WATER EROSION ON SOIL SLOPES AND A SUGGESTED METHOD FOR ASSESSING SUSCEPTIBILITY OF MINE TAILINGS TO WATER EROSION

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DECLARATION

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

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ABSTRACT

Environmental impacts from tailings impoundments differ according to their mineral constituents. Erosion is one of the processes that aggravate the environmental impacts from tailings due to the transportation of particles, and knowing the susceptibility mechanisms of those tailings particles for erosion will provide understanding of how to prevent impacts arising from erosion. Laboratory pinhole erosion tests were used to determine the susceptibility of tailings particles to erosion. Compacted tailings samples were used, as compaction is an important parameter of erosion susceptibility.

The study entails investigation of factors that affect erosion from the slopes of tailings deposits in order to evaluate mitigation measures. The results could help to provide more effective methods to reduce gully formation and enhance environmental protection. It is advisable to prevent environmental impacts at the source, before they become detrimental and costly to mitigate.

To both Dad and Mom, with fellow siblings for your undying love and support.

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CONTENTS **PAGE**

LIST OF FIGURES **PAGE**

LIST OF TABLES **PAGE**

LIST OF SYMBOLS

Symbol	Quantity
Gs	specific gravity
kPa	kilo Pascal
τ	shear stress
w_l	liquid limit
w_p	plastic limit
w_s	shrinkage limit
I_p	plastic limit
w	water content
pH	potential of hydrogen

1 INTRODUCTION

1.1 Background Information to the Dissertation

Erosion is the word derived from the Latin word *erodere* meaning to gnaw away (Roose 1996). Erosion is the removal and the transportation of earth materials that overly the earth's surface by the action of flowing water. It is regarded as a natural process because when rain falls on the surface; water will flow over the land, even though a high percentage of water may infiltrate. Construction activities, such as tailing disposal, play a crucial role in promoting and increasing destruction by the natural erosion process.

Tailings are usually disposed of without cover, and may remain exposed to the erosion agents of moving water and wind for long periods of time. Motion of water and wind over the unprotected tailings surface detaches and then transports tailings particles. Most mine tailings are milled to the size of silt grains and have no cohesion and therefore are dislodged easily. This facilitates the transporting of tailings material for long distances.

The presence of unprotected tailings dams facilitates impacts on the surroundings, both environmentally and economically. The transportation of sediments from tailings dams result in and is responsible for degradation of the surrounding environment. For example, when sediments from tailings dams are deposited on a flat area they reduce the fertility of that area and can also be carried into the river system, thus reducing its flow capacity. The deposited sediments may also carry toxic elements that can be responsible for deterioration of riverine animal and plant life.

Due to the fact that most tailings dams are only vegetated after disposal has taken place and they are being rehabilitated, they are subjected to deterioration because they are exposed for long periods to erosion agents and other forms of disturbance.

Some tailings dams have been rehabilitated by planting the surface with grass as it is considered the most cost-effective method to combat the development of erosion channels, but, after a short period of time, the surfaces lose their cover and may appear, as though they had never been vegetated. As a result of the failure and unsustainability of previous methods of erosion control, there is an interest in developing techniques that will promote long-term erosion-protection of tailings slopes.

1.2 Statement of the Dissertation

Waste materials from the mining industries are disposed either as tailings or waste rock, depending on the extraction process applied during beneficiation. Of the two wastes mentioned above, tailings are composed mainly of fine materials, which are easily carried away by erosion agents. Apart from the way in which they are disposed, they also contain small concentrations of toxic compounds, which may pose serious environmental threats to the surrounding areas. Some of the particles can be removed by erosion from the tailings dams where they are stored and eventually end up in river channels, decreasing the flow capacity of the river, while the toxic elements affect the riverine environment.

There are widely reported cases in which tailings dams failed, and also claimed a number of lives. There is clear evidence that some of the known failures were erosion-related, for example, the failures at Bafokeng and Merriespruit both resulted from overtopping of the tailings dams, followed by the formation of an erosion gully, and then shear failure.

The slopes of the tailings dams make up the periphery of the enclosing dams. The top surfaces of tailings dams are relatively flat areas wherein there is limited motion of water, which could cause erosion, whereas slopes facilitate the runoff of water, which gains momentum as it flows downwards. Water flowing on the slopes tends to erode the material, forming channels for transporting both tailings and water. Because of the cohesionless nature of the material on the slopes of the tailings dams, this material easily erodes under the actions of flowing water.

1.3 Objectives of the Dissertation

The main objective of this research is to develop a method for assessing erosion-susceptibility of tailings materials, while the secondary objectives are to review the literature:

- to review previous research:
  - fundamentals of erosion
  - erosion processes
  - factors affecting erosion
- to investigate mechanisms of gully erosion in order to increase understanding of the process;
- to evaluate mechanisms causing the growth of gullies through understanding of the flow movement of soil and water on slopes.
- to assess the methodology for determining the rate of erosion on the slopes of tailings dams.

1.4 Justification for the Research

Mining operations and other industries such as the fertilizer and electrical power industries, all produce wastes from their operations. For continuous, long-term sustainability of tailing dams and other waste deposits, disposal should be done in an efficient manner that will minimize environmental impacts.

The development of gullies on the slopes of tailings dams leads to difficulties when rehabilitating. Some tailings dams have been vegetated to minimize the erosion problem, but having lost their vegetation as result of unchecked erosion, are left completely exposed to continuing erosion. Therefore, research should be undertaken to develop methodologies that will serve better than existing and previous methods. Although complete prevention of erosion channels may be impossible, substantial prevention would be a great improvement on the present situation.

Disposal of mine waste by means of tailings dams will continue to pose one of the mining and energy industries greatest environmentally associated problems. Minimizing environmental impacts requires efficient and effective planning from the start of the mining or extraction processes and the rehabilitation process should start when extraction operations begin. This will help ensure that impacts during and after abandonment will be reduced. Richards Bay Minerals, for example, have a policy that an essential component of every mining operation is minimization of its impact on the environment. This aims to return the environment to a state similar to that prior to mining (Richards Bay Minerals, 2004).

1.5 Practical Potential Application of the Dissertation

Erosion is an environmental problem that occurs as a result of alteration of the in-place soil environment by man, either by reducing erosion resistance or by exposing loose material to erosion. To reduce the erosion problem requires the implementation of solutions in the field. Although a complete halt of the problem would be difficult, it is considered that the information contained in this dissertation could have a positive influence in the ongoing maintenance of a sustainable natural environment.

2 REVIEW OF PREVIOUS RESEARCH

2.1 Introduction

The extraction of the minerals from the ground and storing the waste materials on surface exposes the waste to weathering, which is the breaking down of the both soil particles and parent materials. As extraction continues, tailings disposal also progresses. As tailings are highly erodible, they are easily carried away, either by wind or water and may cause siltation of streams, rivers, low-lying areas and adjacent agricultural lands. Most of the slopes of the tailings dams built in South Africa are extremely steep, about 35^0 (Blight *et al*., 1981) and the protection of such slopes against erosion is difficult (Blight and Caldwell, 1984). The absence of the surface protection on slopes leads to accelerated erosion (Dacosta and Blight, 2003).

2.2 The Fundamentals of the Process of Erosion of Soil Slopes by Water

Erosion is regarded as an ongoing natural process, which is accelerated by anthropogenic activities. Erosion caused by human activities results in degradation of the slopes of a particular surface area. When human activities accelerate erosion beyond a certain threshold, irreversible damage can occur to the land. The problem is to prevent erosion by preventing the formation of gullies and limiting the expansion of any existing gullies. Once a gully forms, it requires quick treatment or the erosion will accelerate during ensuing storm events. As compared to rills on moderate slopes, which can be graded and revegetated, gullies on steep slopes tend to become permanent features of the landscape (Gipe, 2003).

Processes whereby runoff water accumulates in narrow channels and, over a period, removes the soils from this narrow area to considerable depths develop gullies. Agriculturally, they are regarded as channels that are too deep to ameliorate with ordinary farm tillage equipment, with a size ranging from 500 mm to 3 m (Posen *et al*., 2002). Heavy rains falling on the slopes of tailings dams are capable of generating sheet and rill erosion, which could eventually lead to gullying.

Gullying tends to be more detrimental and could eventually lead to failure (Wu *et al*., 1997, Blight, 2000), especially on a structure like tailings dam, for example, the overtopping and accelerated gully formation that resulted in the failure of Bafokeng and Merriespruit tailings dams. Gullies are difficult to control and are environmentally unfriendly on any unprotected soil slope (Blight and Dacosta, 2003).

2.2.1 Detachment

Soil erosion begins with detachment of a particle from the surrounding material. Erosion by water can take place in one of the two processes, detachment by rainfall and detachment by runoff. Detachment by rainfall starts when raindrops hit the surface and dislodge particles, which are then carried away downslope in increasing quantities as the flow rate increases.

The downslope component of the weight of the drop is transferred in full to the surface, but only a small portion of the component normal to the surface is transferred. When the raindrop hits the surface, two possible effects may occur: it provides a consolidation force, compacting the surface or it imparts a velocity to the loosened material and dislodges it. Raindrops are more effective in dislodging particles as the slope angle steepens (Pidwirny, 1999), but because the horizontal projection of the area reduces, fewer raindrops strike a steeper slope.

Detachment by runoff occurs during a heavy rain or rainstorm when the soil water storage or infiltration capacity has been exceeded. For the flow of water to detach particles, a certain retentive force has to be overcome before detachment can occur (Pidwirny, 1999).

2.2.2 Entrainment

Entrainment is the process of particle lifting by the agent of erosion. This stage is variously known as the threshold of movement or the critical stage. It can be specified in terms of a value of the boundary shear stress, the critical boundary shear stress. The value of the critical boundary shear stress depends chiefly on the nature of the sediment making up the bed, which may be distinguished as either cohesionless or cohesive.

Cohesionless sediments are formed of loose grains that are not bound together in any way by surface or electrochemical forces, such as clean sands and gravels (Pidwirny, 1999).

Entrainment of grains is controlled by individual grain size characteristics and the sediment properties such as the grain size distribution, sorting, grain orientation, packing arrangement, porosity and the degree of cohesion. During sediment transportation particles are sorted according to size, shape and density (Pye, 1994).

It has been found that there is a strong relationship between the velocity of flow of a river, the boundary shear stress, and the size of particles eroded, transported or deposited. In the early 1930s Hjulström carried out experiments to define the velocities necessary to initiate the movement (erosion), transport and deposition of sediment of different sizes.

Hjulström presented his results as a graph showing the relationship between velocity (Y-axis) and the sediment diameter (X-axis) in the form of two curves, one plotting the erosion velocity, which is the velocity at which particles of a particular size can be eroded. The second line plots the settling velocity at which deposition is initiated. Between them transport will occur, Hjulström found that once in motion, particles do not require such high velocities for continuing in motion. The critical erosion velocity is lowest for sand-sized particles, because the particles do not have the cohesive property of clay.

Higher velocities are necessary to entrain both finer and coarser sediment particles. Finer particles, such as silt and clay, require a greater critical velocity to get them moving because of their cohesive nature, which makes them stick together. For coarser sediments such as gravel, pebbles and cobbles, the higher critical velocity is purely a result of their greater weight. Due to the size differences, it requires more velocity to transport clay and less velocity for gravel. The maximum size of particles transportable by a river is called its competence (Myers, 2005).

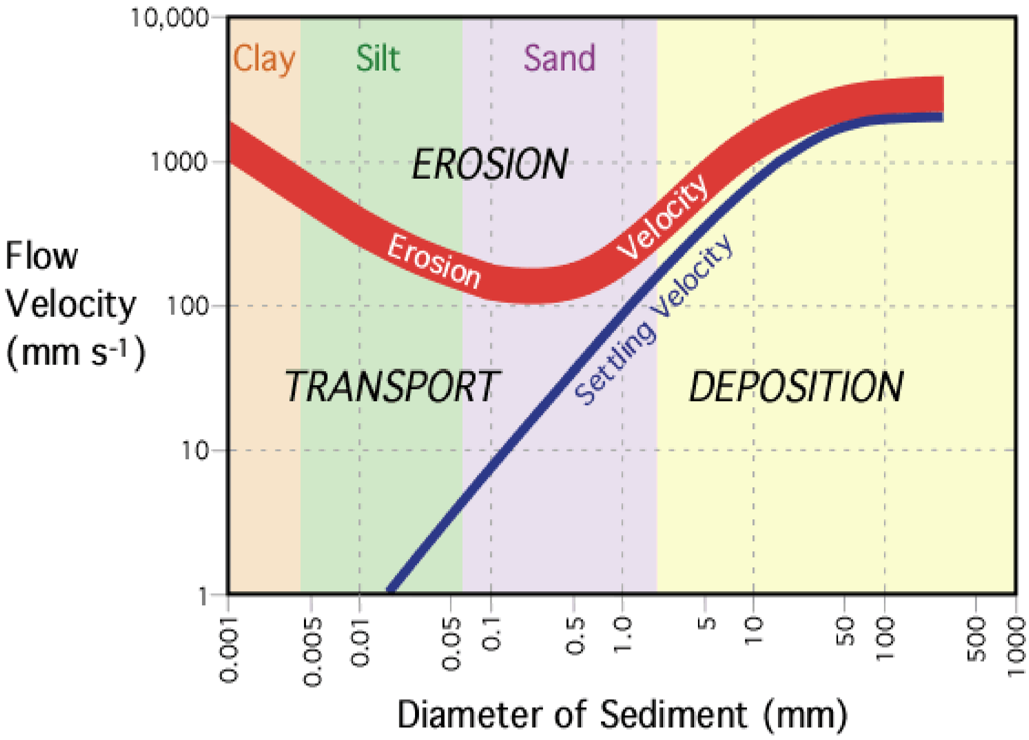

Figure 2.1 Relationship between flow velocity and particle erosion, transport and deposition. Originally proposed by Hjulstrőm (Source: Pidwirnry 1999-2004)

The critical entrainment velocity curve indicates that particles below a certain size are just as resistant to entrainment as particles with larger sizes and masses. Fine silt and clay particles have higher resistance to entrainment because of the strong cohesive bonds between particles.

Figure 2.1 describes the relationship between the stream flow velocity and particle erosion, transport and deposition. The curve representing erosion velocity describes the velocity required to entrain particles from the stream's bed. The line indicated as the settling velocity shows at what velocity certain sized particles settle out and are deposited (Pidwirny, 1999). This happens when the velocity of water flow no longer has the energy essential to transport the specific sediment size (Axelsson, 2002).

2.2.3 Transport

Within the water, as the medium of transport, transport can occur either as a suspension where particles are carried by the medium without touching the soil surface; saltation where particles move from the surface to the medium with a quick continuous repeated jumping motion; traction where the movement of the particles is by rolling, and shuffling along the eroded surface; and solution where eroded materials are dissolved and carried along in water as individual ions (Pidwirny, 1999). The material that a stream takes with it is known as its stream load.

Fine, insoluble matter such as silt and clay with fine sand is carried in suspension in the water and is known as the suspension load. The water lifts grains of sand and gravel, which are too heavy to be carried in suspension, every now and again before they can sink to the bottom again. Sand and gravel that saltates is known as the saltation load (Rix *et al*., 1986).

2.3 Erosion Processes

2.3.1 Sheet erosion

Sheet erosion is the soil movement from raindrop splash resulting in the breakdown of soil surface structure and surface runoff. It occurs fairly uniformly over the slope (Wall *et al*., 1987). The often-thin layer of topsoil disappears gradually, making it difficult to monitor, because the damage is not immediately perceptible (http://www.netc.net.au).

Raindrop action on bare soil disrupts aggregates, dislodges soil particles and compacts the erodible soil surface. Continuous rainfall causes turbulence within the flow that may increase the water’s erosive effect. Erosion may also result in the removal of seeds or seedlings and reduce the soil’s ability to store water for plants to draw upon between rainfall events (http://www.netc.net.au).

Sheet erosion can cover large areas of sloping land and go unnoticed for some time. Sheet erosion can be recognized by either soil deposition at the footslope, or by the presence of light-coloured subsoil appearing on the surface. If left unattended, sheet erosion may gradually, on mine tailings dams, move weathered acid tailings from one area to another. Only fine material is transported by sheet erosion, therefore the erosive force must be larger than the transporting force (Swart, 2004).

2.3.2 Rill erosion

Rill erosion results when surface runoff concentrates forming small well-defined channels (Wall *et al*., 1987). Rill erosion occurs with sheet erosion following the high intensity rainfall. It is easily identified as a series of small channels or rills up to 300 mm deep. If rainfall exceeds infiltration, a surface film of water forms. Rill erosion results from a concentration of this surface film into deeper, faster flowing channels, which follow depressions or low points. The shearing power of the water detaches, entrains and transports soil particles, making these channels the preferred routes for sediment transport. Rill erosion is described as the intermediate stage between sheet and gully erosion (http://www.netc.net.au).

2.3.3 Gully erosion

Gullies are an advanced stage of rill erosion. Gullies are open erosion channels of at least 300 mm deep. Gullies develop due to the decrease in erosional resistance of the soil and a concentration of the erosional forces acting on the soil surface (Bettis, 1983).

Gullies often develop as a result of intense erosion caused by flow over a steep overfall at the top of the gully. This overfall, called a headcut, moves upstream in a natural drainage-way, and can be initiated off-site and move into a field or up the slope of a tailings dam. Gullies can also be enlarged by lateral erosion, sloughing of the sidewalls and cleaning out of debris by storm flow. Subsurface seepage through the gully walls can significantly reduce soil strength and accelerate erosion**.** The characteristics of rill and gully erosion are summarized in Table 2.1.

Table 2.1 Comparative characteristics between rill erosion, ephemeral gully erosion and classical gully erosion (after Zheng and Huang, 2002)

Rill erosion	Ephemeral erosion gully	Classical erosion gully
Rills are erased by tillage and usually do not reoccur in the same place.	Ephemeral gullies are temporary features, usually obscured by tillage; recur in the same location.	Gullies are not obscured by normal tillage operations.
Usually smaller than ephemeral gullies.	Larger than rills and smaller than permanent gullies.	Usually larger than ephemeral gullies.
Cross-sections tend to be narrow relative to depth.	Cross-sections tend to be wide relative to depth.	Cross-sections tend to be narrow relative to depth.
Flow pattern develops as small-disconnected parallel channels ending at ephemeral gullies;	Forms dendritic pattern along depression watercourses. Tillage, crop rows might influence flow patterns.	Tend to form a dendritically pattern along natural watercourses.

2.3.4. Channel erosion

The final level of erosion is channel erosion, which occurs in watercourse channels and streams. Both the size and quantity of material, which can be eroded and transported increase as the velocity and volume of runoff increase. Channel erosion can be reduced by decreasing the volume and peak rate of runoff leaving the site (Bigatel *et al*., 1998).

A channel is a concentrated flow path for water leaving a field or watershed. Erosion in channels is mostly caused by downward scour due to flow shear stress (τ). Sidewall sloughing can also occur during widening of the channel caused by large flows. Channel erosion can be the first developed stage of the gully (Swart, 2004). Cumulative erosion on the slopes of the tailings dams may eventually result in gullies, which can enlarge and even cause shear failure or breaching of the dam (Blight, 2000; Blight and Dacosta, 2003).

2.3.5 Gully classification

Gullies can be classified by various criteria such as plan form, position in the landscape, cross-sectional shape, type of soil in which a gully has been developed and its temporary or permanent nature. Six characteristic gully forms have been recognized, produced by physical and land use factors influencing the drainage: linear, bulbous, dendritic, trellis, parallel and compound gullies. As result of the use of the plan form of the gully as a criterion, three main gully types were found to be: axial gullying with a single headcut, digitate gullying involving the development of several headcuts, and the frontal gullying which generally starts from river banks (Poesen et al., 2002).

Considering position in the landscape as a criterion, gullies have been classified as valley-floor, valley-side and valley-head, and each type can be discontinuous or continuous (Poesen *et al*., 2002). That is, each consists of the headward advance (see Figure 2.2), upstream migration of secondary knick points, and the widening of the gully channel (see Figure 2.3) (U S Department of Agriculture).

Table 2.2 Hierarchy of soil erodibility (Source: Gray and Sotir, 1996) (see page 32).

Soil type	Erodibility classification
Low plastic silt	Most erodible ↓
Silty sand	
Clayey sand	
High plasticity silt	
Low plasticity organic soil	
Low plasticity clay	
High plasticity clay	
Silty gravel	
Well graded sand	
Poorly graded sand	
Well graded gravel	Least erodible

Figure 2.2 Headward advance gully (Source: www.osondu.com)

Figure 2.3 Widening gully (Source: www.osondu.com)

2.4 Factors Affecting Erosion

There are four principal factors in soil erosion. These are climate, soil characteristics, topography and ground cover.

2.4.1 Climate

Climate affects erosion directly or indirectly. Directly is wherein rain acts as the driving force of erosion. Raindrops dislodge soil particles; uplift them, and then running water carries them away. The erosive power of the rain is determined by rainfall intensity and the size of droplets. A highly intense rainfall within a short period is likely to produce far more than a long-duration storm of low intensity. Storms with large raindrops are more erosive than misty rains with small droplets (Goldman *et al*., 1986). Lighter aggregate materials such as very fine sand, silt, clay and organic matter can be easily removed by raindrop splash and runoff water. Soil movement by rainfall is greatest and noticeable during short duration, high intensity thunderstorms (Wall *et al*., 1987).

2.4.2 Soil types and characteristics (see Table 2.2 on page 29)

Soil characteristics that are important in determining the soil erodibility are texture, organic matter content, structure and permeability. Soil erodibility is an estimate of the ability of soil to resist erosion, based on the physical characteristics of the soil. Generally, soils with faster infiltration rates, higher levels of organic matter and improved soil structure have a greater resistance to erosion (Wall *et al*., 1987).

Soil texture is regarded as the sizes and the proportions of the particles making up the type of soil. It depends on the proportions, by weight, of sand, silt and clay in a soil. Sandy soils are coarse textured and water may infiltrate such soils which reduces runoff and erosion potential. Soils with high content of clay and silts are fine textured. Clays are sticky, binding soil particles together, which in turn makes soil resistant to erosion. Fine materials, when eroded, can be transported for long distances before being deposited (Goldman *et al*., 1986).

Organic matter consists of decomposed wastes of animals and plants. It improves soil structure, increases permeability and soil fertility. In an undisturbed land, it serves as a mulch cover, which reduces runoff and erosion potential (Goldman *et al*., 1986).

Soil structure refers to the arrangement of the particles in the soil. It affects a soil's ability to absorb water. Loose granular soils absorb and retain water, which reduces runoff and erosion more than the compacted soil surface (Goldman *et al*., 1986).

Permeability refers to the ability of the soil strata to allow fluid to move through the soil. All the above-mentioned soil characteristics contribute to permeability. Highly permeable soils produce less runoff, which minimizes erosion potential (Goldman *et al*., 1986).

2.4.3 Topography

The critical factors of topography are slope length and slope steepness, since they determine the velocity of runoff. Long, continuous slopes allow runoff to build up momentum. High velocity runoff tends to concentrate in narrow channels and produce rills and gullies. The shape of the slope has a major bearing on erosion (Goldman *et al*., 1986), because the top of the slope is more susceptible to erosion than the base as a result of the deposition of the material at the base of the slope.

Material eroded from the top parts of the slopes would be eventually deposited at the footslope (i.e. surface retreat taking place at the upper section with deposition occurring towards the toe of the slope. It has also been observed that the vegetation percentage tends to increase from the top to bottom of the slope (Dacosta and Blight, 2003).

Wall *et al*. (1987) has once indicated that the steeper the slope, and the greater the amount of soil loss from erosion by water. The above statement is contrary to Dacosta and Blight, who showed that the erosion rate is low at both very flat and very steep slope angles. Maximum erosion occurs at slopes angles between 25^0 and 35^0, which are traditionally used for tailings dam slopes (Dacosta and Blight, 2003).

2.4.4 Ground cover

Ground cover usually refers mainly to vegetation, but can include surface treatments such as mulches, jute netting, wood chips and crushed rock. Vegetation is usually regarded as the most effective cover and is the most widely used form of erosion control. Vegetation shields the surface from the impact of falling rain, slows the velocity of runoff, holds soil particles in place and maintains the soil's capability to absorb water (Goldman *et al*., 1986).

The erosion-reducing effectiveness of vegetation cover depends on the type, extent and the quantity of the cover (Wall *et al*., 1987). Most of the slopes of tailings dams in South Africa were once rehabilitated by vegetation to guard against erosion. Due to the semi-arid nature of the climate, and the steep slope angles (about 33^0) on which vegetation was established, vegetation is difficult to maintain. After some time, vegetation may be completely lost as a result of drought, fires in the dry season and erosion (Blight and Dacosta, 1999).

Figure 2.4 The presence of gully erosion on the slopes of tailings dam (after Truong, 2003)

2.5 Empirical Models of Soil Erosion

Erosion of slopes has been a major subject of investigation since the magnitude of losses by soil erosion in many countries was recognized (Bennett, 1939). Basic understanding of most factors affecting soil erosion was developed from qualitative studies and measurements from experimental plots. The use of erosion plots under experimental and field conditions permitted the development of a number of empirical equations. In 1940, Zingg related soil loss to slope steepness and length expressed as: $\mathbf{A=CS^{m}L^{n-1}}$**,** where **A** is the average loss per unit area from the land slope of unit width, and **C** is a constant of variation. **C** combines the effects of rainfall, crop cover, soil characteristics and land management. **S** is the angle of the slope, **L** is the projected horizontal length of the slope, and **m** and **n** are the exponents of angle and horizontal length of land slope respectively (Pye, 1994).

The relationship of soil loss to ground conditions and rainfall intensity was expressed by Musgrave in 1947 in the formula:
$\mathbf{E=(0.00527)IRS^{1.35}L^{0.35}P_{30}^{1.75}}$ where **E** represents soil loss in mm per year, **I** is the inherent erodibility of a soil at 10% slope and 22 m slope length in mm per year, **R** is the vegetation cover factor, **S** is the slope angle in percent, **L** is the length of slope in m, and $\mathbf{P_{30}}$ is the maximum rainfall in 30 minutes (i.e. mm/30 min) (Pye, 1994).

In 1947, Smith and Whitt developed a method of estimating soil loss from clay pan soils of Missouri by the equation: **A=CSLKP**, where **A** is the average soil loss, **C** is the average annual rotation soil loss from plots, and **S, L, K** and **P** are the multipliers to adjust the plot soil loss, **C** for the slope steepness (**S**), length (**L**), soil group (**K**) and conservation practice (**P**) (Pye, 1994).

As a result of compilation and evaluation of over 8 000 plot-years of data from 36 locations and 21 states in the U.S.A., a new evaluation of data and factors affecting soil loss led to the development of the prediction method called Universal Soil Loss Equation (USLE) by Smith and Wischmeier (1957) in the formula: A=RKLSCP, where A is the soil loss, R is the rainfall erosive factor, K is the soil erodibility factor, L is the slope length factor, S is the erosion control practice factor, C is the management factor and P is the erosion control practice factor. Some of the purposes of the USLE were to predict average annual loss of soil from a cultivated field and estimates soil loss from areas that are not in agricultural use. (Pye, 1994). The USLE predicts average loss; it does not predict gully erosion and sediment delivery (Gray and Sotir, 1996).

The latest empirical formula to be used in the estimation of soil loss through erosion is the Revised Universal Soil Loss Equation (RUSLE). It was developed as a result of revising USLE. RUSLE is claimed to be land use independent and to be applicable to cropland, disturbed forestland, rangeland, construction sites, mined land, reclaimed land, landfills, waste disposal sites and other lands where rainfall and its associated overland flow cause soil erosion (Gray and Sotir, 1996).

Both RUSLE and USLE can be expressed as: A=RKLSCP where A is the estimated average soil loss in tons per acre per year, R is the rainfall-runoff erosivity factor, K is the soil erodibility factor, L is slope length factor, S is the slope steepness factor, C is the management cover and P is the support practice factor (Gray and Sotir, 1996).

It is not applicable to the calculation of soil loss from gullies or streams, but has been used for estimating average annual soil loss and sediment yield resulting from interill and rill erosion (Spaeth *et al*., 2003).

2.6 Prevention of Erosion

2.6.1 Seeding and vegetation methods

In most cases seed is sown immediately before the expected reliable rains or the break of the season. This can serve as a rehabilitation method to facilitate long-term stability against erosion (Rix *et al*., 1986). The loss or absence of vegetation on a slope can result in increased rates of erosion and possibly even slope failure. Vegetation plays an important role in controlling rainfall erosion. Maintaining a dense cover of grasses, or vegetation can decrease soil losses due to rainfall erosion (Gray and Sotir, 1996).

2.6.2 Biotechnical stabilization and soil bioengineering

Biotechnical stabilization and soil bioengineering both entail the use of live materials. Biotechnical stabilization utilizes mechanical elements (structures) in combination with biological elements (plants) to prevent slope failures and erosion. Both biological and mechanical elements must function together in an integrated and complementary manner. Biotechnical stabilization can be characterized by the conjunctive use of live vegetation with retaining structures (Gray and Sotir, 1996).

Gray and Sotir (1996), revealed that the use of primarily vegetation or other biological materials, without the inclusion of inert structural materials like rock, stone or wood is called soil bioengineering. Soil bioengineering can be regarded as a subset of biotechnical stabilization, because plant parts such as roots and stems serve as the main structural and mechanical elements in the slope protection system. Live cuttings and rooted plants are embedded in the ground in such way that they serve as soil reinforcements, drains and barriers to earth movements (Gray and Sotir, 1996).

3 THE OCCURRENCE OF EROSION ON THE SLOPES OF TAILINGS DAMS

3.1 Soil Erosion and Erosion Prevention

Tailings dams, alongside waste rock and overburden and ore stockpiles are well-known sources of erosion associated with the mining industry. Soil erosion may be caused by wind and rain runoff or a combination of the two. Due to the small particle sizes that compose tailings, such materials are easily transported by the agents of erosion, which may lead to sheet erosion, followed by the development of rills and gullies. The surfaces of natural slopes are usually covered by vegetation with some rocks, which serve as the obstacles in reducing the velocity of the surface runoff.

Slopes of tailings dams are usually steeper than the earth slopes agriculturalists consider. Therefore, finding new methods for erosion protection such as cement stabilizing, covering surfaces with stones, etc, are being studied. Not the whole of a tailings dam needs to be protected, but mainly the slopes and attention must be given to slope length and slope angle because of their effect on erosion resistance.

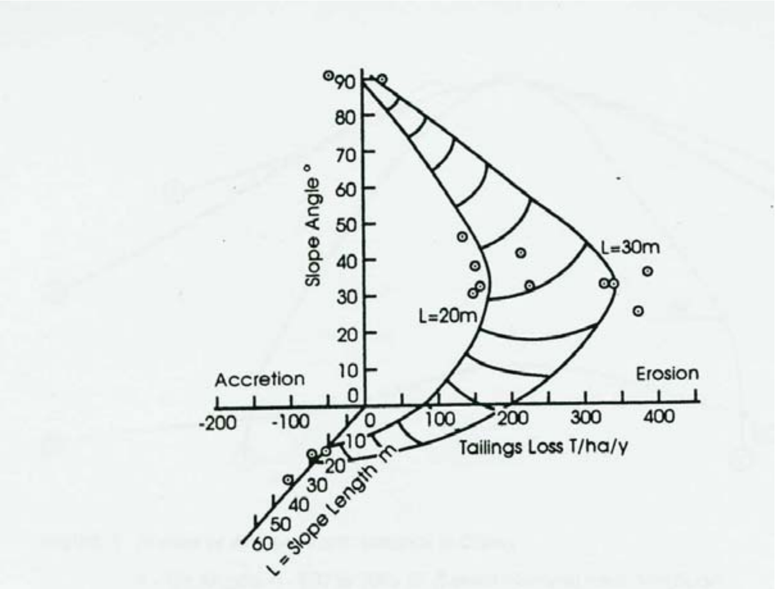

Figure 3.1 Erosion rate data for unprotected tailings dam slopes in (slope angle-slope length-erosion loss) space (after Blight and Dacosta, 2004)

Erosion-resistant methods are intended to reduce, if not to prevent the occurrence of erosion processes. It is believed that a surface cover of vegetation together with gravel and boulders plays a significant role in the reduction of erosion. Due to the nature of the conditions prevailing on the slopes of the tailings dams in South Africa, gullies or erosion channels exist on most tailings dams.

Methods of resisting erosion could be useful during repair of already damaged slopes of existing tailings dams. For example, vetiver grass has been applied during rehabilitation of tailings dams in Congo (Truong, 2003) along the channels developed on the slopes of the tailings dams. However, vetiver grass should not be introduced in South Africa without careful investigations, as it may prove to be an invasive alien species.

Erosion on the slopes of the tailings dams is one of the ongoing impacts associated with the tailings disposal and is mostly noticeable during the post-closure stage of the mine than during the operational periods. A surface-stable condition for tailings dams or impoundments, both during and after the mining operation should be an essential factor in future planning and design of tailings dams.

Table 3.1 shows that control erosion is high on the slopes of tailings dams. Although previously most of the tailings were rehabilitated through planting vegetation, there are other simple treatment techniques that can also be used in combating erosion on tailings dams slopes. Although mining companies may be willing to spend less in preventing erosion on the tailings slopes, it will be advisable to apply an effective method, which could last long-term. Of all the methods mentioned below, panel 10 relatively yields good results and this promotes the consideration of panel 3, 5 and 10 in Table 3.1.

Table 3.1 Cost-effectiveness evaluation of slope protection methods (Source: Blight and Dacosta, 2004)

Panel No.	Treatment	Level & compact	Level only	Relative cost ha^{-1} C(%)	Erosion rate t/ha/yr Phase 2	Erosion rate t/ha/yr Phase 3	Relative erosion E (%) Phase 2	Relative erosion E (%) Phase 3	Cost-effectiveness C x E (%) Phase 2	Cost-effectiveness C x E (%) Phase 3	Cost-effectiveness ranking Phase 2	Cost-effectiveness ranking 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

3.2 Rehabilitation of Tailings Dams and Repair of Erosion Damage

An important part of rehabilitation is aimed at the repair of existing erosion problems by increasing the erosion resistance of the materials in the flow path and by protecting these materials from direct attack by flowing water. The rehabilitation of tailings dams can be demanding, as these structures are likely to remain permanently where constructed, unless tailings remining or retreatment takes place.

The long-term presence of a tailings dam could gradually result in land degradation, especially where there is a lack of environmental monitoring. The development of sheet erosion and erosion channels on the slopes of tailings dams could be an important source of land degradation.

Environmental impacts associated with the mine tailings dams can be reduced or prevented through the application of various prevention techniques such as the use of compacted tailings to fill eroded channels on the slopes of the tailings dams, flattening the sides of developed gullies, the sowing of vegetation, specially along developed erosion gullies, and the use of silt-retaining walls at the mouths of gullies and surrounding tailings dams.

It appears that, since consideration has been given the environmental impacts associated with either the mining or energy industries, vegetation has been the principal technique used in the reduction of the impacts and pollution, without proper understanding the characteristics of those particular tailings dams. Not all of the vegetated tailings dams have been successfully rehabilitated.

Vegetation as a means of rehabilitation has the capability to restore the land affected by mining operations to the vegetation ecosystem, and this might support the aspect of it being the most common rehabilitation method (see, e.g. Figure 3.2). Vegetation has been widely used in the past as the most common effective method for reducing the risks of erosion, but there are various non-vegetative rehabilitation methods, that may be cheaper than the conventional vegetation, such as covering the slopes fine and coarse rocks (see Table 3.1).

Figure 3.2 Vetiver grass planted along the developed gully to prevent gully erosion (after Truong, 2003)

3.3 Gullies on Slopes of Tailings Dams

The existence of gullies in slopes of tailings dams may be attributed to various factors, including the nature of the mineral components disposed and the period at which the tailings dam remain exposed to water erosion. It is known that because of the steep slopes of tailings dams, protection of such slopes tends to be very difficult (Blight *et al*., 1984).

Erosion in its early stages can be fairly combated, but eliminating gullies can be demanding. Gullies can be dealt with by constructing crest walls, which prevent water accumulating on the top surface from flowing down the slopes (Blight *et al*., 1984). Apart from serving as a storm water deviation, crest walls may also retain already eroded materials. The introduction of berms along the steep slopes can also aid in the reduction of erosion by reducing the length of slope (Blight and Dacosta, 1999).

Because sheet and rill erosion on the slopes of the tailings dams is no easily visible, it may be assumed that a tailings deposit is stable. Both of these erosion types or processes may occur on slopes covered with vegetation, which effectively hides the erosion damage. In areas without protection, such damage will be clearly visible (Blight and Dacosta, 1999) and may also graduate to gully development.

4 LABORATORY INVESTIGATION

4.1 The Comet Erosion Tester (Chamber of Mines Erosion Tester)

This is an erosion tester that was used by Blight *et al*. (1981) to measure the erodibility of the surfaces of gold tailings dams. The Comet directs a 0.8 mm diameter jet of water onto the surface of the soil from a distance of 25 mm. The pressure behind the jet is increased at a steady rate until the surface breaks. The pressure at which the jet breaks the surface is recorded as a measure of the erosion resistance. It helps in determining the effectiveness of stabilizing materials applied to reduce erosion of tailings surfaces.

The Comet test was firstly conducted on the flat, top surfaces of tailings dams, as well as on the slopes. Erosion associated with tailings dams occurs mainly from the outer slopes of the dams.

There was an expectation during its early trials that the erosion resistance of the surface could be directly related to the readings of the Comet test and that erosion loss would decrease with increasing Comet readings. However, it was found, in fact, that for unstabilized surfaces, higher Comet readings were related to higher erosion losses.

The problem with this test appeared to be that the water jet is pressurized whereas the impact of raindrops is much less disruptive. Also, when the jet impinges on a dry unstabilized surface, the capillary stresses providing the strength of the surface are destroyed, the soil softens and the water jet then breaks the surface. With a stabilized surface, the strength may reduce when wetted, but the stabilizer provides a wet strength that resists erosion. Hence, when used on stabilized surfaces, increasing Comet resistance does indicate increasing erosion resistance.

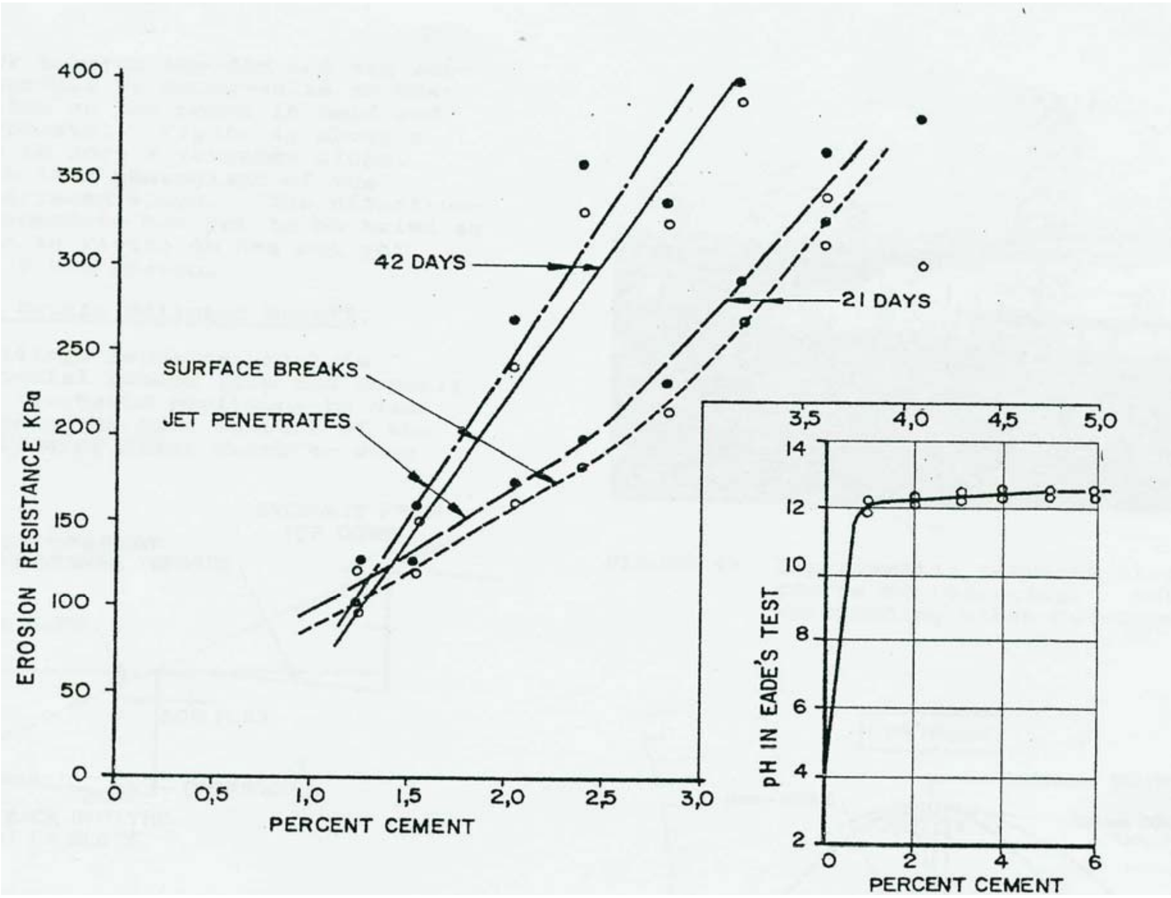

Figure 4.1 Results of experimental stabilization of tailings with cement for 21 and 42 days (after Blight *et al.*, 1981)

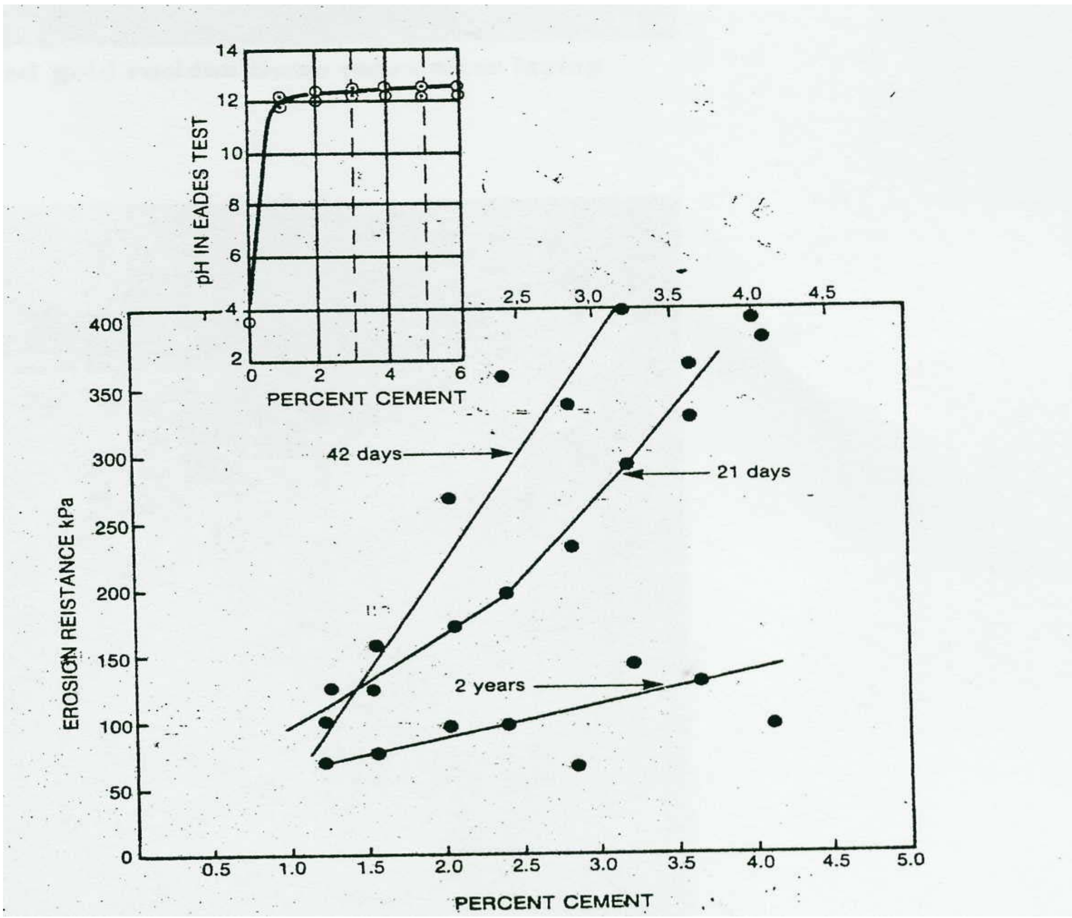

Figure 4.2 Results of experimental stabilization of tailings with cement for 21 and 42 days with 2years (after Blight *et al*., 1984).

Figure 4.1 and 4.2 above show that erosion resistance on a cement stabilized tailings layer 42 days after placing was better than at 21 days, but the material slowly deteriorated with time and after two years the erosion resistance had markedly deteriorated. This may be attributed to the low pH and the sulphate content of the gold tailings. Figure 4.1 and 4.2 show that cement, as a stabilizer is strong at early ages, with the addition of the cement content increasing both the pH values and the erosion resistance.

4.2 The Pinhole Erosion Test

The pinhole erosion test is one of four laboratory tests usually used to identify dispersive soils, the others being Crumb Test, the US Soil Conservation Service Dispersion Test and soil pore water chemistry correlation. It was developed to identify dispersive soils in order to prevent internal erosion by piping caused by dispersive characteristics. Dispersive soils are soils in which a fraction erodes in the presence of water by a process of deflocculating. Dispersive soils cannot be identified by conventional index tests such as particle size distribution, Atterberg limits or permeability tests.

Rainfall erosion on the slopes of earth dams is one of the problems associated with dispersive soils (Sherard *et al*., 1976). In this study, the pinhole erosion test was used as a possible indication of soil erodibility, whether or not the soil soil is dispersive. It is being considered as a possible alternative to the Comet test. If the results are considered promising, the next step will be to devise a version of the pinhole test that can be applied in the field.

The pinhole test applies erosive energy to the soil sample via water flow through a pinhole of 1.05 mm initial diameter formed in a compacted soil specimen. Distilled water is passed through the pinhole. Visual inspection for effects of erosion of the pinhole is carried out after testing is complete. Dispersive clay soils produce turbid water with an eroding hole. Nondispersive clay soils result in clear water at the collection outlet and little change in pinhole dimensions (Vacher *et al*., 2004). It was assumed that unstabilized tailings would behave rather like dispersive soils, while tailings stabilized with cement or other agents such as synthetic resins would be more resistant to erosion.

4.3 Laboratory Work

Platinum, gold and coal tailings were used as test materials. The following tests were aimed at characterizing the various materials. All of the tests below were established by standard procedures.

4.3.1 Particle size distribution

Grain size distribution has an influence on the erodibility of the soil. Wall *et al*., (1987) state that soil erodibility is a measure of the ability of soils to resist erosion, based on the physical characteristics of each soil. Soils with little or no bonding materials are more prone to erosion than soils with bonding materials. This is contrary to the statement that sand, sandy loam and loam textured soils tend to be less erodible than silt, very fine sand and certain clay textured soils (Wall *et al*., 1987) because the latter mostly contain clay which in turn serves as the bonding material.

According to the hierarchy of soil erodibility by Gray and Sotir, (1996) which was based on the gradation and plasticity indices of remolded or disturbed soils, soils with low-plasticity silt were the most erodible as compared to the well-graded gravel as the least erodible soil. (Refer to Table 2.2, Hierarchy of Soil Erodibilty). The particle size curves for the tailings are presented in Figure 4.1. This enables a comparison of the distribution of grain sizes. Soil is classified into gravel (ranging from 2 to 100 mm), sand (ranging from 0.06 to 2 mm), silt (ranging from 0.002 to 0.06 mm) and clay (less than 0.002 mm).

4.3.1.1 Platinum tailings

Platinum tailings are composed mainly about 98 percent of particle sizes ranging from 0.6 mm to 0.075 mm.

4.3.1.2 Gold tailings

Gold tailings used in this study do not seem typical and are believed to be a mixture of gold tailings and gravel, hence the gap-graded curve in Figure 4.1.

4.3.1.3 Coal tailings

The particle size distribution for coal tailings, which is similar to that of platinum tailings, is also shown in Figure 4.1.

Table 4.1 Particle Size Analysis using Sieve Analysis Method

Platinum tailings		Gold tailings		Coal tailings	
Sieve analysis method		Sieve analysis method		Sieve analysis method	
Sieve size (mm)	Percentage passing (%)	Sieve size (mm)	Percentage passing (%)	Sieve size (mm)	Percentage passing (%)
1.180	100	19.000	100	2.360	100
0.600	99.8	13.200	99.1	1.180	99.1
0.425	98.8	9.500	95.7	0.600	82.4
0.300	94.9	6.700	90.3	0.425	65.8
0.150	60.4	4.750	85.6	0.300	49.1
0.075	1.70	2.360	71.3	0.150	18.8
		1.180	61.4	0.075	0.33
		0.600	55.5		
		0.425	53.0		
		0.300	50.9		
		0.150	40.6		
		0.075	3.5		

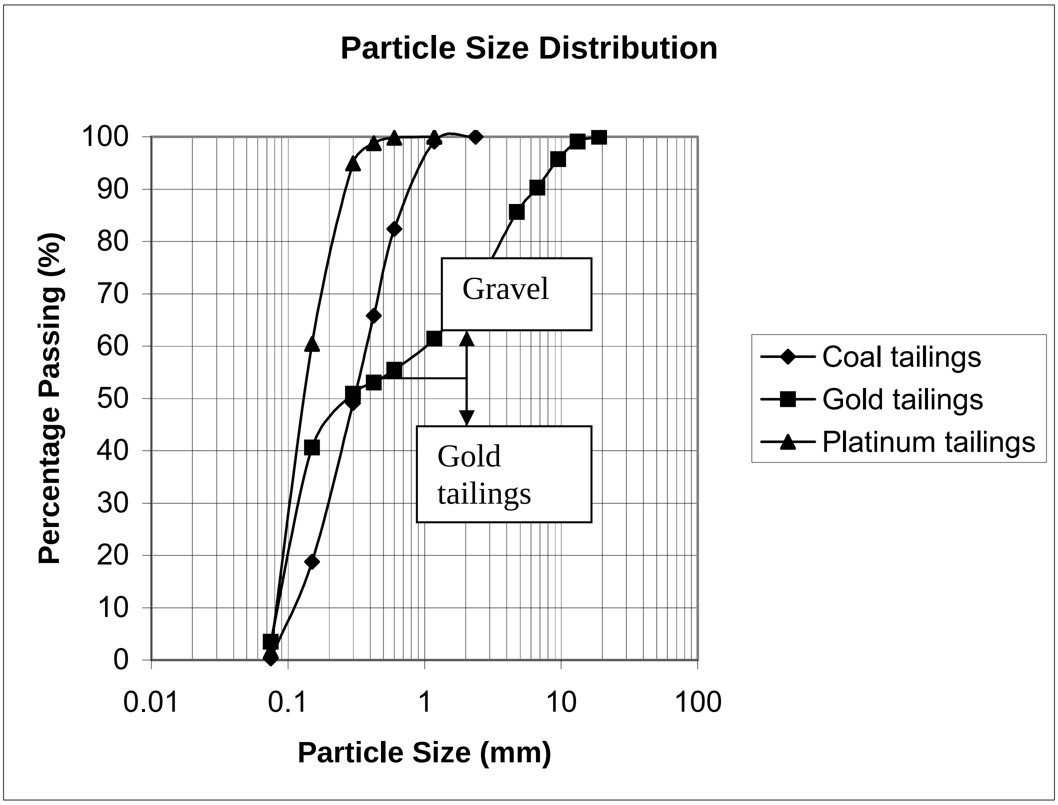

Figure 4.3 The particle size distribution using sieve analysis

4.3.2 Specific gravity

Table 4.2 Specific gravity of platinum, gold and coal tailings

	Platinum tailings		Gold tailings		Coal tailings	
Specimen number	1	2	1	2	1	2
Average	3.43	3.41	2.68	2.81	1.71	1.73
(Gs)	3.42		2.75		1.72	

4.3.3 Atterberg limits

Table 4.3 Liquid limit and plastic limits of platinum, gold and coal tailings

	Platinum tailings	Gold tailings	Coal tailings
Liquid limit (w_l)	None	24	27
Plastic limit (w_p)	None	19	22
Plastic index (I_p)	None	5	5
Linear shrinkage	None	1	None

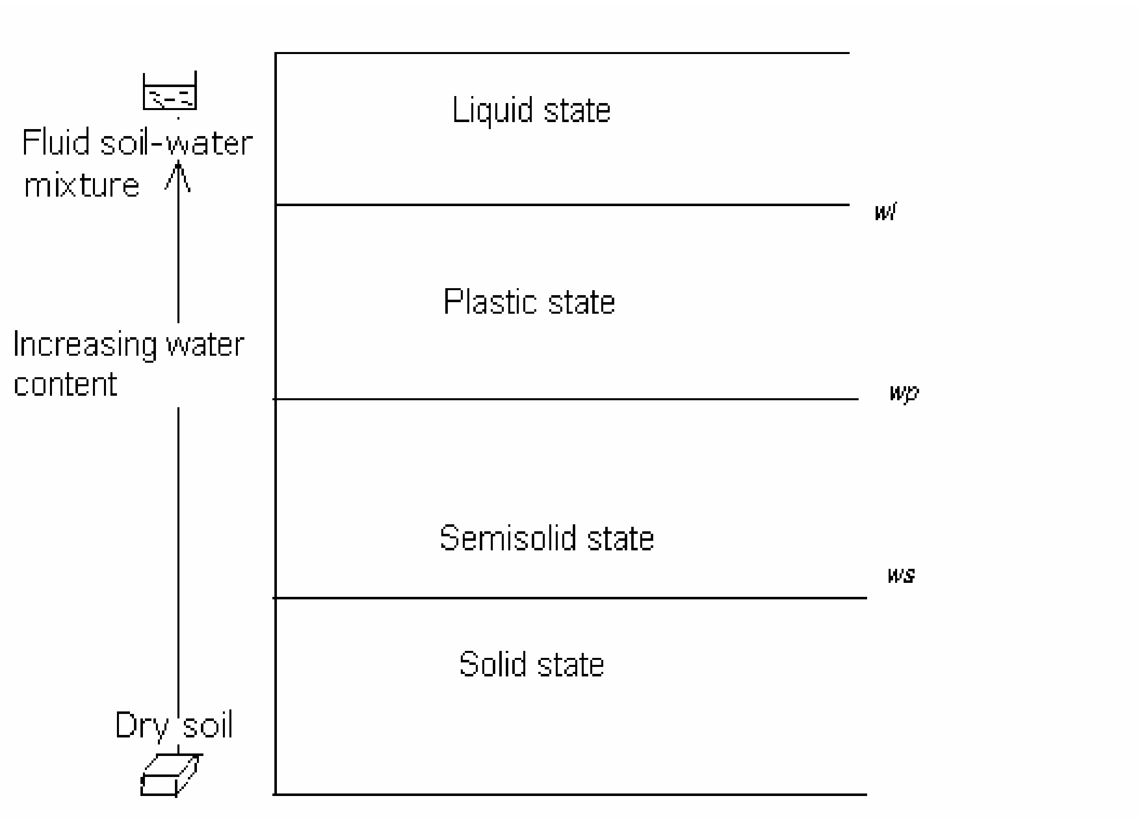

Figure 4.4 Atterberg limits and related indices (after Lambe and Whitman, 1969)

4.3.4 Moisture-density relationships (Standard Proctor compaction test)

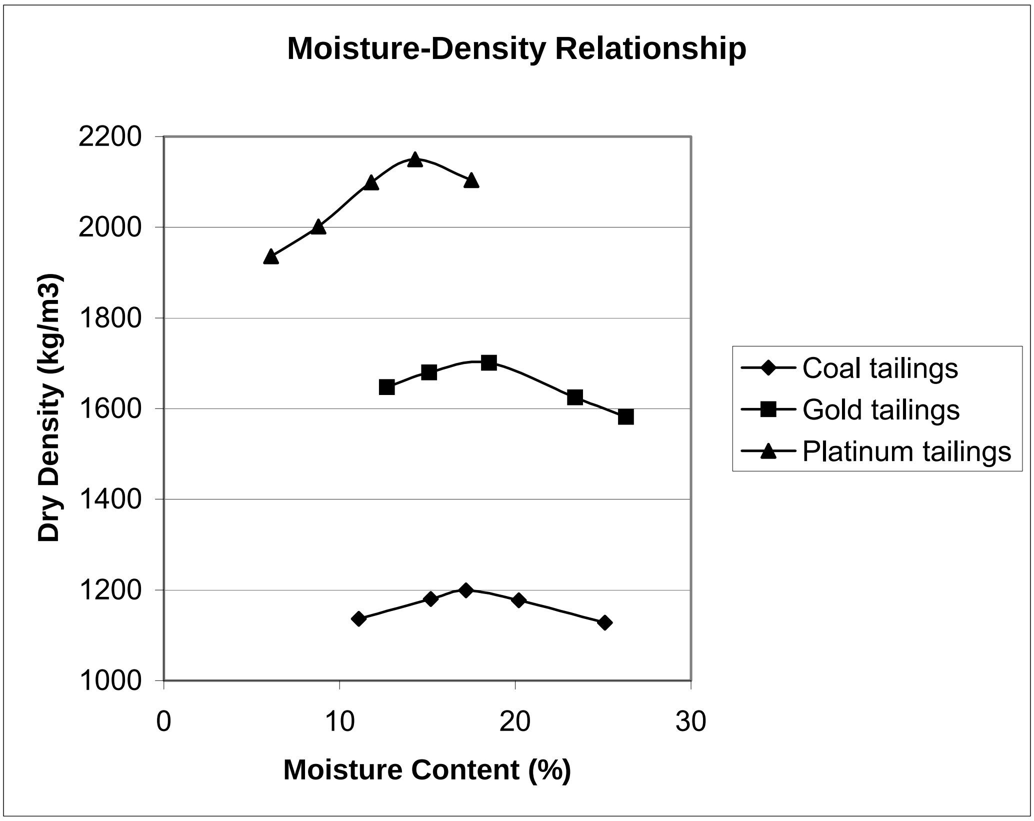

Figure 4.5 Moisture-density relationship of tailings

Figure 4.5 presents the compaction test results for the three tailings: platinum, gold and coal. Each of the curves shows the optimum water content and maximum dry density used in the preparation of pinhole the erosion test. Platinum tailings have a maximum dry density of 2150 kg/m^3 obtained at 14.3% water content. Gold tailings has a maximum dry density of 1701 kg/m^3 obtained at 18.5% optimum water content while coal has a maximum dry density of 1999 kg/m^3 obtained at optimum water content of 17.2%.

Table 4.4 Compaction tests at 97%, 95% and 90% of the original maximum dry density of 1701 kg/m^3, at optimum water content of 18.5% along –2 and+2 % of 1 day old

Compaction percentage	Age (days)	Moisture content (%)	Dry density (kg/m^3)
97%	1	20.9	1682
	1	20.0	1687
	1	23.9	1659
95%	1	17.7	1624
	1	23.3	1612
	1	21.5	1616
90%	1	18.9	1538
	1	22.3	1537
	1	22.6	1526

5 DETAILS OF THE PINHOLE EROSION TEST

5.1 Introduction

A general description of the test is given in section 4.2. The practical details of the test are set out below.

5.2 Apparatus

Tailings were compacted in a mould of known volume of 70.3 cm^3). Knowing the required compacted density of the soil, enabled the mass of loose soil to be determined that, when compacted to 70.3 cm^3, would give the correct density. The diameter of the mould is 37.4 mm and the length of 93 mm. The base mould has a wire built in to form the pinhole. The compaction mould has a slight taper to facilitate extrusion of the sample. This pinhole formed by the wire serves as the channel for the flow of distilled water.

The sample is clamped with the hole vertical and the plastic pipe providing the water, feeding into the hole and connected to a container filled with distilled water. The difference between the highest level of water to the lowest point of the stand is 0.5 m. The supporting stand is placed in a basin collecting the outflow to observe the eroded tailings. Distilled water is passed through the sample for 10 minutes, or until no further erosion occurs.

All-purpose Portland cement was added to the tailings materials for preparing the samples, to stabilize the tailings against flowing distilled water. The particle size analysis and Atterberg limits show that platinum and coal tailings lack clay, capable of bonding materials together for a considerable period before excessive eroding.

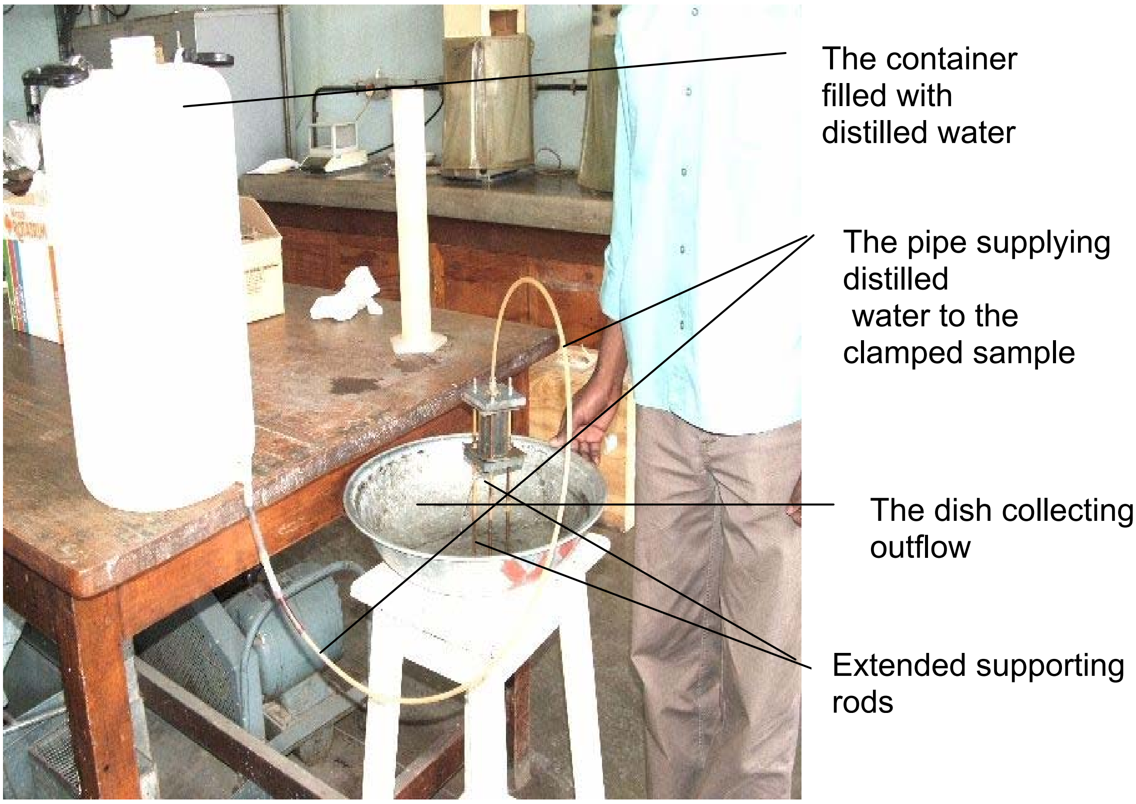

Figure 5.1 The pinhole erosion test

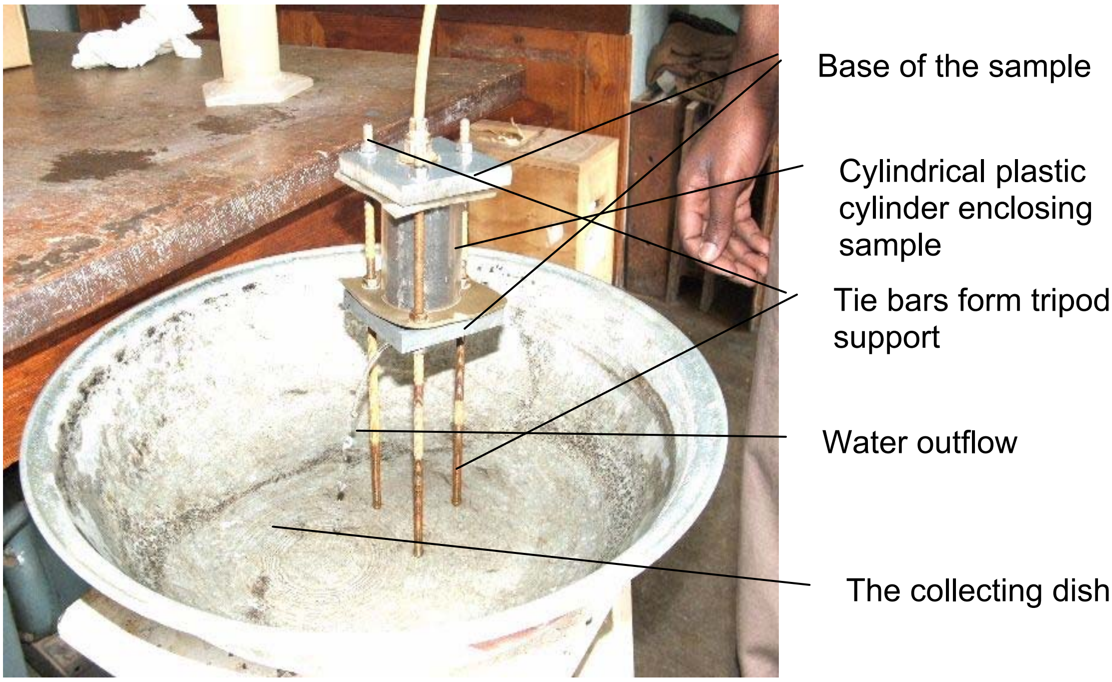

Figure 5.2 The outflow-collecting dish with the apparatus inside

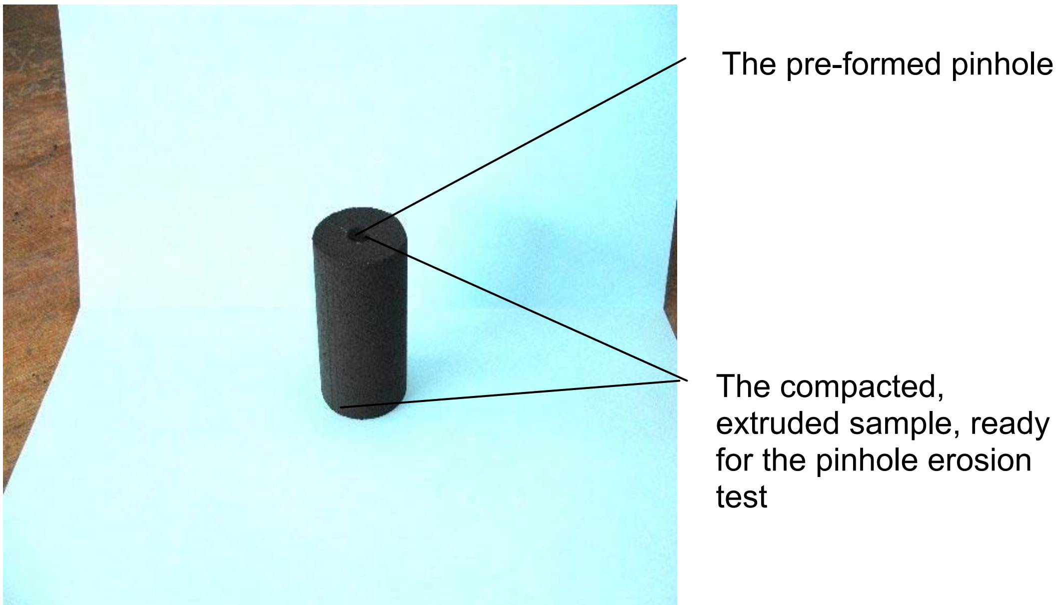

Figure 5.3 The sample ready for the pinhole erosion test

5.3 Testing Procedures

Samples were prepared and subjected to erosion by the distilled water. Due to the differences in the age of the cured and uncured cement samples, cured samples had been wrapped in a plastic and sealed for 14 days to prevent evaporation. They were then tested at the age of 14 days. Uncured and non-cement samples were subjected to erosion the same day of preparations.

5.3.1 Pinhole erosion test

A similar procedure was used for gold, platinum and coal tailings. Loading a measured mass of prepared soil to a predetermined length, thus achieving a predetermined dry density in a compression machine, compacted the material inside the mould.

The air-dried material was mixed with water to a pre-determined series of water contents (*w*), based on the Proctor Compaction tests done previously (See Figure 4.4. For the above figures, the required mass of loose sample to be placed inside the mould and compacted to a known volume could be calculated (i.e. dry mass =volume $\times$ dry density; wet mass = dry mass $\times$ 1 + *w*).

All three tailings used were dried in the oven for overnight and no sieving or crushing was done to allow materials to pass a certain designated size. Samples were reduced at about 300 g in respective beakers in relation to the quantity of cement added. Cement added ranged from 1 to 7%. The mixture was slightly over-saturated with distilled water and mixed for 30 seconds in every 10 minutes for about an hour, whereafter the pH was measured. The pH electrode was gently inserted and slightly shaken continuously until the pH meter gave a constant value (after Ballantine and Rossouw, 1989).

5.4 Results of Pinhole Erosion Test

Table 5.1 Pinhole Erosion Tests of Gold Tailings

Stabilizer		Erosion Loss (% Dry Mass)	Compaction Dry Density (kg/m^3)
	0% cement	0.030	1701
		0.040	1687
		0.055	1624
		0.077	1538
Uncured cement	3% cement	0.017	1701
		0.025	1687
		0.027	1624
		0.030	1538
	5% cement	0.021	1701
		0.024	1687
		0.029	1624
		0.032	1538
	7% cement	0.014	1701
		0.027	1687
		0.029	1624
		0.034	1538
Cured cement (14 days)	3% cement	0.009	1701
		0.011	1687
		0.028	1624
		0.036	1538
	5% cement	0.014	1701
		0.021	1687
		0.026	1624
		0.039	1538
	7% cement	0.009	1701
		0.011	1687
		0.018	1624
		0.032	1538

5.4.1 Gold tailings

The results of the pinhole erosion tests have been tabulated in Table 5.1 and are graphed in Figure 5.4a, which shows erosion loss (as a percent of initial dry mass) versus dry density for various cement contents. The results of tests on both uncured and cured specimens are shown. All of the graphs show that erosion loss decrease with increasing dry density. However, the addition of only 3% of cement caused a considerable reduction in erosion loss at all dry densities. It is also remarkable that the reduction in erosion loss occurs in both cured and uncured specimens. With cement additions of 3 and 5%, uncured and cured specimens have almost the same erosion loss, and it is only when the cement content is increased to 7% that curing appears to have a noticeable effect. It is thus obviously not the curing and the hardening of the tailings by cementation that is causing the reduction in erosion loss.

Figure 5.4b shows the effect of cement addition on the pH of tailings freshly mixed with up to 7% of cement. The figure shows that 3% of cement raised the pH from 5.8 to 10. Thereafter increasing the cement content to 7% increased the pH to 10.9. It appears that increasing the pH from acidic to alkaline had a major effect on reducing the erodibility of tailings.

Table 5.2 Experimental results of the relationship between pH and cement of gold tailings

Cement	pH
0%	5.85
3%	9.99
5%	10.67
7%	10.91

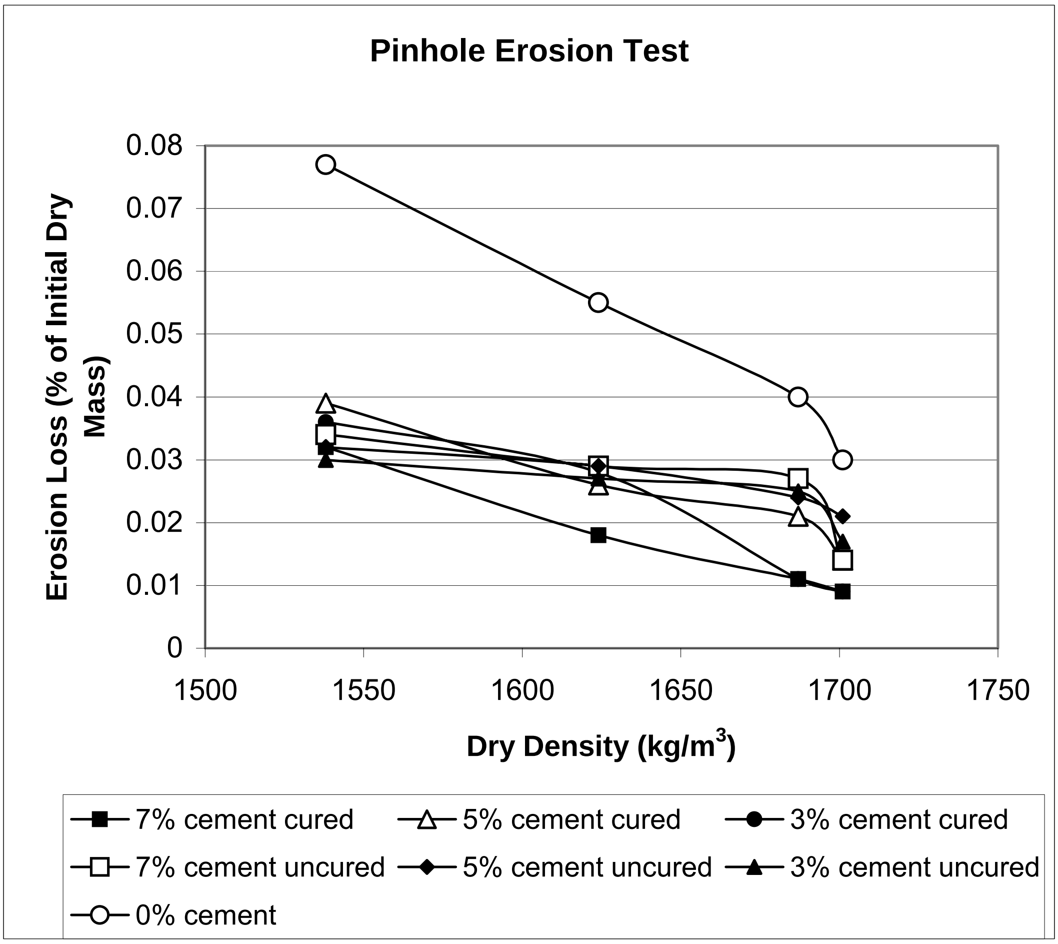

Figure 5.4a Pinhole erosion test on the gold tailings

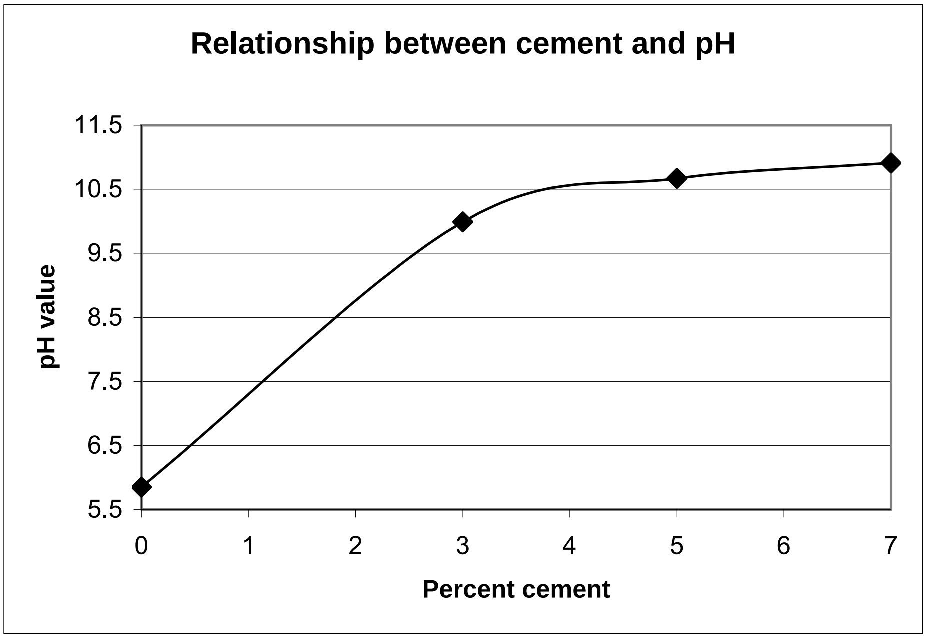

Figure 5.4b Relationship between cement and pH values of gold tailings

5.4.2 Platinum tailings

Increasing dry density also helped in reducing erosion of platinum tailings, as Table 5.2 shows that erosion loss for platinum tailings decreased with increasing dry density. Figure 5.5b shows that platinum tailings are weakly alkaline in their chemistry, as revealed by the pH value of 8.85 for tailings without cement added. Cement is regarded as a strong base, ranging in pH from 12 to 13 (Trahan, 1999) and this caused the progressive rise of the pH of the mixture as the cement content was increased.

Samples without cement suffered fairly high erosion losses and the addition of cement also reduced losses in uncured specimens, as was the case with gold tailings. Cured specimens suffered higher erosion losses than uncured specimens and specimens without cement. This unexpected behaviour occurred with cured specimens at all cement contents from 1 t0 5% and cannot at present be explained.

Table 5.3 Pinhole erosion test of platinum tailings

Pinhole Erosion Test		Erosion Loss (% Dry Mass)	Compaction Dry Density (kg/m^3)
	0% cement	0.072	2150
		0.098	2043
		0.111	1935
		0.117	1828
Uncured cement	1% cement	0.069	2150
		0.088	2043
		0.095	1935
		0.098	1828
	3% cement	0.073	2150
		0.090	2043
		0.095	1935
		0.099	1828
	5% cement	0.082	2150
		0.098	2043
		0.104	1935
		0.107	1828
Cured cement (14 days)			
	1% cement	0.084	2150
		0.097	2043
		0.123	1935
		0.158	1828
	3% cement	0.089	2150
		0.111	2043
		0.124	1935
		0.154	1828
	5% cement	0.085	2150
		0.103	2043
		0.126	1935
		0.149	1828

Table 5.4 Experimental results of the relationship between pH and cement of platinum tailings

Cement	pH
0%	8.80
1%	10.82
3%	11.42
5%	11.66

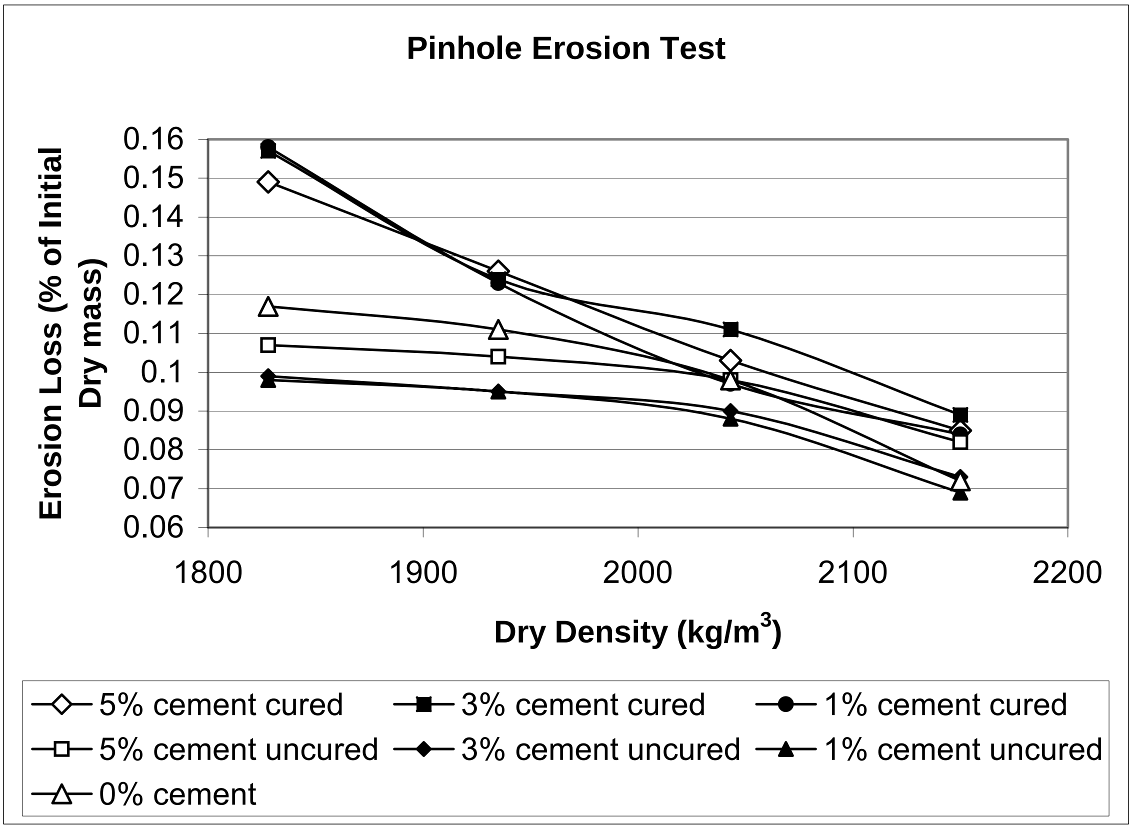

Figure 5.5a Pinhole erosion test of platinum tailings

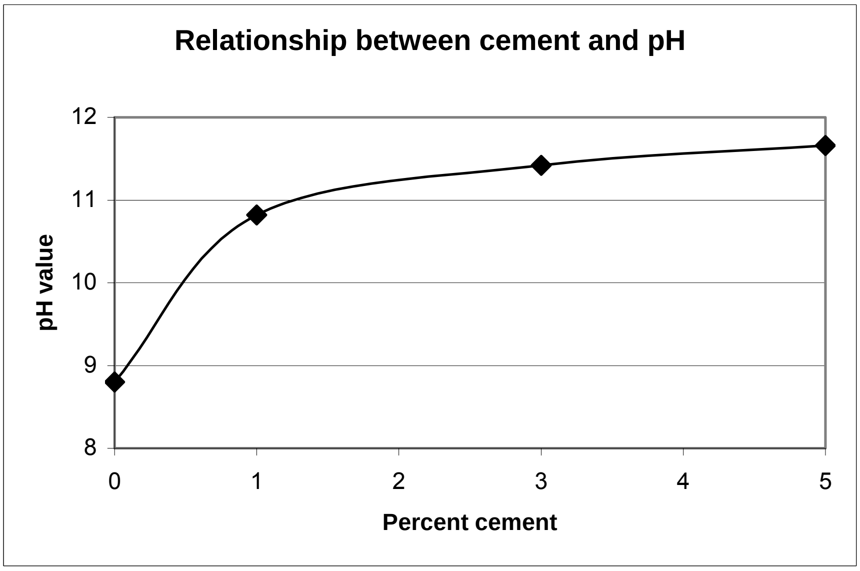

Figure 5.5b Relationship between cement and pH value of platinum tailings

5.4.3 Coal tailings

Coal materials produced results different from the other tailings materials subjected to the pinhole erosion test. This is because, in most samples, the pinhole collapsed, rather than enlarging by losing materials by erosion. It might be that more stabilizer should be used, although it would be costly to treat a large deposit in the field with large contents of cement. In these tests also, the cured cemented specimens eroded more readily than the uncured cemented samples.

Table 5.5 Pinhole erosion test of coal tailings

Stabilizer		Erosion Loss (% Dry Mass)	Compaction Dry Density (kg/m^3)
	0% cement	0.040	1199
		0.043	1139
		0.055	1079
		0.058	1019
Uncured cement	3% cement	0.050	1199
		0.037	1139
		0.016	1079
		0.005	1019
	5% cement	0.039	1199
		0.010	1139
		0.144	1079
		0.029	1019
Cured cement (14 days)	1% cement	0.045	1199
		0.070	1687
		0.047	1079
		0.050	1019
	3% cement	0.051	1199
		0.085	1139
		0.101	1079
		0.207	1019
	5% cement	0.060	1199
		0.096	1139
		0.078	1079
		0.167	1019

Table 5.6 Experimental results of the relationship between pH and cement of coal tailings

Cement	pH
0%	7.92
1%	9.75
3%	10.93
5%	10.95

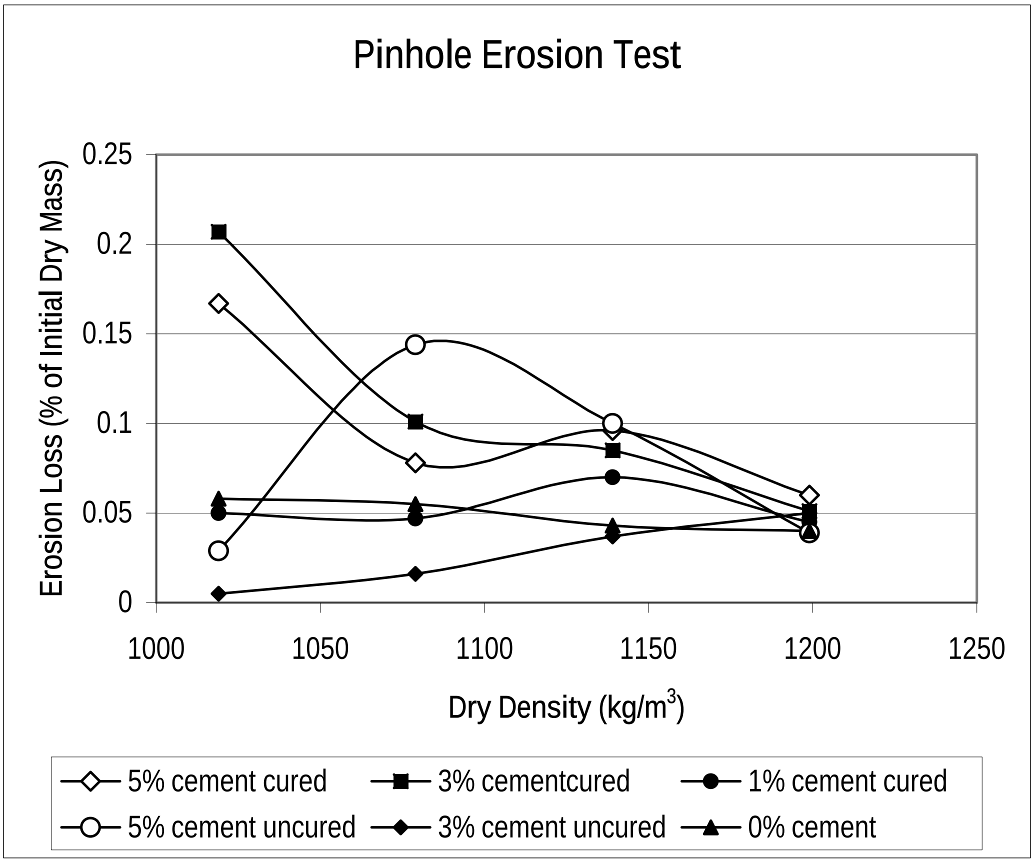

Figure 5.6a Pinhole erosion test of coal tailings

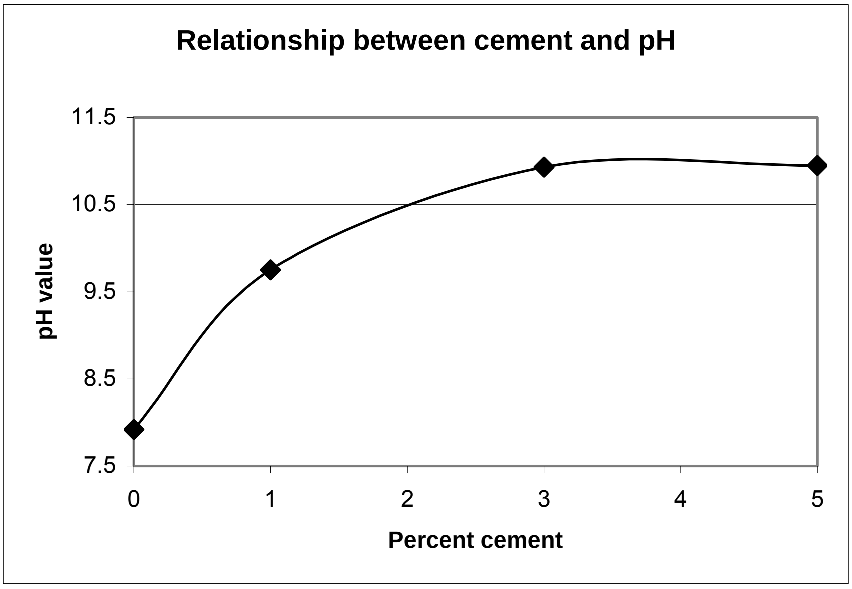

Figure 5.6b Relationship between cement and pH value of coal tailings

There is a significant increase in pH between 0% cement tailings (pH 7.9) and 1% cement added to tailings (pH 9.7). A further increase occurred with 1% and 3% cement, but tailed off to pH = 10.9 from 3% to 5% cement.

5.4.4 Further observations

Densification increases the strength of materials. All compacted materials, on which erosion tests were conducted, appeared to vary in density, and therefore erosion resistance, from top to bottom. Visual inspection showed that after an erosion test there was an increase in pinhole size at the bottom as compared to no or little size change at the top of the pinhole. For this reason, samples tended to collapse from the bottom of the sample. The use of the cement added in the mixture of the sample was aimed at reducing erosion.

It was observed from the values obtained (refer Appendix B) and the graphs above that the higher the cement content, the more erosion resulted. Uncured samples with cement seemed to be less erodible than plain tailings materials.

The evaluation of the pinhole test was aimed at determining the degree of erosion susceptibility of the tailings. The tailings showed different mechanisms of erosion. Gold tailings released clear outlet water for some time, followed by cloudy yellowish water. For coal, the outflow water is blackened from the start of the test while the grayish colour of platinum tailings wasn't strong enough to discolour the effluent.

6 SUMMARY AND CONCLUSIONS

6.1 Summary

Materials eroded with different magnitudes and rates depending on the addition of cement and the density level. All three types of tailings used in the pinhole erosion test showed that most erosion took place at the bottom part of the sample where compaction appeared to be less as compared to the top part of the sample. In the field, runoff water will be in contact with the overlying covering materials with compaction probably higher on the surface, and the less compacted tailings at depth will initially not be exposed to the effects of erosion.

Cement added as a stabilizer, seemed to have both negative and positive effects in terms of susceptibility of tailings to erosion. In most of the tests in which cement was added, there was a reduction in erosion loss as compared to uncemented tailings, but curing appeared to reduce, or have little positive effect on the erosion resistance of cemented tailings.

Figures 5.4b, 5.5b and 5.6b show that only the gold tailings were acidic as compared to platinum and coal, which were weakly alkaline, yet the addition of cement appeared to affect all three materials in a similar manner.

6.2 Conclusions

The aim of the study was to give a better understanding of the mechanisms of formation of erosion channels on the slopes of tailings dams. This study showed that the pinhole erosion test can be used to compare differences in the erodibility of materials and can illustrate the effects of density, pH cementation on potential erodibilty. However, the results were unexpected and will need further research to be fully understood.

APPENDIX: A

DESCRIPTION OF PARTICLES

Table A1 The sieve test of platinum tailings

Sieve size (mm)	Mass retained (g)	Percentage retained (%)	Percentage passing (%)
1.180	-	0	100.00
0.600	0.7	0.2	99.8
0.425	4.1	1.0	98.8
0.300	16.1	3.9	94.9
0.150	141.5	34.5	60.4
0.075	241.0	58.7	1.7
-	6.7	1.6	0.1

CALCULATIONS

The value of the initial weight before washing was 410.50 g while the value of the sum of the material washed, dried and passed through the stack of sieves was 410.10 g. Therefore, the lost material was 0.1% (i.e. 410.1/410.5 x 100)

Mass regained = mass of the materials left in the sieve of each size

Percentage retained = mass retained in each sieve/ mass of dry materials after washing

Percentage passing = 100 - percentage retained

Table A2 The sieve test of gold tailings

Sieve size (mm)	Mass retained (g)	Percentage retained (%)	Percentage passing (%)
19.00	-	0	100
13.20	1.6	0.9	99.1
9.50	6.0	3.4	95.7
6.70	9.5	5.4	90.3
4.75	8.3	4.7	85.6
2.36	25.1	17.3	71.3
1.180	17.4	9.9	61.4
0.600	10.3	5.9	55.5
0.425	4.3	2.5	53.0
0.300	3.6	2.1	50.9
0.150	18.1	10.3	40.6
0.075	65.1	37.2	3.5
-	6.0	3.4	0.1

CALCULATIONS

The value of the initial weight before washing was 175.6 g while the value of the sum of the material washed, dried and passed through the stack of sieves was 175.3 g. Therefore, the lost material was 0.1% (i.e. 175.3/ 175.6x 100)

Mass regained = mass of the materials left in the sieve of each size

Percentage retained = mass retained in each / mass of dry materials after washing

Table A3 The sieve test of the coal tailings

Sieve size (mm)	Mass retained (g)	Percentage retained (%)	Percentage passing (%)
2.360	-	0	100.00
1.180	1.100	0.87	99.13
0.600	21.10	16.69	82.44
0.425	21.00	16.61	65.83
0.300	21.10	16.69	49.14
0.150	38.30	30.30	18.84
0.075	23.40	18.51	0.33
pan	0.40	0.32	0.10

CALCULATIONS

The value of the initial weight before washing was 126.70 g while the value of the sum of the material washed, dried and passed through the stack of sieves was 126.40 g. Therefore, the lost material was 0.2% (i.e. 126.4/ 126.7x 100)

Mass regained = mass of the materials left in the sieve of each size

Percentage retained = mass retained in each sieve/ mass of dry materials after washing

Percentage passing = 100 - percentage retained

APPENDIX B

PINHOLE EROSION TEST DETAILS

TYPICAL CALCULATIONS FOR PINHOLE TEST

Mould: diameter =37.1 mm

Length = 64 mm

Mould area =22/7 x r^2 Volume =area $\times$ length

10.96 cm^2 = 70.310 cm^3

Cone: length = 4.9 and 10 mm

Height =12.5 mm

Volume of cone = $1/3\pi r^2 h$

(Top cone) = 1/3x π x $(0.5)^2$ x 2.15

= 0.5629 cm^3 (x 2 cones, top and bottom cones inside the mould

Volume of cone = $1/3\pi\ r^2 h$

(Bottom cone) = 1/3x π x $(0.245)^2$ x 0.9

= 0.0566 cm^3

Total volume of the cone = 0.5629 – 0.0566

= 0.5063 cm^3

Area of wire string = 22/7 x r^2

= 0.01768 cm^2

Volume of wire string = area x 3.9

= 0.0689 cm^3

Total volume of sample = 70.310 – (0.5063 - 0.5063) – 0.0689

= 69.2285 cm^3

Erosion Loss (% of initial dry mass) =

$$\left(\frac{\text{mass of tailings after erosion} - \text{mass of wet tailings before erosion}}{\text{calculated required dry mass}}\right)$$ and the

$$\text{dry density} = \frac{\text{mass of dry materials}}{\text{volume of the compaction mould}}.$$

EXAMPLE OF CALCULATION

GOLD TAILINGS

Compaction at 100% dry density (1701 kg/m^3) and optimum water content (18.5%).

Dry density = 1701 kg/m^3, water content = 18.5%

Mass = volume x dry density

= 69.2285 x 1701

Dry mass = 117.758 g

Therefore, wet mass = 139.543 g and mass of water is 21.785 g

B1 Uncured material

Cement content	Mass of container (g)	Tailings before erosion (g)	Mass of tailings after erosion (g)	Difference between tailings after and before erosion (g)	Mass of the dry tailings (g)	Erosion Loss (%)	Dry density (kg/m^3)	Required calculated dry mass (g)
0%	189.90	138.5	142.1	3.6	119.1	0.030	1701	117.8
	189.825	139.2	143.9	4.7	116.3	0.032	1687	116.8
	178.429	132.0	138.2	6.2	113.1	.0.055	1624	112.4
	173.699	126.3	134.5	8.2	102.1	0.077	1538	106.5
3%	176.076	138.3	140.3	2.0	116.4	0.017	1701	117.8
	176.168	139.5	142.4	2.9	114.9	0.025	1687	116.8
	161.388	132.0	134.0	3.0	111.2	0.027	1624	112.4
	182.480	127.1	120.3	3.2	103.8	0.030	1538	106.5
5%	178.311	138.9	141.3	2.4	117.6	0.021	1701	117.8
	176.095	139.2	142.0	2.8	114.7	0.024	1687	116.8
	173.665	131.7	134.9	3.2	108.2	0.029	1624	112.4
	189.819	129.9	132.3	3.4	100.1	0.032	1538	106.5
7%	173.529	138.4	140.1	1.7	116.0	0.014	1701	117.8
	171.074	138.5	142.7	3.2	114.4	0.027	1687	116.8
	175.718	131.8	135.1	3.3	110.6	0.029	1624	112.4
	172.584	126.5	130.1	3.6	104.8	0.034	1538	106.5

B2 Cured material

Cement content	Mass of container (g)	Tailings before erosion (g)	Mass of tailings after erosion	Difference between tailings	Mass of the dry tailings (g)	Erosion Loss (%)	Dry density (kg/m^3)	Required calculated dry mass (g)
3%	175.7	138.4	140.4	1.1	119.1	0.009	1701	117.8
	172.6	139.4	140.7	1.3	117.2	0.011	1687	116.8
	173.7	130.6	133.7	3.1	112.2	0.028	1624	112.4
	182.5	125.6	129.4	3.8	107.4	0.036	1538	106.5
5%	175.6	138.7	140.4	1.6	118.1	0.014	1701	117.8
	178.3	137.9	140.3	2.4	117.0	0.021	1687	116.8
	176.1	131.2	134.1	2.9	112.4	0.026	1624	112.4
	189.5	125.1	129.2	5.2	106.2	0.039	1538	106.5
7%	189.8	138.5	139.6	1.1	118.8	0.009	1701	117.8
	176.1	138.7	140.0	1.3	117.6	0.011	1687	116.8
	176.2	130.9	132.9	2.0	112.2	0.018	1624	112.4
	176.9	125.5	128.4	3.4	107.2	0.032	1538	106.5

EXAMPLE FOR PLATINUM TAILINGS

Compaction at 100% dry density (2150 kg/m^3) and optimum water content (14.3%).

Dry density = 2150 kg/m^3, water content = 14.3%

Mass = volume x dry density

= 69.2285 x 2150

Dry mass = 148.841 g

Therefore, wet mass = 170.125 g and mass of water is 21.284 g

B3 Uncured material

Required calculated dry mass (g)	148.8	141.4	134.0	126.6	148.8	141.4	134.0	126.6	148.8	141.4	134.0	126.6	148.8	141.4	134.0	126.6
Dry density (kg/m^3)	2150	2043	1935	1828	2150	2043	1935	1828	2150	2043	1935	1828	2150	2043	1935	1828
Erosion Loss (%)	0.072	0.098	0.111	0.117	0.069	0.088	0.095	0.098	0.073	0.090	0.095	0.099	0.082	0.098	0.104	0.107
Mass of the dry tailings (g)	147.6	140.4	130.9	118.9	145.9	138.4	132.1	112.9	144.3	138.6	128.4	116.2	147.1	138.0	128.1	113.3
Difference between tailings	10.7	13.9	14.9	14.9	10.3	12.5	12.8	12.4	10.9	12.7	12.8	12.5	12.1	13.9	14.0	13.6
Mass of tailings after erosion (g)	180.4	175.2	167.5	159.3	179.7	173.8	165.4	156.7	180.4	173.9	165.4	156.8	181.6	175.2	166.7	157.9
Tailings before erosion (g)	169.7	161.3	152.6	144.5	169.3	161.3	152.6	144.3	169.5	161.3	152.6	144.2	169.5	161.3	152.7	144.3
Mass of container (g)	176.1	176.2	172.6	182.5	173.7	176.2	175.7	182.5	175.7	176.1	189.5	172.6	173.7	175.7	189.5	175.6
Cement content	0%				1%				3%				5%			

B4 Cured material

Cement content	Mass of container (g)	Tailings before erosion (g)	Mass of tailings after erosion	Difference between tailings	Mass of the dry tailings (g)	Erosion Loss (%)	Dry density (kg/m^3)	Required calculated dry
0%	175.8	168.7	181.1	12.4	148.8	0.084	2150	148.8
	161.4	162.1	175.7	13.7	138.8	0.097	2043	141.4
	173.7	155.8	172.2	16.4	130.0	0.123	1935	134.0
	176.3	148.9	168.9	20.0	120.6	0.158	1828	126.6
1%	176.4	168.9	182.1	13.2	153.9	0.089	2150	148.8
	189.9	162.4	178.1	15.7	144.5	0.111	2043	141.4
	176.1	155.9	172.5	16.6	134.3	0.124	1935	134.0
	182.5	149.0	168.5	19.5	125.9	0.154	1828	126.6
3%	176.1	169.0	181.5	12.6	153.3	0.085	2150	148.8
	189.5	162.4	177.0	14.6	143.8	0.103	2043	141.4
	178.3	162.0	178.9	16.9	135.2	0.126	1935	134.0
	176.4	149.1	167.9	18.8	123.9	0.149	1828	126.6

EXAMPLE FOR COAL TAILINGS

Compaction at 100% dry density (1199 kg/m^3) and optimum water content (17.2%).

Dry density = 1199 kg/m^3, water content = 17.2%

Mass = volume x dry density

= 69.2285 x 1199

Dry mass = 83.005 g

Therefore, wet mass = 97.282 g and mass of water is 14.227 g

B5 Uncured material

Required calculated dry mass (g)	83.0	78.9	74.7	70.5	83.0	78.9	74.7	70.5	83.0	78.9	74.7	70.5
Dry density (kg/m^3)	11199	1139	1079	1019	1199	1139	1079	1019	1199	1139	1079	1019
Erosion Loss (%)	0.040	0.043	0.055	0.058	0.050	0.037	0.016	0.005	0.039	0.100	0.144	0.029
Mass of the dry tailings (g)	54.2	65.6	79.1	54.3	83.5	66.3	54.3	56.6	82.8	57.9	84.3	53.4
Differenc e between tailings	3.3	3.4	4.1	4.1	4.2	2.9	1.2	0.4	3.2	7.9	10.8	2.1
Mass of tailings after erosion (g)	92.5	89.2	83.2	78.1	101.5	89.2	86.2	82.0	100.2	84.3	76.5	80.4
Tailings before erosion (g)	95.8	92.6	87.3	82.2	97.4	92.1	87.4	82.3	97.0	92.2	87.3	82.4
Mass of container (g)	175.8	173.7	178.1	189.5	175.8	189.5	173.7	176.9	178.3	175.6	176.1	189.9
Cement content	0%				3%				5%			

B6 Cured material

Cement content	Mass of container (g)	Tailings before erosion (g)	Mass of tailings after erosion	Difference between tailings after and	Mass of the dry tailings (g)	Erosion Loss (%)	Dry density (kg/m^3)	Required calculated dry mass (g)
1%	172.6	95.6	99.4	3.8	82.5	0.045	1119	83.0
	175.7	91.4	96.9	5.5	78.8	0.070	1139	78.9
	176.9	86.5	83.0	3.5	47.0	0.047	1079	74.7
	173.7	81.8	85.3	3.5	54.7	0.050	1019	70.5
3%	182.5	96.2	100.5	4.3	82.8	0.051	1199	83.0
	176.3	91.4	98.1	6.7	79.2	0.085	1139	78.9
	178.4	86.6	94.1	7.5	74.0	0.101	1079	74.7
	176.2	81.5	96.1	14.6	68.3	0.207	1019	70.5
5%	176.1	96.4	101.4	5.0	83.5	0.060	1199	83.0
	175.7	91.7	99.3	7.6	79.5	0.096	1139	78.9
	189.9	86.7	92.5	5.8	75.4	0.078	1079	74.7
	171.1	81.7	93.5	11.8	71.1	0.167	1019	70.5

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