This combination should work together in a complementary way (Sotir and Gray, 1996).

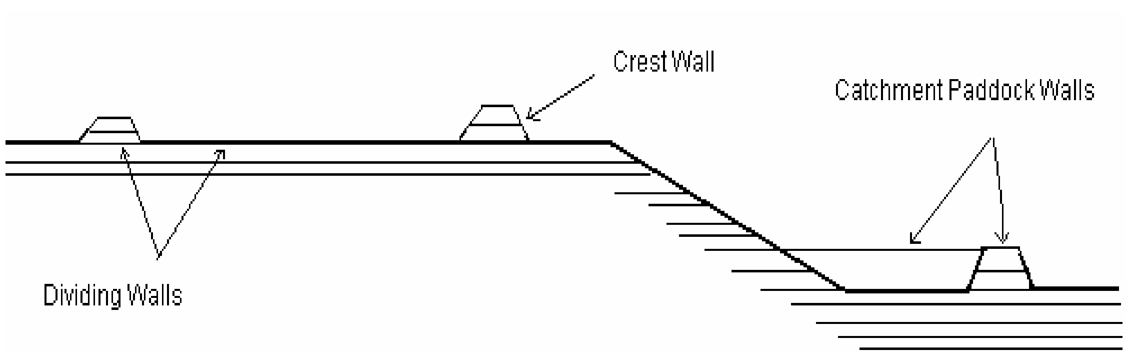



Figure 3.8 Crest walls and catchments paddock walls (Chamber of Mines, 1996)

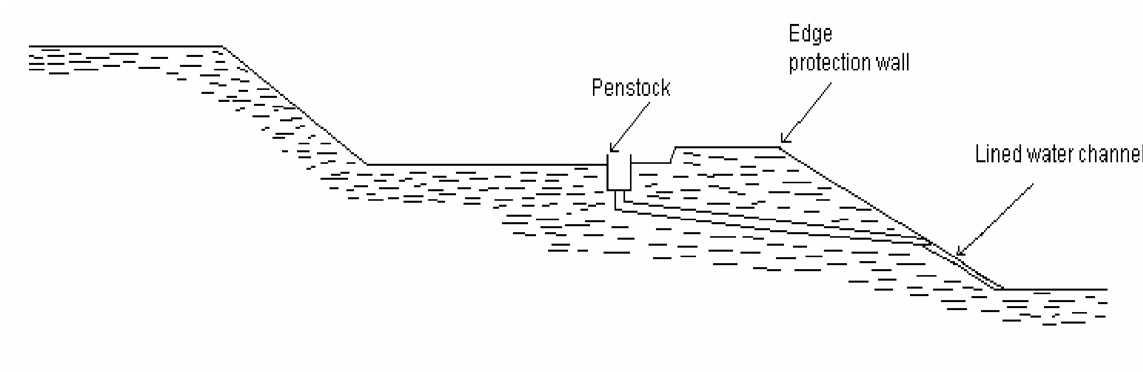



Figure 3.9 Erosion catchments berms (Chamber of Mines, 1996)

3.4.3 Biotechnical Stabilization

Biotechnical stabilization utilizes mechanical elements in combination with biological elements to arrest and prevent soil erosion. The inert components may include concrete, wood, stone, and geofabrics. Both biological and mechanical elements must function together in an integrated and complimentary manner to reduce erosion (Gray & Sotir, 1996). This method provides important advantages: Vegetation alone is inappropriate, for example, where highly toxic conditions prevail or in sites subjected to high water velocities or extreme wave action, in this case soil bioengineering becomes a good choice. This technique also relies on the use on native materials such as plants and plant stems or branches, rocks, wood, and earth. Biotechnical stabilisation requires minimal access for equipment, workers, and cause relatively minor site disturbance during installation.

### 3.4.4 Cement and Chemical Stabilisation

Another way to improve tailings dams so that they can better resist erosion is by stabilization with cement. Cement is widely used in soil stabilisation, and it is one of the most promising strategies for soil stabilisation (Osinubi, 2006). The most common cementing or binding agents are Ordinary Portland Cement, lime, bitumen and tar. The reason for the widespread use of the above binders is that they are applicable to a considerable range of soils, are also widely obtainable and efficient, and furthermore are environmentally acceptable (Hausmann, 1990).

Blight et al (1984) showed that, little cement is necessary to raise the pH of gold tailings from pH of 3.5 to 12.5 (see Figure 3.10). It is also noted that, even if gold residue contains no clay minerals, it does contain a certain amount of amorphous silica, which can be expected at pH values exceeding 12 to react with hydrated lime forming calcium silicates. If the residue contains sulphates, these sulphates might cause aggression to the products of cement hydration. Nevertheless, at the pH beyond 12, the sulphates should be in the form of gypsum, which, being sparingly soluble, is not as aggressive as other forms of sulphate (Blight et al, 1984).

Tailings-cement-water reactions form cementitious calcium silicate and aluminate hydrates, which bind tailings particles together. Hydration releases slaked lime ($Ca(OH)_2$), which in turn may react with the components of tailings such as clay minerals. Although hydration occurs immediately upon contact of cement and water, secondary reactions are slow and may go on for several months, similar to soil-lime interactions. Since the primary reaction (hydration) is independent of the soil type, cement stabilization is effective for a wide range of soils. Problems may be encountered with highly organic soils or coarser gravels. If the latter need stabilization at all, additional admixtures may assist. With fine-grained materials, limits of application may be imposed by the difficulty of mixing.

Blight and Caldwell (1984) have conducted a study to investigate the possible use of cement for reducing erosion of gold tailings dams. In this study a series of large tests panels measuring 30 m in length by 5 m in width and stabilized to a depth of 150 mm were laid out using 2, 3 4 per cent by mass of both lime and cement. The moisture content was adjusted to optimum for compaction, and the panels were compacted by pneumatic rolling. Erosion resistance of stabilized tailings was assessed with a portable Comet erosion tester, which directs a jet of water 0.8 mm in diameter at the surface from a distance of 25 mm. The pressure behind the jet is increased at a steady rate until the surface breaks up, the pressure at which the disruption occurs being recorded as a measure of the erosion resistance.

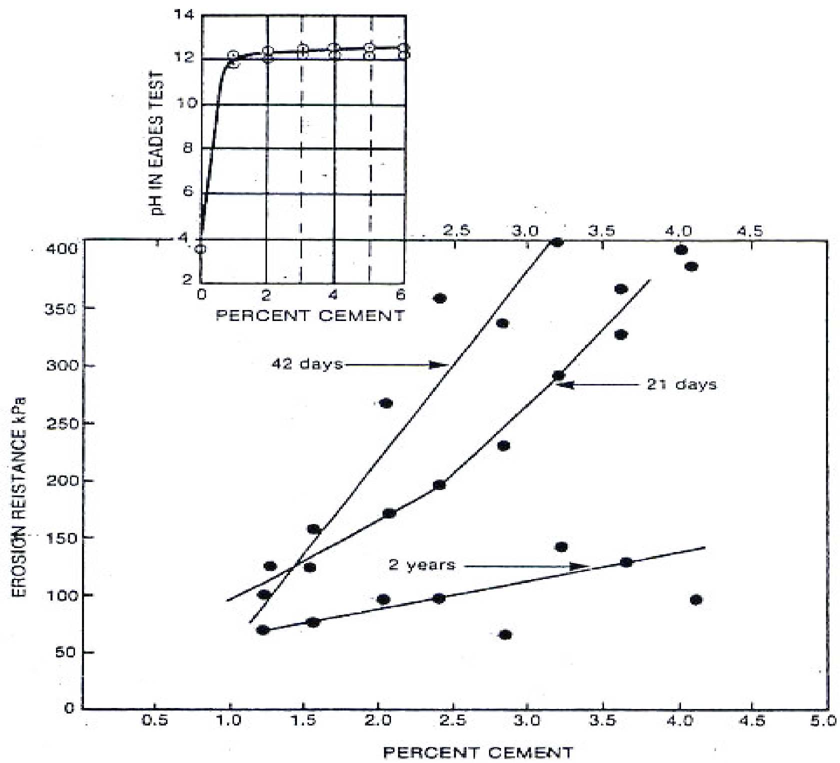



Figure 3.10 Results of tests on the stabilization of gold tailings with Portland cement (Blight and Caldwell, 1984).

Figure 3.10 shows the measurements of erosion resistance plotted against percentage cement at times of 21 days, 42 days, and 2 years after stabilizing. At first Comet readings increased with increasing curing period, however this was the opposite after a period of 2 years, where Coment reading decreased considerably. The decrease of the Coment reading after 2 years can be attributed to at least two causes:

(i) Attack on the cement by sulphates was severe than expected, and
(ii) soluble salts, drawn to the surface by evaporation gradients and crystallizing out at the surface, disrupted material at the surface.

Comet resistance of lime-stabilized panels showed a similar decrease after two years to that of the cement-stabilized panels. As attack by sulphates can be ruled out in the former panels, disruption by salts crystallization and acid attack appears to be the major causes of deterioration. It was noted that even though the Comet resistance of the Panels is low, they now stand proud of their surrounding, showing that they are more erosion resistance than the unstabilized surfaces (Blight and Caldwell, 1984).

### 3.5 Evaluation of Slope Protection Methods

The methods for reducing erosion of the slopes of mine tailings have been discussed in the previous section. This section will provide the cost-effectiveness evaluation of the methods for reducing erosion of tailings discussed earlier. Blight and Amponsah-Dacosta (2004) conducted a study to evaluate the cost-effectiveness of different methods for reducing erosion of tailings dams.

In this study, the experimental site was a South-facing slope with a slope angle of $16^0$ over the lower two thirds of the slope length of 20 m and $28^0$ over the upper one-third. The slope was divided into 11 panels, each measuring 20 m long (upslope) by 10 m wide (see Figure 3.11). Each panel was isolated from its neighbours by means of 0.5 m high metal sheets partly dug into the tailings surface to form a low vertical wall. Each panel was originally equipped with a sprinkler irrigation system to simulate rain, 3 rain gauges, and a set of 10 surface level pegs. The toe of each panel terminates in the catchments paddock to capture and hold solids removed from the slope by water erosion. Simulated rain have been used to obtain initial results, and then the slopes were exposed to natural weather for 4 years.

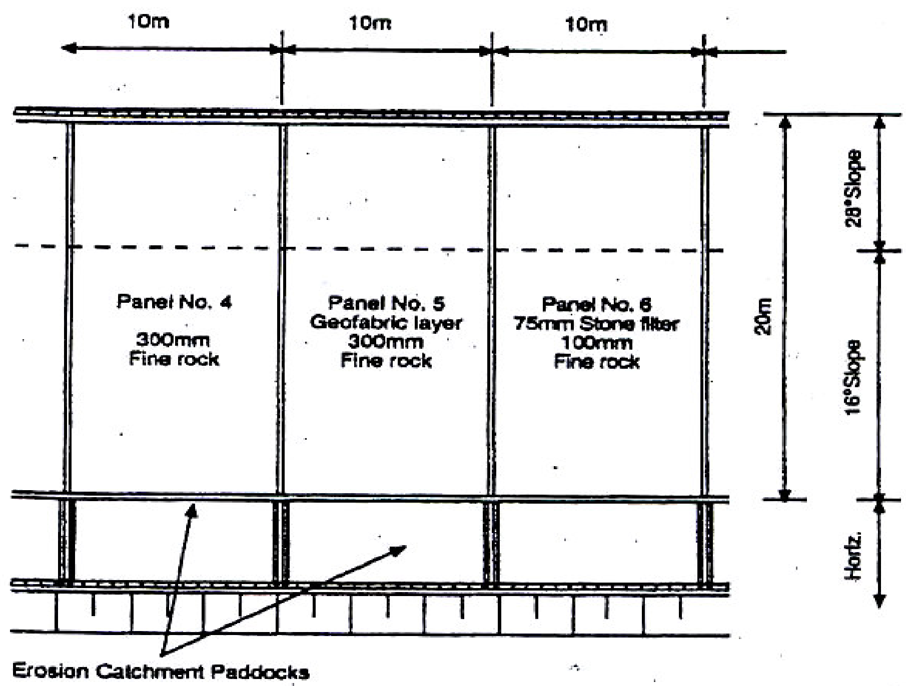



Figure 3.11 Port layout of large-scale erosion experiment (Blight and Amponsah-Dacosta, 2004).

Table 3.1 shows the type of surface protection and its relative cost, actual erosion rates in t $ha^{-1}yr^{-1}$, relative erosion rates and a cost effectiveness number represented by the product of relative cost (C) and relative erosion (E). Erosion rates were measured differently for phases 1 to 2 and 3 to 4 of the experiment. For phases 1 and 2 the material eroded off each panel was caught in the catchments paddocks at the toe of the slope, then collected and weighed. During phase 3, an unusually heavy rainstorm caused tailings to be washed onto the test slopes from above, thus rendering the origin of the mass of caught material questionable. For this reason, erosion for phases 3 and 4 were assessed by measuring the retreat of the slope surface against the surface level pegs.

The results of the study shows that conventional grassing method ranks closer to no treatment at all on the basis of cost-effectiveness for phase 2, and for both phases 2 and 3, a soil layer covered with grass sods (panel 10) rated top this was also on the basis of cost-effectiveness (see Table 3.1). However, the grass sods have visibly deteriorated with time and most of it has now dried. Only the presents of grass roots has maintained the effectiveness of the treatment. Panel 9 was having a thicker soil layer and was expected to perform better than Panel 10, but the grass has died and the Panel's rating has dropped from 1 to 8. It is noted that non-vegetative treatments occupy 6 of the first 7 places in the ranking and should therefore be seriously considered for use in future, and that is one of the reasons for undertaking this study.

Table 3.1 Cost-effectiveness evaluations of slope protection methods (Blight andAmponsah-Dacosta, 2004).

| Panel No. | Treatment | Level & compact | Level only | Relative cost $ha^{-1}$ C(%) | Erosion rate t/ha/yr | | Relative erosion E (%) | | Cost-effectiveness C × E (%) | | Cost-effectiveness ranking | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Phase 2 | Phase 3 | Phase 2 | Phase 3 | Phase 2 | Phase 3 | Phase 2 | Phase 3 |
| 1 | conventional grassing | ✓ | – | 100 | 164 | – | 59 | – | 59 | – | 10 | – |
| 2 | 100 mm ballast (50 mm size) | ✓ | – | 67 | 105 | 32 | 38 | 3 | 25 | 2 | 7 | 4 |
| 3 | 300 mm coarse rock | ✓ | – | 62 | 170 | 12 | 61 | 1 | 38 | 1 | 8 | 1 |
| 4 | 300 mm fine rock | ✓ | – | 62 | 38 | 96 | 14 | 9 | 9 | 6 | 3 | 7 |
| 5 | geofabric + 300 mm fine rock | ✓ | – | 120 | 22 | 15 | 8 | 1 | 10 | 1 | 4 | 1 |
| 6 | 75 mm of 6 mm stone + 100 mm fine rock | ✓ | – | 66 | 42 | 82 | 15 | 8 | 10 | 5 | 4 | 6 |
| 7 | 300 mm fine rock | – | ✓ | 54 | 118 | 75 | 43 | 8 | 23 | 4 | 6 | 5 |
| 8 | 250 mm open pit overburden | – | ✓ | 64 | 203 | 161 | 74 | 16 | 47 | 10 | 9 | 9 |
| 9 | 250 mm soil + Ag Lime + grass sods | – | ✓ | 120 | 19 | 72 | 7 | 7 | 8 | 8 | 1 | 8 |
| 10 | 100 mm soil + Ag Lime + grass sods | – | ✓ | 96 | 21 | 15 | 8 | 1 | 8 | 1 | 1 | 1 |
| 11 | zero control (no treatment) | – | – | 0 | 276 | 1029 | 100 | 100 | 0 | 0 | 11 | 10 |

# CHAPTER 4: PHYSICAL AND CHEMICAL PROPERTIES OF MATERIALS

## 4.1 Introduction

Mechanisms of erosion on natural slopes and tailings dams have been established through a literature review in the previous chapters. This chapter will discuss the chemical and physical properties of tailings. It is noted that the rate of erosion largely depends on the properties of tailings such as plasticity, dispersivity, density, chemical composition, and possibly the presence of cementing materials such as iron oxide and clay. Generally, coarse-grained and non-cohesive soils erode more rapidly and also have lower critical shear stresses than fine-grained and cohesive soils (Wan & Fell, 2004). However, this depends very much on their water content.

Physical and chemical properties of tailings may have a major influence on tailings erosion and possible use of cement for tailings stabilisation. (Blight & Caldwell, 1984) noted that sand and gravel fractions are in the main fairly inert; clay minerals are beneficial to cement reactions, while organic matter, acids, and sulphates may be deleterious when exposure to these occurs subsequent to cement hydration. Heavy metals such as lead, copper, cadmium, and nickel do not affect cement hydration reactions directly and are immobilized by formation of relatively insoluble precipitates at higher pH, typically above 9.0 (Wareham & Mackechnie, 2006).

Prior to the core experimental study on soil erodibility, an examination of the chemical and physical properties of the tailings was conducted. The main purpose was to establish the characteristics of the tailings in-terms of their physical and chemical properties. To maintain focus, the details of the laboratory investigation for both chemical and physical properties of tailings are presented in the Appendix.

## 4.2 Chemical Properties of Tailings

Chemical properties of the tailings which were used in the present study include: total dissolved salts (TDS), concentration of Sulphates ($SO_4$), Iron (Fe), Calcium (Ca), and Magnesium (Mg), pH and Electrical Conductivity (EC). These properties may have an effect on tailings erosion and cement stabilisation. Table 4.1 indicates results of the chemical analyses for gold (Au), platinum (Pt), and kimberlite (C1 and C2) tailings. The results presented in Table 4.1 are graphed in Figure 4.1.

Table 4.1 Chemical properties of Au, Pt, C1 and C2 tailings

| Chemical Properties | Au tailings | Pt tailings | C1 tailings | C2 tailings |
|---|---|---|---|---|
| $SO_4$ mg/kg | 8686 | 3612 | 1086 | 430 |
| $Fe^+$ mg/kg | 2360 | 75 | 37 | 93 |
| $Ca^+$ mg/kg | 380 | 186 | 0 | 0 |
| $Mg^+$ mg/kg | 240 | 98 | 52 | 143 |
| TDS mg/kg | 24 | 4.7 | 4.0 | 5.9 |
| pH | 2.1 | 2.7 | 8 | 9.2 |
| EC (ms/m) | 400 | 170 | 140 | 70 |

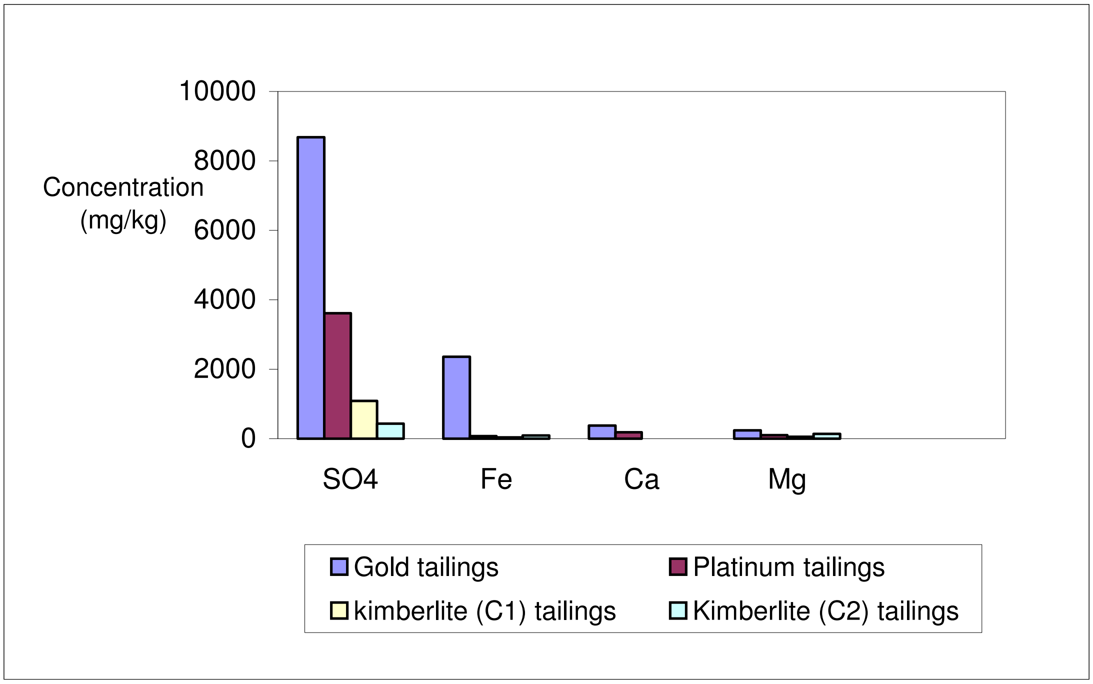



Figure 4.1 Chemical properties of gold, platinum and kimberlite tailings

Gold (Au) tailings were collected from the Doornkop tailings dam, Gauteng Province, South Africa. The concentration of total dissolved salts for Doornkop gold tailings is 24 mg/kg. Concentrations of the metals are as follows: $SO_4$ = 8686 mg/kg, $Fe^+$ = 2360 mg/kg, $Ca^+$ = 380 mg/kg and $Mg^+$ = 240 mg/kg. This elevated concentration of the dissolved ions and sulphates may have a negative consequence on cement stabilisation. Blight and Caldwell (1984) noted that soluble salts drawn to the surface by evaporation gradients and crystallizing at the surface, disrupt the surface of cement-stabilised gold tailings.

Gold tailings contains a high quantity of sulphates and dissolved salts as shown in Figure 4.1. Gold mineralisation is associated with high contents of pyrite, Iron and Magnesium; hence elevated concentrations have been obtained. The higher quantity of sulphates is caused by oxidation of pyrite ($FeS_2$). The low pH (2.1) of gold tailings shows that the pyrite had oxidized, as gold tailings are usually alkaline when deposited.

Platinum (Pt) tailings were collected from Bafokeng, North-West Province, South Africa. The concentration of the total dissolved salts for the platinum tailings is 4.7 mg/kg. The concentration of metals is as follows: $SO_4$ = 3612 mg/kg, $Fe^+$ = 75 mg/kg, $Ca^+$ = 186 mg/kg and $Mg^+$ = 98 mg/kg. Deterioration of cement-stabilized tailings by sulphates and salts crystallization is expected to be minimal for platinum tailings because of the low concentration of this material. On the other hand, the chemical composition of the platinum tailings may change over time as the material continues to weather. However platinum tailings do not show considerable indication of weathering. It is assumed that the chemical compositions of platinum tailings may have been influenced by the geological conditions of the host rock, and to a less degree by the chemicals used for processing the ore.

Two samples of kimberlite tailings were collected from a tailings site in Kimberley, Northern Cape Province, South Africa. The two kimberlite tailings samples do not show significant differences in-terms of their physical properties, but their chemical properties diverge significantly. The two samples were analysed and tested independently in order to evaluate the effect of the chemical properties of the tailings on erosion or efficacy of cement stabilisation. The concentrations of the total dissolved salts are 4.0 and 5.9 mg/kg for fine (C1) and coarse (C2) kimberlite tailings respectively. The concentrations of metals for kimberlite tailings are as follows: $SO_4$ = 1086 mg/kg, $Fe^+$ = 37 mg/kg, $Ca^+$ = 0 mg/kg and $Mg^+$ = 52 mg/kg (C1 tailings), $SO_4$ = 430 mg/kg, $Fe^+$ = 93 mg/kg, $Ca^+$ = 0 mg/kg and $Mg^+$ = 143 mg/kg (C2 tailings). Deterioration of the cement-stabilized tailings could be expected to be least with kimberlite tailings due to the small concentrations of sulphates and dissolved ions.

Measurements of the electrical conductivity (EC) of tailings are essential since it helps to estimate the quantity of the dissolved salts and ions (TDS). EC is controlled by the nature of the parent rock and the climatic conditions in the region. The following EC readings were recorded 400, 170, 140 and 70 ms/m for gold, platinum, fine (C1) and coarse (C2) kimberlite tailings respectively.

### 4.3 Physical Properties of Tailings

The physical properties of tailings can have an important influence on tailings erosion, and may also have an effect on the possible use of cement for tailings stabilization. The physical properties of tailings that may influence erosion and cement stabilization include: particle size distribution and specific gravity, as well as the optimum compaction density and moisture content. Blight (1989, 1991) noted that the strength of the slope surface is one of the key factors affecting erosion of the slope surfaces of the gold tailings dams in South Africa.

The capability of soil to oppose erosion forces is related to the distribution of the particle sizes in a particular soil (Bouyoucos, 1935). Grain size distribution or grading of the tailings has a major effect on erosion of the tailings dams. An increase of clay and organic matter may cause erosion to diminish. Silty loam, loamy fine sandy and sandy loam materials are more susceptible to erosion (Lujan, 2003). Erosion is low in well-graded and coarse gravels. Grain size distribution may also influence the void ratio and moisture content of the soil. Void ratio and moisture content may in-turn have an influence on erodibility of the slopes of tailings dams. Low void ratios and high antecedent moisture content can lessen erosion loss (Gray & Sotir, 1996). The particle size distributions also determine other significant geotechnical characteristics of tailings such as density, permeability, and shear strength (Papageorgiou, 2004).

The particle size distribution, specific gravity, optimum compaction and moisture content are important properties of tailings. These important properties have an influence on the strengths of the slope surfaces of tailings dams. The results of the physical properties of gold, platinum and kimberlite tailings are presented in Table 4.2.

### 4.3.1 Moisture-Density Relationships

The moisture-density relationships were established by using the standard Proctor compaction test. In this test, 3 layers of tailings are compacted at 25 blows per layer. To obtain the mass of tailings required to fill the mould, the density of the tailings is estimated and the mass is then obtained using the following formula:

*Estimated density* × *volume of compaction mould* = *mass of soil*

*Procedure*

The mass is weighted in the large dish and 3 (% by mass) water is added to the tailings and mixed thoroughly. The mould body is secured to the base-plate and the collar to the mould body with the wing nuts. To prevent adhesion of moist soil to the plate, a paper disc is placed on the bottom of the mould. From the original total mass $^{1}\!/_{3}$ is weighed from the original total mass into the container that is flexible on the corners to allow easy transfer of tailings in to the mould (i.e. a container that facilitate easy transfer to the mould). The material in the mould is pressed down firmly and then compacted with the compaction hammer, using 25 blows spaced evenly across the surface of the specimen. The procedure is repeated with the second and the third layers.

After the compaction process has been completed, the collar of the mould is detached and the excess material is removed with a steel straight-edge. The mould and the contained material is weighed. The material is extruded mechanically with a jack; a sample from the middle and ends of the specimens is transferred in to evaporating dish. The evaporating dish with wet tailings is weighed, and reweighed once more after a period of 24 hours in the oven (at a temperature of 105 $^{0}$C). The above procedures are repeated with increased moisture contents. The results of the compaction test are resented on the appendix. D and analyzed in Figure 4.2.

Table 4.2 Physical properties of tailings

| Physical Properties | Au tailings | Pt tailings | C1 tailings | C2 tailings |
|---|---|---|---|---|
| % Clay | 11 | 4 | 3 | 1 |
| % Silt | 54 | 51 | 15 | 12 |
| % Sand | 35 | 45 | 82 | 78 |
| % Gravel | 0 | 0 | 0 | 9 |
| $D_{50}$ | 0.035 | 0.075 | 0.2 | 0.3 |
| Gs | 2.70 | 3.22 | 2.89 | 2.96 |
| $\gamma_{d\ opt}$ (kg/m$^3$) | 1685 | 1900 | 1695 | 1671 |
| $W_{opt}$ (%) | 14 | 18 | 14 | 18 |

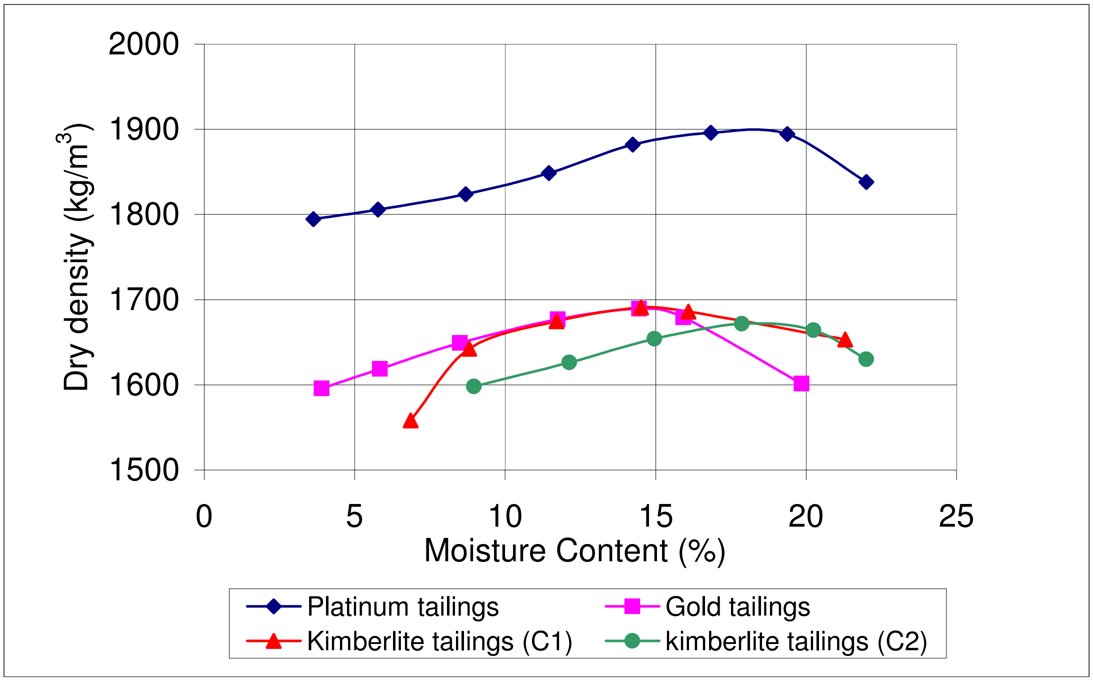


Figure 4.2 Moisture-Density relationships of gold, platinum and kimberlite tailings

Figure 4.2 shows the moisture-density relationships of the gold, platinum and kimberlite tailings. Platinum tailings have the highest dry density (i.e. 1900 kg/m$^3$). Gold, fine (C1), and coarser (C2) kimberlite tailings have similar dry densities of 1685, 1695, and 1671 kg/m$^3$ respectively. Gold tailings have lower optimum moisture content of 14%, when compared to 18% of the platinum tailings. The coarser kimberlite tailings (C2) have a large optimum moisture content; this may be due to the particle size distribution of the material. The specific gravities for gold, platinum, fine (C1) and coarse (C2) kimberlite tailings are 2.70, 3.22, 2.89 and 2.96 respectively.

*Grain Size Distribution*

The particle size distributions of the various tailings are shown in Figure 4.3. The particle size distributions depend on the factors such as: fineness to which the ore is milled and the mineralogy of the ore, which controls weathering, and ore extraction mechanisms (Blight, 1996, Amponsah-Dacosta, 2001 and Gawu, 2003).

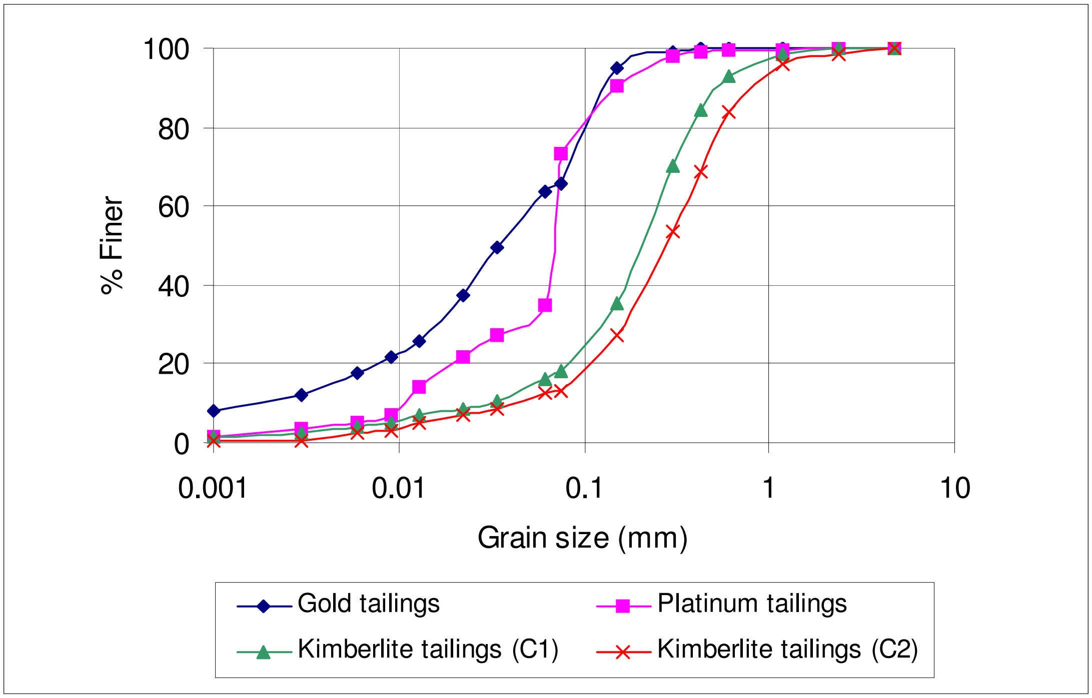



Figure 4.3 Particle size distributions for gold, platinum, kimberlite tailings

Figure 4.3 shows the particle size distributions of the gold, platinum, and kimberlite tailings. The mean particle size ($D_{50}$) of the gold tailings is approximately 0.035 mm. Gold tailings contains about 10% of clay size material which may be essential for binding particles together to lessen erosion. Milling and weathering processes may have influenced the fine texture of the gold tailings.

Gold is usually found in micro-sizes and extraction processes involve crushing and milling to small sizes. Gold deposits may also contain certain quantities of shaly materials, and these materials are susceptible to weathering. If shaly material is associated with gold deposits, the shale may weather to clay.

The platinum tailings are made up of two sub-gradings curves and lack clay-size particles. Platinum tailings have a dominance of coarser particles, with 45% sand-size and 51% silt-size particles. The mean particle size ($D_{50}$) for the platinum tailings is 0.075 mm. Silt-sizes are about 51% for the platinum tailings, and this range is considered the most susceptible to erosion (Lujan, 2003).

The two samples of kimberlite tailings show fairly similar grading curves except in the sand-size region where they differ slightly; in this region kimberlite (C2) is coarser than kimberlite (C1). Kimberlite tailings (C1) have 0% gravel-size and 82% sand-size particles, while tailing (C2) tailings have larger quantities of coarse particles, 9% of gravel-size and 78% of sand-size particles. The silt-size particles are 15 and 12 % for C1 and C2-tailings respectively. The mean ($D_{50}$) particle sizes of the finer and coarser kimberlite tailings are 0.2 mm and 0.3 mm respectively. C2 tailings have a higher percentage of material in the susceptible range, and they only have 1% of clay size particles. Upon weathering of kimberlite, clay minerals such as smectite may form, but the samples collected do not show any evidence of weathering. These clay minerals can change the geochemistry of the kimberlite tailings.

### 4.4 Cementing Materials

Two types of cement were used as stabilizing agents, namely Conbex and ordinary Portland cement (OPC). Conbex is a patented mixture of ground granulated blast furnace slag and lime together with an actuator, thought to be sodium hydroxide. Conbex is extensively used in South Africa to strengthen underground mine backfill, typically in cut and fill or room and pillar mining where high early strength development is not necessary. Conbex has the following physical properties: Specific gravity (2.89), loose bulk density (1 000-1 200 kg/$m^3$), compacted bulk density (1 300-1 400 kg/$m^3$). The pH value is 12.2.

Advantages of Conbex are: it is cost effective, resistant to sulphates and chlorides therefore may be appropriate for tailings stabilisation. Workability of a mix is slightly enhanced, which makes it flow better and create greater impermeability and density.

Ordinary Portland cement has a specific gravity of 3.15 and fineness is $2.9 \times 10^5$ $mm^2$/gm. The main chemical components are: 62.5% CaO, 21% $SiO_2$, 6.5% $Al_2O_3$, 3.8% MgO, 3% $Fe_2O_3$, and 2.1% $SO_3$ (El-Sadani, 2001). The pH of the ordinary Portland cement is 12.6.

# CHAPTER 5: PINHOLE TESTS AND DISCUSSION OF RESULTS

## 5.1 Introduction

The chemical and physical properties of tailings have been discussed in the previous chapter in an analytically tractable way. This chapter will now outline the basis of the pinhole test, and also discuss the results obtained from the tests. The Eades test is also presented. The specimens used for the pinhole test were compacted at densities of 100, 95 and 90% of Proctor maximum dry density and cement contents of 0, 3, 5, and 10% were added to stabilize the tailings. The pinhole test was used to evaluate the erodibility of the compacted and stabilized tailings.

## 5.2 Background of the Pinhole and Eades Test

The pinhole test was initially developed to assess the potential erodibility of soil intended for use in the impervious cores of earth dams. The pinhole test gives reliably reproducible results and differentiates between dispersive and non-dispersive clays (Sherard et al, 1963, Mitchell, 1976 and Wan & Fell, 2004). In the pinhole test distilled water is passed through a 1.0 mm-diameter hole formed through a compacted specimen. In dispersive clay, the water passing through the hole becomes muddy and the hole rapidly erodes. For non-dispersive clays the water is clear and there is no erosion (Mitchell, 1976).

The development of this technique was for the purpose of reliable identification and improved understanding of dispersive clays, which have been shown to be responsible for serious erosion damage and failure of earth dams and other structures (Wan & Fell, 2004). This technique is widely applied in practice due to its ability to give reliable estimates of erosion loss and may also be used for studying tailings erosion.

5.2.1 Preparation of the Specimen and Testing Procedures

Conbex and ordinary Portland cement were used as cementing agents, and the content varied from 3-10 per cent by mass. The required amount of water was based on the optimum moisture content obtained from the standard proctor compaction tests shown on Figure 4.1. The specimens were prepared at 100%, 95% and 90% compaction density in order to assess the effect of density on erosion.

To prepare a specimen, water is sprinkled over the dry mix and mixed thoroughly with a spoon. The mix is transferred into the mould containing an axial central pin and compacted (see Figure5.2). The specimens were compacted with a Losenhausenwerk compression machine in 3 layers. To compact the specimens, the mould (filled with tailings) is placed on the compression machine, and is compressed by the machine. The rammer has a small hole that allows the metal pin to pass through as the specimen is compacted. After compaction the specimen is extruded, and is ready for the pinhole test.

The prepared specimens were either tested straight away (i.e. after extrusion) or wrapped in plastic to keep water content unchanged and allowed to cure for a period of 7-days before they were tested. Curing allows the strength development of the cemented materials, this is illustrated in Figure 5.1.

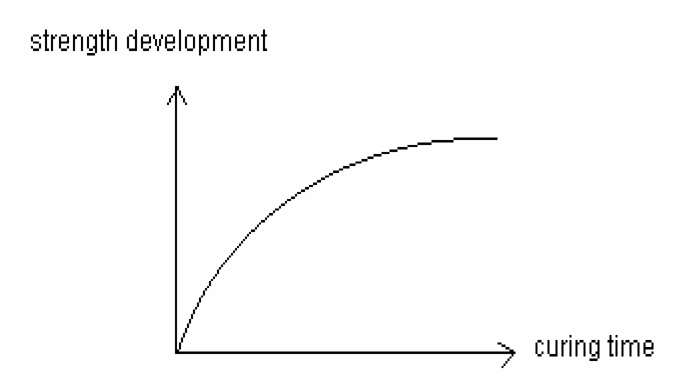



Figure 5.1 Illustration of strength development in cement stabilised materials

Figure 5.2 Mould for preparing specimens

Figure 5.3 Pinhole specimens for gold tailing

Figure 5.4 Set-up of the pinhole test

Figure 5.4 shows the setup for the pinhole test. The test is conducted by passing distilled water through the pinhole for a period of 10 minutes. A constant head of 50 cm is maintained during the flow of water through the specimen. The response of the specimen in-terms of discolouration of the effluent water is noted. The tailings eroded are caught in the basin as shown in Figure 5.4. The amount of tailings eroded by water is determined by weighing the mass of the eroded tailings caught in the basin, after oven drying.

### 5.2.3 Eades (ICL) Test

The Eades test was originally developed by Eades and Grim (1964). The Eades test is also known as the initial lime consumption test (ICL). The main objective of the Eades test is to control the pH in lime and cement stabilised soil in order to allow the possible formation of cementing minerals, calcium silica hydrates in particular and for proper modification of clay minerals to take place (Ballantine and Rossouw, 1989). The procedures followed in conducting the Eades test for the present study are those described by Ballantine and Rossouw (1989). Ballantine and Rossouw made the following variations from the original version of the Eades test (Eades and Grim, 1964).

- testing construction materials as a whole (crushed to pass a 19 mm sieve) in place of the –0.425 mm fraction only,
- using a 200g sample in place of 20g, and
- reducing the water content to just above saturation moisture content (pore moisture) so dispensing with the necessity of applying a correction factor for lime water saturation (Ballantine and Rossouw, 1989).

## 5.3 Analyses and Discussion of the Results

5.3.1 Eades Tests for Gold, Platinum, and Kimberlite Tailings

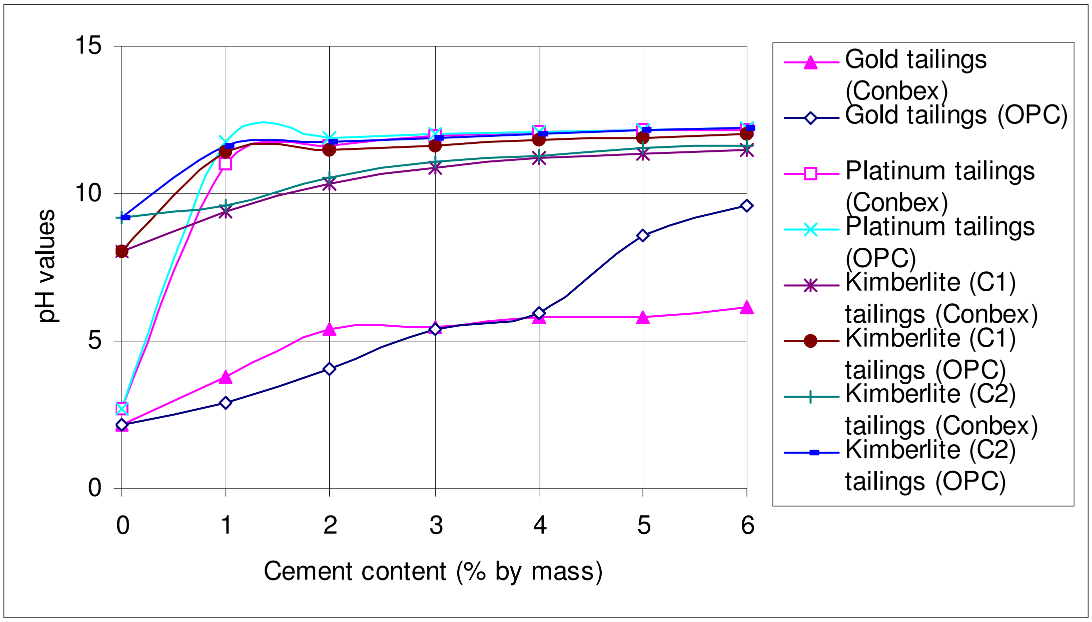



Figure 5.5 Eades tests for gold, platinum and kimberlite tailings

Analyses of results obtained from the Eades tests for gold, platinum and kimberlite tailings are shown in Figure 5.5. Gold and platinum tailings are more acidic than kimberlite tailings, pH 2.1 and 2.7 respectively. Gold tailings stabilized by ordinary Portland cement produced a higher pH when compared to the same tailings treated with Conbex cement. The dissimilarity of the pH for the same tailings is attributed to the higher alkalinity of ordinary Portland cement when compared to Conbex, pH 12.6 and 12.2 respectively.

Stabilizers that produce highly alkaline mixtures such ordinary Portland cement are the most favourable, since they generate a condition that is appropriate for the formation of cement minerals. The Conbex produced higher pH than ordinary Portland cement at low cement contents (i.e. at 2% by mass).  Both Conbex and ordinary Portland cement produced relatively comparable pH curves when utilized for gold tailings (at cement contents of 3 and 4% by mass).

Results of the Eades test for platinum tailings are similar for tailings treated with either conbex or ordinary Portland cement. As noted earlier, platinum tailings are highly acidic (i.e. pH of 2.7), but smaller additions of either ordinary Portland cement or conbex (i.e. 1% by mass) raised the pH from 2.7 to slightly above 12. An addition of 1% by mass of ordinary Portland cement produced a slightly higher pH than Conbex. In general, both Conbex and ordinary Portland cement produced comparable pH-curves for platinum tailings. Tailings treated with ordinary Portland cement show a sharp rise of pH while tailings treated with conbex cement display a more gradual rise of pH.

Both samples of kimberlite tailings produced results that are comparable for Conbex and ordinary Portland cement. Although, it can be seen that there is a slight difference, i.e., Portland cement produced a slightly higher pH than Conbex for both C1 and C2 tailings. The pH of both samples of kimberlite tailings was also similar to that of platinum tailings.

### 5.3.2 Pinhole Test for Gold Tailings

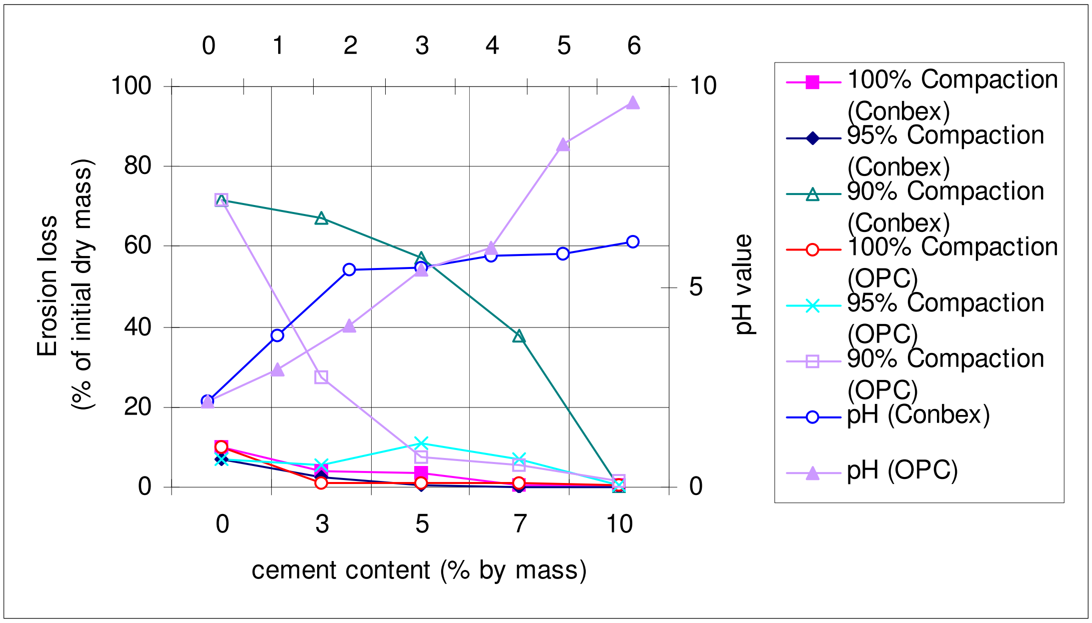



Figure 5.6 Analyses of the pinhole test for non-cured gold tailings

Analyses of results of the pinhole test for non-cured gold tailings treated with Conbex and ordinary Portland cement are shown in figure 5.6. The left hand y-axis shows erosion loss with cement contents ranging from 0 to 10% by mass (on the x-axis). The right hand y-axis shows the Eades test with cement contents ranging from 1 to 6% by mass (on the x-axis). The percentages compaction listed in Figure 5.6 are percentages of maximum dry density for Proctor compaction effort.

A strong positive connection exists between cement content and erosion loss for non-cured gold tailings. Erosion is higher for non-cured cement-stabilized gold tailings compared to the 7-days cured cement-stabilized tailings. Erosion resistance of non-cured cement-stabilized gold tailings is higher than expected. It is believed that the particle size distribution of gold tailings contributed significantly to the higher erosion resistance of non-cured gold tailings. Gold tailings is dominated with fine particles which can easily cling together forming stable aggregates, and it is for this reason that non-cured cement-stabilized gold tailings didn't collapse during the pinhole test.

Little additions of cement (i.e. 3 per cent by mass) produced a remarkable reduction in the loss of tailings by erosion. A cement content of 10% produced little or no erosion for all compaction densities, and for both cement products as shown in Figure5.6. Erosion losses for 100 and 95% compaction density is approximately 15% (of initial dry mass). However higher erosion rates (i.e. greater than 70%) were noted for the specimens compacted at a density of 90%.

In most cases, gold tailings stabilized with either Conbex or ordinary Portland cement produced a higher resistance to water erosion even without curing. It can be seen in Figure 5.6 that ordinary Portland cement gave slightly better erosion resistance than Conbex, particularly at a compaction density of 90%. It will also be seen in Figure 5.6 that erosion resistance increases with increasing percentage compaction. Generally, erosion loss decreased with increasing cement content and compaction density. The water passed through the pinhole was discolored for the specimens compacted at 90% density (see Figure 5.4). Increasing the cement content resulted in elevated densities and less erosion loss.

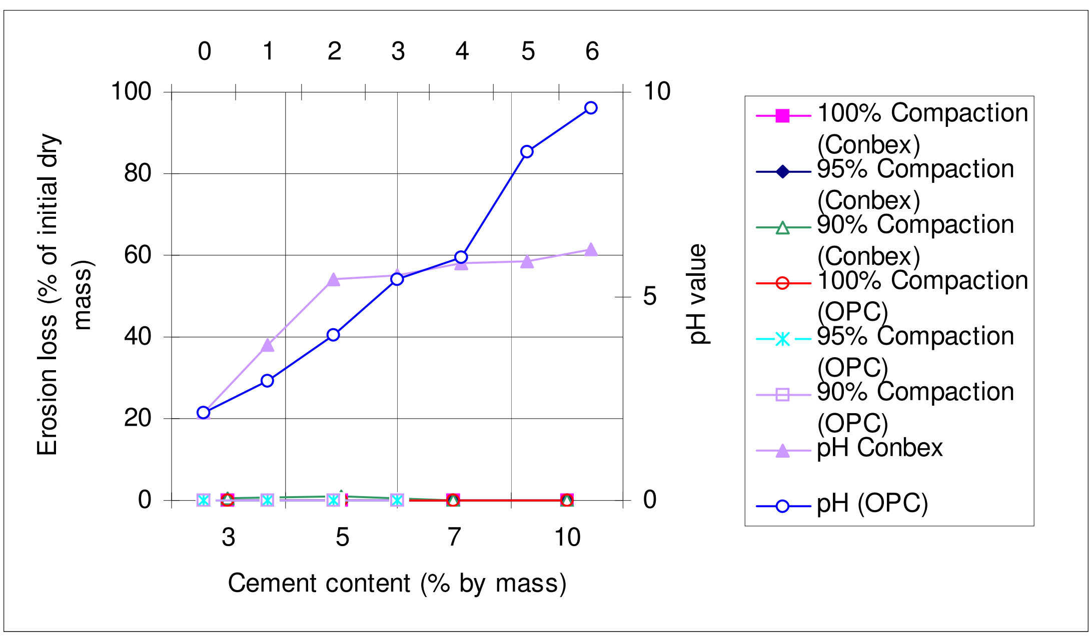



Figure 5.7 Analyses of the pinhole test for 7 days cured gold tailings

Analyses of results of the Pinhole and Eades test for gold tailings that were treated with Conbex and ordinary Portland cement, and cured for 7 days are shown in Figure 5.7. The left hand y-axis shows erosion loss with cement contents ranging from 0 to 10% by mass (on the x-axis). The right hand y-axis shows the Eades test with cement contents ranging from 1 to 6% by mass (on the x-axis).

Tailings compacted on a density of 100 and 95% and cured for 7-days produced no erosion for cement-stabilized gold tailings. The water passed through the specimens was crystal clear. Minor erosion (0.26 and 0.74% of initial dry mass) was recorded for tailings that were stabilized with 5 and 7% Conbex respectively (at 90% compaction density). In these tests the water was slightly discolored after the pinhole test. Generally, gold tailings that were cured for 7-days produced slight or no erosion loss for all tailings and cement products.

The absence of erosion for gold tailings tested after 7-days curing can be attributed to cement hydration that lead to dissociation of calcium ions that reacted with tailings silica and possibly tailings alumina leading to the development of pozzolanic products. The pozzolanic products bound the finer particles together; and produced physical bonds that resulted in a stronger matrix of tailings. More resistance to erosion is anticipated with time, provided there is sufficient water available for the hydration process and the consequent pozzolanic reactions to continue taking place.

### 5.3.3 Pinhole Test for Platinum Tailings

Erosion loss for non-cured cement-stabilized platinum tailings is not analysed graphically because the tests failed due to collapse and clogging of the pinhole. The specimens clogged and collapsed even when stabilized with the highest cement contents (i.e. 10% by mass). Most of the tests clogged within the first 5 minutes instead of the 10 minutes standard time. Specimens of platinum tailings are very susceptible to water erosion, and were easily eroded during the pinhole test. Clogging of the tests can be attributed to the cohesionless nature of platinum tailings, as well as the lack of cement minerals to facilitate the immediate pozzolanic reactions.

Analysis of the particle size distribution reveals that the platinum tailings have a bi-modal, gap graded particle size distribution curve as shown in figure 4.3. Platinum tailings also have a domination of coarse particles, with 45% sand-size and 51% silt-size particles, which falls within the susceptible range. Generally, the poor sorting of the platinum tailings and lack of adequate time for cement minerals to form, before carrying out the pinhole tests contributed significantly to the high susceptibility of uncured platinum tailings to erosion.

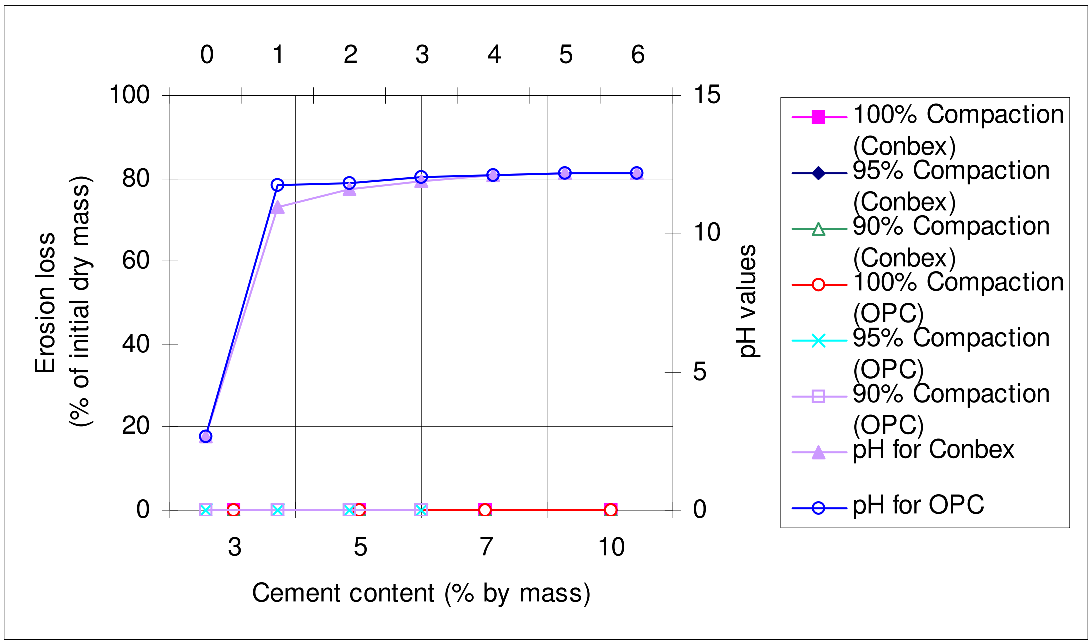



Figure 5.8 Analyses of the pinhole test for 7 days cured platinum tailings

Analyses of results of the pinhole test for platinum tailings that were treated with Conbex and ordinary Portland cement, and cured for 7 days are shown in figure 5.8. The left hand y-axis shows erosion loss with cement contents ranging from 0 to 10% by mass (on the x-axis). The right hand y-axis shows the Eades test with cement contents ranging from 1 to 6% by mass (on the x-axis).

Platinum tailings present an excellent illustration of the consequence of curing and hardening of tailings with cement. Curing is essential for platinum tailings, since all specimens of cement-stabilized platinum tailings that were cured for 7-days produced no erosion when tested, as shown in Figure 5.8. The water passed through the specimens of the platinum tailings that were cured for 7-days was perfectly clear. Even the smallest amount of cement (3% by mass) produced this result.

The high stability of platinum tailings after 7-days curing can be attributed to the products of cement hydration that leads to the dissociation of calcium ions which in the end reacted with the platinum tailing's silica and alumina leading to the formation of pozzolanic products. Erosion resistance of the platinum tailings will increase with time provided that there is sufficient water for hydration reactions to continue taking place.

### 5.3.4 Kimberlite Tailings

Erosion loss of both samples of non-cured kimberlite tailings has not been analysed graphically because the tests failed due to collapse and clogging of the pinhole. Most of the tests clogged within the first 2 minutes instead of the 10 minutes standard time. Clogging and collapse of the tests may be attributed to elevated susceptibility of kimberlite tailings to erosion owing to lack of fundamental minerals to assist the instant reactions with cement.

Kimberlite tailings appear fresh and do not have clay minerals that normally come about as a result of weathering, smectite being a typical example. Generally, the particles size distribution and lack of clay minerals for immediate reactions with cement probably contributed to the poor reactions of kimberlite tailings with cement, these in the end lead to increased susceptibility of uncured kimberlite tailings to erosion. It is also noted that kimberlite tailings requires sufficient time for the cement minerals to develop.

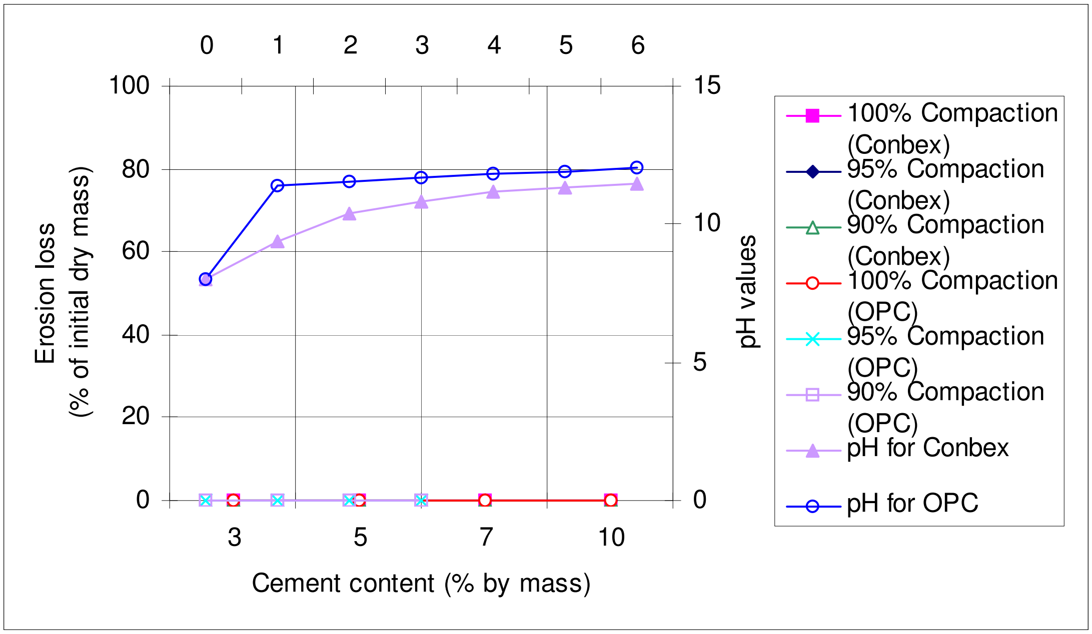



Figure 5.9 Analyses of the pinhole test for 7-days cured Kimberlite (C1) tailings

Analyses of the results of the pinhole test for 7-days cured cemented kimberlite (C1) tailings are shown in figure 5.9. The left hand y-axis shows erosion loss with cement contents ranging from 0 to 10% by mass (on the x-axis). The right hand y-axis shows the Eades test with cement contents ranging from 1 to 6% by mass (on the x-axis).

Dissimilarity of erosion between cured and non-cured tailings is noted as well for kimberlite (C1) tailings. Erosion is on the zero-line for all cured cement-stabilized kimberlite (C1) tailings. It is apparent from the results obtained in Figure 5.9 that kimberlite (C1) tailings require time for the cement minerals to form. With adequate curing time, the amount of cement and compaction density could be limited. Figure 5.9 plainly reveals that even the specimens prepared with smallest cement contents and density produced no erosion (.i.e. erosion is along the zero line). The results in Figure 5.9 also substantiate that very little cement is required to eliminate erosion.

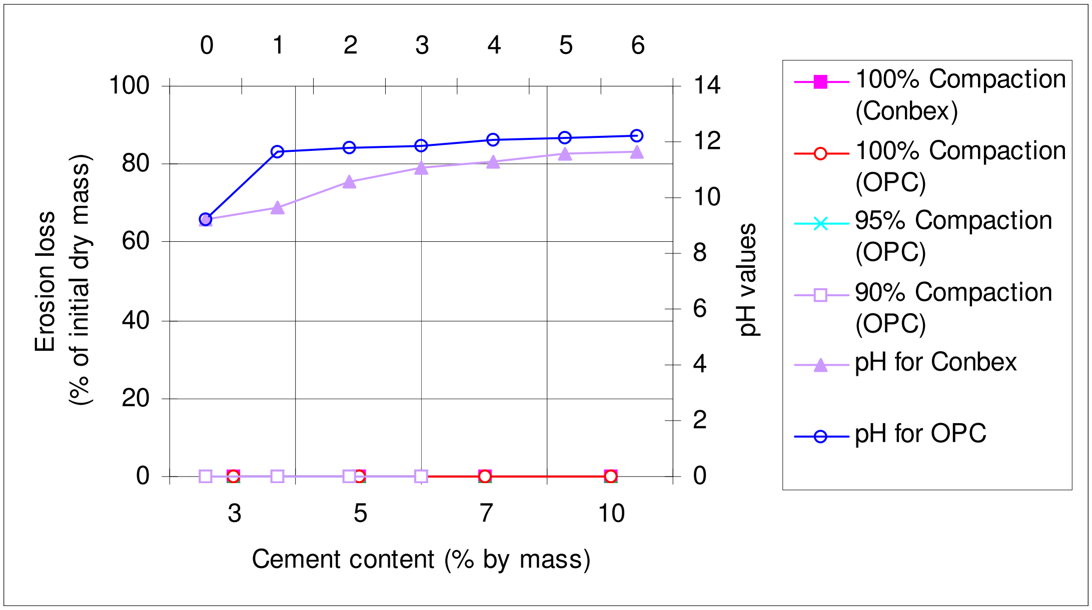



Figure 5.9 Analyses of the pinhole test for 7-days cured Kimberlite (C2) tailings

Analysis of the results of the pinhole test for kimberlite (C2) tailings treated with conbex and ordinary Portland cement respectively are shown in Figure 5.9. The left hand y-axis shows erosion loss with cement contents ranging from 0 to 10% by mass (on the x-axis). The right hand y-axis shows the Eades test with cement contents ranging from 1 to 6% by mass (on the x-axis).

Non-cured kimberlite (C2) tailings are susceptible to erosion as noted earlier. Erosion loss is still high for 7-days cured OPC-stabilized kimberlite (C2) tailings. Conbex-stabilized 7-days cured specimens of the kimberlite (C2) tailings all collapsed, except for those compacted at a density of 100% and 10% cement. Conversely all the OPC-stabilized tailings produced clear water after the pinhole test irrespective of the cement contents and compaction densities.

Generally, the kimberlite (C2) tailings are less stable than the kimberlite (C1) tailings. This distinction can be explained in terms of the chemical and physical properties of the individual samples of kimberlite as discussed in the previous chapter. The kimberlite (C1) tailings have a high content of sulphates and are dominated by fine particles whereas kimberlite (C2) tailing is dominated by coarser particles and a reduced amount of sulphates. In this case, use of the OPC is superior and is recommended for tailings of similar characteristics.

# CHAPTER 6: STRENGTH PROPERTIES OF THE MATERIALS

## 6.1 Introduction

The erosion resistance of slopes of mine tailings increases with the strength of their surfaces. If the slope is composed of loose and uncompacted material, it will erode easily, but if it is compacted and covered with larger particles that roughen the slope, it will better resist erosion (Cruse and Larson, 1977, Blight and Amponsah-Dacosta, 2004). Stabilization of tailings by cement will also increase the strength of the surface layer of tailings against erosion as demonstrated by the pinhole tests.

In practice, stabilization of tailings by cement can be applied in many ways, these may include: treating a surface layer of the tailings dam with cement up to a certain depth (Blight and Caldwell, 1978). Stabilization of this nature may present the following problems: field mixing is extremely difficult; working on the steep slopes makes compaction difficult and inefficient. A layer of bricks made of cement-stabilized tailings over the slopes of the tailings dams may also reduce erosion. The other possible strategy would be to roughen the slope surfaces of the tailings dams by rubble and gravel made of cement-stabilized tailings.

The bricks, rubble and gravel are expected to generate a more positive outcome than stabilization of a continuous layer due to the following advantages: high compaction densities can be achieved, and less cement would be necessary, for the reason that the work can be carried out as an industrial operation in factory conditions. Erosion-resistant particles on the slopes of tailings dams will create an irregular surface that will lessen the velocity of water running off the slopes of the tailings dams, thus limiting the surface erosion.

In order to appraise the prospective use of cement for reducing slope erosion, it was decided to examine the strength characteristics of the cement-stabilized tailings. The present chapter will present the results of this examination.

## 6.2 Unconfined Compressive Strength (UCS)

### 6.2.1 Background of the Unconfined Compressive Strength (UCS) Test

Figure 5.1 shows the apparatus for testing unconfined compressive strength of soil. The unconfined compressive strength is defined as the stress at which the specimen reaches maximum compressive resistance. The test is used to determine the strength of materials such as stabilized soil, concrete and rocks. An axial load is applied, typically by stress control. In this case remoulded specimens, which have been compacted at the optimum moisture and cured for 7-days, have been tested for strength characteristics. The unconfined compressive strength of the specimen is calculated by dividing the maximum load at failure by the sample cross-sectional area:

$$\sigma_c = \frac{F}{A}$$

*Where:*

$\sigma_c$ = Unconfined Compressive Strength (kPa)
F = Maximum Failure Load (kPa)
A = Cross-sectional area of the core sample ($mm^2$)

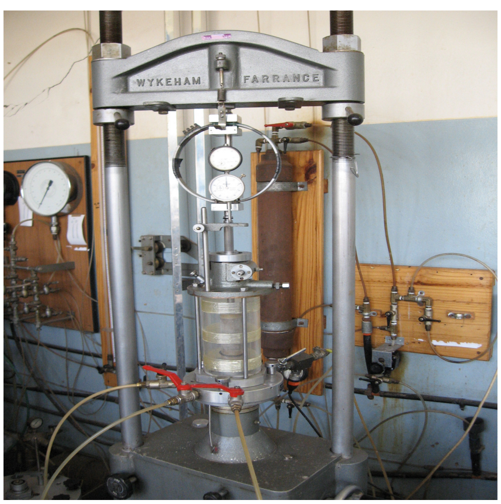



Figure 6.1 Apparatus for testing UCS

## 6.3 Analyses and Discussion of Results

6.3.1 Unconfined Compressive Strengths for Gold Tailings

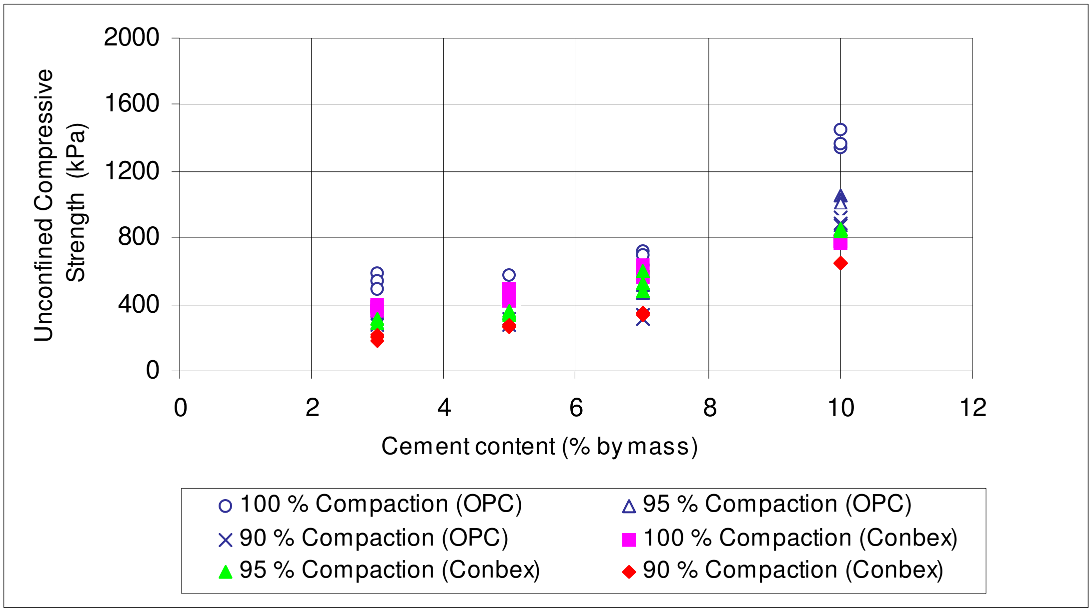



Figure 6.2 UCS of 7-days cured gold tailings

Figure 6.2 shows unconfined compressive strength of gold tailings following a curing period of 7-days. Cement content influences the pH and the compaction density of the materials, for this reason cement has a vital role to play in tailings stabilisation. Figure 6.2 reveals a strong positive correlation between cement content and unconfined compressive strengths of gold tailings. An increase of cement resulted in high UCS strengths. A cement content of 10% produced unconfined strengths greater than 1600 kPa (for 100% compaction). These high strengths values may perhaps be attributed to density, and the cement minerals formed at this cement content. Cement contents of 0, 3, 5 and 7 % produced strengths values which are less than 800 kPa, and these low strengths can be attributed to deficiency of cement minerals at these cement contents, calcium silica hydrate in particular which usually develop at higher pH.

The specimens compacted at a density of 100% produced slightly higher strengths than specimens compacted at a density of 95 and 90% as shown in figure 6.2. Gold tailings compacted at a density of 90% never exceeded 400 kPa for 3, 5 and 7% cement as shown in Figure 6.2. Nevertheless, the strength for the 10% Conbex-stabilized gold tailings (90% compaction density) is slightly below 800 kPa. Perhaps this may explain the reason why the 7-days cured gold tailings produced slightly discoloured water in the pinhole test.

Tailings that were stabilised with Conbex cement produced lower strengths than those stabilised with ordinary Portland cement. This may be explained in terms of the capacity of a particular kind of cement to elevate the pH to conditions where pozzolanic reactions can take place. It is also noted that sulphates should be in the form of gypsum at pH above 12, which being sparingly available is not as aggressive as the other forms of sulphates (Blight and Caldwell, 1984). Ordinary Portland cement produced higher pH than Conbex as shown in the Eades test in Figure 5.5. Conbex cement produced higher pH values at lower cement contents (i.e. less than 3%), but subsequent to 3% cement, Portland cement produced higher pH than Conbex, this too is shown in Figure 5.5.

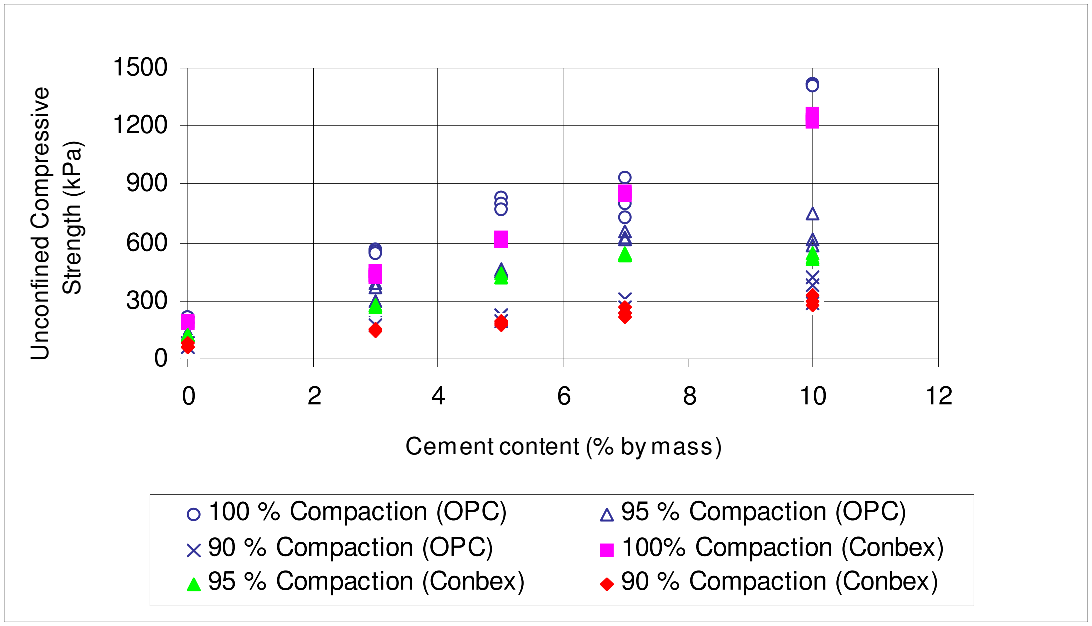



Figure 6.3 UCS for non-cured gold tailings

Figure 6.3 shows unconfined compressive strength for non-cured cement-stabilized gold tailings. The purpose of testing strength characteristics of uncured tailings was to evaluate weather it will be possible to mould bricks and remove the mould immediately without the brick crumbling. Non-cured strengths tests provide the initial strength characteristics of the brick after curing. The strength values for non-cured cement-stabilized gold tailings are somewhat small as compared to the 7-days cured cement-stabilized gold tailings. The strength values for non-cured gold tailings are less than 1000 kPa, even with 7% cement. Once more, compaction density seems to have a considerable impact on strengths of cement stabilised tailings. Specimens compacted at a density of 100% produced higher strengths values than those compacted at a density of 95 % and 90% (see Figure 6.3).

Specimens compacted at a density of 100%, and a cement content of 5-7% produced higher strengths than specimens compacted at a density of 95 and 90% having much higher cement (i.e. 10 % by mass). The specimens compacted at a density of 95 and 90% produced strengths that are less than 900 kPa even at 10% cement. The observation explained on the above sentence is an emphasis of the significance of the compaction density during tailings stabilization.

The maximum strength produced by the specimens compacted at a density of 90% for non-cured gold tailing is 400 kPa for both Conbex and ordinary Portland cement. While the maximum strength produced by the specimens compacted at a density of 95% is less than 900 kPa. These emphasize the significance of the curing period. Higher strength can be achieved if tailings can be afforded ample time to cure.

Ordinary Portland cement produced higher strengths than Conbex especially at higher cement content (i.e. from 7 to 10 % by mass). This can also be explained in terms of the capability of cement to elevate the pH values and the capability to provide instant reactions with tailings. Generally, both cement and compaction density seems to have an immense impact on the strengths of the tailings.

The specimens without cement produced strengths values not exceeding 300 kPa (see Figure 6.3). The low strengths values for the gold tailings without cement provide a good estimate of the capability of a particular soil to resist erosion at a natural state. Additions of cement in-turn present a good measure of the effect of curing and hardening gold tailings with cement. There is a steady increase of the strengths for gold tailings, which corresponds to the increase of the cement content and compaction density. For non-cured gold tailings increasing strengths which corresponding to cement content can be attributed to density increase as a results of high cement content. From the observations made on Figure 6.3 it can be concluded that non-cured gold tailings have sufficient strengths to allow brick moulding to commence without having to wait for the strength gain due to formations secondary minerals. The moulding process will be faster because the same mould will be immediately available to mould the next brick.

### 6.3.2 Unconfined Compressive Strengths for Platinum tailings

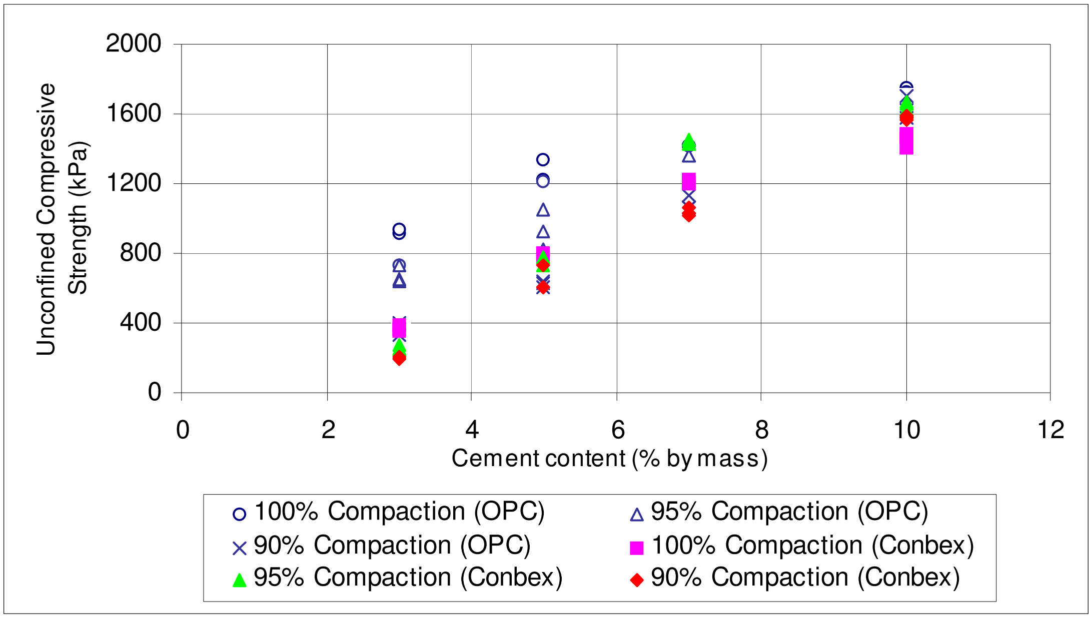



Figure 6.4 UCS for 7-days cured platinum tailings

Figure 6.4 shows unconfined compressive strength for cement-stabilized (7-days cured) platinum tailings. The strong positive correlation between compaction density and unconfined compressive strengths exists as well in platinum tailings. The specimens compacted at a density of 90% produced lower strengths than specimens compacted at a density of 95 and 100%. The later compaction densities produced moderate and higher strengths respectively. The function of the compaction density is visibly shown at 3 and 5% cement contents in Figure 6.4. In this case higher compaction density produced higher strengths.

The pH of the material plays an essential role in determining the strength of the materials that have been stabilised by cement, because it controls the formation of cement minerals, which may be essential for pozzolanic reactions. Both Conbex and ordinary Portland cement have closely related characteristics in terms of elevating the pH of platinum tailings to levels where Pozzolanic reactions can take place; this is shown on Figure 5.5. The maximum strengths values for platinum tailings (2000 kPa) are higher than for gold tailings (1600 kPa). This may be attributed to the higher pH for platinum tailings, which is greater 12, compared to pH 10 for gold tailings treated with ordinary Portland cement.

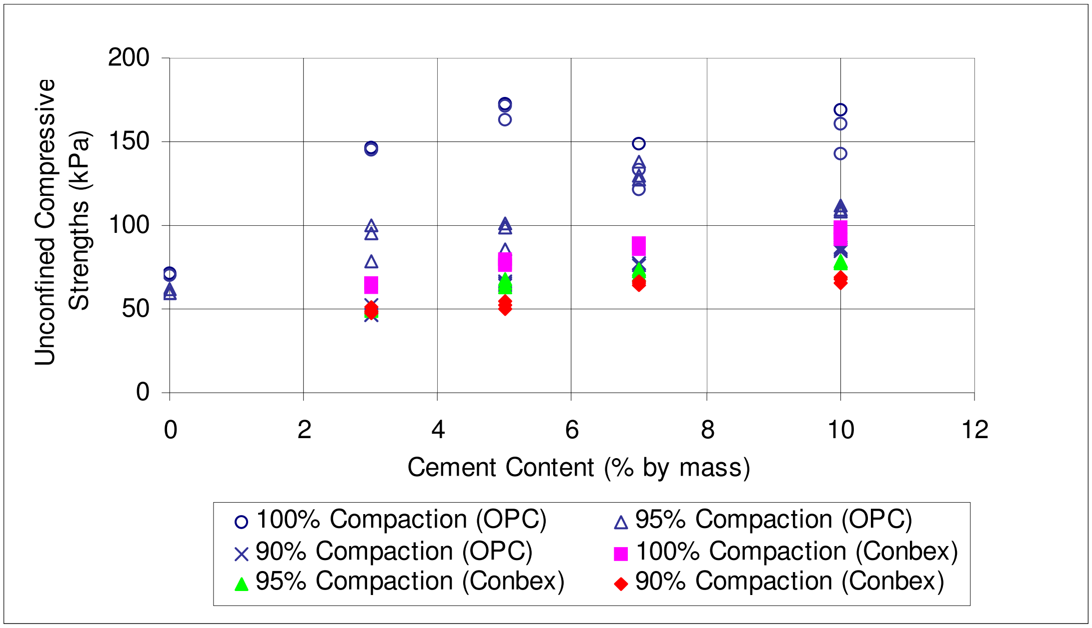



Figure 6.5 UCS for non-cured platinum tailings

Figure 6.5 shows unconfined compressive strength for cement-stabilized non-cured platinum tailings. Non-cured platinum tailings have very low strength values. The maximum strength is less than 200 kPa, and the minimum strength is lower than 50 kPa. Specimens of platinum tailings, which have been prepared without cement, produced the least strength values about 60 kPa. A cement content of 10% resulted in the strength of about 170 kPa, and this is not much greater than the strength of the specimens without cement. The specimens compacted at a density of 90% produced the least strengths, with the maximum not exceeding 70 kPa for Conbex stabilized tailings.

Lack of curing is the main reason why the non-cured platinum tailings produced such low strengths. The non-cured platinum tailings were highly susceptible to erosion during the pinhole test, and this can now be explained in-terms of the strengths characteristics of the tailings which shows that the material was susceptible to erosion because of low strengths. It will be more appropriate to leave the bricks in one place for at least 7-days to allow the secondary minerals to form so that the strength of the bricks can be enhanced.

### 6.3.3 Unconfined Compressive Strength for kimberlite (C1) tailings

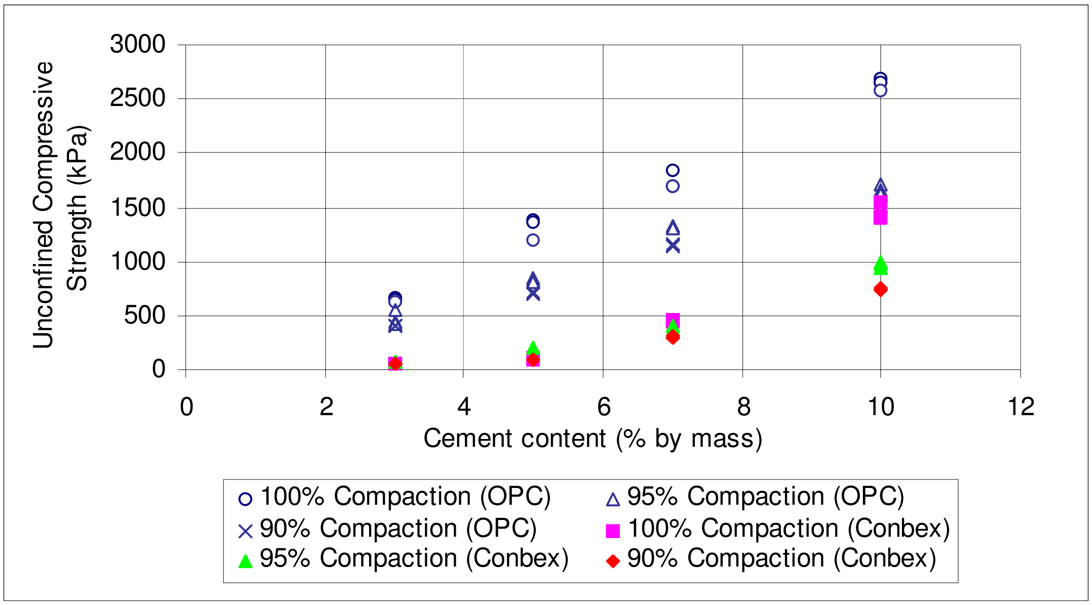



Figure 6.6 UCS for 7-days cured kimberlite (C1) tailings

Figure 6.6 shows the Unconfined Compressive Strengths for cement-stabilized (7-days cured) kimberlite (C1) tailings. Specimens of platinum tailings show great differences in their strengths properties. There is a noticeable strength enhancement corresponding to the cement content increase. 3% OPC produced strengths values that are slightly greater than 500 kPa, whereas the 10% of the same cement resulted in the strength of more than 2500 kPa. The strengths obtained from the 10% cement-stabilized kimberlite (C1) show that 10% cement is sufficient for tailings stabilization because a strength value of 2500 kPa is sufficient to be used for building houses. Heavy traffic is not expected on tailings dams. Judging by the strengths values obtained one can safely say: 10% cement-stabilized platinum tailings would be adequately erosion resistant.

Once more, compaction density seems to be having a greater influence on the strengths properties of the platinum tailings. A compaction density of 100% produced higher strength than densities of 95 and 90%, which produced moderate and less strengths respectively. Platinum (C1) tailings that were compacted at density of 100% produced more than 2500 kPa while the same cement (OPC) and tailings compacted at a density of 95 and 90% produced only about 1500 kPa as shown in Figure 6.6.

Figure 6.6 plainly illustrates that Conbex cement is less effective than OPC. The maximum strengths obtained for Conbex-stabilized kimberlite (C1) tailings is 1500 kPa compared to 2500 kPa for OPC-stabilized kimberlite (C1) tailings. Conbex-stabilized kimberlite (C1) tailings also produced the least strength values fortifying that Conbex is less effective.

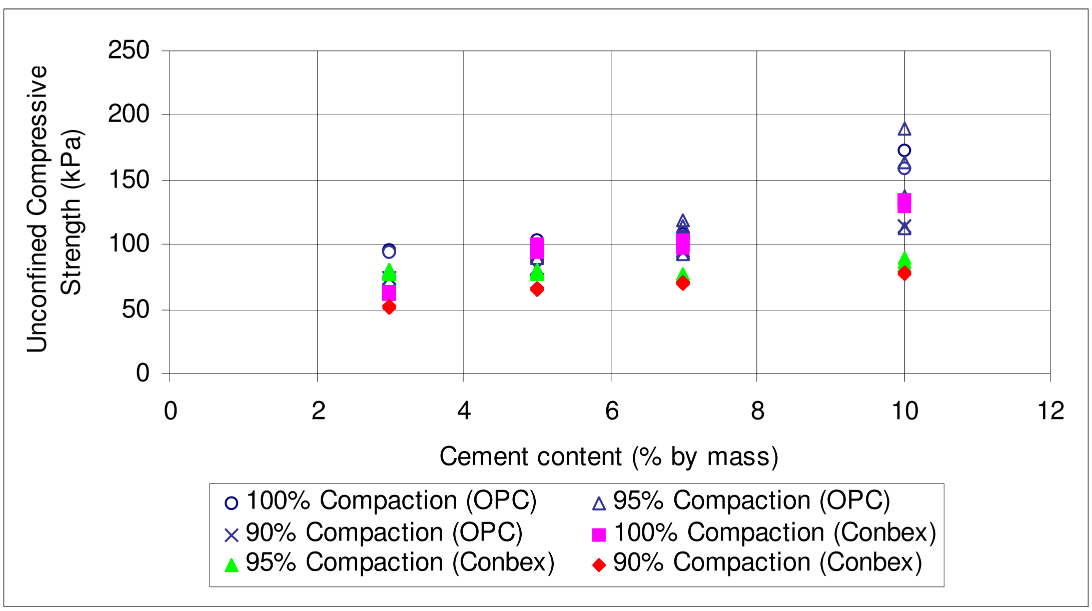



Figure 6.7 UCS for non-cured kimberlite (C1) tailings

Figure 6.7 shows the Unconfined Compressive strength for non-cured cement stabilized kimberlite (C1) tailings. Strengths characteristics of the non-cured cement-stabilized kimberlite (C1) tailings do not show significant contrast especially with low cement (i.e. 3 and 5% by mass cement). Generally, cement content of 3 and 5 % produced strengths within 100 and 50 kPa irrespective of the type of cement or compaction density; although specimens compacted at density of 100% are slightly about 100 kPa. Moulding bricks could be difficult for kimberlite (C1) tailings with cement contents of 3 and 5% by mass, unless these bricks remains in one place until after 7-days curing.

Strength of the cement-stabilized non-cured kimberlite (C1) tailings is generally low; and the maximum strength is less than 200 kPa. This stresses the significance of a sufficient curing period for the secondary reactions to take place. It is also evident from figure 6.7 that addition of cement did not make any serous impact on strengths characteristics, although minor strengths gain can be appreciated due to addition of cement as a result of density increase. The low strengths values of the cement-stabilized non-cured kimberlite tailings give good reason for the collapse and clogging of the pinhole noted during earlier (see section 5.3.4).

6.3.4 Unconfined Compressive Strength for kimberlite (C2) tailings

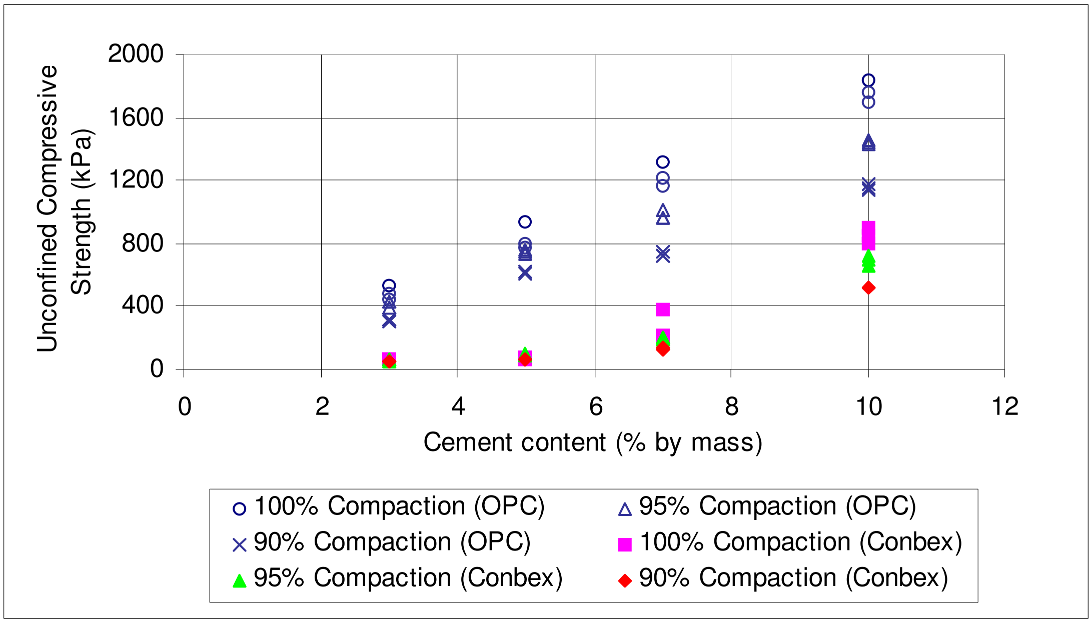



Figure 6.8 UCS for 7-days cured kimberlite (C2) tailings

Figure 6.8 shows the Unconfined Compressive Strengths for cement-stabilized (7-days cured) kimberlite (C2) tailings. The Conbex-stabilized (C2) tailings (7-days cured) produced very low strengths values. The minimum values are less than 200 kPa and the maximum values are slightly greater than 800 kPa. The correlation between the pinhole tests and the strengths characteristics of the kimberlite (C2) tailings agrees, because it was noted earlier that Conbex-stabilized specimens of the kimberlite (C2) tailings clogged, except those compacted at a density of 100% (with 10% cement).

The strengths of the Conbex-stabilized kimberlite tailings for specimens compacted at a density of 90 and 95% is low (i.e. less than 400 kPa). The strength of less 400 kPa was sufficient to reduce erosion of kimberlite (C2) tailings. At a point just above 400 kPa erosion was significantly reduced, because there was no erosion at this cement content during the pinhole test (see 5.3.4).

OPC-stabilized tailings are technically superior compared to Conbex. The minimum strength for the cement-stabilized kimberlite (C2) tailings was about 400 kPa and maximum was greater than 1600 kPa. This justifies why there was no erosion on OPC-stabilized kimberlite (C2) tailings, because all the OPC-stabilized tailings had strengths values close or above 400 kPa as shown in Figure 6.8.

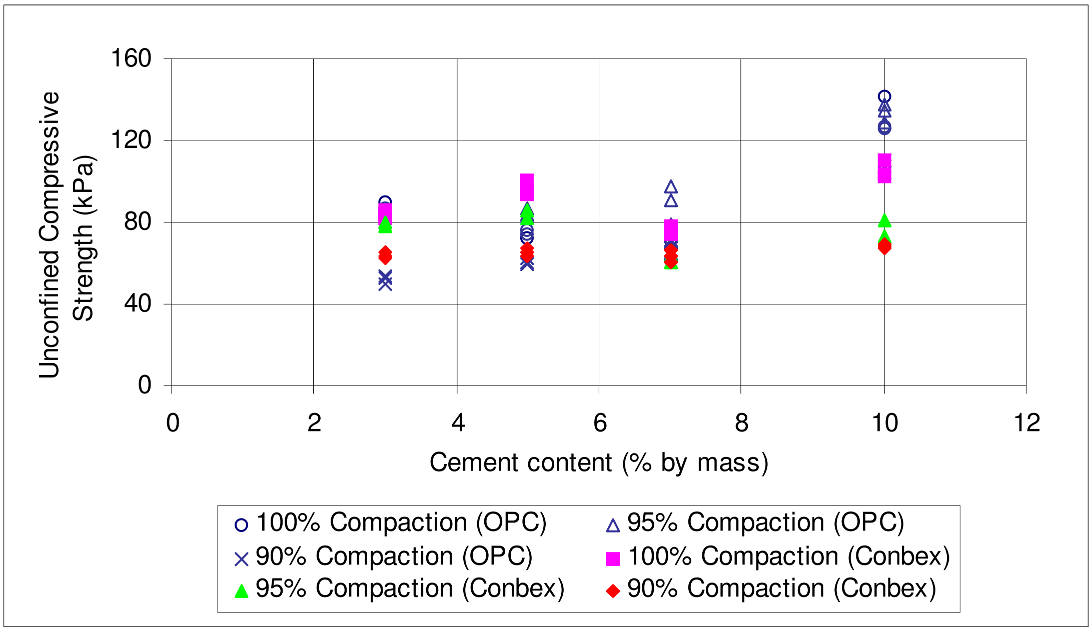



Figure 6.9 UCS for non-cured cured kimberlite (C2) tailings

Figure 6.9 shows the Unconfined Compressive strength for non-cured cement stabilized kimberlite (C2) tailings. The non-cured cement stabilized kimberlite tailings has very low strengths values, this is probably one of the smallest value encountered. The maximum strength was less than 160 kPa and the minimum is just above 50 kPa. In this case even the increasing density as a result of high cement and compaction density was not satisfactory to develop any meaningful strength. The effects of the type of stabilizers and cement contents is insignificant for non-cured cement stabilized tailings. Once more there is a great emphasis of the curing period to be ample, because the strength produced after 7-curing is far-off better than non-cured tailings, especially for OPC-stabilized tailings (see Figure 6.8). Bricks should be moulded even though the non-cured kimberlite C2 tailings have low strength because it is known that the strengths after 7-days will be far much higher. However care must be exercised because these material have a tendency to crumble upon the removal of the mould.

# CHAPTER 7: SUMMARY AND CONCLUSIONS

## 7.1 Summary

Use of cement to reduce erosion of the slopes of mine tailings dams has been investigated. The effect of curing and hardening tailings with cement has also been investigated. The study further investigated the amount of cement that is required for stabilization of mine tailings to reduce water erosion, as well as the effect of the physical and chemical properties of tailings on cement stabilization of tailings. The pinhole test was used to investigate erodibility of the kimberlite, gold, platinum tailings. The specimens were compacted at a density of 100, 95 and 90%. The cement contents were ranged from 3, 5, 7 and 10% by mass during stabilization, with moisture content at optimum. The strengths properties of the cement-stabilized tailings were also investigated to assess the potential use of brick or rubble made of cement-stabilized tailings for reducing erosion.

The results indicate that cement can be effectively used for stabilization of the slopes of mine tailings dams to reduce erosion. Physical properties of tailings has a strong influence on the effective use of cement for stabilization of tailings to reduce erosion. There is a strong positive relationship between cement content, compaction density, compressive strengths and erosion loss. High cement content, compaction density, compressive strengths coincide with the low erosion loss. 3% by mass of ordinary Portland cement produced no erosion for gold, platinum and kimberlite (C1), although this have been observed for specimens that were tested after 7-days curing. Ordinary Portland cement has a more positive consequence on tailings resistance to water erosion than Conbex, although the effect of Conbex is also considerable. 3% by mass of Conbex produced zero-erosion for platinum and kimberlite (C1) tailings, and only minor erosion losses have been observed for gold tailings. Erosion loss for Conbex-stabilized coarse kimberlite (C2) tailings was very high, and the pinhole tests collapsed (even after 7-days curing). It is believed that Conbex can be superior if used for stabilisation of finer tailings such as gold tailings.

The study has successfully established that Conbex and ordinary Portland cement can be used for stabilization of gold, kimberlite and platinum tailings to reduce erosion, although a period of curing is a requisite. The study also established that 7-days curing is sufficient for proper hydration to take place, because erosion was greatly reduced for gold, platinum and kimberlite (C1) tailings irrespective of the cement that was used after 7-days curing. There is a notable increase on the erosion resistance of kimberlite and platinum tailings after 7-days curing, even though both of them behaved in the same way exclusive of curing (i.e. collapsed and clogged). In this respect ordinary Portland cement produced more stable tailings than Conbex. It is also noted that cement-stabilized (non-cured) platinum and kimberlite tailings are more susceptible to erosion than gold tailings. However, the platinum and kimberlite (C1) tailings appear more stable than gold tailings after 7-days curing. The effect of Conbex and ordinary Portland cement is closely related for non-cured cement-stabilized and 7-days cured cement-stabilized gold tailings. It can be concluded that effect of curing gold tailings is more significant for low compactions densities (e.g. 95 and 90% compaction) than for higher compaction density.

The use of bricks and rubble made of cement-stabilized tailings for reducing erosion was also investigated. It was established that the strength characteristics of the cement-stabilized tailings is sufficient to provide adequate stability against erosion. In some cases the strengths values were higher such that material could be used for building low price houses (i.e. strengths of 1600-2600 kPa). As discussed earlier, the non-cured strengths determines whether the mould can be removed immediately without the brick crumbling. In this respect, gold, platinum, and kimberlite tailings have sufficient strengths to allow the mould to be removed immediately after moulding without having to wait for the secondary minerals to form. These means that one mould can be used immediately after moulding, which makes the whole operation faster and more efficient.

The strengths properties of the cement-stabilized tailings were higher than expected, although this may not necessarily be the case for any gold, platinum and kimberlite tailings. Use of cement-stabilized brick and /or rubble appears more feasible for field application, because material with high durability can be established at a minimum cost. Blight and Amponsah-Dacosta (1999) showed that slopes surface probably does not have to be completely covered with gravel, and this will reduce the cost with little of no loss in effectiveness. The strength tests also shows that it can be possible to mould as many bricks with one mould without crumbling.

### 7.2 Conclusions

It should be noted that the results obtained in this study will not be necessarily be the same for any tailings unless they have the same properties. Based on the observations and analyses from the laboratory tests the following conclusions can be drawn from the study:

- Conbex and ordinary Portland cement can be used to reduce erosion of the slopes of tailings dams.
- At least 3% by mass cement is required to produce zero erosion loss.
- The stability of tailings to erosion can be enhanced by increasing compaction density, curing period and cement content.
- Ordinary Portland Cement is technically superior compared with Conbex, although Conbex may be considerable for fine tailings.
- Cement-stabilized tailings can be used to make bricks and rubble to be used for reducing erosion of the slopes of mine tailings dams, and as little as 10% by mass of cement and 7-days curing is required to produce unconfined compressive strength of 1600-2600 kPa.

### 7.3 Recommendations

Blight and Caldwell (1984) have conducted some field tests to investigate the long-term (up to 2 years) stability of surfaces of tailings stabilized with ordinary Portland cement. The writer recommends further expansion of the study so that enough information can be available to provide a sound framework for the development of this strategy for reducing tailings erosion. The most imperative aspects that call for more investigation are:

- Evaluation of the long-term stability of cemented tailings (at least 5 years)
- Financial feasibility of this stabilization measure
- Feasibility of using other cheaper stabilizers
- Use of cement stabilized tailings to produce brick and rubble for reducing tailings erosion.

**APPENDIX**

Appendix A. Sieve analysis

Sieve analyses computations:

mass of sample before washing = A (522.3)

mass of sample after washing = B (187.6)

% retained = $\frac{mass\ retained}{A\ x\,100}$

%Passing = $\frac{A - sum\ of\ mass\ retained}{A}\ x\,100$

A1 Sieve analysis for gold tailings

| Sieve no | Sieve size, mm | Mass retained g | %Retained | %Passing |
|---|---|---|---|---|
| 4 | 4.750 | 0.0 | 0.0 | 100.0 |
| 8 | 2.360 | 0.0 | 0.0 | 100.0 |
| 16 | 1.180 | 0.0 | 0.0 | 100.0 |
| 28 | 0.600 | 0.0 | 0.0 | 100.0 |
| 40 | 0.425 | 0.0 | 0.0 | 100.0 |
| 50 | 0.300 | 4.0 | 0.8 | 99.2 |
| 100 | 0.150 | 22.9 | 4.4 | 94.9 |
| 200 | 0.075 | 152.4 | 29.2 | 65.7 |
| | Pan | 8.5 | | |
| | Total mass | 187.8 | | |

A 2 Sieve analysis for platinum tailings

| Sieve no | Sieve size, mm | Mass retained g | %Retained | %Passing |
|---|---|---|---|---|
| 4 | 4.750 | 0.0 | 0.0 | 100.0 |
| 8 | 2.360 | 0.3 | 0.1 | 99.9 |
| 16 | 1.180 | 1.1 | 0.2 | 99.7 |
| 28 | 0.600 | 1.5 | 0.3 | 99.4 |
| 40 | 0.425 | 2.4 | 0.5 | 98.9 |
| 50 | 0.300 | 4.4 | 0.9 | 98.0 |
| 100 | 0.150 | 36.7 | 7.8 | 90.2 |
| 200 | 0.075 | 80.9 | 17.2 | 73.0 |
| | Pan | 8.4 | | |
| | Total mass | 134.7 | | |

A=470.7
B=136.5

A3 Sieve analysis for kimberlite (C1) tailings

| Sieve no | Sieve size, mm | Mass retained g | %Retained | %Passing |
|---|---|---|---|---|
| 4 | 4.750 | 0.0 | 0.0 | 100.0 |
| 8 | 2.360 | 0.0 | 0.0 | 100 |
| 16 | 1.180 | 8.0 | 1.3 | 98.7 |
| 28 | 0.600 | 36.2 | 5.7 | 93 |
| 40 | 0.425 | 54.2 | 8.5 | 84.5 |
| 50 | 0.300 | 91.4 | 14.4 | 70.1 |
| 100 | 0.150 | 220.7 | 34.8 | 35.3 |
| 200 | 0.075 | 108.8 | 17.1 | 18.2 |
| | Pan | 2.0 | | |
| | Total mass | 521.3 | | |

A=634.6
B=521.9

A4 Sieve analysis for kimberlite (C2) tailings

| Sieve no | Sieve size, mm | Mass retained g | %Retained | %Passing |
|---|---|---|---|---|
| 4 | 4.750 | 0.0 | 0.0 | 100.0 |
| 8 | 2.360 | 7.9 | 1.7 | 98.3 |
| 16 | 1.180 | 11.8 | 2.5 | 95.8 |
| 28 | 0.600 | 58.0 | 12.2 | 83.6 |
| 40 | 0.425 | 70.0 | 14.7 | 68.9 |
| 50 | 0.300 | 74.0 | 15.6 | 53.3 |
| 100 | 0.150 | 123.4 | 25.9 | 27.4 |
| 200 | 0.075 | 68.2 | 14.4 | 13.0 |
| | Pan | 2.8 | | |
| | Total mass | 416.1 | | |

A=474.7
B=416.4

Appendix B. Hydrometer analysis

Hydrometer analysis computations:

Dispersing agent is Galgon

$R_a$ = Actual reading
$R_c$ = Corrected Reading
$C_T$ = Temperature correction factors $C_T$
$W_s$ = Weight of sample = 50g
R = Ra corrected for meniscus

$G_s$ = 2.70
Meniscus correction = 1 unit
Zero correction = + 6 units
a = 0.99

i.e. Rc = $R_{actual}$-zero correction + $C_T$

% finer = $\frac{Rc(a)}{Ws}$

Diameter = K $\sqrt{L/t}$

% passing = $\frac{corrected\ hydrometer\ reading\ x\ 2\ x\ \%\ pas\sin g\ 0.425\ mm\ sieve}{100}$

B 1 Hydrometer analysis for gold tailings

| Time (t) | $R_a$ | Temp $^0C$ | R | Rc | % finer | Approx Particle, mm | Actual Particle, mm |
|---|---|---|---|---|---|---|---|
| 18 sec | 38 | 24 | 39 | 33 | 65.7 | 0.075 | 0.087 |
| 40 sec | 37 | 24 | 38 | 32 | 63.4 | 0.050 | 0.061 |
| 2 min | 30 | 24 | 31 | 25 | 49.5 | 0.040 | 0.034 |
| 5 min | 24 | 24 | 25 | 19 | 37.6 | 0.026 | 0.022 |
| 15 min | 18 | 24 | 19 | 13 | 25.7 | 0.015 | 0.013 |
| 30 min | 16 | 24 | 17 | 11 | 21.8 | 0.010 | 0.009 |
| 60 min | 14 | 24 | 15 | 9 | 17.8 | 0.0074 | 0.006 |
| 250 min | 11 | 24 | 12 | 6 | 11.9 | 0.0034 | 0.003 |
| 1440 min | 9 | 22 | 10 | 4 | 7.9 | 0.0015 | 0.001 |

B 2 Hydrometer analysis for platinum tailings

| Time (t) | $R_a$ | Temp $^0C$ | R | $R_c$ | % Finer | Approximate Particle | Actual Particle mm |
|---|---|---|---|---|---|---|---|
| 18 sec | 44 | 19 | 45 | 39 | 72.5 | 0.075 | 0.087 |
| 40 sec | 25 | 19 | 26 | 18.7 | 34.8 | 0.050 | 0.061 |
| 2 min | 21 | 19 | 22 | 14.7 | 27.3 | 0.040 | 0.034 |
| 5 min | 18 | 19 | 19 | 11.7 | 21.8 | 0.026 | 0.022 |
| 15 min | 14 | 19 | 15 | 7.7 | 14.3 | 0.015 | 0.013 |
| 30 min | 10 | 19 | 11 | 3.7 | 6.9 | 0.010 | 0.009 |
| 60 min | 9 | 19 | 10 | 2.7 | 5.0 | 0.0074 | 0.006 |
| 250 min | 8 | 20 | 9 | 2.0 | 3.7 | 0.0034 | 0.003 |
| 1440 | 7 | 19 | 8 | 0.7 | 1.3 | 0.0015 | 0.001 |

B 3 Hydrometer analysis for kimberlite (C1) tailings

| Time (t) | $R_a$ | Temp $^0$C | R | $R_c$ | % finer | Approximate Particle | Actual Particle mm |
|---|---|---|---|---|---|---|---|
| 18 sec | 16 | 19 | 17 | 9.7 | 18.2 | 0.075 | 0.087 |
| 40 sec | 15 | 19 | 16 | 8.7 | 16.4 | 0.050 | 0.061 |
| 2 min | 12 | 19 | 13 | 5.7 | 10.7 | 0.040 | 0.034 |
| 5 min | 11 | 19 | 12 | 4.7 | 8.8 | 0.026 | 0.022 |
| 15 min | 10 | 19 | 11 | 3.7 | 6.9 | 0.015 | 0.013 |
| 30 min | 9 | 19 | 10 | 2.7 | 5.1 | 0.010 | 0.009 |
| 60 min | 8 | 21 | 9 | 2.2 | 4.1 | 0.0074 | 0.006 |
| 250 min | 7 | 21 | 8 | 1.2 | 2.3 | 0.0034 | 0.003 |
| 1440 min | 7 | 19 | 8 | 0.7 | 1.3 | 0.0015 | 0.001 |

B 4 Hydrometer analysis for kimberlite (C2) tailings

| Time (t) | Ra | Temp $^0$C | R | $R_c$ | % Finer | Approximate Particle | Actual Particle mm |
|---|---|---|---|---|---|---|---|
| 18 sec | 14 | 19 | 15 | 7.7 | 14.5 | 0.075 | 0.086 |
| 40 sec | 13 | 19 | 14 | 6.7 | 12.6 | 0.050 | 0.061 |
| 2 min | 11 | 19 | 12 | 4.7 | 8.8 | 0.040 | 0.034 |
| 5 min | 10 | 19 | 11 | 3.7 | 6.9 | 0.026 | 0.022 |
| 15 min | 9 | 19 | 10 | 2.7 | 5.1 | 0.015 | 0.013 |
| 30 min | 8 | 19 | 9 | 1.7 | 3.2 | 0.010 | 0.009 |
| 60 min | 7 | 21 | 8 | 1.2 | 2.3 | 0.0074 | 0.006 |
| 250 min | 6 | 21 | 7 | 0.2 | 0.4 | 0.0034 | 0.003 |
| 1440 min | 6 | 21 | 7 | 0.2 | 0.4 | 0.0015 | 0.001 |

Appendix C. Specific gravity

C 1 Specific gravity for gold tailings

| Bottle number | 1 | 5 |
|---|---|---|
| Mass of bottle W1 | 28.682 | 28.569 |
| Mass of Bottle & dry soil W2 | 38.389 | 39.590 |
| Mass of bottle, soil & water W3 | 84.899 | 85.982 |
| Mass of bottle & water W4 | 78.803 | 79.027 |
| Specific gravity Gs | 2.688 | 2.710 |
| Average Gs | 2.70 | |

C 2 Specific gravity for platinum tailings

| Bottle number | 1 | 5 |
|---|---|---|
| Mass of bottle W1 | 28.678 | 28.565 |
| Mass of Bottle & dry soil W2 | 38.440 | 39.353 |
| Mass of bottle, soil & water W3 | 85.537 | 86.471 |
| Mass of bottle & water W4 | 78.816 | 79.031 |
| Specific gravity Gs | 3.21 | 3.22 |
| Average Gs | 3.22 | |

C 3 Specific gravity for kimberlite 1 tailings

| Bottle number | 1 | 5 |
|---|---|---|
| Mass of bottle W1 | 28.689 | 28.562 |
| Mass of Bottle & dry soil W2 | 38.790 | 39.667 |
| Mass of bottle, soil & water W3 | 85.446 | 86.329 |
| Mass of bottle & water W4 | 78.854 | 79.036 |
| Specific gravity Gs | 2.879 | 2.913 |
| Average Gs | 2.89 | |

C 4 Specific gravity for kimberlite 2 tailings

| Bottle number | 4 | 6 |
|---|---|---|
| Mass of bottle W1 | 29.700 | 28.599 |
| Mass of Bottle & dry soil W2 | 38.886 | 39.807 |
| Mass of bottle, soil & water W3 | 85.752 | 83.461 |
| Mass of bottle & water W4 | 79.658 | 76.052 |
| Specific gravity Gs | 2.970 | 2.950 |
| Average Gs | 2.96 | |

Appendix D. Proctor compaction test

Proctor compaction test computation:

Water content determination

$$W = \frac{Ww}{Ws} x\,100$$

Where:

W = Water content (%)
Ww = Weight of water present in the soil
Ws = weight of soil solids

Dry density determination

Wet mass of soil = (wet mass of soil + mass of mould) – mass of mould

$$\text{Bulk density (kg/m}^3\text{)} = \frac{wet\ mass\ of\ soil}{volume\ of\ mould}$$

$$\text{Dry mass of soil} = \frac{wet\ mass\ of\ soil}{1 + moisture\ content\ as\ a\ ratio}$$

$$\text{Dry density (Kg/m}^3\text{)} = \frac{dry\ mass\ of\ soil}{volume\ of\ mould}$$

D 1 Proctor compaction test for gold tailings

| | | |
|---|---|---|
| Compaction effort: Proctor | Number of blows: 25 | Number of layers: 3 |
| Mass of hammer: | Drop of hammer: | Specific gravity: 2.70 |
| Mass of mould: 3965.89 g | Volume of mould: 933.86 cm | Hygroscopic moisture content: |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Mass of mould+ wet material (g) | 5514 | 5565 | 5590 | 5700 | 5766 | 5778 | 5758 |
| Mass of wet material (g) | 1548 | 1600 | 1624 | 1735 | 1800 | 1812 | 1792 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Container number | 28 | 4 | 3-1 | P3 | 15 | W1 | 20 |
| Mass of container + wet mass (g) | 514.7 | 539.5 | 655.5 | 781.1 | 658.3 | 911 | 663.2 |
| Mass of container + dry material (g) | 502.0 | 519.3 | 618.0 | 717.5 | 597.4 | 826.5 | 584.8 |
| Mass of container (g) | 176.5 | 173.7 | 176.9 | 176.4 | 176 | 285.4 | 189.8 |
| Moisture content (%) | 3.90 | 5.84 | 8.50 | 11.75 | 14.45 | 15.6 | 19.85 |
| Dry density ($kg/m^3$) | 1595 | 1618 | 1649 | 1662 | 1684 | 1679 | 1601 |

D 2 Proctor compaction test for platinum tailings

| | | |
|---|---|---|
| Compaction effort: Proctor | Number of blows: 25 | Number of layers: 3 |
| Mass of hammer: | Drop of hammer: | Specific gravity: 3.22 |
| Mass of mould: 3868 g | Volume of mould: 933.86cm | Hygroscopic moisture content: |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Mass of mould + wet material (g) | Mass of wet material (g) | 5670 | 5676 | 5775 | 5876 | 5929 | 5980 | 5962 |
| Mass of wet material (g) | Mass of wet material (g) | 1802 | 1808 | 1907 | 2008 | 2061 | 2112 | 2094 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Container number | 20 | 20 | P3 | 26 | 4 | 3E | 1 | 53 |
| Mass of container + wet mass (g) | 790 | 795 | 756 | 796 | 824 | 995 | 1072 | 1089 |
| Mass of container + dry material (g) | 769 | 762 | 710 | 732 | 743 | 878 | 926 | 925.0 |
| Mass of container (g) | 190 | 190 | 176 | 173 | 174 | 183 | 173 | 177 |
| Moisture content (%) | 3.63 | 5.77 | 8.69 | 11.45 | 14.24 | 16.83 | 19.4 | 22.0 |
| Dry density ($kg/m^3$) | 1794 | 1824 | 1781 | 1832 | 1882 | 1889 | 1894 | 1837 |

D 3 Proctor compaction test for kimberlite (C1) tailings

| | | |
|---|---|---|
| Compaction effort: Proctor | Number of blows: 25 | Number of layers: 3 |
| Mass of hammer: | Drop of hammer: | Specific gravity: 2.89 |
| Mass of mould: 3868.0 | Volume of mould: 933.86cm | Hygroscopic moisture content: |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mass of mould + wet material (g) | 5423.0 | 5537.0 | 5610.0 | 5676 | 5685.0 | 5750.0 |
| Mass of wet material (g) | 1555.0 | 1669.0 | 1742.0 | 1808.0 | 1817.0 | 1882.0 |

| Container number | 1 | 11R | P3 | 3-1 | 13A | 53 |
|---|---|---|---|---|---|---|
| Mass of container + wet mass (g) | 548.0 | 673.0 | 634.0 | 689.0 | 630.0 | 660.0 |
| Mass of container + dry material (g) | 524.0 | 633.0 | 586.0 | 632.0 | 569.0 | 575.0 |
| Mass of container (g) | 174.0 | 179.0 | 176.0 | 177.0 | 190.0 | 176.0 |
| Moisture content (%) | 6.86 | 8.81 | 11.71 | 14.51 | 16.09 | 21.30 |
| Dry density (kg/m$^3$) | 1558.24 | 1642.50 | 1669.84 | 1690.73 | 1676.02 | 1661.41 |

D 4 Proctor compaction test for Kimberlite (C2) tailings

| | | |
|---|---|---|
| Compaction effort: Proctor | Number of blows: 25 | Number of layers: 3 |
| Mass of hammer: | Drop of hammer: | Specific gravity: 2.96 |
| Mass of mould: 3868.0 | Volume of mould: 933.86cm | Hygroscopic moisture content: |

| | | | | | | |
|---|---|---|---|---|---|---|
| Mass of mould + wet material (g) | 5494.0 | 5571.0 | 5621.0 | 5708.0 | 5737.0 | 5726 |
| Mass of wet material (g) | 1626.0 | 1703.0 | 1753.0 | 1840.0 | 1869.0 | 1858 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Container number | 15 | 11R | 1 | 13A | 3-1 | 3-1 |
| Mass of container + wet mass (g) | 553.0 | 678.0 | 658.0 | 784.0 | 860.0 | 776.2 |
| Mass of container + dry material (g) | 522.0 | 624.0 | 595.0 | 694.0 | 745.0 | 670.2 |
| Mass of container (g) | 176.0 | 179.0 | 174.0 | 190.0 | 177.0 | 190.0 |
| Moisture content (%) | 8.96 | 12.13 | 14.96 | 17.86 | 20.25 | 22.0 |
| Dry density ($kg/m^3$) | 1597 | 1626 | 1632 | 1671 | 1664 | |

Appendix E. Chemical analysis of the tailings

Computations for Total Dissolved Salts

Mass of beaker = W1
Mass of beaker after evaporating the sample = W2
Total dissolved salts =TDS

TDS = W2-W1

E 1 Total dissolved salts for gold, platinum, and kimberlite tailings

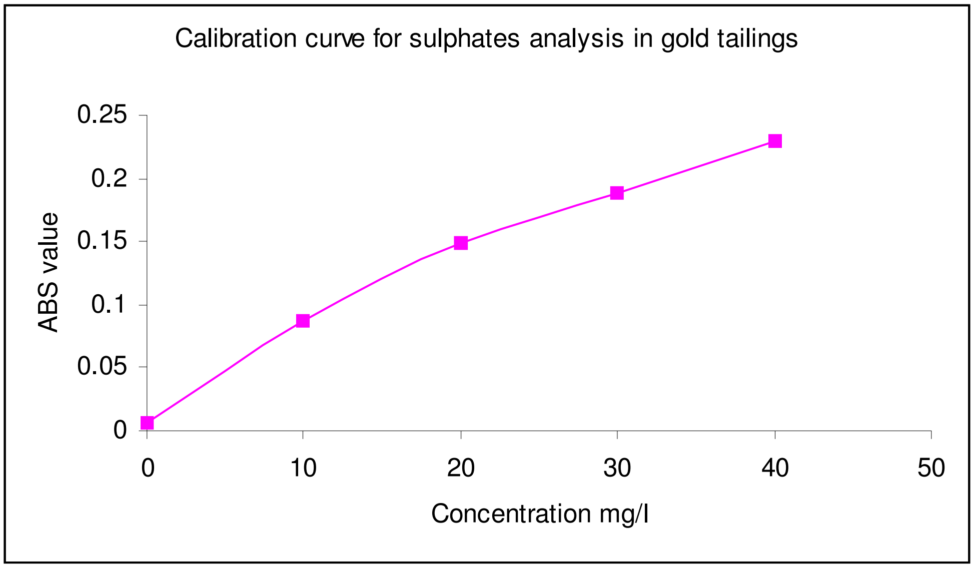
| | Gold tailings | Platinum tailings | Kimberlite (C1) tailings | Kimberlite (C2) tailings |
|---|---|---|---|---|
| W1 | 83.2701 | 82.3284 | 83.3288 | 82.2585 |
| W2 | 83.3899 | 82.3521 | 83.3487 | 82.2879 |
| TDS | 23.96 | 4.74 | 3.98 | 5.88 |

Analysis of Sulphates ($SO_4$)

Equipment for Analysis: UV-Visible Spectrophotometer
Model: UV-1601 (Shimadzu)
Laboratory: Water Lab (Civil) University of Witwatersrand

E 2 Analysis of sulphates for gold tailings

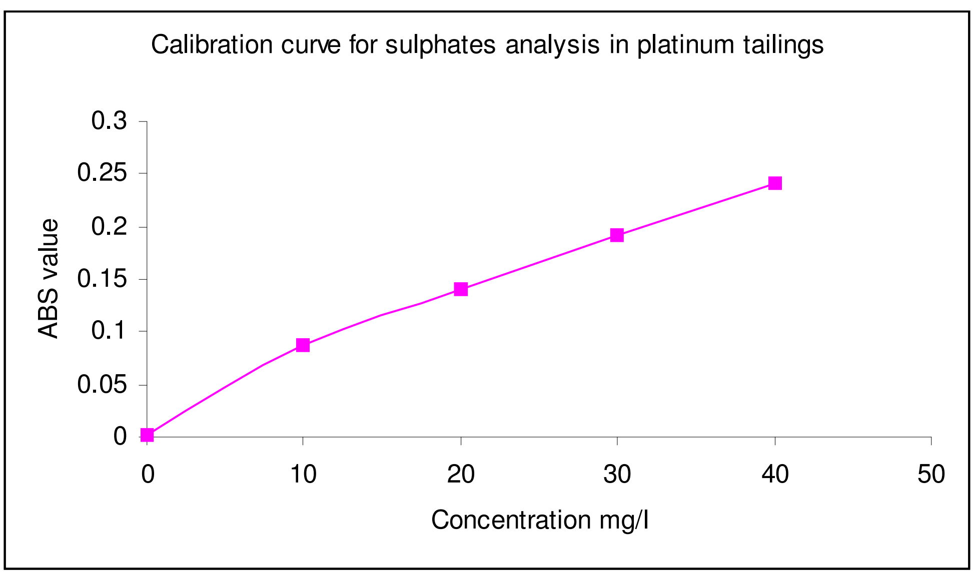
| Sample | Concentration (mg/l) | ABS value |
|---|---|---|
| Blank | 0.0 | 0.006 |
| Standard 1 | 10 | 0.087 |
| Standard 2 | 20 | 0.148 |
| Standard 3 | 30 | 0.188 |
| Standard 4 | 40 | 0.230 |
| Sample Au | 217.15 | 0.155 |




Calibration curve for sulphates analysis in gold tailings

E 3 Analysis of sulphates for platinum tailings

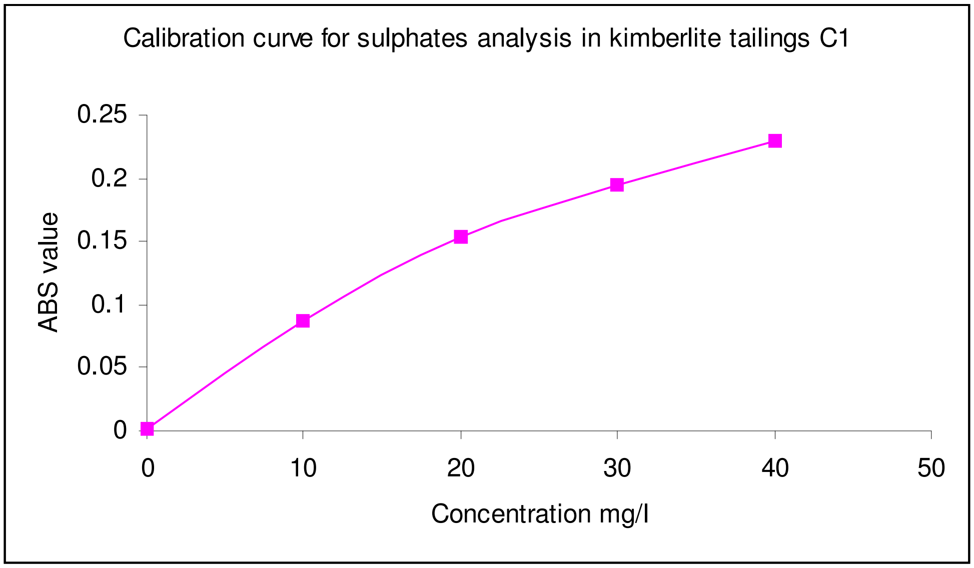
| Sample | Concentration (mg/l) | ABS value |
|---|---|---|
| Blank | 0.0 | 0.001 |
| Standard 1 | 10 | 0.087 |
| Standard 2 | 20 | 0.141 |
| Standard 3 | 30 | 0.192 |
| Standard 4 | 40 | 0.242 |
| Sample Pt | 90.32 | 0.073 |




Calibration curve for sulphates analysis in gold tailings

E 4 Analysis of sulphates for C1 tailings

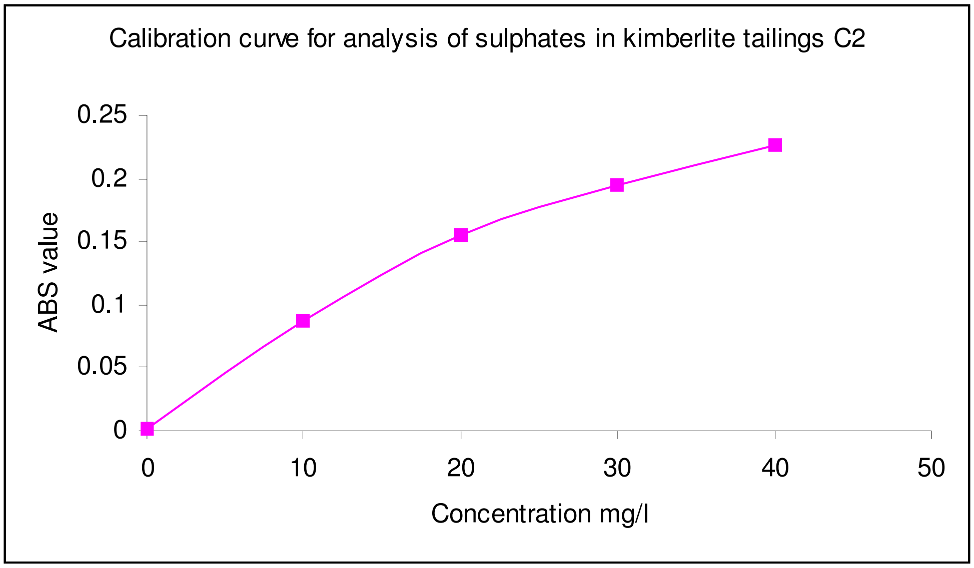
| Sample | Concentration (mg/l) | ABS value |
|---|---|---|
| Blank | 0.0 | 0.002 |
| Standard 1 | 10 | 0.087 |
| Standard 2 | 20 | 0.190 |
| Standard 3 | 30 | 0.194 |
| Standard 4 | 40 | 0.236 |
| Sample C1 | 27.15 | 0.185 |




Calibration curve for sulphates analysis in gold tailings

E 5 Analysis of sulphates for C2 tailings

| Sample | Concentration (mg/l) | ABS value |
|---|---|---|
| Blank | 0.0 | 0.002 |
| Standard 1 | 10 | 0.087 |
| Standard 2 | 20 | 0.190 |
| Standard 3 | 30 | 0.194 |
| Standard 4 | 40 | 0.236 |
| Sample C2 | 10.75 | 0.088 |



Calibration curve for sulphates analysis in gold tailings

Analyses of iron (Fe), calcium (Ca) and magnesium (Mg)

Equipment for analysis: Flame emission spectrophotometer
Model: AA-6601 (Shimadzu)
Laboratory: Water Lab (Civil) University of Witwatersrand

E 6 Analysis of Calcium for C1 and C2 tailings

| STANDARD | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0096 | 0 | 0 |
| STD | Standard1 | -0.01 | 0 | 0 |
| STD-REP | std1 | -0.0086 | 0 | 0 |
| STD-REP | std1 | -0.0073 | 0 | 0 |
| STD-REP | std1 | -0.0096 | 0 | 0 |
| STD-REP | Std1 | -0.0079 | 0 | 0 |
| STD-AVG | std1 | -0.0094 | 0 | 0 |
| STD | Standard2 | 0.1354 | 5 | 5 |
| STD-REP | std2 | 0.1384 | 5 | 5 |
| STD-REP | std2 | 0.1366 | 5 | 5 |
| STD-REP | std2 | 0.1349 | 5 | 5 |
| STD-AVG | std2 | 0.1356 | 5 | 5 |
| STD | Standard3 | 0.2415 | 10 | 10 |
| STD-REP | std3 | 0.2397 | 10 | 10 |
| STD-REP | std3 | 0.2387 | 10 | 10 |
| STD-AVG | std3 | 0.24 | 10 | 10 |
| STD | Standard4 | 0.4492 | 20 | 20 |
| STD-REP | std4 | 0.4469 | 20 | 20 |
| STD-REP | std4 | 0.4453 | 20 | 20 |
| STD-AVG | std4 | 0.4472 | 20 | 20 |
| COR | std3 | 0.2355 | 10 | 10 |
| COR-REP | std3 | 0.2346 | 10 | 10 |
| COR-REP | std3 | 0.2355 | 10 | 10 |
| COR-AVG | std3 | 0.2352 | 10 | 10 |
| Sample | C1 | -0.0018 | -0.5218 | -0.5324 |
| Sample -REP | C1 | -0.0012 | -0.5003 | -0.5104 |
| Sample -REP | C1 | -0.0035 | -0.5918 | -0.6038 |
| Sample -REP | C1 | -0.0029 | -0.5685 | -0.58 |
| Sample -REP | C1 | -0.0024 | -0.5482 | -0.5593 |
| Sample -AVG | C1 | -0.003 | -0.5696 | -0.581 |
| Sample | C2 | -0.0127 | -0.9605 | -0.9605 |
| Sample -REP | C2 | -0.0115 | -0.914 | -0.914 |

| | | | | |
|---|---|---|---|---|
| Sample -REP | C2 | -0.0121 | -0.9384 | -0.9384 |
| - Sample REP | C2 | -0.0123 | -0.9464 | -0.9464 |
| - Sample REP | C2 | -0.0132 | -0.9818 | -0.9818 |
| - Sample AVG | C2 | -0.0124 | -0.9484 | -0.9484 |

E 7 Analysis of Calcium for platinum tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | 0.0035 | 0 | 0 |
| STD | Standard1 | 0.0017 | 0 | 0 |
| STD-REP | std1 | 0.0014 | 0 | 0 |
| STD-REP | std1 | 0.0009 | 0 | 0 |
| STD-REP | std1 | 0.0034 | 0 | 0 |
| STD-REP | std1 | 0.0019 | 0 | 0 |
| STD-AVG | std1 | 0.0017 | 0 | 0 |
| STD | Standard | 0.2775 | 5 | 5 |
| STD-REP | std2 | 0.2773 | 5 | 5 |
| STD-REP | std2 | 0.2792 | 5 | 5 |
| STD-AVG | std2 | 0.278 | 5 | 5 |
| STD | Standard | 0.5597 | 10 | 10 |
| STD-REP | std3 | 0.5616 | 10 | 10 |
| STD-REP | std3 | 0.5625 | 10 | 10 |
| STD-AVG | std3 | 0.5612 | 10 | 10 |
| STD | Standard | 0.1025 | 20 | 20 |
| STD-REP | std4 | 1.0322 | 20 | 20 |
| STD-REP | std4 | 1.0341 | 20 | 20 |
| STD-AVG | std4 | 1.0305 | 20 | 20 |
| COR | Standard | 0.562 | 10 | 10 |
| COR-REP | std3 | 0.5639 | 10 | 10 |
| COR-REP | std3 | 0.5647 | 10 | 10 |
| COR-AVG | std3 | 0.5636 | 10 | 10 |
| Sample | Pt | 0.267 | 4.6498 | 4.6307 |
| Sample-REP | Pt | 0.269 | 4.6842 | 4.665 |
| Sample-REP | Pt | 0.2701 | 4.7044 | 4.6851 |
| Sample-REP | Pt | 0.2687 | 4.6795 | 4.6603 |

E 8 Analysis of Calcium for gold tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0124 | 0 | 0 |
| STD | Standard | -0.0021 | 0 | 0 |
| STD-REP | std1 | -0.003 | 0 | 0 |
| STD-REP | std1 | -0.0032 | 0 | 0 |
| STD-REP | std1 | -0.0044 | 0 | 0 |
| STD-REP | std1 | -0.0047 | 0 | 0 |
| STD-AVG | std1 | -0.0027 | 0 | 0 |
| STD | Standard | 0.321 | 5 | 5 |
| STD-REP | std2 | 0.3282 | 5 | 5 |
| STD-REP | std2 | 0.3284 | 5 | 5 |
| STD-REP | std2 | 0.3285 | 5 | 5 |
| STD-AVG | std2 | 0.3284 | 5 | 5 |
| STD | Standard | 0.6484 | 10 | 10 |
| STD-REP | std3 | 0.6473 | 10 | 10 |
| STD-REP | std3 | 0.6462 | 10 | 10 |
| STD-AVG | std3 | 0.6473 | 10 | 10 |
| STD | Standard | 1.1449 | 20 | 20 |
| STD-REP | std4 | 1.1517 | 20 | 20 |
| STD-REP | std4 | 1.146 | 20 | 20 |
| STD-AVG | std4 | 1.1475 | 20 | 20 |
| COR | Standard | 0.6465 | 10 | 10 |
| COR-REP | std3 | 0.6424 | 10 | 10 |
| COR-REP | std3 | 0.6426 | 10 | 10 |
| COR-AVG | std3 | 0.6438 | 10 | 10 |
| Sample | Au | 0.0087 | 0.0224 | 19.8764 |
| Sample-REP | Au | 0.0229 | 0.3973 | 39.7733 |
| Sample-REP | Au | 0.0211 | 0.3733 | 37.2642 |
| Sample-REP | Au | 0.0209 | 0.3688 | 36.9212 |
| Sample-REP | Au | 0.0199 | 0.3549 | 35.5278 |
| Sample-REP | Au | 0.0201 | 0.3571 | 35.7422 |
| Sample-AVG | Au | 0.0203 | 0.3603 | 36.0637 |

E 9 Analysis of Iron C1 and C2 tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | 0.001 | 0 | 0 |
| STD | Standard | 0.0018 | 0 | 0 |
| STD-REP | std1 | 0.0069 | 0 | 0 |
| STD-REP | std1 | 0.0018 | 0 | 0 |
| STD-REP | std1 | 0.002 | 0 | 0 |
| STD-REP | std1 | 0.002 | 0 | 0 |
| STD-AVG | std1 | 0.0019 | 0 | 0 |
| STD | Standard | 0.0359 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0354 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0357 | 0.5 | 0.5 |
| STD-AVG | std2 | 0.0357 | 0.5 | 0.5 |
| STD | Standard | 0.0759 | 1 | 1 |
| STD-REP | std3 | 0.0766 | 1 | 1 |
| STD-REP | std3 | 0.0773 | 1 | 1 |
| STD-AVG | std3 | 0.0766 | 1 | 1 |
| STD | Standard | 0.1384 | 2 | 2 |
| STD-REP | std4 | 0.1374 | 2 | 2 |
| STD-REP | std4 | 0.1385 | 2 | 2 |
| STD-AVG | std4 | 0.1381 | 2 | 2 |
| COR | Standard | 0.0795 | 1 | 1 |
| COR-REP | std3 | 0.0778 | 1 | 1 |
| COR-REP | std3 | 0.0769 | 1 | 1 |
| COR-REP | std3 | 0.0775 | 1 | 1 |
| COR-AVG | std3 | 0.0774 | 1 | 1 |
| Sample | C1 | 0.0719 | 0.9654 | 0.9466 |
| Sample-REP | C1 | 0.0724 | 0.9718 | 0.9529 |
| Sample-REP | C1 | 0.0705 | 0.9444 | 0.9261 |
| Sample-REP | C1 | 0.0705 | 0.9447 | 0.9263 |
| Sample-REP | C1 | 0.0705 | 0.3464 | 0.9267 |
| Sample-AVG | C1 | 0.0705 | 0.9447 | 0.9264 |
| Sample | C2 | 0.1606 | 2.3844 | 2.3158 |
| Sample-REP | C2 | 0.1599 | 2.3719 | 2.3036 |
| Sample-REP | C2 | 0.1573 | 2.3251 | 2.2581 |
| Sample-REP | C2 | 0.1611 | 2.3937 | 2.3248 |
| Sample-AVG | C2 | 0.1605 | 2.3833 | 2.3147 |

E 10 Analysis of Iron for platinum tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0143 | 0 | 0 |
| STD | Standard | -0.0035 | 0 | 0 |
| STD-REP | std1 | -0.0066 | 0 | 0 |
| STD-REP | std1 | -0.0058 | 0 | 0 |
| STD-REP | std1 | -0.0078 | 0 | 0 |
| STD-REP | std1 | -0.0063 | 0 | 0 |
| STD-AVG | std1 | -0.0062 | 0 | 0 |
| STD | Standard | 0.0164 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0153 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0135 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0162 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0169 | 0.5 | 0.5 |
| STD-AVG | std2 | 0.0165 | 0.5 | 0.5 |
| STD | Standard | 0.0296 | 1 | 1 |
| STD-REP | std3 | 0.0303 | 1 | 1 |
| STD-REP | std3 | 0.0316 | 1 | 1 |
| STD-REP | std3 | 0.03 | 1 | 1 |
| STD-REP | std3 | 0.0314 | 1 | 1 |
| STD-AVG | std3 | 0.03 | 1 | 1 |
| STD | Standard | 0.0674 | 2 | 2 |
| STD-REP | std4 | 0.0712 | 2 | 2 |
| STD-REP | std4 | 0.0702 | 2 | 2 |
| STD-REP | std4 | 0.0693 | 2 | 2 |
| STD-REP | std4 | 0.0686 | 2 | 2 |
| STD-AVG | std4 | 0.0694 | 2 | 2 |
| COR | Standard | 0.0284 | 1 | 1 |
| COR-REP | std3 | 0.0278 | 1 | 1 |
| COR-REP | std3 | 0.0273 | 1 | 1 |
| COR-AVG | std3 | 0.0276 | 1 | 1 |
| Sample | Au | 0.0078 | 0.3459 | 3.7494 |
| Sample-REP | Au | 0.0091 | 0.3798 | 4.1173 |
| Sample-REP | Au | 0.0074 | 0.3356 | 3.6386 |
| Sample-REP | Au | 0.0083 | 0.3577 | 3.878 |
| Sample-AVG | Au | 0.0078 | 0.3464 | 3.7553 |

E 11 Analysis of Iron for gold tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0037 | 0 | 0 |
| STD | Standard | -0.002 | 0 | 0 |
| STD-REP | std1 | -0.00664 | 0 | 0 |
| STD-REP | std1 | -0.0071 | 0 | 0 |
| STD-REP | std1 | -0.0062 | 0 | 0 |
| STD-REP | std1 | -0.0076 | 0 | 0 |
| STD-AVG | std1 | -0.0066 | 0 | 0 |
| STD | Standard | 0.0286 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0264 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0269 | 0.5 | 0.5 |
| STD-REP | std2 | 0.0265 | 0.5 | 0.5 |
| STD-AVG | std2 | 0.0266 | 0.5 | 0.5 |
| STD | Standard | 0.0542 | 1 | 1 |
| STD-REP | std3 | 0.0539 | 1 | 1 |
| STD-REP | std3 | 0.0552 | 1 | 1 |
| STD-REP | std3 | 0.0531 | 1 | 1 |
| STD-REP | std3 | 0.0577 | 1 | 1 |
| STD-AVG | std3 | 0.0538 | 1 | 1 |
| STD | Standard | 0.1123 | 2 | 2 |
| STD-REP | std4 | 0.1118 | 2 | 2 |
| STD-REP | std4 | 0.1132 | 2 | 2 |
| STD-AVG | std4 | 0.1125 | 2 | 2 |
| COR | Standard | 0.0573 | 1 | 1 |
| COR-REP | std3 | 0.0574 | 1 | 1 |
| COR-REP | std3 | 0.0576 | 1 | 1 |
| COR-AVG | std3 | 0.0575 | 1 | 1 |
| Sample | Au | 0.1381 | 2.4731 | 114.7018 |
| Sample-REP | Au | 0.1354 | 2.4237 | 112.4123 |
| Sample-REP | Au | 0.1368 | 2.4489 | 113.5824 |
| Sample-AVG | Au | 0.1367 | 2.4486 | 113.5648 |

E 12 Analysis of Magnesium for C1 and C2 tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | 0.0045 | 0 | 0 |
| STD | Standard | 0.0231 | 0 | 0 |
| STD-REP | std1 | 0.0243 | 0 | 0 |
| STD-REP | std1 | 0.0227 | 0 | 0 |
| STD-REP | std1 | 0.0234 | 0 | 0 |
| STD-REP | std1 | 0.0213 | 0 | 0 |
| STD-AVG | std1 | 0.0231 | 0 | 0 |
| STD | Standard | 0.3446 | 0.5 | 0.5 |
| STD-REP | std2 | 0.3472 | 0.5 | 0.5 |
| STD-REP | std2 | 0.3488 | 0.5 | 0.5 |
| STD-AVG | std2 | 0.3468 | 0.5 | 0.5 |
| STD | Standard | 0.621 | 1 | 1 |
| STD-REP | std3 | 0.6268 | 1 | 1 |
| STD-REP | std3 | 0.6283 | 1 | 1 |
| STD-AVG | std3 | 0.6254 | 1 | 1 |
| STD | Standard | 1.1177 | 2 | 2 |
| STD-REP | std4 | 1.1351 | 2 | 2 |
| STD-REP | std4 | 1.1409 | 2 | 2 |
| STD-REP | std4 | 1.1419 | 2 | 2 |
| STD-AVG | std4 | 1.1393 | 2 | 2 |
| COR | Standard | 0.6193 | 1 | 1 |
| COR-REP | std2 | 0.6257 | 1 | 1 |
| COR-REP | std2 | 0.625 | 1 | 1 |
| COR-AVG | std2 | 0.6234 | 1 | 1 |
| Sample | C1 | 0.7791 | 1.2738 | 1.2779 |
| Sample-REP | C1 | 0.7865 | 1.2876 | 1.2917 |
| Sample-REP | C1 | 0.7865 | 1.2878 | 1.2919 |
| Sample-AVG | C1 | 0.784 | 1.2831 | 1.2872 |
| Sample | C2 | 1.4308 | 2.6854 | 2.6939 |
| Sample-REP | C2 | 1.4405 | 2.7101 | 2.7187 |
| Sample-REP | C2 | 1.4417 | 2.7131 | 2.7218 |
| Sample-AVG | C2 | 1.4376 | 2.7028 | 2.7115 |

E 13 Analysis of magnesium for platinum tailings

| | Analyte | ABS values | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0074 | 0 | 0 |
| STD | Standard | -0.0059 | 0 | 0 |
| STD-REP | std1 | -0.0069 | 0 | 0 |
| STD-REP | std1 | -0.007 | 0 | 0 |
| STD-REP | std1 | -0.0058 | 0 | 0 |
| STD-REP | std1 | -0.0061 | 0 | 0 |
| STD-AVG | std1 | -0.0059 | 0 | 0 |
| STD | Standard | 1.0468 | 1 | 1 |
| STD-REP | std2 | 1.0513 | 1 | 1 |
| STD-REP | std2 | 1.0515 | 1 | 1 |
| STD-AVG | std2 | 1.0498 | 1 | 1 |
| STD | Standard | 1.5087 | 2 | 2 |
| STD-REP | std3 | 1.5138 | 2 | 2 |
| STD-REP | std3 | 1.5125 | 2 | 2 |
| STD-AVG | std3 | 1.5116 | 2 | 2 |
| COR | Standard | 1.0444 | 2 | 2 |
| COR-REP | std3 | 1.0501 | 2 | 2 |
| COR-REP | std3 | 1.0528 | 2 | 2 |
| COR-AVG | std3 | 1.0491 | 2 | 2 |
| Sample | pt | 0.5899 | 0.494 | 4.9403 |
| Sample-REP | pt | 0.5901 | 0.4942 | 7.2366 |
| Sample-REP | pt | 0.591 | 0.4951 | 7.2492 |
| Sample-AVG | pt | 0.5903 | 0.4944 | 4.9443 |

E 14 Analysis of magnesium for gold tailings

| | Analyte | abs | Conc (mg/l) | Final Conc (mg/kg) |
|---|---|---|---|---|
| Blank | Water | -0.0031 | 0 | 0 |
| STD | Standard | 0 | 0 | 0 |
| STD-REP | std1 | -0.002 | 0 | 0 |
| STD-REP | std1 | -0.0028 | 0 | 0 |
| STD-REP | std1 | -0.0026 | 0 | 0 |
| STD-REP | std1 | -0.0025 | 0 | 0 |
| STD-AVG | std1 | -0.0026 | 0 | 0 |
| STD | Standard | 1.0593 | 0.5 | 0.5 |
| STD-REP | std2 | 1.0617 | 0.5 | 0.5 |
| STD-REP | std2 | 1.0658 | 0.5 | 0.5 |
| STD-AVG | std2 | 1.0623 | 0.5 | 0.5 |

| | | | | |
|---|---|---|---|---|
| STD | Standard | 1.519 | 1 | 1 |
| STD-REP | std3 | 1.5227 | 1 | 1 |
| STD-REP | std3 | 1.5222 | 1 | 1 |
| STD-AVG | std3 | 1.5213 | 1 | 1 |
| STD | Standard | 1.9616 | 2 | 2 |
| STD-REP | std4 | 1.9607 | 2 | 2 |
| STD-REP | std4 | 1.9623 | 2 | 2 |
| STD-AVG | std4 | 1.9615 | 2 | 2 |
| COR | Standard | 1.5123 | 1 | 1 |
| COR-REP | std3 | 1.5181 | 1 | 1 |
| COR-REP | std3 | 1.5199 | 1 | 1 |
| COR-AVG | std3 | 1.5168 | 1 | 1 |
| Sample | Au | 1.093 | 1.1896 | 11.9318 |
| Sample-REP | Au | 1.0877 | 1.1822 | 11.8576 |
| Sample-REP | Au | 1.0877 | 1.1823 | 11.8584 |
| Sample-AVG | Au | 1.0895 | 1.1847 | 11.8825 |

E 15 Summary of chemical analysis for gold, platinum and kimberlite tailings

| Metal | Gold tailings | Platinum tailings | C 1tailings | C 2 tailings |
|---|---|---|---|---|
| $SO_4$ | 8686.0 | 3612.8 | 1085.9 | 429.9 |
| Fe | 2360.0 | 75.2 | - | - |
| Ca | 380.0 | 186.4 | 0 | 0 |
| Mg | 240.0 | 98.8 | 51.6 | 142.8 |

E 16 Conductivity of tailings

| Material tested | Gold tailings | Platinum tailings | C 1 tailings | C 2 tailings |
|---|---|---|---|---|
| Temperature | $23^0C$ | $23^0C$ | $21^OC$ | $21^OC$ |
| Conductivity (ms/m) | 400 | 170 | 70 | 140 |

E 17 pH of tailings

| Material tested | Au tailings | | Pt tailings | | C 1 tailings | | C 2 tailings | |
|---|---|---|---|---|---|---|---|---|
| Temperature ($^OC$) | 23 | 23 | 23 | 23 | 25 | 25 | 25 | 25 |
| pH | 2.13 | 2.13 | 8.00 | 8.02 | 8.55 | 8.56 | 9.19 | 9.20 |
| Average pH | 2.13 | | 8.01 | | 8.55 | | 9.19 | |

Appendix F. Pinhole Test

Computations for the pinhole test

Volume of the sample = volume (mould-cones-metal string)

<u>Volume of the mould:</u>

Diameter = 37.55 mm
Length = 62.7 mm

Mould area = $\pi r^2$
= 11.07 $cm^2$

Volume of mould = area x length
= 69.409

<u>Volume of cone:</u>

Volume of top cone = $\frac{1}{3}\pi r^2 h$

= 0.506 $cm^3$

Volume of bottom cone = $\frac{1}{3}\pi r^2 h$

= 0.570 $cm^3$

<u>Volume of metal sting:</u>

Area of metal string = $\pi r^2$
= 0.0177 $cm^2$

Volume of metal string = area x lengths
= 0.069 $cm^3$

<u>Total volume of the sample = 69.745 $cm^3$</u>

$$\text{Erosion loss (\% of initial dry mass)} = \frac{M2 - M1}{M3} x100$$

M1= Mass of the specimen before pinhole test

M2= Mass of the specimen after pinhole test

M3= Dry mass required to prepare a specimen for the pinhole test

$$\text{Dry density} = \frac{mass\ of\ \ dry\ tailings\ required\ to\ prepare\ a\ specimen}{volume\ of\ \ mould}$$

F 1 Pinhole test for gold tailings at 100% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 116.650 | 1684.10 | 130.969 | 118.852 | 11.844 | 10.15 |
| 3 | 120.150 | 1735.56 | 135.023 | 125.436 | 4.587 | 3.82 |
| 5 | 122.480 | 1769.21 | 138.791 | 134.497 | 4.294 | 3.51 |
| 7 | 124.816 | 1802.96 | 140.634 | 139.725 | 0.909 | 0.73 |
| 10 | 128.315 | 1850.90 | 146.315 | 145.879 | 0.436 | 0.34 |

F 2 Pinhole test for gold tailings at 95% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) (g) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 110.820 | 1600.79 | 123.020 | 115.425 | 7.595 | 6.85 |
| 3 | 114.145 | 1648.82 | 127.862 | 124.899 | 2.963 | 2.60 |
| 5 | 116.361 | 1680.83 | 129.913 | 129.203 | 0.710 | 0.61 |
| 7 | 118.577 | 1712.84 | 135.247 | 132.081 | 0.166 | 0.14 |
| 10 | 122.485 | 1760.84 | 139.485 | 135.443 | 0.155 | 0.13 |

F 3 Pinhole test for gold tailings at 90% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 104.99 | 1516.57 | 117.345 | 42.345 | 75.000 | 71.44 |
| 3 | 108.14 | 1562.07 | 121.577 | 48.928 | 72.649 | 67.18 |
| 5 | 110.24 | 1592.41 | 124.258 | 61.435 | 62.823 | 57.00 |
| 7 | 112.34 | 1622.74 | 126.853 | 84.351 | 42.502 | 37.83 |
| 10 | 116.656 | 1685.09 | 131.650 | 131.374 | 0.276 | 0.24 |

F 4 Pinhole test for gold tailings at 100% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.150 | 1735.56 | 132.253 | 131.248 | 1.311 | 1.09 |
| 5 | 122.480 | 1769.21 | 134.559 | 134.497 | 1.380 | 1.13 |
| 7 | 124.816 | 1802.96 | 142.113 | 140.924 | 1.189 | 0.95 |
| 10 | 128.315 | 1853.49 | 143.194 | 142.496 | 0.698 | 0.54 |

F 5 Pinhole test for gold tailings at 95% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.145 | 1651.34 | 127.862 | 121.420 | 6.442 | 5.64 |
| 5 | 116.361 | 1685.04 | 129.913 | 116.962 | 12.951 | 11.13 |
| 7 | 118.577 | 1718.74 | 133.225 | 125.087 | 8.138 | 6.86 |
| 10 | 122.485 | 1769.29 | 135.598 | 134.763 | 0.835 | 0.68 |

F 6 Pinhole test for gold tailings at 90% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 108.14 | 29.714 | 122.491 | 92.777 | 29.714 | 27.47 |
| 5 | 110.24 | 8.410 | 123.594 | 115.184 | 8.410 | 7.62 |
| 7 | 112.34 | 5.871 | 125.943 | 120.072 | 5.871 | 5.59 |
| 10 | 116.656 | 1.665 | 130.953 | 129.288 | 1.665 | 1.43 |

F 7 Pinhole test for Gold tailings at 100% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.150 | 1735.56 | 135.895 | 135.895 | 0 | 0 |
| 5 | 122.480 | 1769.21 | 136.853 | 136.853 | 0 | 0 |
| 7 | 124.816 | 1802.96 | 139.177 | 139.177 | 0 | 0 |
| 10 | 128.315 | 1850.90 | 143.585 | 143.585 | 0 | 0 |

F 8 Pinhole test for Gold tailings at 95% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.145 | 1648.82 | 127.759 | 127.759 | 0 | 0 |
| 5 | 116.361 | 1680.83 | 131.341 | 131.341 | 0 | 0 |
| 7 | 118.577 | 1712.84 | 133.899 | 133.899 | 0 | 0 |
| 10 | 122.485 | 1760.84 | 137.831 | 137.831 | 0 | 0 |

F 9 Pinhole test for gold tailings at 90% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 108.14 | 1562.07 | 123.288 | 123.012 | 0.276 | 0.26 |
| 5 | 110.24 | 1592.41 | 123.997 | 123.178 | 0.819 | 0.74 |
| 7 | 112.34 | 1622.74 | 124.168 | 124.101 | 0.067 | 0.10 |
| 10 | 116.656 | 1685.09 | 129.963 | 129.963 | 0.0 | 0.0 |

F 10 Pinhole test for Gold tailings at 100% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.150 | 1735.56 | 135.722 | 135.722 | 0 | 0 |
| 5 | 122.480 | 1769.21 | 136.823 | 136.823 | 0 | 0 |
| 7 | 124.816 | 1802.96 | 139.577 | 139.577 | 0 | 0 |
| 10 | 128.315 | 1853.50 | 143.175 | 143.755 | 0 | 0 |

F 11 Pinhole test for Gold tailings at 95% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density ($Kg/m^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.145 | 1648.82 | 126.259 | 126.259 | 0 | 0 |
| 5 | 116.361 | 1680.83 | 131.542 | 131.542 | 0 | 0 |
| 7 | 118.577 | 1712.84 | 133.00 | 133.00 | 0 | 0 |
| 10 | 122.485 | 1769.29 | 136.255 | 136.255 | 0 | 0 |

F 12 Pinhole test for gold tailings at 90% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 108.14 | 1562.07 | 123.288 | 123.012 | 0.276 | 0.0 |
| 5 | 110.24 | 1592.41 | 123.997 | 123.178 | 0.819 | 0.0 |
| 7 | 112.34 | 1622.74 | 124.168 | 124.101 | 0.067 | 0.0 |
| 10 | 116.656 | 1685.09 | 129.963 | 129.963 | 0.0 | 0.0 |

F 13 Pinhole test for platinum tailings at 100% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 135.476 | 1956.94 | 156.323 | 156.323 | 0.0 | 0.0 |
| 5 | 138.107 | 1994.94 | 158.423 | 158.423 | 0.0 | 0.0 |
| 7 | 140.737 | 2032.95 | 161.511 | 161.511 | 0.0 | 0.0 |
| 10 | 144.683 | 2089.93 | 163.877 | 163.877 | 0.0 | 0.0 |

F 14 Pinhole test for platinum tailings at 95% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 128.706 | 1859.15 | 148.643 | 148.643 | 0.0 | 0.0 |
| 5 | 131.205 | 1895.25 | 150.094 | 150.094 | 0.0 | 0.0 |
| 7 | 133.704 | 1931.34 | 154.390 | 154.390 | 0.0 | 0.0 |
| 10 | 137.453 | 1985.50 | 157.725 | 157.725 | 0.0 | 0.0 |

F 15 Pinhole test for platinum tailings at 90% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 121.930 | 1761.27 | 140.813 | 140.813 | 0.0 | 0.0 |
| 5 | 124.299 | 1795.49 | 143.697 | 143.697 | 0.0 | 0.0 |
| 7 | 126.667 | 1829.69 | 147.998 | 147.998 | 0.0 | 0.0 |
| 10 | 118.380 | 1880.99 | 147.352 | 147.352 | 0.0 | 0.0 |

F 16 Pinhole test for platinum tailings at 100% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 135.476 | 1956.94 | 155.333 | 155.333 | 0.0 | 0.0 |
| 5 | 138.107 | 1994.94 | 158.443 | 158.443 | 0.0 | 0.0 |
| 7 | 140.737 | 2032.95 | 161.526 | 161.526 | 0.0 | 0.0 |
| 10 | 144.683 | 2089.93 | 164.366 | 164.366 | 0.0 | 0.0 |

F 17 Pinhole test for platinum tailings at 95% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 128.706 | 1859.15 | 148.666 | 148.666 | 0.0 | 0.0 |
| 5 | 131.205 | 1895.25 | 151.256 | 151.256 | 0.0 | 0.0 |
| 7 | 133.704 | 1931.34 | 154.489 | 154.489 | 0.0 | 0.0 |
| 10 | 137.453 | 1985.50 | 157.776 | 157.776 | 0.0 | 0.0 |

F 18 Pinhole test for platinum tailings at 90% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 121.930 | 1761.27 | 140.822 | 140.822 | 0.0 | 0.0 |
| 5 | 124.299 | 1795.49 | 143.566 | 143.566 | 0.0 | 0.0 |
| 7 | 126.667 | 1829.69 | 147.889 | 147.556 | 0.0 | 0.0 |
| 10 | 118.380 | 1880.99 | 147.256 | 147.256 | 0.0 | 0.0 |

F 19 Pinhole test for kimberlite tailings (C1) at 100% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 116.996 | 1689.99 | 134.61 | Clogged | - | - |
| 3 | 120.506 | 1740.69 | 137.61 | Clogged | - | - |
| 5 | 122.846 | 1774.50 | 136.95 | Clogged | - | - |
| 7 | 125.186 | 1808.30 | 136.59 | Clogged | - | - |
| 10 | 128.696 | 1859.00 | 145.73 | Clogged | - | - |

F 20 Pinhole test for kimberlite tailings (C1) at 95% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 111.150 | 1605.56 | 125.651 | Clogged | - | - |
| 3 | 114.480 | 1653.65 | 129.480 | Clogged | - | - |
| 5 | 116.710 | 1685.87 | 131.610 | Clogged | - | - |
| 7 | 118.930 | 1717.93 | 134.930 | Clogged | - | - |
| 10 | 122.265 | 1766.11 | 138.585 | Clogged | - | - |

F 21 Pinhole test for kimberlite tailings (C1) at 90% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 105.290 | 1520.91 | 120.401 | Clogged | - | - |
| 3 | 108.450 | 1566.56 | 122.973 | Clogged | - | - |
| 5 | 110.550 | 1596.89 | 125.103 | Clogged | - | - |
| 7 | 112.660 | 1627.36 | 126.292 | Clogged | - | - |
| 10 | 115.820 | 1673.01 | 130.819 | Clogged | - | - |

F 22 Pinhole test for kimberlite tailings (C1) at 100% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 116.996 | 1689.99 | 134.852 | Clogged | - | - |
| 3 | 120.506 | 1740.69 | 137.611 | Clogged | - | - |
| 5 | 122.846 | 1774.50 | 136.999 | Clogged | - | - |
| 7 | 125.186 | 1808.30 | 136.556 | Clogged | - | - |
| 10 | 128.696 | 1859.00 | 146.731 | Clogged | - | - |

F 23 Pinhole test for kimberlite tailings (C1) at 95% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 111.150 | 1605.56 | 125.644 | Clogged | - | - |
| 3 | 114.480 | 1653.65 | 129.481 | Clogged | - | - |
| 5 | 116.710 | 1685.87 | 131.658 | Clogged | - | - |
| 7 | 118.930 | 1717.93 | 134.333 | Clogged | - | - |
| 10 | 122.265 | 1766.11 | 138.588 | Clogged | - | - |

F 24 Pinhole test for kimberlite tailings (C1) at 90% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 105.290 | 1520.91 | 121.236 | Clogged | - | - |
| 3 | 108.450 | 1566.56 | 122.956 | Clogged | - | - |
| 5 | 110.550 | 1596.89 | 125.556 | Clogged | - | - |
| 7 | 112.660 | 1627.36 | 126.336 | Clogged | - | - |
| 10 | 115.820 | 1673.01 | 131.986 | Clogged | - | - |

F 25 Pinhole test for kimberlite tailings (C1) at 100% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.51 | 1740.69 | 137.614 | - | - | - |
| 5 | 122.85 | 1774.50 | 136.949 | 136.95 | 0 | 0 |
| 7 | 125.19 | 1808.30 | 136.593 | 136.59 | 0 | 0 |
| 10 | 128.69 | 1859.00 | 145.726 | 145.73 | 0 | 0 |

F 26 Pinhole test for kimberlite tailings (C1) at 95% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.480 | 1653.65 | 129.043 | Clogged | - | - |
| 5 | 116.710 | 1685.87 | 130.963 | Clogged | - | - |
| 7 | 118.930 | 1717.93 | 135.153 | Clogged | - | - |
| 10 | 122.265 | 1766.11 | 136.834 | Clogged | - | - |

F 27 Pinhole test for kimberlite tailings (C1) at 90% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 108.450 | 1566.56 | 123.561 | Clogged | - | - |
| 5 | 110.550 | 1596.89 | 124.515 | Clogged | - | - |
| 7 | 112.660 | 1627.36 | 128.771 | Clogged | - | - |
| 10 | 115.820 | 1673.01 | 131.552 | Clogged | - | - |

F 28 Pinhole test for kimberlite tailings (C1) at 100% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.51 | 1740.69 | 135.622 | 135.622 | 0 | 0 |
| 5 | 122.85 | 1774.50 | 137.556 | 137.556 | 0 | 0 |
| 7 | 125.19 | 1808.30 | 137.993 | 137.993 | 0 | 0 |
| 10 | 128.69 | 1859.00 | 145.526 | 145.526 | 0 | 0 |

F 29 Pinhole test for kimberlite tailings (C1) at 95% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.480 | 1653.65 | 129.001 | Clogged | - | - |
| 5 | 116.710 | 1685.87 | 130.564 | Clogged | - | - |
| 7 | 118.930 | 1717.93 | 134.562 | Clogged | - | - |
| 10 | 122.265 | 1766.11 | 136.811 | Clogged | - | - |

F 30 Pinhole test for kimberlite tailings (C1) at 90% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 108.450 | 1566.56 | 122.661 | Clogged | - | - |
| 5 | 110.550 | 1596.89 | 124.554 | Clogged | - | - |
| 7 | 112.660 | 1627.36 | 128.871 | Clogged | - | - |
| 10 | 115.820 | 1673.01 | 131.665 | Clogged | - | - |

F 31 Pinhole test for kimberlite tailings (C2) at 100% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 122.67 | 1771.95 | 141.07 | Clogged | - | - |
| 3 | 126.35 | 1825.06 | 144.07 | Clogged | - | - |
| 5 | 128.79 | 1860.49 | 146.24 | Clogged | - | - |
| 7 | 131.17 | 1894.68 | 151.62 | Clogged | - | - |
| 10 | 134.93 | 1949.09 | 150.21 | Clogged | - | - |

F 32 Pinhole test for kimberlite tailings (C2) at 95% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 116.530 | 1683.270 | 131.753 | Clogged | - | - |
| 3 | 120.020 | 1733.680 | 137.010 | Clogged | - | - |
| 5 | 122.360 | 1767.480 | 139.360 | Clogged | - | - |
| 7 | 124.690 | 1801.137 | 142.432 | Clogged | - | - |
| 10 | 128.183 | 1851.593 | 146.306 | Clogged | - | - |

F 33 Pinhole test for kimberlite tailings (C2) at 90% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 110.680 | 1598.764 | 125.904 | Clogged | - | - |
| 3 | 114.000 | 1646.720 | 130.112 | Clogged | - | - |
| 5 | 116.214 | 1678.701 | 132.746 | Clogged | - | - |
| 7 | 118.430 | 1710.712 | 134.655 | Clogged | - | - |
| 10 | 121.750 | 1758.669 | 137.975 | Clogged | - | - |

F 34 Pinhole test for kimberlite tailings (C2) at 100% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 122.67 | 1771.95 | 142.669 | Clogged | - | - |
| 3 | 126.35 | 1825.06 | 144.477 | Clogged | - | - |
| 5 | 128.79 | 1860.49 | 146.556 | Clogged | - | - |
| 7 | 131.17 | 1894.68 | 149.665 | Clogged | - | - |
| 10 | 134.93 | 1949.09 | 150.778 | Clogged | - | - |

F 35 Pinhole test for kimberlite tailings (C2) at 95% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 116.530 | 1683.270 | 132.556 | Clogged | - | - |
| 3 | 120.020 | 1733.680 | 136.012 | Clogged | - | - |
| 5 | 122.360 | 1767.480 | 139.456 | Clogged | - | - |
| 7 | 124.690 | 1801.137 | 142.778 | Clogged | - | - |
| 10 | 128.183 | 1851.593 | 146.669 | Clogged | - | - |

F 36 Pinhole test for kimberlite tailings (C2) at 90% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 0 | 110.680 | 1598.764 | 125.444 | Clogged | - | - |
| 3 | 114.000 | 1646.720 | 130.225 | Clogged | - | - |
| 5 | 116.214 | 1678.701 | 131.747 | Clogged | - | - |
| 7 | 118.430 | 1710.712 | 134.736 | Clogged | - | - |
| 10 | 121.750 | 1758.669 | 137.999 | Clogged | - | - |

F 37 Pinhole test for kimberlite tailings (C2) at 100% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 126.35 | 1825.06 | 144.07 | Clogged | - | - |
| 5 | 128.79 | 1860.49 | 146.24 | Clogged | - | - |
| 7 | 131.17 | 1894.68 | 151.62 | 151.62 | 0 | 0 |
| 10 | 134.93 | 1949.09 | 150.21 | 150.21 | 0 | 0 |

F 38 Pinhole test for kimberlite tailings (C2) at 95% Compaction (7 days cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.020 | 1733.680 | 136.243 | Clogged | - | - |
| 5 | 122.360 | 1767.480 | 139.693 | Clogged | - | - |
| 7 | 124.690 | 1801.137 | 142.430 | Clogged | - | - |
| 10 | 128.183 | 1851.593 | 146.206 | Clogged | - | - |

F 39 Pinhole test for kimberlite tailings (C2) at 90% Compaction (non-cured)

| % Conbex cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.000 | 1646.720 | 129.243 | Clogged | - | - |
| 5 | 116.214 | 1678.701 | 132.737 | Clogged | - | - |
| 7 | 118.430 | 1710.712 | 135.423 | Clogged | - | - |
| 10 | 121.750 | 1758.669 | 138.925 | Clogged | - | - |

F 40 Pinhole test for kimberlite tailings (C2) at 100% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 126.35 | 1825.06 | 144.772 | Clogged | - | - |
| 5 | 128.79 | 1860.49 | 147.244 | Clogged | - | - |
| 7 | 131.17 | 1894.68 | 19.662 | 151.62 | 0 | 0 |
| 10 | 134.93 | 1949.09 | 150.333 | 150.21 | 0 | 0 |

F 41 Pinhole test for kimberlite tailings (C2) at 95% Compaction (7 days cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 120.020 | 1733.680 | 136.556 | Clogged | - | - |
| 5 | 122.360 | 1767.480 | 139.445 | Clogged | - | - |
| 7 | 124.690 | 1801.137 | 143.877 | Clogged | - | - |
| 10 | 128.183 | 1851.593 | 146.988 | Clogged | - | - |

F 42 Pinhole test for kimberlite tailings (C2) at 90% Compaction (non-cured)

| % Ordinary Portland cement | Calculated required dry mass (g) | Compaction dry density (Kg/m$^3$) | Mass of specimen before erosion (g) | Mass of specimen after erosion (g) | Mass of eroded tailings (g) | Erosion loss (% of initial dry mass) |
|---|---|---|---|---|---|---|
| 3 | 114.000 | 1646.720 | 129.887 | Clogged | - | - |
| 5 | 116.214 | 1678.701 | 132.739 | Clogged | - | - |
| 7 | 118.430 | 1710.712 | 136.325 | Clogged | - | - |
| 10 | 121.750 | 1758.669 | 138.774 | Clogged | - | - |

Appendix G. Eades Test

G 1 Eades test for gold tailings

| Temperature | % Conbex | pH Value |
|---|---|---|
| 21 | 1 | 3.80 |
| 21 | 2 | 5.41 |
| 21 | 3 | 5.49 |
| 21 | 4 | 5.79 |
| 21 | 5 | 5.84 |
| 21 | 6 | 6.13 |

G 2 Eades test for platinum tailings

| Temperature | % Conbex | pH Value |
|---|---|---|
| 21 | 1 | 10.98 |
| 21 | 2 | 11.59 |
| 21 | 3 | 11.93 |
| 21 | 4 | 12.10 |
| 21 | 5 | 12.17 |
| 21 | 6 | 12.19 |

G 3 Eades test for kimberlite tailings 1

| Temperature | % Conbex | pH Value |
|---|---|---|
| 21 | 1 | 9.36 |
| 21 | 2 | 10.36 |
| 21 | 3 | 10.85 |
| 21 | 4 | 11.20 |
| 21 | 5 | 11.35 |
| 21 | 6 | 11.50 |

G 4 Eades test for kimberlite tailings 2

| Temperature | % Conbex | pH Value |
|---|---|---|
| 21 | 1 | 9.61 |
| 21 | 2 | 10.57 |
| 21 | 3 | 11.06 |
| 21 | 4 | 11.31 |
| 21 | 5 | 11.54 |
| 21 | 6 | 11.62 |

G 5 Eades test for gold tailings

| Temperature | % OPC | pH Value |
|---|---|---|
| 21 | 1 | 2.93 |
| 21 | 2 | 4.04 |
| 21 | 3 | 5.40 |
| 21 | 4 | 5.97 |
| 21 | 5 | 8.55 |
| 21 | 6 | 9.60 |

G 6 Eades test for platinum tailings

| Temperature | % OPC | pH Value |
|---|---|---|
| 21 | 1 | 11.75 |
| 21 | 2 | 11.86 |
| 21 | 3 | 12.03 |
| 21 | 4 | 12.09 |
| 21 | 5 | 12.17 |
| 21 | 6 | 12.20 |

G 7 Eades test for Kimberlite (C1) tailings

| Temperature | % OPC | pH Value |
|---|---|---|
| 21 | 1 | 11.39 |
| 21 | 2 | 11.51 |
| 21 | 3 | 11.65 |
| 21 | 4 | 11.81 |
| 21 | 5 | 11.91 |
| 21 | 6 | 12.04 |

G 8 Eades test for kimberlite (C2) tailings

| Temperature | % OPC | pH Value |
|---|---|---|
| 21 | 1 | 11.62 |
| 21 | 2 | 11.78 |
| 21 | 3 | 11.88 |
| 21 | 4 | 12.04 |
| 21 | 5 | 12.14 |
| 21 | 6 | 12.20 |

Appendix H. Unconfined Compressive Strengths (UCS)

Computations for compressive strength test

The details of the stress-strain relationships are not presented since they required a large number of pages. Only the maximum compressive resistance are presented.

The unit strain is computed as:

$$\text{Strain} = \frac{\Delta L}{Lo}$$

Where $\Delta L$ = total sample deformation (axial), mm
$L_o$ = original sample length, mm

$$A' = \frac{Ao}{1-\varepsilon}$$

$A_o$ = original area of the sample

The instantaneous test stress $\sigma_c$ on the sample is computed as:

$$\sigma_c = \frac{P}{A}$$

where: $\sigma_c$ = Unconfined compressive strength
$P$ = load on the sample at any instant for corresponding value of $\Delta L$
$A'$ = Cross-section area of specimen for the corresponding load $P$

H 1 UCS for gold tailings (7 days cured)

| Compaction density | 3% OPC | 5% OPC | 7% OPC | 10% OPC |
|---|---|---|---|---|
| 100 | 591.582 | 576.839 | 718.722 | 1338 |
| | 544.785 | 453.935 | 629.935 | 1448.433 |
| | 490.848 | 427.723 | 695.684 | 1366 |
| 95 | 395.067 | 451.333 | 518.261 | 1053.617 |
| | 383.91 | 436.18 | 484.054 | 1036.731 |
| | 380 | 411.893 | 471.675 | 1006.328 |
| 90 | 298.583 | 373.116 | 333.871 | 919.213 |
| | 292.787 | 310.395 | 308.655 | 883.627 |
| | 281.15 | 271.687 | 307.284 | 876.802 |

H 2 UCS for gold tailings (7 days cured)

| Compaction density | 3% Conbex | 5% Conbex | 7% Conbex | 10% Conbex |
|---|---|---|---|---|
| 100 | 398.856 | 490.316 | 638.956 | 779.278 |
| | 377.944 | 461.645 | 566.058 | 761.809 |
| | 354.521 | 418.723 | 565.556 | 779.278 |
| 95 | 314.597 | 358.095 | 599.512 | 851.999 |
| | 305.802 | 353.149 | 525.205 | 847.951 |
| | 291.503 | 339.759 | 479.781 | 834.948 |
| 90 | 211.558 | 280.098 | 353.139 | 647.927 |
| | 208.195 | 260.522 | 353.037 | 645.727 |
| | 185.215 | 259.811 | 331.172 | 642.804 |

H 3 UCS for platinum tailings (7 days cured)

| Compaction density | 3% OPC | 5% OPC | 7% OPC | 10% OPC |
|---|---|---|---|---|
| 100 | 919.963 | 1331.729 | 1422.429 | 1751.993 |
| | 935.605 | 1227.175 | 1419.395 | 1726.33 |
| | 730.363 | 1217.134 | 1418.071 | 1711.743 |
| 95 | 730.363 | 1051.389 | 1362.955 | 1713.265 |
| | 655.698 | 929.66 | 1208.914 | 1708.914 |
| | 641.845 | 819.306 | 1208.704 | 1608.156 |
| 90 | 398.709 | 607.574 | 1132.728 | 1708.448 |
| | 370.418 | 642.527 | 1066.135 | 1626.419 |
| | 328.735 | 630.368 | 1059.234 | 1580.298 |

H 4 UCS for platinum tailings (7 days cured)

| Compaction density | 3% Conbex | 5% Conbex | 7% Conbex | 10% Conbex |
|---|---|---|---|---|
| 100 | 388.68 | 799.006 | 1217.184 | 1486.72 |
| | 365.113 | 796.409 | 1200 | 1458.091 |
| | 359.494 | 767.283 | 1199.639 | 1404.025 |
| 95 | 279.467 | 776.972 | 1448.656 | 1673.087 |
| | 254.609 | 773.803 | 1434.104 | 1655.134 |
| | 254.609 | 736.978 | 1424.247 | 1627.675 |
| 90 | 210.451 | 736.978 | 1065.243 | 1587.9 |
| | 197.559 | 611.237 | 1033.725 | 1574.507 |
| | 200 | 609.237 | 1015.655 | 1561.706 |

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