SEDIMENTATION AND DESICCATION OF GOLD MINE TAILINGS

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South Africa, with its world leadership in the mining sector, and well-developed industrial sector, understandably has many tailings dams of various types. South Africa's tailings dams are among the largest in the world in terms of delivered tailings tonnages, plan size and height. Obviously tailings disposal from the mining and industrial sectors in South Africa can have a major impact on the environment and the safety of human life if the dam design and tailings deposition process are not properly controlled.

In South Africa there is a growing awareness of the importance of the environment and of the safety of the tailings dams. Catastrophes like the Merriespruit Gold Tailings dam failure in February 1994, where 17 people died and widespread devastation and environmental damage was caused, has sparked the renewal of research into tailings dam stability and safety.

The rate of rise of tailings dams has an influence on the safety and stability of a tailings dam. If rate at which a tailings dam is built is too high, the dam may become unstable and be at risk of failure. There are many factors that control the rate of rise of tailings dams that are not very well understood. This research deals with sedimentation and desiccation of gold mine tailings. Sedimentation and desiccation are factors that influence the rate of rise.

This research looked at how the gold mine tailings behave when sedimentation and desiccation occur. This was achieved through laboratory experiments, which consisted of column settling tests and drying box tests, and field tests. A model that predicts the behaviour of sedimentation and desiccation of tailings was also analysed.
It was found that tailings sedimentation occurs very quickly. It was also found that suctions play an important role during the desiccation of the tailings.

**Key words:** Gold mine tailings, sedimentation, desiccation, cracks, linear shrinkage, suction, drying box, sedimentation and desiccation model
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LIST OF SYMBOLS

\( v \) = Settling velocity of the interface between settled material and clarified water for a given height of settle solids (mm/day)
\( v_o \) = Unhindered average settling velocity (i.e. Stokes)
\( k_o \) = Material constant
\( V_s \) = Total volume expressed as a height of solid material (mm)
\( H \) = Given height of settled solids (mm)
\( H_f \) = Final height at which sedimentation ceases (mm)
\( k_h \) = Material constant
\( \phi \) = Material constant
\( w_1 \) = Average gravimetric water content at the end of stage-one evaporation
\( H_s \) = Depth of the soil profile at the commencement of stage-one evaporation (mm)
\( k_1 \) = Material constant
\( G_s \) = Specific gravity
\( e_p \) = Evaporation potential (mm/day)
\( D_o \) = Material constant
\( t_1 \) = Duration of the first stage of evaporation (days)
\( w_s \) = Water content
\( w_1 \) = Average gravimetric water content at the end of stage-one evaporation
\( t \) = Time since the start of evaporation (days)
\( E \) = Normalized cumulative water loss
\( E_o \) = Fitting parameter shown in Fig. 2-11
\( t_o \) = Fitting parameter shown in Fig. 2-11
\( b_s \) = The rate of change of \( E \) with respect to the square root of \((t - t_o)\), usually called sorptivity.
\( \hat{e}_p \) = Normalized evaporation potential
\( S \) = Saturation
\( w_{sat} \) = Equivalent saturated water content
\( w \) = Water content
\( w_{ub} \) = Upper bound for \( w_{sat} \)
\( w_i \) = Initial water content
\( H_i \) = Initial height of settled solids
\( \rho_w \) = Density of water (kg/m\(^3\))
\( \rho_d \) = Dry density (kg/m\(^3\))
\( w_{lb} \) = Lower bound for \( w_{sat} \)
\( \rho_{d_{max}} \) = Maximum dry density (kg/m\(^3\))
\( w_{rewet} \) = Lower bound for \( w_{sat} \)
\( V_{\text{rain}} \) = Volume of rain per unit area
\( u_a \) = Pore-air pressure
\( u_w \) = Pore-water pressure
\( \pi \) = Osmotic suction
\( LL \) - Liquid limit
\( PL \) - Plastic limit
\( PI \) - Plasticity index
\( LS \) - Linear shrinkage
\( M_w \) = Initial mass of water (kg)
\( M_T \) = Initial mass of tailings (kg)
\( M_{DB} \) = Mass of drying box (kg)
\( M_B \) = Mass of empty drying box (kg)
\( e_w \) = Amount of water evaporated (kg)
\( M_{wl} \) = Initial mass of water (kg)
\( e \) = Void ratio
\( V_v \) = Volume of voids
\( V_s \) = Volume of tailings
\( \rho_w \) = Density of water (1000 kg/m\(^3\))
\( V_T \) = Volume of sample
\( \rho_b \) = Bulk density
\( L_D \) = Length after drying
\( L_i \) = Initial Length
\( D \) = Average diameter
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INTRODUCTION

1.1 BACKGROUND

The Merriespruit gold tailings dam failure occurred in February 1994 when 600 000 m$^3$ of liquid tailings rushed through the Merriespruit village causing the death of 17 people, widespread devastation and environmental damage. This catastrophic failure sparked a campaign of renewed investigation into the safety of impoundment structures in South Africa.

With the stability of tailings dams being the focus of this renewed investigation, a great amount of research has been conducted on factors that influence the stability of these dams. One of these factors is the rate of rise of tailings dams. There are still many unknowns surrounding the phenomenon of rate of rise. One of the factors that influence the rate of rise is the sedimentation and desiccation of the tailings slurry. This dissertation aims to try and understand the behaviour of tailings during sedimentation and desiccation, as well as to research a method to predict various parameters surrounding sedimentation and desiccation.

1.2 OBJECTIVES

The aim of this study was to investigate the sedimentation and desiccating behaviour of gold mine tailings. A sedimentation and desiccation model from Swarbrick (1992) was also analysed. This model predicts various parameters surrounding sedimentation and desiccation. This study determined whether the semi-empirical model was suited to South African gold mine tailings.

Swarbrick (1992) built a semi-empirical model that predicts various tailings properties during sedimentation and desiccation. Their research was performed on iron ore, coal and bauxite tailings from Australia.

The objective of this research was to determine the sedimentation and desiccation behaviour of gold mine tailings and whether the semi-empirical model was suited to South African gold mine tailings.
1.3 SCOPe

The scope of the research can be summarised as follows:

- The material that was tested was gold mine tailings, a product from Vaal River Operations which is situated in the west of the Witwatersrand.
- Only one gold tailings dam was chosen for field testing, i.e. Mispah Tailings Dam. Tube samples and field measurements were taken from Mispah Tailings Dam.
- Only the daywall of Mispah Tailings Dam was used for field tests and measurements. The daywall is the part that gives the tailings dam strength and keeps it stable.
- Laboratory tests were conducted on the tailings from Mispah. These laboratory tests consisted of column settling tests and drying box tests.
- The study concentrated on the sedimentation and desiccating behaviour of gold mine tailings.

1.4 METHODOLOGY

To investigate the sedimentation and desiccating behaviour of gold mine tailings the following methodology was followed:

- A literature review was conducted to find all relevant information pertaining to sedimentation and desiccation of tailings as well as any related information.
- Laboratory tests were setup to quantify the concepts of sedimentation and desiccation. The laboratory tests consisted of column settling tests and drying box tests.
- These laboratory tests were conducted and various parameters were measured during the duration of tests. The results obtained were analysed.
- The sedimentation and desiccation model was setup using some of the parameters that were obtained during the laboratory testing. The model was used to predict certain parameters for Mispah Tailings Dam.
Field tests were conducted to measure various parameters on Mispah Tailings Dam. These field tests were used to compare to the model prediction and to the results of the laboratory tests.

1.5 ORGANISATION OF THE DISSERTATION

The dissertation consists of the following chapters:

- **Chapter 1** serves as an introduction to the report.
- **Chapter 2** presents a literature review on gold tailings with focus being put on the sedimentation and desiccation.
- **Chapter 3** summarises all the experimental work, which includes laboratory and field tests as well as model determination.
- **Chapter 4** presents the results of the experimental work that was conducted in the form of graphs and tables.
- **Chapter 5** discusses the results of the experimental program.
- **Chapter 6** contains the conclusions and recommendations of the study.

--oOo--
CHAPTER 2
LITERATURE REVIEW

2.1 INTRODUCTION

Chapter 2, the Literature Review, serves as an introduction to tailings and the mechanisms that controls its behavior. This chapter lays the foundation for the rest of the chapters contained in this book. The objective of this chapter is, not only to present a literature review of tailings, but also to create a basic understanding of tailings and its behaviour.

The focus of the research is sedimentation and desiccation of tailings, specifically gold mine tailings. To gain an understanding into sedimentation and desiccation, the basics of tailings, its production and deposition as well as the characteristics and properties of tailings have to be discussed.

Chapter 2 also looks at research conducted by Swarbrick and Fell (1992), as their work pertains to sedimentation and desiccation. Swarbrick (1992) built a semi-empirical model that predicts various tailings properties during sedimentation and desiccation. The research that was conducted for this project was based on this sedimentation and desiccation model.

The discussion in Chapter 2 begins with tailings, what it is, how it is produced, how it is disposed, etc. and it makes its way to the focus of the research, sedimentation and desiccation of tailings.

2.2 TAILINGS PRODUCTION AND DEPOSITION

2.2.1 Introduction

To gain a better understanding of tailings and its behavior, an introduction into what tailings is, how it is produced and how it is disposed, is required.

Tailings are waste material. It is a by-product of the ore extraction process. The ore bearing rock is finely ground to either liberate the desired mineral or allow it to be chemically processed. Most extractive processes in mining are wet processes, and the tailings discharged at the end of the process are therefore in slurry form.
Since tailings are waste material, it cannot be further utilized for other purposes or converted into another form and it has to be disposed of in some way or another. Disposal facilities or impoundments are used for the disposal of the tailings slurry. These impoundments are known as tailings dams (Henderson, 1998).

2.2.2 Tailings Production

In order to understand tailings and tailings dams more fully, some background is necessary on how tailings are produced. This section gives a brief description of the procedures in tailings production.

There are some fundamental steps in the processes of ore extraction, which are common to many ores. These steps are illustrated in Figure 2-1 below and are summarized as follows:

1) **Crushing and grinding:** Crushing is performed in stages with the aim of reducing rock fragments from mine-run size to a size that can be accepted as feed to grinding equipment. Grinding further reduces size of the rock fragments produced by crushing (Vick, 1990).

2) **Concentration:** The purpose of concentration is to separate those particles with high values (concentrate) from those with lower values (tailings). Methods for concentration vary according to ore type, but three general classes are in use: gravity separation, magnetic separation, and froth flotation.

3) **Leaching or heating:** Optional processes following or supplanting concentration may include leaching or heating.

4) **Dewatering:** The final stage in the process is recovering excess water from the tailings in preparation for pumping the tailings slurry to the disposal impoundment. The term dewatering in a mill process context refers not to complete drying of the tailings, but rather to the process of removing some of the water in the tailings-water slurry following concentration. The most common means of dewatering is by thickeners (Vick, 1990).
2.2.3 Tailings Transport

The tailings are collected after the dewatering process and are almost universally transported in slurry form to the tailings impoundment. Transport of tailings slurry is sometimes by gravity flow through open launders but more commonly through pipes, either with or without pumping depending on relative elevations.

The tailings slurry is usually abrasive and has a high viscosity. The common measure of slurry density is pulp density (defined as the weight of solids per unit weight of slurry), which is most commonly in the range of 40 - 50% (Vick, 1990).

2.2.4 Tailings Dams

A tailings dam is a structure that stores tailings as well as the water used to transport the tailings to the tailings dam. The outer structure of the tailings dam may be formed by using the tailings itself, or from earth or rock fill as in the case of a water storage dam (Williamson, 1994).

As with water-retaining dams, each tailings dam is an individual, dependent for its detailed design on the site conditions, the type and rate of delivery of the tailings, availability of other waste materials from the mining or industrial processes, climatic conditions, and other factors. Despite individual details, tailings dams can be classified
by the materials from which they are constructed (Penman, 1994). Types of tailings dams:

- Those built from borrowed earth fill or earth/rock wastes from a mining or industrial process.
- Pure tailings dams using only the tailings themselves for construction.
- Those that use both the tailings and other fills.

In South Africa’s mining and industrial sectors it is common practice for the outer retaining structure of the tailings dam to be formed by using a portion of the waste itself, with the rest of the tailings being deposited behind this outer impoundment. A small earth or rock starter wall is first placed to define the toe of the dam (Williamson, 1994).

Most tailings dams are built in two stages. **Stage I**, the initial starter dam, is constructed before mining operation starts and provides the starting point for construction of the ultimate tailings dam. The type of starter dam selected usually depends on the method of construction to be used for the remainder of the tailings dam. **Stage II** involves the construction of the remainder of the tailings dam. This phase of construction constitutes the major portion of tailings dam construction. **Stage II** construction is a continuous operation, which begins with the start-up of mining operations and continues until mining operations cease, or the tailings dam is filled (Messrs et al, 1989).

Although the function of a tailings dam is to dispose of the waste solids, it also invariably stores a portion of the water used to transport the tailings slurry to the dam. Excess water is generally removed from the dam by means of a specially designed outlet or decant structure and returned to the plant by pipeline for re-use. Whereas a water storage dam is conventionally built to its final design height and water is then stored behind the dam structure, a tailings dam is different, as it only has to store the wet tailings solid fraction at the rate it is generated from the mining operation. The outer retaining structure of the tailings dam is therefore raised progressively and may take ten or twenty years or even longer to reach full height and storage capacity.

A water storage dam is most often constructed across a river valley so as to intercept and store the water flowing in the river. A tailings dam, however, would not be appropriate if built across a river valley as, firstly, its design and function would seldom
enable it to retain the dammed river flow and, secondly, the tailings may have an unacceptable contamination level and should therefore not be allowed to come into contact with uncontaminated river or stormwater. Tailings dams are therefore most often formed on flat ground, on a hill slope, or in the upper reaches of a valley where they fill the valley and where stormwater flow would not be affected by the presence of the tailings dam.

Categories of impoundment layouts can be defined that are generally compatible with various topographic settings, i.e. flat ground, on a hill slope, or in the upper reaches of a valley. General impoundment layout types (Vick, 1990) include:

- (a) **Ring dikes**: They are suited to flat terrain, they require a relatively high quantity of embankment fill in relation to the storage volume produced and they are laid out with regular geometry.

- (b) **Cross-valley impoundments**: These impoundments are confined by a dam extending from one valley wall to another. They can be nearly universally applied to almost any natural topographic depression.

- (c) **Sidehill impoundments**: The impoundment is enclosed by embankments on three sides; they are best suited for Sidehill slopes of less than 10% grade. On steeper slopes, fill volumes may become excessive in relation to storage volume achieved.

- (d) **Valley-bottom impoundments**: They represent a compromise between cross-valley and Sidehill layouts; they are well suited for cases where the drainage catchment area would be too large for cross-valley layouts, but hillslope slopes are too steep for practical application of the Sidehill option.

**Figure 2-2** below depicts the various impoundment layout types listed above.
2.2.5 Construction and Operation of tailings dams

2.2.5.1 Deposition Procedures (Vick, 1990)

The deposition adopted to form the outer tailings impounding wall generally consists of one of the following types:

- Upstream Deposition
- Downstream Deposition
- Centerline Deposition

(a) **Upstream Deposition**

Upstream deposition is illustrated in Figure 2-3 below:
Figure 2-3: Sequential raising, upstream embankment (Vick, 1990).

- **Figure 2-5(a):** Initially a starter dike is constructed, and tailings are discharged peripherally from its crest to form a beach.
- **Figure 2-5(b):** The beach then becomes the foundation for a second perimeter dike.
- **Figure 2-5(c) & (d):** This process continues as the embankment increases in height.

Central to the application of the upstream method is that the tailings form a reasonably competent beach for support of the perimeter dikes.

The major advantages of the upstream method are cost and simplicity. Only minimal volumes of mechanically placed fill are necessary for construction of the perimeter dikes, and large embankment heights can be attained at very low cost. Factors that constrain the application of the upstream method include phreatic surface control, water storage capacity, and seismic liquefaction susceptibility.
The rate at which upstream embankments can be safely raised is limited. Raising rates are determined by the rate of mill tailings production and topographic configuration of the impoundment site. Rapid rates of height increase can produce excess pore pressures within the deposit, particularly in slimes zones because of the lower coefficient of consolidation of this material. Failures attributable to excess pore pressures have occurred because the rates of height increase are too rapid.

(b) **Downstream Deposition**

Downstream deposition is illustrated in Figure 2-4 below:

![Figure 2-4: Sequential raising, downstream embankment (Vick, 1990).](image)

Initially tailings are discharged behind a starter dike. Subsequent raises are constructed by placing embankment fill on the downstream slope of the previous raise. This method is amenable to the incorporation of structural measures within the embankment (for example, impervious cores and drains) for positive control of the phreatic surface.

Downstream raising methods are well suited to conditions where significant storage of water along with tailings is necessary. Because the phreatic surface can be maintained at low levels within the embankment and because the entire body of the
fill can be compacted, downstream raising methods are liquefaction resistant and can be used in areas of high seismicity. Unlike upstream embankments, raising rates are essentially unrestricted because the downstream raises are structurally independent of the spigotted tailings deposit.

Downstream raising methods require careful advance planning. Because the toe of the dam progresses outward as its height increases, sufficient space must be left during layout of the starter dike to prevent encroachment of the dam toe on property lines, roads, utilities etc.

The major disadvantage of the downstream raising method is the comparatively large volume of embankment fill required and the corresponding high cost. The volume of fill required for each successive downstream raise often increases exponentially as the embankment increases in height.

(c) Centerline Deposition
Centerline deposition is a compromise between upstream and downstream deposition in many respects. As a result, it shares to a degree the respective advantages of the two methods, while mitigating their disadvantages. Centerline deposition is depicted in Figure 2-5.
Figure 2-5: Sequential raising, centerline embankment (Vick, 1990).

Initially, a starter dike is constructed, and tailings are peripherally spigotted from the dike crest to form the beach. Subsequent raises are constructed by placing fill onto the beach and onto the downstream slope of the previous raise. The centerlines of the raises are coincident as the embankment progresses upward, giving rise to the method’s name.

Because internal drainage zones can be provided within the embankment, control of the phreatic surface is not so sensitive to the location of ponded water as it is for upstream deposition.

Unlike downstream embankments, the centerline method cannot be used for permanent storage of large depths of water. The water can be allowed to rise temporarily during floods, however, without adversely affecting stability of the structure provided that proper internal impervious and/or drainage zones are incorporated.
The overall raising rate is not generally restricted by considerations related to pore pressure dissipation. Because the main body of the embankment fill can be compacted and saturation levels controlled by internal drainage, the centerline method has generally good seismic resistance.

The volume of fill required for a given embankment height is intermediate between that for upstream and downstream methods, resulting in intermediate costs.

2.2.5.2 Deposition Techniques

Three primary techniques are used in South Africa for the placing of wet tailings from the tailings slurry delivery pipeline onto the tailings dam, to form the outer impoundment and fill the central storage area, and they are:

- **The paddock system** – The paddock deposition system has traditionally been used in South Africa’s gold-mining industry and is specifically suited to gold, tin and gypsum tailings and power-station ash; and is generally applied to flat topography.
- **The spigot or spraybar system** – Spigot systems are typically used on platinum, vanadium, andalusite, diamond and sugar bagass tailings dam construction.
- **The hydrocyclone system** – Cyclone separation is conventionally best suited to tailings having a wide particle grading, to sites with awkward topography where high rate of rise may apply and to situations where manual labour or mechanism may not be suitable or available.

The deposition technique that is most widely used for gold mine tailings is the Paddock Deposition System. Since the focus of the research is gold mine tailings, the Paddock Deposition system is discussed in more detail in the section below.

**The Paddock Deposition System**

In the paddock deposition system the outer impoundment is formed by filling some of the tailings slurry into a grid of perimeter paddocks, with the remainder discharged into the central floor area, as illustrated in Figure 2-6 below.
Figure 2-6: Paddock deposition system (McPhail & Wagner, 1987).
The low paddock walls are formed at the start of deposition with earthfill and subsequently with partially dried deposited tailings. The perimeter paddocks are known as the daywall, and as the name indicates, it is constructed during the day. The central floor area is known as the nightpan or floor and tailings are deposited here during the night. The daywall and nightpan are shown in **Figure 2-6b**.

The daywall height may vary from 0.1 to 1.5m and the overall dam height may rise from 0.6 to 3.0m per year. The daywall is designed to provide sufficient freeboard to retain the accumulated water from deposited tailings and that from the design storm. The daywall is generally 10 – 30m wide (Wagner & Jacobsz, 1999), at an average slope of 35˚ (Blight, 1988) and is sectioned into paddocks around the perimeter, each paddock being filled from its midpoint by delivery station.

The paddocks are filled with tailings slurry and as the solid particles settle, the water is led off into the inner floor of the tailings impoundment, together with any excess of fine slimes. A drying period of the material deposited in the paddock has to be allowed before the sequence of raising and filling is repeated. This period can vary from four to 28 days, depending on the climate and the fineness of the product. As the method relies on evaporative drying it is best suited to application in areas where the evaporation rate significantly exceeds the rainfall.

Paddock deposition is successful when the tailings product is fairly uniform in grading, the particles remain in suspension until the slurry is placed, the slurry density does not vary, and the rate of rise of the dam matches the drying time of the tailings.

A consistent feature of tailings impoundments is the highly layered nature of the profile as a result of depositional practices, soil forming processes and variations in milling consistencies (McPhail & Wagner, 1987). Often this layering takes the form of alternating fine and coarse deposits, with up to 50% variation in fineness over a depth of 10 to 200 mm.

On the gold fields of South Africa evaporation generally exceeds rainfall (McPhail & Wagner, 1987). Provided that rates of rise are low enough, therefore, the surface, with the exception of the pool area, becomes desiccated and large shrinkage cracks develop. These cracks are filled and re-filled by successive lifts of
tailings. This desiccation is a fundamental requirement of paddocked dam construction. Drying results in densification, which gives the gold tailings the required strength. In addition the cracks tend to become filled with coarser material, which improves vertical drainage. Rate of rise must be controlled in order to ensure that desiccation does occur. The allowable maximum rate of rise is dependent on tailings moisture content.

2.2.5.3 Effluent Decant Systems

The tailings dams that have been described in this research receive tailings in slurry form. There is therefore, a need to separate the tailings solids from the tailings water. The tailings slurry is deposited on the daywall and night pan / floor area of the talings dam. The excess, or supernatant, water is collected in the tailings pool in the central area of the dam and decanted.

In general terms, after losses due to evaporation and due to filling the voids between the tailings particles are subtracted, approximately 40 to 50% of the water of the tailings slurry can be recovered by the decant system for return to the processing plant and re-use (Williamson, 1994).

The supernatant water is removed from the dam by a variety of techniques such as:

- **A decant penstock tower and pipe system**, consisting of a vertical tower located in the pool and connected to a horizontal outlet pipe located under the tailings deposit. Water enters the tower and is discharged by gravity through the tower-and-pipe system to the outer perimeter. The tower is raised in small increments as the depth of the tailings deposit increases.

- **A floating pump barge system**, consisting of a floating pump station located on the tailings dam pool, which removes excess water by pumping.

- **Other decant systems** for specific applications, such as siphon decants, side-hill spillways and side-hill (inclined) intake shafts.

2.3 TAILINGS PHASE RELATIONSHIPS

An essential element in physical characterization of tailings is to relate the solid, liquid and air phases of the mass of material, whether in slurry or settled form. **Figure 2-7**
shows an idealized representation of the three phases completely separated from one another, with mass and volume components defined for the three phases. The solid and liquid phases are always present; air may or may not exist in the tailings mass, depending on its degree of saturation (Vick, 1990).

**Figure 2-7:** Separation of air, liquid, and solid phases by mass and volume (Vick, 1990).

Fundamental parameters that describe tailings phase relationships include pulp density for slurry, and void ratio, water content, porosity, specific gravity, and degree of saturation for settled tailings. These parameters are defined below with reference to **Figure 2-7**:

\[
\text{Void ratio} \quad e = \frac{V_v}{V_s} \tag{2-1}
\]

\[
\text{Degree of Saturation} \quad S = \frac{V_w}{V_v} \tag{2-2}
\]

\[
\text{Porosity} \quad n = \frac{V_v}{V} \tag{2-3}
\]
\[ G = \frac{\gamma_s}{\gamma_w} \]  
\[ \text{Specific Gravity} \]

Where \( \gamma_s \) = unit weight of the solids = \( \frac{M_s}{V_s} \)  
And \( \gamma_w \) = unit weight of water = \( \frac{M_w}{V_w} \)

\[ w = \frac{M_w}{M_s} \]  
\[ \text{Water Content} \]

\[ P = \frac{M_s}{M} \]  
\[ \text{Pulp Density} \]

2.4 BASIC CHARACTERISTICS OF GOLD MINE TAILINGS

2.4.1 Introduction

In Section 2.2 the reader was introduced to tailings, what it is and how it is disposed of. This section is an introduction to gold mine tailings, where the basic characteristics of gold mine tailings and tailings dams are discussed. As gold mine tailings are the focus of the research, it was thought to be appropriate for it to be introduced next.

2.4.2 Gold Mine Tailings

Concentration by froth flotation is generally used for gold ores, especially for low-grade disseminated deposits. The end product of the milling operation may be gold concentrate, or the concentrate may be further processed by sodium cyanide leaching. This further process has obvious effects on the character of the tailings slurry. Cyanide leaching, if performed, requires slightly alkaline conditions, usually achieved by the addition of lime.

Gradation curves for gold mine tailings is shown in Figure 2-8 below:
The grading curves in Figure 2-8 above illustrates that gold tailings has a broad grading envelope. This is due to the grade of the ores that is processed. Gold extraction efficiency by in-mill leaching is directly related to the specific surface area of the particles and therefore the fineness of the grind. Rich ores may result in relatively coarse tailings, with the more finely disseminated but more common ores producing finer tailings (Vick, 1990).

Gold ores generally contain little clay, and tailings produced are usually low to nonplastic (Hamel and Gunderson, 1973). Gold tailings exhibit very little plasticity and no cohesiveness and classify, based upon their Atterberg Limits, as low to high plasticity silts on the Casagrande chart. Typical values for gold mine tailings are given in Table 2-1 below:
Table 2-1: Typical characteristics of gold mine tailings.

<table>
<thead>
<tr>
<th>Basic Characteristic</th>
<th>Value</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit</td>
<td>33</td>
<td>Vermeulen, 2001</td>
</tr>
<tr>
<td>Plastic Limit</td>
<td>28</td>
<td>Vermeulen, 2001</td>
</tr>
<tr>
<td>Plasticity Index</td>
<td>5%</td>
<td>Vermeulen, 2001</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.6 – 2.7</td>
<td>Soderberg and Busch, 1977</td>
</tr>
<tr>
<td></td>
<td>3.1</td>
<td>Hamel and Gunderson, 1973</td>
</tr>
<tr>
<td></td>
<td>2.74</td>
<td>Vermeulen, 2001</td>
</tr>
</tbody>
</table>

Gold mine tailings can be divided into tailings sands and tailings slimes. Tailings sands constitute the tailings fraction by weight that is coarser than 75 μm and tailings slimes constitute the tailings fraction by weight that is finer than 75 μm.

The pulp densities of gold mine tailings slurry range between 25 and 50% (dry density of 300 to 750 kg/m$^3$) when delivered to the impoundment site. The in-situ dry density of the tailings slimes is close to 1000 kg/m$^3$ and for the tailings sands range between 1250 and 1650 with an average of 1450 kg/m$^3$ (Vermeulen, 2001).

2.4.3 South African Gold Mine Tailings Dams

Gold mine tailings dams in South Africa are generally constructed using the upstream semi-dry paddock method. Dams constructed using this method comprise of two components, viz the daywall and nightwall/nightpan. This deposition technique is described in Section 2.2.5.2 of this book.

The distance between delivery stations in the daywall paddock generally varies from 200 m to 1000 m and is an important aspect of the dam construction and performance. The slurry flows from the delivery station into the daywall paddock and distributes by gravity in the daywall zone. The slurry is then allowed to settle out before draining the excess water into the body of the dam through decant pipes located through the inner wall. The deposited material is then left to dry and consolidate while deposition takes place at another delivery station. Over-consolidation is achieved by desiccation. This wall-building operation takes place during the day, hence the name daywall. In order to achieve operational safety, discharge of tailing slurry at night takes place into the body
of the dam; hence the body or basin of the dam is known as the nightwall or nightpan. Water and slurry discharged into the nightpan runs down the concave surface or beach to the dam towards the penstock, which is intended to be centered in the pool where it can be used to drain excess water off the dam (Jones and Wagner, 1996).

2.5 ENGINEERING PROPERTIES OF TAILINGS

2.5.1 Introduction
Central to an understanding of tailings behavior is the nature of the depositional processes that tailings undergo (Vick, 1990). The engineering properties of tailings are determined by a number of factors, namely:

- the characteristics of the material;
- the nature of the deposit; and
- the operating procedures of the tailings dam.

The more significant engineering properties that are discussed further in this section are the permeability, consolidation and shear strength of tailings.

2.5.2 Permeability
More than any other engineering property of tailings, permeability is difficult to generalize. Permeability varies as a function of grain size and plasticity, depositional mode, and depth within deposit (Vick, 1990).

The grain size of the tailings is determined by the type and grade of ore and the milling process. Estimates of the average permeability have been made using the Hazen's formula \( k = d_{10}^{2.6} \) that is based on the grain size \( d_{10} \) for which 10% of the particles pass by weight.

Estimates of average permeability on the basis of grain size, however, cannot account for several important factors that control the permeability of the tailings deposit as a whole. These factors are as follows (Vick, 1990):

- **Effects of Anistropy:** Because of their layered nature, tailings deposits exhibit considerable variation in permeability between the horizontal and vertical directions. However, desiccation cracks and the preferential filling of these cracks with coarser material on the next deposition cycle, tend to reduce the
effects of layering so that vertical permeability is only some 1.5 and 3 times lower than horizontal permeability (McPhail and Wagner, 1987).

- **Effects of Distance from Discharge:** There has been much debate about the degree to which tailings permeability can be expected to vary as a function of distance from point of discharge. A Model (Kealy and Busch, 1971) has been proposed where different zones of permeability exist dependent on distance from the point of discharge. In this model a zone of high-permeability sands exist near the point of discharge, next a zone of intermediate permeability, and furthest away from the point of discharge, a low-permeability slimes zone.

- **Effects of Void Ratio:** The change of permeability with decreasing void ratio is reasonably consistent for most tailings sands and low-plasticity slimes. Over the range of void ratios encountered with depth in most tailings deposits, sands show a permeability decrease of about a factor of 5. The permeability of slimes, on the other hand, may decrease by roughly a factor of 10 because of their higher compressibility.

As a result of the greater permeability decrease exhibited by slimes layers, which generally control vertical permeability, the anisotropy ratio $k_v/k_h$ may tend to increase with depth in a deposit of interlayered sands and slimes.

### 2.5.3 Compressibility and Consolidation

Compressibility is not so widely varying, but tailings are generally more compressible than corresponding types of natural soils because of the looser state they usually assume upon deposition. Consolidation characteristics are a function of both permeability and compressibility and as a result are very complex. Consolidation characteristics are important in evaluating the time rate of pore pressure dissipation within the tailings deposit.

### 2.5.4 Shear Strength

The shear strength of tailings is generally of importance only where tailings are used for embankment construction (Robertson, 1998).

The shear strength properties for tailings are as follows:
- **Cohesion**: Tailings are cohesionless, but there are rare exceptions. Apparent cohesion only develops under partially saturated conditions as a function of pore water pressure and electrical charge attraction between clay minerals, if present. Aggregate interlock following compaction can also induce some apparent cohesive strength.

- **Frictional Strength Parameter**: Tailings are characterized by high frictional strength parameters. To develop frictional strength requires the dissipation of excess pore pressures resulting from imposed loads.

  Tailings have an effective angle of internal friction, $\phi'$, ranging between 30 and 40°. The internal friction angle can be assumed largely independent of grading, density, overconsolidation and effective stress level up to the onset of particle crushing.

  The shear strength of tailings is often higher than that for similar natural soils due to the high degree of particle angularity exhibited by most tailings.

  Sand sized tailings are usually sufficiently rapidly draining that they may be used for embankment construction by any of the construction methods. Silt sized tailings are generally so slow draining that they cannot be used for embankment construction by any of the conventional methods except the paddock system in which dewatering is achieved by evaporative drying (Robertson, 1998).

2.5.5 **Gold Mine Tailings**

Gold tailings exhibit no plasticity and no cohesive characteristics (McPhail and Wagner, 1987). The effective angle of friction of fine gold mine tailings such as would be found around the penstock is the same as for coarse tailings at the delivery on to the dam. The important difference between the coarse and fine products lies in their permeability and consolidation characteristics. The fines will take longer to consolidate and, if loaded too rapidly, the available shear strength can be reduced by excess pore pressures.
2.6 SUCTION

2.6.1 Introduction
The decrease in pore water pressure in the tailings caused by evaporation will assist in the increase of effective stress (Swarbrick & Fell, 1992). High pore suctions resulting from evaporative drying results in the consolidation and cracking of the surficial tailings layers. This method of dewatering and consolidation is exploited to advantage for the creation of the consolidated drained zone of the outer portion of the retaining embankment in the paddock construction system (Robertson, 1998).

Section 2.6.2 below describes what suction is and how it is measured.

2.6.2 Total Suction
The total suction, \( \psi \), of a soil is made up of two components, namely, the matric suction, \( (u_a - u_w) \), and the osmotic suction, \( \pi \). Equation (2-15) gives the equation for total suction.

\[
\psi = (u_a - u_w) + \pi
\]  

(2-9)

Where:
\( u_a \) = Pore-air pressure
\( u_w \) = Pore-water pressure
\( \pi \) = Osmotic suction

The total suction corresponds to the free energy of the soil water, while the matric and osmotic suctions are the components of the free energy.

The matric suction component is commonly associated with the capillary phenomenon arising from the surface tension of water. The capillary phenomenon is usually illustrated by the rise of a water surface in a capillary tube. In soils, the pores with small radii act as capillary tubes that cause the soil water to rise above the water table. The capillary water has a negative pressure with respect to the air pressure, which is generally atmospheric (i.e. \( u_a = 0 \)) in the field. At low degrees of saturation, the pore-water pressures can be highly negative.

Osmotic suction is related to the salt content in the pore-water, which is present in both saturated and unsaturated soils. Osmotic suction changes have an effect on the mechanical behaviour of a soil.
Most engineering problems involving unsaturated soils are commonly the result of environmental changes. These changes primarily affect the matric suction component. Osmotic suction changes are generally less significant. Generally osmotic suction is ignored, and a change in matric suction is equivalent to a change in total suction.

There are a variety of suction measurement devices such as filter paper, the psychrometer, thermal blocks, the tensiometer, various suction probes etc. For the purpose of this research only one of these will be briefly discussed, namely the mid-plane suction probe. The original mid-plane suction probe was designed and constructed by Theron (2000). The probe contains a pressure transducer which is embedded in a cavity leaving a gap of 0.1 mm for the water reservoir between the surface of the transducer and a ceramic. The body of the probe is machined from stainless steel. The water reservoir is small enough to inhibit the formation of air bubbles in the reservoir (cavitation).

2.7 THE SOIL-WATER CHARACTERISTICS CURVE

The soil-water characteristics curve (SWCC), which is also known as a water retention curve, may be defined as the variation of suction with the water storage capacity within the macro and micro pores of a soil. The curve is generally plotted as the variation of gravimetric water content, w, or volumetric water content, θ, or degree of saturation, S, with suction. In geotechnical engineering practice, gravimetric water content, w, which is the ratio of the mass of water to the mass of solids (see Equation 2-7 on page 2-16), is most commonly used.

The soil-water characteristics curve can be used to estimate various parameters used to describe unsaturated soil behaviour. There is, for example, a good correlation between the shear strength behavior of an unsaturated soil and the soil-water characteristics curve. A typical soil-water characteristics curve is given in Figure 2-9 below, where volumetric water content is plotted against soil suction (on a logarithmic scale).

The SWCC is a semi-log graph with the soil suction plotted on a logarithmic scale. The volumetric water content at zero matric suction is called the saturated volumetric water content, θₛ, and corresponds to the porosity of the soil that represents the total volume of water that the soil can store (Fredlund and Xing, 1994).
Figure 2-9: Typical soil-water characteristic curves (Fredlund, Xing and Huang, 1994).

The main curve shown in Figure 2-9 is a desorption curve, with the adsorption curve differing from the desorption curve as a result of hysteresis. The nonuniformity in pore size distribution in a soil results in hysteresis in the soil-water characteristics curve. At a given matric suction, the soil water content during the wetting and drying process are different (Fredlund and Rahardjo, 1993). The endpoint of the adsorption curve may differ from the starting point of the desorption curve because of air entrapment in the soil (Fredlund and Xing, 1994).

The ratio of water content and the change in soil matric suction represents the storage potential. The steeper the slope over a specific range of soil suctions, the greater water storage potential (Leong and Rahardjo, 1997).

The soil matric suction that corresponds to the initial draining of the soil pores is referred to as the air entry value, \( \psi_b \). Beyond the air entry value, the specimen starts to desaturate and continues to desaturate as the suctions increase.
The water content at which the SWCC begins to flatten after the air entry value is called the residual water content, $\theta_r$. Below the residual water content, a large increase in suction is required to remove additional water from the soil.

2.8 DEPOSITION, SEDIMENTATION AND DESICCATION OF TAILINGS

The formation of a hydraulic fill is very much like the formation of natural sediments; transportation is followed by deposition, sedimentation and eventually by consolidation due to self-weight and external loading (Schiffman et al., 1988). The difference is age; compared to natural sediments, hydraulic fills are young with a very recent stress history. The study of the sedimentation and consolidation behaviour of tailings following deposition is of major concern in the design of tailings impoundments, not only from a stability point of view but also determining the storage capacity and allowable rate-of-rise on the structures.

Transportation of sediments, sedimentation and consolidation are simultaneous parts of the tailings deposition process (Consoli & Sills, 2000).

Consolidation occurs throughout the entire history of tailings drying either in a saturated or unsaturated form. Sedimentation is only present during deposition and for a short period after deposition ceases. Desiccation is essentially the combined effects of partial saturation brought about by solar drying and subsequent unsaturated consolidation driven by internal negative pore pressures (i.e. soil suction) (Swarbrick, 1992).

Where evaporation is significant, tailings deposited subaerially in shallow layers (i.e. less than 2 m) may desiccate. Successful dewatering by desiccation increases density and shear strength and reduces compressibility. This promotes optimum land use and in the longer term, increases the chances of rehabilitation and reuse of the dam area.

2.9 METHOD FOR PREDICTION OF SEDIMENTATION AND DESICCATION

2.9.1 Introduction

Swarbrick (1992) developed a semi-empirical model to predict sedimentation and desiccation as part of his Doctorate. This semi-empirical model was published by Swarbrick and Fell (1992) in the Journal of Geotechnical Engineering. The model uses
the observations of laboratory behavior coupled with soil physics and Geotechnical principles to predict sedimentation and desiccation behavior.

Swarbrick developed the model using tailings from five mines in Australia. The type of tailings that were used during development of the model is as follows:

- Iron ore
- Coal
- Bauxite

The purpose of this research was to apply the semi-empirical model to gold mine tailings from South Africa and determine if it could be used accurately to model the sedimentation and desiccation of these tailings.

2.9.2 Background

The mining industry produces large quantities of waste including overburden and tailings. Of these wastes, tailings generally pose the most problems upon disposal. Tailings slurry is deposited hydraulically into confined disposal facilities whose primary function is to store the waste either permanently or temporarily. The purpose of the research by Swarbrick (1992) was to develop a model that aimed at predicting the deposited properties of these wastes over time in order to determine the capacity of the disposal facility to store the waste.

The details of the tailings that were researched by Swarbrick (1992) are summarized below in Table 2-2:
Table 2-2: Classification of tailings researched by Swarbrick (1992).

<table>
<thead>
<tr>
<th>Mine:</th>
<th>Hamersley</th>
<th>Newman</th>
<th>Riverside</th>
<th>Wambo</th>
<th>Weipa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Mine:</td>
<td>Iron ore</td>
<td>Iron ore</td>
<td>Coal</td>
<td>Coal</td>
<td>Bauxite</td>
</tr>
<tr>
<td>% Solids</td>
<td>34</td>
<td>25</td>
<td>29</td>
<td>24</td>
<td>20</td>
</tr>
<tr>
<td>Soil Particle Density (t/m³)</td>
<td>3.76</td>
<td>3.84</td>
<td>1.74</td>
<td>1.86</td>
<td>2.77</td>
</tr>
<tr>
<td>Liquid Limit (%)</td>
<td>30</td>
<td>33</td>
<td>44</td>
<td>74</td>
<td>43</td>
</tr>
<tr>
<td>Plasticity Index (%)</td>
<td>9</td>
<td>11</td>
<td>16</td>
<td>46</td>
<td>17</td>
</tr>
<tr>
<td>% Clay (&lt;2 μm)</td>
<td>42</td>
<td>29</td>
<td>39</td>
<td>57</td>
<td>32</td>
</tr>
<tr>
<td>% Sand (&gt;0.6 mm)</td>
<td>4</td>
<td>10</td>
<td>12</td>
<td>8</td>
<td>24</td>
</tr>
</tbody>
</table>

The deposition characteristics of these tailings impoundments for each mine that was researched by Swarbrick (1992) is given in Table 2-3.

Table 2-3: Deposition characteristics (Swarbrick, 1992).

<table>
<thead>
<tr>
<th>Mine:</th>
<th>Hamersley</th>
<th>Newman</th>
<th>Riverside</th>
<th>Wambo</th>
<th>Weipa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Mine:</td>
<td>Iron ore</td>
<td>Iron ore</td>
<td>Coal</td>
<td>Coal</td>
<td>Bauxite</td>
</tr>
<tr>
<td>Deposited Depth (m/yr)</td>
<td>10.18</td>
<td>2.67</td>
<td>1.84</td>
<td>9.39</td>
<td>8.28</td>
</tr>
<tr>
<td>Rate of Rise (m/yr)</td>
<td>3.75</td>
<td>1.00</td>
<td>1.40</td>
<td>4.00</td>
<td>1.47</td>
</tr>
</tbody>
</table>

The deposited properties of the tailings for each mine are summarized in Table 2-4. This table provides information concerning the average solids content, saturation, water content and dry density of the tailings.
Table 2-4: Deposited properties (Swarbrick, 1992).

<table>
<thead>
<tr>
<th>Mine:</th>
<th>Hamersley</th>
<th>Newman</th>
<th>Riverside</th>
<th>Wambo</th>
<th>Weipa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of Mine:</td>
<td>Iron ore</td>
<td>Iron ore</td>
<td>Coal</td>
<td>Coal</td>
<td>Bauxite</td>
</tr>
<tr>
<td>Ave Solids Content (%)</td>
<td>65</td>
<td>74</td>
<td>45</td>
<td>45</td>
<td>56</td>
</tr>
<tr>
<td>Ave Saturation (%)</td>
<td>77</td>
<td>77</td>
<td>87</td>
<td>82</td>
<td>95</td>
</tr>
<tr>
<td>Ave Water Content (%)</td>
<td>54</td>
<td>35</td>
<td>120</td>
<td>120</td>
<td>79</td>
</tr>
<tr>
<td>Ave Dry Density (t/m^3)</td>
<td>1.00</td>
<td>1.40</td>
<td>0.51</td>
<td>0.50</td>
<td>0.84</td>
</tr>
</tbody>
</table>

2.9.3 Development of the Semi-Empirical Model

Traditionally, semi-empirical methods have played an important role in predicting geotechnical behavior. As a consequence of the non-linear and complex nature of soils, empirical methods are often better at predicting behavior than more sophisticated theoretical models. The general success of empirical models is often attributed to the way in which the behavioral complexities have been isolated.

The approach taken with the semi-empirical model has integrated basic geotechnical and soil physics principles and laboratory and field desiccation experimentation. Swarbrick (1992) included all five tailings materials in the development of the semi-empirical model. Because of the varied behavior of the five different tailings, the resulting model is very flexible relying upon theoretical principles, which apply to all porous media.

2.9.4 Modeling Approach

2.9.4.1 Assumptions Made

The semi-empirical approach has required several simplifying assumptions. These assumptions were necessary in order to simplify the theoretical behavior of desiccating tailings and due to the limitations on the amount and type of experimentation undertaken.

The following are the assumptions that were made to develop the semi-empirical model:
a) *Sedimentation is not affected by the rate and amount of desiccation.* The assumption is reasonable as the sedimentation of particles will be largely unaffected by the effects of desiccation. The decrease in pore water pressure caused by evaporation will assist in the increase of effective stress and, hence, aid the process of sedimentation to some degree. This means that this assumption will be slightly conservative.

b) *Drainage is not significant for these materials.* The laboratory desiccation experiments did not include for drainage effects. This assumption will not apply during the early stages of sedimentation, but the soil suction gradient will quickly overcome the downward gravity component of flow for these high-clay-content materials.

c) *The movement of fluid and soil particles within the slurry during sedimentation and desiccation are essentially one dimensional,* i.e. vertically downward. This assumption is reasonable considering the complex nature of the theory.

d) *The supplied tailings as a uniform sample are representative of the tailings in the tailings dam.*

e) *Water contents and densities are uniform in any one layer of deposited tailings.* This allows for a simpler theory to be applied and greatly reduces the computational effort required. This assumption will be reasonable, and the layer depth is kept below that commonly used in sub-aerial deposition. While this is so, the effects of nonuniform water content and density profile may be accounted for in the assumed relationships by empirical means.

f) *Evaporation may be analysed as a two-stage process, as commonly done in soil physics theory.* The assumption is justified by the fact that laboratory experiments have proven the behavior of tailings to be identical to that of an isotropic porous medium.

g) *All bleed water becomes runoff and is reclaimed.* This assumption is generally true of tailings dams operated for sub-aerial deposition.

Another important consideration omitted in this model is the effect of slow deposition upon sedimentation.
The approach taken in predicting desiccation was based upon average properties of a given layer of tailings. The total process was divided into two component processes: sedimentation and desiccation. Separate experiments for these two components were conducted in the laboratory, namely, column settling tests and desiccation experiments. Both processes are allowed to occur simultaneously within the model but no interaction between them is allowed for. The effects of consolidation are included in both components.

The sedimentation component relies upon empirical prediction of the settled height based upon Kynch (1952) sedimentation theory. The sedimentation parameters are derived from column settling tests. The evaporation component is comprised of two stages: the first or constant rate stage of evaporation and the second or falling rate stage. Both of these stages are unaffected by rate of sedimentation except that the first stage of evaporation may not commence until the evaporative potential exceeds the bleed rate. The second stage of evaporation is controlled by the layer height at the end of the first stage of evaporation and the potential evaporation rate and the duration of the first stage.

The initial and boundary conditions in the model are the initial tailings height, $H_i$, the initial water content, $w_i$, and the evaporation and rainfall.

The model does not include drainage. This is appropriate for the relatively shallow nature of sub-aerially deposited layers (less than 2m). Under these conditions, the soil suction gradient quickly overcomes the downward gravity component of flow diminishing drainage.

### 2.9.5 Modeling Method

A description of the method is given below. The main variable predicted during sedimentation and desiccation is water content, $w$. Saturation is determined from the predicted water content and measured water content assuming the layer is saturated.

An important factor in the modeling method is the height of solids in a layer, which is assumed constant. This quantity, $H_z$, is determined from the initial height and water content using:
2.9.5.1 Sedimentation and Consolidation

This model component covers the settling of flocs to a state where particles-to-particle interaction becomes substantial and significant effective stresses have been developed (Yong, 1984). Most theoretical approaches to sedimentation do not allow for the electrostatic repulsion and attraction forces characterized by hindered settling of suspended clay solids (Kynch, 1952). More recent theories incorporating fluid-particle interaction (Concha and Bustos, 1987; Shih et al., 1987) require a level of computational effort unsuited to many practical situations. A suitable approach is to use an empirical adaptation of Kynch theory i.e., that the velocity of the particle is some function of the solids concentration. From several suggested relationships (Yong, 1984), the most suitable approach in terms of experimental observations for the tailings used in this research is based upon solids volume concentration of the form (Thomas, 1964).

\[ v = v_0 \left(10^{(k_0 H_2/H)}\right) \]  

(2-11)

Where:
- \( v \) = Settling velocity of the interface between settled material and clarified water for a given height of settle solids (mm/day)
- \( v_0 \) = Unhindered average settling velocity (i.e. Stokes)
- \( k_0 \) = Settling Velocity Material constant
- \( H_2 \) = Total volume expressed as a height of solid material (mm)
- \( H \) = Given height of settled solids (mm)

In view of the fact that a range of particle sizes typically exists in tailings, both \( v_0 \) and \( k_0 \) are determined by regression analysis from sedimentation tests for a particular tailings, and hence, \( v_0 \) represents an appropriate average value. To obtain the actual height of settled solids at any given point in time, one must numerically integrate (2-11).

While (2-11) predicts the rate of settlement for a given tailings, it does not predict when sedimentation ceases or becomes insignificant. The final height \( H_l \), at which sedimentation ceases, is a function of effective stress (Schiffman et al., 1988; Pane and Schiffman, 1985) and is mainly dependent upon the height of solids.
The compressibility relationship is given by

\[ e = A \sigma' B + e_f \]  

(2-12)

Where:

- \( e \) = Void Ratio, \( \frac{V_v}{V_s} \)
- \( A \) = Compression Parameter
- \( \sigma' \) = Effective Stress (kPa)
- \( B \) = Compression Exponent
- \( e_f \) = Void ratio under air dry conditions

Equation (2-12) is a relationship that was proposed by Carrier and Beckman (1984) which when plotted is similar to the graph of void ratio versus effective stress for the data obtained by Swarbrick (1992) from the laboratory drying and field experiments.

The parameter \( e_f \), which is the lower bound of \( e \), may readily be determined from material parameters by:

\[ e_f = \frac{G_s}{(\rho_d^{\text{MAX}})} - 1 \]  

(2-13)

Where:

- \( e_f \) = Void ratio under air dry conditions
- \( G_s \) = Soil Particle Density
- \( \rho_d^{\text{MAX}} \) = Maximum Dry Density under air dry conditions

If Equation (2-12) is used for the compressibility relationship, then the following approach can be used to determine compressibility data from column tests. This allows an expression relating the final settled height, \( H_z \), to the parameters in Equation (2-12) to be found.

For a unit area the height of solids, \( H_z \), remains constant during sedimentation / consolidation, its value being

\[ H_z = \frac{H_{t,i}}{(1 + e_{i}^{\text{avg}})} \]  

(2-14)
for the initial height of tailings, $H_{t,i}$, and the initial average void ratio $e_{i}^{avg}$ which is assumed to be uniform. The final average void ratio is determined from the final height of tailings, $H_{t,\infty}$, by

$$e_{w}^{avg} = \frac{H_{t,\infty} - 1}{H_{z}} \quad (2-15)$$

Assuming full saturation, the effective stress at time, $t$, is (as proven by Swarbrick, 1992)

$$\sigma'(z,t) = \gamma_{s}(H_{z} - z) + \gamma_{w} \int_{z}^{H_{t}} e(z,t) \, dz - \gamma_{w} h(z,t) \quad (2-16)$$

Once consolidation has ended the pore pressure is purely hydrostatic, hence

$$h(z, \infty) = \int_{z}^{H_{z}} (1 + e(z,\infty)) \, dz \quad (2-17)$$

The effective stress then becomes

$$\sigma'(z,\infty) = \gamma_{w}(G_{s} - 1)(H_{z} - z) \quad (2-18)$$

Assuming that the relationship $e = e_{o} - C_{c} \log (\sigma')$ applies over the depth of the sample and that the sample is fully consolidated when there is no more measurable change in settled height over time. Expressing the final void ratio by using material coordinates and evaluating the integral by using Equation (2-18) yields the following

$$e_{w}^{avg} = (1/H_{z}) \int_{0}^{H_{z}} [e_{o} - C_{c}\log\{\gamma_{w}(G_{s} - 1)(H_{z} - z)\}] \, dz \quad (2-19)$$

$$= e_{o} - C_{c} \left[ \log\{\gamma_{w}(G_{s} - 1)(H_{z})\} - 1 \right] / \ln 10$$

By plotting $e_{w}^{avg}$ vs $[\log\{\gamma_{w}(G_{s} - 1)(H_{z})\} - 1] / [\ln 10]$ for several column tests estimates of $e_{o}$ and $C_{c}$ may be found.

The resulting equation, which allows an expression relating the final settled height $H_{f}$, is

$$H_{f} = H_{z}\{1 + (A/(B + 1))\} [\gamma_{w}(G_{s} - 1)H_{z}]^{B} + e_{f} \} \quad (2-20)$$
The material constants $A$ and $B$ are determined using non-linear regression techniques. Equation (2-12) and (2-20) describe the combined effects of sedimentation and consolidation of a homogeneous saturated layer.

### 2.9.5.2 Evaporation

**First Stage of Evaporation**

During the first stage of evaporation the rate of evaporation is constant and equal to the available potential. The main consideration is determining the duration of this stage. Analysis of the first or constant stage of evaporation (e.g. Gardner and Hillel, 1962) generally involves an expression relating the water content of the soil to the evaporation potential $e_p$ (mm/day) and the depth of the soil profile at the commencement of stage-one evaporation $H_s$ (mm). This relationship depends upon the way in which the diffusivity of the soil of approximated together with an approximate analytical solution. These solutions are for nondeformable media and, therefore the choice of profile depth is important.

Gardner and Hillel (1962) developed an expression for the average water content within a profile at the end of stage-one evaporation. Assuming this relationship to hold for tailings results in the following equation:

$$w_1 = \left[\frac{H_s}{k_1 G_s h_z}\right] \ln \left[1 + \left(\frac{e_p k_1 H_s}{2D_o}\right)\right] \quad (2-21)$$

Where:

- $w_1$ = Average gravimetric water content at the end of stage-one evaporation
- $H_s$ = Depth of the soil profile at the commencement of stage-one evaporation (mm)
- $k_1$ = Material constant
- $G_s$ = Specific gravity
- $h_z$ = Total volume expressed as a height of solid material (mm)
- $e_p$ = Evaporation potential (mm/day)
- $D_o$ = Material constant

Here, the average gravimetric water content at the end of stage-one evaporation, $w_1$ ($M_w/M_s$), is found from $e_p$ and $H_s$. Having obtained $w_1$, the duration of the first stage of evaporation is found knowing $e_p$ using:
\[ t_1 = \frac{[(w_s - w_1)G_s h_2]}{e_p} \]  

(2-22)

Where:
- \( t_1 \) = Duration of the first stage of evaporation (days)
- \( w_s \) = Water content
- \( w_1 \) = Average gravimetric water content at the end of stage-one evaporation
- \( G_s \) = Specific gravity
- \( h_2 \) = Total volume expressed as a height of solid material (mm)
- \( e_p \) = Evaporation potential (mm/day)

The parameters \( D_0 \) and \( k_1 \) in Equation (2-22) are empirical and by definition, are from the approximate relationship using relating diffusivity and water content. To enable their use for deforming media, they have been determined from the laboratory drying box experiments.

**Second Stage of Evaporation**

Once the first stage of evaporation has ended, the rate of evaporation is reduced due to the reduced ability of the profile to deliver water to the surface. As the profile continues to desaturate the rate of evaporation continues to fall. Earlier work on the second stage of evaporation (Philip, 1957; Gardner, 1959) uses analytical approaches to determine the second, or falling rate, stage of evaporation.

As noted previously (Philip 1957, Gardner and Hillel 1962), it is clear that, as the applied evaporation potential decreases, the duration of stage one, \( t_1 \), increases. This is evident from theory because the rate of increase in \( w_1 \) from Equation (2-21) is not as great as the increase in \( t_1 \) due to Equation (2-22), hence \( t_1 \) increases. As a result of this increase, the rate at which the second-stage rate falls will be less pronounced. Gardner and Hillel's (1962) work involved a comparison of available potential evaporation with Gardner's theoretical solution with an infinitely high evaporation rate (Gardner, 1959).

Gardner and Hillel (1962) concluded that the cumulative evaporation during the second stage of evaporation follows that of the theoretical solution for an infinitely high rate of potential evaporation after some point on the theoretical curve. This point depends upon the available potential evaporation and the initial conditions of the layer. This only applies when cumulative evaporation (CE) is expressed as a normalized water loss, i.e. \( CE/V_{ws} \) where \( V_{ws} \) is the total amount of water to be evaporated at the commencement
of stage-one evaporation. In Figure 2-10, the normalized water loss has been plotted against time for a particular value of $e_p$. Gardner’s theoretical solution for $e_p = \infty$ will describe the rate of water loss during the second stage if its origin with respect to commencement of stage-one evaporation, i.e. $t_o$ and $E_o$ is known. The determination of $t_o$ and $E_o$ is detailed in the following.

![Figure 2-10: Normalised water loss against time (Swarbrick and Fell, 1992).](image)

As the second stage is approximated by assuming that cumulative evaporation is proportional to the square root of time, then, using the aforementioned observations, a general relationship is proposed:

$$t = \left[ \frac{(E - E_o)}{(b_s)} \right]^2 + t_o$$  \hspace{1cm} (2-23)

which can be rewritten as:

$$E = b_s \sqrt{t - t_o} + E_o$$  \hspace{1cm} (2-24)

Where:
- $t$ = Time since the start of evaporation (days)
- $E$ = Normalized cumulative water loss
- $E_o$ = Fitting parameter shown in Fig. 2-10
- $t_o$ = Fitting parameter shown in Fig. 2-10
- $b_s$ = The rate of change of $E$ with respect to the square root of $(t - t_o)$, usually called normalized sorptivity.
The fitting parameters $E_o$ and $t_o$ are determined by known conditions at the commencement of stage one evaporation, $t_i$. Letting $\hat{e}_p$ denote normalized evaporation potential (i.e. $\hat{e}_p = e_p/V_{ws}$), then the known conditions at $t_i$ are $E(t_i) = \hat{e}_pt_i$ and $dE(t_i)/dt = \hat{e}_p$. Substitution into Equation (2-24) yields the following expressions for the parameters $E_o$ and $t_o$:

\[
E_o = \frac{\hat{e}_p t_1}{2\hat{e}_p} - (b_s)^2 \tag{2-25}
\]

\[
t_o = t_1 - \left(\frac{b_s}{2\hat{e}_p}\right)^2 \tag{2-26}
\]

Where:

- $E_o$ = Fitting parameter shown in Fig. 2-10
- $\hat{e}_p$ = Normalized evaporation potential
- $t_1$ = Duration of the first stage of evaporation (days)
- $b_s$ = The rate of change of $E$ with respect to the square root of $(t - t_o)$, usually called
  \textit{normalized sorptivity.}
- $t_o$ = Fitting parameter shown in Fig. 2-10

Expansion of Equation (2-24) using Equation (2-25) and Equation (2-26) gives:

\[
t = \frac{1}{(b_s)^2} E^2 + \frac{1}{(e_p)^2} - \frac{2e_pt_1}{(b_s)^2} + \frac{(e_p^2)(t_1^2)}{(b_s)^2} \tag{2-27}
\]

Where:

- $t$ = Time since the start of evaporation (days)
- $E$ = Normalized cumulative water loss
- $e_p$ = Evaporation potential (mm/day)
- $t_1$ = Duration of the first stage of evaporation (days)
- $b_s$ = The rate of change of $E$ with respect to the square root of $(t - t_o)$, usually called
  \textit{normalized sorptivity.}

which can be solved by polynomial regression using least squares. Once solved, $b_s$, $e_p$ and $t_1$ may be found. In practice, $e_p$ and $t_1$ are obtained from the drying box experiments and are often difficult to ascertain accurately when the measurements are discontinuous or when the experiment is disrupted. The computed values of $e_p$ and $t_1$ enable to
comparison against their values determined from laboratory experiments, helping to smooth possible errors in the data.

Applying this method to a given material means that only one material constant, $b_s$, is required, which in conjunction with $e_p$ and $t_1$ fully describes the second stage of evaporation.

### 2.9.5.3 Calculation of Saturation

One of the critical parameters needed for design purposes is the average density of the layer during desiccation. While the bleed rate from sedimentation exceeds the available evaporation, the tailings remain saturated, and calculation of density is straightforward. Once evaporation exceeds the bleed rate, desaturation begins, and an estimation of saturation is required.

If the equivalent saturated water content, $w_{sat}$, is known then the level of saturation would simply be $w/w_{sat}$. In deforming soils the deformation behavior is non-linear in the following manner. As $S$ decreases, pore pressures are increased. This increase in pore pressure causes deformation of the skeleton. Subsequently, the deformation of the layer effects $S$. It has been found that for these materials, $S$ may be approximated by the bulk density divided by the equivalent bulk density assuming full saturation. This may be expressed in terms of $w$ by:

$$S \approx [(1 + 1/w_{sat})/(1 + 1/w)]$$

Where:

- $S$ = Saturation
- $w_{sat}$ = Equivalent saturated water content
- $w$ = Water content

This approach provides a good approximation to $S$ because as $S$ decreases, the decrease in equivalent saturated bulk density caters for the reduction in height due to desiccation. After some point during desiccation, no more shrinkage can occur and $w_{sat}$ will not change. The value of $S$ during desiccation after this point will be entirely dependent upon $w$.

During the desiccation process, it is necessary to determine $w_{sat}$. The most suitable approach being linear interpolation between an upper and lower bound. These bounds
may be determined theoretically. The upper bound for \( w_{\text{sat}} \) is the saturated water content after full sedimentation has occurred. This is termed \( w_{\text{ub}} \) and is calculated by:

\[
w_{\text{ub}} = w_i - (H_i - H_f)/(G_s V_s)
\]  \hspace{1cm} (2-29)

Where:
- \( w_{\text{ub}} \): Upper bound for \( w_{\text{sat}} \)
- \( w_i \): Initial water content
- \( H_i \): Initial height of settled solids
- \( H_f \): Final height of settled solids due to sedimentation alone
- \( G_s \): Specific gravity
- \( V_s \): Volume of solids

The lower bound is dependent upon the final dry density of the profile, which reaches a maximum after some period during desiccation. This maximum value is generally independent of the drying history and may be assumed constant. To this known density we may equate the known saturation at this point (i.e., \( S = 0 \)) and water content (\( w = 0 \)) to determine a lower bound for \( w_{\text{sat}} \). Letting \( \rho_d \) denote dry density at water content \( w \) and letting \( \rho_w \) denote the density of water, then:

\[
S = [(1 + 1/w_{\text{sat}})/(1 + 1/w)]
\]  \hspace{1cm} (2-30)

\[
= G_s w \rho_d/(G_s \rho_w - \rho_d)
\]

Rearrangement gives:

\[
w_{\text{sat}} = (G_s \rho_w - \rho_d)/[G_s((1 + w) \rho_d - \rho_w) + \rho_d]
\]  \hspace{1cm} (2-31)

Where:
- \( S \): Saturation
- \( w_{\text{sat}} \): Equivalent saturated water content
- \( w \): Water content
- \( G_s \): Specific Gravity
- \( \rho_w \): Density of water (kg/m\(^3\))
- \( \rho_d \): Dry density (kg/m\(^3\))
For our lower bound, we let $w = 0$; $\rho_d = \rho_{d_{\text{max}}}$ (maximum dry density); and $w_{\text{sat}} = w_{\text{lb}}$ at this point. Substitution of these into Equation (2-31) yields Equation (2-32).

$$W_{\text{lb}} = \frac{(G_s\rho_w - \rho_{d_{\text{max}}})}{G_s(\rho_{d_{\text{max}}} - \rho_w) + \rho_{d_{\text{max}}}}$$ (2-32)

Where:
- $w_{\text{lb}}$ = Lower bound for $w_{\text{sat}}$
- $G_s$ = Specific gravity
- $\rho_{d_{\text{max}}}$ = Maximum dry density (kg/m$^3$)

Having obtained the two extreme values of $w_{\text{sat}}$, linear interpolation between the upper and lower bounds using the previous minimum value of saturation ($S_{\text{min}}$) is used to estimate $w_{\text{sat}}$. Once $w_{\text{sat}}$ is known, $S$ is determined from Equation (2-28).

If sedimentation is still occurring during evaporation, which is usually the case, $w_{\text{sat}}$ should be determined using the height prediction by sedimentation.

2.9.6 Rainfall

Rainfall events are modelled on a daily basis, $w$ is not allowed to rewet above the current value of $w_{\text{sat}}$, assuming $S_{\text{min}}$ does not increase. This is represented algebraically by:

$$W_{\text{rewet}} = \text{maximum of } (w + \frac{V_{\text{rain}}}{G_s V_s}) \text{ or } (w_{\text{sat}})$$ (2-33)

Where:
- $w_{\text{rewet}}$ = Lower bound for $w_{\text{sat}}$
- $V_{\text{rain}}$ = Volume of rain per unit area
- $w$ = Water content
- $G_s$ = Specific gravity
- $V_s$ = Volume of solids
- $w_{\text{sat}}$ = Equivalent saturated water content

where $V_{\text{rain}}$ represents the volume of rain per unit area (in millimetres) of rainfall for that particular period. Due to the way in which saturation is calculated, $H$ may appear to rise slightly after a dry profile experiences a rain event. This effect is not intentional, but it
does reflect typical tailings behaviour, which is to swell slightly after rewetting, behaving in an over-consolidated manner.

2.5 INFLUENCE OF RATE OF RISE

Rate of rise is the term globally applied to describe qualitatively the controlling influence of drainage and consolidation. High rates of rise on poorly draining soils can severely affect (McPhail and Wagner, 1987):

- The position of the phreatic surface – with severe stability implications;
- The degree of consolidation of the foundation soil and hence the shear strength of the tailings;
- Operation of the dam in cases where cycle times prove inadequate to facilitate drainage drying and desiccation of the daywall tailings. In the case of paddock dams this could result in piping through the pack-out walls (i.e. the dykes) when new deposition takes place. Inadequate drying will also affect access for packing-out tailings (i.e. dyke buildings).

The rate at which a slimes dam is constructed depends on a number of factors, which again may influence one another. In practical terms for gold tailings, the maximum rate of rise is the rate of deposition that allows a low enough cycle time on the dam’s day paddocks to facilitate drying out (desiccation) of the slime. Desiccation of the slime is essential in that (Jones and Wagner, 1996):

- Firstly it consolidates the material, and
- Secondly, from a practical point of view, slime must be reasonably dry to allow access to humans and/or mechanical equipment to facilitate construction of a relatively impervious impoundment wall on the inner and outer shoulders of the day paddock.

Furthermore the cycle time should also be low enough to limit recharging of the phreatic surface within the tailings dam. A high recharge rate results in a rise in the phreatic surface and may result in unstable conditions.

The cycle time is also affected by the relative density (RD) of the deposited slurry. The relative density of the slurry is the density of the slurry divided by the density of water. It
is thus evident that the more solids the slurry contain the higher the relative density and visa versa. Normally gold tailings are deposited at relative densities of between 1,15 and 1,45 (Jones and Wagner, 1996). It is clear that the lower the RD, the more water the slurry contains and the longer it will take to dry out.

The recommended rate of rise for slimes dams on dolomite is 0,9 m/year for a RD of 1,3 with a maximum recommended rate of rise of 1,15 for a RD of 1,3 (Jones and Wagner, 1996). With normal foundation conditions, using optimal dam building procedures, the rate of rise can be increased to around 2 m/year for a RD of 1,3 (Jones and Wagner, 1996).

The recommended rate of rise for wet disposal surface impoundments constructed using upstream or centerline methods is limited by excess pore pressures generated by construction. Because downstream construction uses relatively permeable materials, the rate of rise is only limited by the rate at which construction can occur. Vick (1983) recommends that rate of rise in upstream construction be limited to less than 10 m per year.

2.10 SUMMARY

This is a summary of all the concepts that have been discussed in Chapter 2. These concepts surround tailings, how they are produced as well as the storage facilities that contain them, rate of rise, sedimentation and desiccation of tailings, suctions and soil-water characteristics curves.

- Tailings are the by-product or waste output of the ore extraction process. Tailings can be divided into tailings sands and tailings slimes.

- Gold concentrate may be the end product of the milling operation. Alternatively, concentrate may be further processed in some mills by sodium cyanide leaching, with obvious effects on the character of the liquid tailings effluent.

- Gold tailings exhibit very little plasticity and no cohesiveness and classify, based upon their Atterberg Limits, as low to high plasticity silts on the Casagrande chart.
Gold tailings dams in South Africa are generally constructed using the upstream semi-dry paddock method. Dams constructed using this method comprise of two components, viz the daywall and nightwall/nightpan.

The important difference between the coarse and fine gold tailings product lies in their permeability and consolidation characteristics. The fines will take longer to consolidate and, if loaded too rapidly, the available shear strength can be reduced by excess pore pressures.

In practical terms for gold tailings, the maximum rate of rise is the rate of deposition that allows a low enough cycle time on the dam’s day paddocks to facilitate drying out (desiccation) of the slime.

The study of the sedimentation and consolidation behaviour of tailings following deposition is of major concern in the design of tailings impoundments, not only from a stability point of view but also determining the storage capacity and allowable rate-of-rise on the structures.

The total suction corresponds to the free energy of the soil water, while the matric and osmotic suctions are the components of the free energy.

The soil-water characteristics curve (SWCC) may be defined as the variation of suction with the water storage capacity within the macro and micro pores of a soil.

This study aims to investigate a model that predicts various tailings properties during sedimentation and desiccation by Swarbrick (1992). Another aim that this study investigates is the general behaviour of the tailings during sedimentation and desiccation.

--oOo--
3.1 INTRODUCTION

Sedimentation and desiccation of gold mine tailings were researched separately in the laboratory with the use of two separate tests, i.e. column settling tests and drying box tests. Theoretically, however, it is assumed that sedimentation and desiccation occur simultaneously. These tests were used to monitor and observe the behavior of gold mine tailings during sedimentation and desiccation as well as to determine material-dependent parameters. These parameters are used for modeling the behavior of gold mine tailings using a semi-empirical model proposed by Swarbrick, 1992.

Sedimentation of tailings was observed using column settling tests, where three different size columns were used. This provided information about the general settling behaviour of tailings. The columns that were used to conduct the sedimentation experiments are glass cylinders and are standard laboratory equipment.

The desiccating behavior of tailings was observed with the use of a drying box. The drying box had to be constructed specifically for the purpose of these experiments. The details of the drying box and its design are discussed in the following section, Section 3.2.

3.2 EXPERIMENTAL EQUIPMENT

3.2.1 Drying Box Setup

The basic design of the drying box was obtained from Swarbrick and Fell, 1992; Figure 3-1 gives a representation of their drying box they used in their research. The drying box used in this research project was, however, adapted and changed due to certain factors and limitations. Figure 3-2 shows two photographs of the drying box that was constructed for the purpose of this research project.
The factors that influenced the design of the drying box were cost and availability of materials. The drying box had to be constructed as economically as possible due to limited resources. Some of the materials used were recycled from old projects; an example was the glass tank.

The drying box consists of a glass tank supported by a steel frame. The glass tank is approximately 450 mm high, 600 mm long and 435 mm wide and has a volume of
roughly $1.1745 \times 10^4$ mm$^3$. The glass tank is sealed at the bottom and on all four sides, which did not allow for the drainage of excess water. The steel frame has steel supports that lift it 220 mm off the floor.

**Lighting System**

Two removable steel rods bent in a U-shape are used to support four lights. They can be adjusted to vary the height of the lights above the drying box. The four lights, two on each steel rod are 300W halogen lights which can be tilted at various angles. The lights are roughly 220 mm above the edge of the glass box and are tilted at an angle of 30° to the horizontal. The lights were used to simulate sunlight.

The lights were connected to timers which regulated the duration of radiation to the tailings. The lights were generally on for two hour periods and off for half hour periods, this was done to prevent overheating of the lighting system. A fan was also present to cool the lights and blew directly on the lights.

**Weighing System**

The drying box has wire cables attached to each steel support. These cables are in turn attached to a load cell above the drying box. The load cell was connected to a crane and an amplifier which was used to pick up the drying box and give an output reading, respectively. This was done to be able to weigh the drying box and its contents. The drying box weighs 27.5 kg when it is empty.

**Height, Temperature and Suction Measurement**

A stainless steel ruler was attached on the outside of the glass tank. The ruler was used as a settlement gauge to determine the height of the settled tailings material as it dried out. The air and soil temperatures were measured using a normal thermometer and a soil thermometer, respectively. The suction pressures between the soil particles were measured using a suction probe connected to an amplifier.

**Sampling System**

Samples of the tailings material was taken using a tube sampler whose design was modified. The original tube sampler used by Dr NJ Vermeulen, 2001 was made smaller so that the disturbance of the tailings material in the box could be kept to a minimum. The modified sampler has an inside diameter of $\pm$ 27.5 mm and a wall thickness of 1 mm. **Figure 3-3** shows the original and modified samplers.
3.3 TEST MATERIAL

3.3.1 Material Origin

The tailings material used for the research was obtained from Mispah tailings dam. Bulk samples were taken from the daywall at locations on opposite ends of the tailings dam. Mispah tailings dam is run by Vaal River Operations, which is situated on the Vaal River bordering the Northwest Province and the Freestate Province between Potchestroom and Klerksdorp. The mine operates on the Vaal Reef of the Witwatersrand Complex.

Figure 3-4 gives a plan and aerial view of Mispah tailings dam. Mispah was commissioned in November 1993. The final planned height of the dam is 60 m and the total surface area is approximately 165 Ha. The dam receives roughly 150 000 tons of tailings per month. It has ten deposition stations around the perimeter. The average rate of rise is 2.4 meters per year with one deposition cycle taking approximately 2 weeks.
Mispah tailings dam was chosen because previous research had been done by Dr NJ Vermeulen on the tailings material from this dam. From this research various basic material properties such as specific gravity and grading had been obtained.

### 3.3.2 Material Used

As stated in **Section 3.3.1** above, the tailings material used for the research was obtained from the daywall at locations on opposite ends of the tailings dam. These bulk samples were collected on different days at different locations from the daywall. This
resulted in there being a difference in the grading of the two bulk samples that were taken.

The first bulk sample contained a greater percentage of fine material and the second bulk sample contained a greater percentage of coarser material.

The material used for the column settling tests and drying box experiments consisted of samples taken from the fine material (first bulk sample), the coarse material (second bulk sample) and a combination of the two. In Table 4-1 and 4-2, in Chapter 4, reference is made to fine, mix, coarse etc. in the test column. This fine, mix, and mix refers to the sample material, which was either taken from the fine, coarse or a combination of the two bulk samples.

Water from the tailings dam was also collected for the research. This was done because the chemical content of tailings water was not tested and therefore, it was unknown and could not be recreated in the laboratory. Thus, if distilled water were to be used, we would not know what effect it would have on the results, compared to that of the tailings water.

3.3.3 Material Properties

Grading and Atterberg limits were performed on Mispah tailings material that was used in the drying box tests. Four samples of the tailings were tested. Basic indicator tests were also performed by Dr NJ Vermeulen on tailings material from the same dam. The Atterberg limits and Specific gravity (Gs) of Mispah tailings are given in Table 3-1 below.

**Table 3-1:** Atterberg limits and Specific gravity of Mispah tailings.

<table>
<thead>
<tr>
<th>SOURCE</th>
<th>Gs (Mg/m³)</th>
<th>LL (%)</th>
<th>PL (%)</th>
<th>PI (%)</th>
<th>LS (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vermeulen</td>
<td>2.74</td>
<td>29</td>
<td>22</td>
<td>7</td>
<td>2.0</td>
</tr>
<tr>
<td>Sample 1</td>
<td>-</td>
<td>28</td>
<td>24</td>
<td>4</td>
<td>2.0</td>
</tr>
<tr>
<td>Sample 2</td>
<td>-</td>
<td>27</td>
<td>22</td>
<td>5</td>
<td>1.5</td>
</tr>
<tr>
<td>Sample 3</td>
<td>-</td>
<td>20</td>
<td>16</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>Sample 4</td>
<td>-</td>
<td>28</td>
<td>23</td>
<td>5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Where:

Gs - Specific gravity  
LL - Liquid limit  
PL - Plastic limit  
PI - Plasticity index  
LS - Linear shrinkage
Mispah tailings classify as low plasticity silt/clay, and on the standard plasticity chart or Casagrande A-line chart, the tailings can be plotted right on the intersection of the A-line and the low/intermediate plasticity boundary. **Figure 3-5** shows the plasticity chart. **Figure 3-6** gives the grading of sample 1 and 2, as well as a grading from Dr NJ Vermeulen and a Jones & Wagner report.

![Plasticity Chart](image)

**Figure 3-5**: Plasticity chart showing classification of Mispah Tailings.
3.3.4 Limitations

Due to limiting factors, we were only able to obtain two bulk samples from Mispah tailings dam. As stated above in Section 3.3.2, these two bulk samples were different in grading from one another. The tests that were performed on the tailings material, were done using material from each sample and a combination of the two samples. This was done in order to try to obtain a better representation of the material on site.

Another limitation of this research was that the tailings water was not tested to obtain the chemical composition. It was felt that this was not part of the scope of the project and
thus testing of the tailings water was not done. To overcome this limitation, tailings water from Mispah tailings dam was used as not to influence the results of the experiments.

The four samples, (Sample 1 to 4), used for the grading and Atterburg limits was taken at random. Not all the material from each drying box test had a grading and Atterburg limits performed. This is a limitation on the research.

3.4 EXPERIMENTAL TEST METHOD

3.4.1 Column Settling Tests

Before column settling tests began, the material had to be oven dried first at a temperature between 60ºC and 100ºC. The water used in the column tests was taken directly from the tailings dam. This had been done to obtain values as realistic as possible because the tailings dam water contains various chemicals that affect the behavior of the tailings material.

When the tailings slurry was poured it had a certain density. This density can be expressed as a ratio of mass of water to mass of tailings. The ratio of the water to tailings was obtained from the Vaal River Operations mine and was also tested on site. From both sources of information, it was determined that the ratio of mass of water to mass of tailings was roughly 1.3.

Three different size columns were used for the column settling tests, namely the 250 ml, 500 ml and 1000 ml columns. From density calculations the amount of water and tailings for each test was determined. For the 250 ml column, 196 ml of water was added to 151 g of tailings material; for the 500 ml column, 392 ml of water was added to 302 g of soil and for the 1000 ml column, 784 ml of water was added to 604 g of soil. Using these quantities the initial height in the columns was 250 ml, 500 ml and 1000 ml, respectively.

The density calculations that were used for the determination of the above quantities of tailings and water were based on slurry samples taken from Mispah Tailings Dam. The volume and mass of the tailings and water were determined for these samples. The moisture content had also been determined. These values were then used for obtaining the right quantities of tailings and water for the column settling tests, as given above.
The correct amount of tailings material was weighed for the column test using the amounts given in the above paragraph for the specific column that had been used, i.e. the 250 ml, 500 ml or 1000 ml column. The amount of tailings dam water was also weighed off and was then added to the tailings material. This was mixed thoroughly so that there were no clots left in the material.

The tailings slurry had been poured into the column and the time was noted, as this was the start time of the column settling test. The height of the slurry was also recorded at the start time. The height of the material, as it settled in the water was recorded as time passed. The intervals of time that readings were taken, were very short in the beginning of the test, because the material started to settle at a high rate and as time passed, this rate of settlement decreased and so the time interval became greater. The rate of settlement became less and settlement eventually ceased. Figure 3-7 shows a column settling test that is in progress.

![Figure 3-7: Column settling test in progress.](image)

The column settling tests were mainly used to determine height versus time for the tailings material. They were also used to determine other parameters as well as the model parameters for sedimentation.
3.4.2 Drying Box Tests

The tailings material that was used for this test was oven dried in the same way as for the column settling test. The same water as for column settling tests had been used, i.e. water directly from the tailings dam. This was to simulate realistic conditions because the chemicals in the tailings water may affect the behavior of the tailings material.

(a) Pouring

Once the tailings material was ready for use, the test was started. First the drying box was weighed before the material was poured into it, it had a mass of 27.5 kg as stated in section 3.2.2. From density calculations, the specific amounts of tailings and water were determined. For the test, 55.2 kg of tailings and 71.77 lt of tailings dam water was used. The tailings slurry was poured at roughly the same density as it had been poured on the daywall. The slurry density is expressed as a ratio, and the ratio of the mass of water to tailings was 1.3 for the daywall and for this test.

The tailings slurry was mixed in four portions because it makes it easier to mix, and to pour in the drying box. Each portion contained 13.8 kg tailings material and 17.94 lt of water. The tailings material was weighed and thrown into the mixing bucket. The tailings dam water was then weighed and also added into the mixing bucket. The two materials were mixed thoroughly until there were no more clots. The mixed slurry was then poured into the drying box.

This process had been repeated four times, each time the slurry was added to the drying box. Once all the slurry was poured, it was mixed again in the drying box because some sedimentation has already taken place. Figure 3-8 shows the drying box test just after the tailings slurry has been poured; settlement has started to take place.
Figure 3-8: The drying box test after the slurry has been poured.

(b) **Start of Test**

The height and time were recorded at the start time. The initial height of the tailings slurry was about 35 cm. The initial weight of the drying box was also measured using the system explained above in Section 3.2.2, and was in the range of 154 to 158 kg. **Figure 3-9** illustrates the weighing system using the load cell and crane setup. The height versus time was recorded as time passed. The air temperature that resulted because of the light system was also recorded against time.
Figure 3-9: The drying box being weighed.

(c) Sedimentation

Sedimentation took place first before evaporation and the height of the tailings material was recorded as it settled. The time was always recorded when the height readings were taken. The stainless steel ruler on the outside of the drying box was used to take height readings. The mass of the drying box was also recorded each day. It took roughly a day for sedimentation to be completed. Figure 3-10 shows the drying box after considerable sedimentation has occurred.
Once the sedimentation was complete, the excess water was drained off so that the material itself could start to dry. From the commencement of the drying box test the lights were placed on the drying box and had been turned on.

(d) **First Stage of Evaporation**

The next stage after sedimentation had been completed, was the first stage of evaporation when all the material was saturated and no cracks had occurred on the surface of the tailings yet. During this stage the pressure between the particles was still positive and as time passes it started to become negative. **Figure 3-11** shows the surface of the tailings material in the drying box before cracking starts to take place.
The height of the tailings was still recorded against time as drying took place. The box was weighed everyday using the load cell. The air and soil temperatures were measured along with the height measurements. These readings continued through to the next stage of evaporation. In Section 3.2.2 above, the measurement equipment is explained.

The suctions were still very low, however, the suction probe was still used to check the suctions on the surface of the tailings material. These readings continued until cracks started appearing on the surface of the tailings material. No samples of the material were taken at this stage of testing.

(e) **Second Stage of Evaporation**
Cracking of the tailings material started and the suctions started to increase as the tailings material began to dry. **Figure 3-12** shows the cracks on the surface of the tailings during a drying box test. The crack widths were monitored and measured every day until the test ended. A vernier was used to measure the crack widths.

The height, air temperature, soil temperature and suction readings was measured and were recorded against time. **Figure 3-13** shows the suction probe connected to the amplifier while it is being used to take readings in the drying box. The weight of the drying box was still recorded once a day.

**Figure 3-11:** Drying box before cracking starts.
Figure 3-12: Drying box once cracking of tailings material starts to take place.

Figure 3-13: Suction readings being taken using the suction probe.

Cracking now influenced the accurate determination of volume and therefore samples were taken. Using the sampler described in Section 3.2.2 above, samples were taken from the drying box each day. The sampler was pushed into the drying box with the valve open until the required depth was reached. The valve was then closed and the sampler was pulled out of the tailings with the sample inside. The tailings sample could be pulled out because there was a vacuum in the sampler due to the closed valve. The valve was opened and the tailings sample was blown out.
Figure 3-14 shows the sampler once it has been inserted into the soil and the valve has been closed, before the sample is extracted.

The hole in the drying box caused by the sampling was closed using tailings at approximately the same moisture content as that in the drying box. The amount of tailings put into the whole was weighed. Once the moisture content of the tailings went below 30%, it was difficult to mix the tailings and water because it was too dry. Therefore, the minimum moisture content used for the tailings used to fill the holes was 30%.

The tailings sample was measured using the vernier; the height and diameter were taken at various points. This had been used to determine the sample volume. The sample was weighed and then oven dried overnight at a temperature of 60 to 100°C. The sample, which was now dried, had been weighed again. The moisture content and saturation could then be determined.

During this stage of evaporation the height had reached a constant value, and only horizontal shrinkage continued, i.e. the cracks continued to grow larger. The tailings material also de-saturated during this stage and air entry took place.

These measurements were continued until suction values of over -200 kPa had been reached. By this time the material was so dry that when samples were taken, the tailings material shattered.
The measurements that were obtained from the drying box test were plotted on graphs of height, temperature, suction and mass versus time. Other parameters were then determined from those that were measured; these included moisture content, evaporation, saturation etc. and had also been plotted against time. Lastly these parameters were used to determine the model parameters used in the model by Swarbrick and Fell. All these measurements have been discussed in detail in Section 3.5.

3.5 COLUMN SETTLING TEST MEASUREMENTS

Column settling tests were used to measure the sedimentation characteristics of the tailings material. The height of the tailings was measured as it settled. This produced data of height versus time which was plotted on a graph. The height of the tailings had also been plotted against the log of time.

Figure 3-15 shows an approximation of the tailings settling characteristics (Swarbrick and Fell, 1991), i.e. height of solids versus the log of time. This graph is applied to the column tests to determine the initial \(H_i\) and final \(H_f\) heights as well as the initial \(t_i\) and final \(t_f\) time.

![Figure 3-15: Approximation of tailings settling characteristics (Swarbrick and Fell, 1991).](image)

The initial moisture content \(w_i\) of the column settling tests was needed for determining the model parameters and was determined as follows:
\[ w_i = \frac{M_w}{M_T} \] 

(3-1)

Where:

\( w_i \) = Initial moisture content  
\( M_w \) = Initial mass of water (kg)  
\( M_T \) = Initial mass of tailings (kg)

Moisture content is a ratio and has no units; it is expressed as a ratio or a percentage.

3.6  DRYING BOX TEST MEASUREMENTS

The drying box test produced direct and indirect results. The direct results were measured against time and are as follows:

- Height
- Temperature
- Suction
- Mass of drying box

These results were plotted against time for the various parameters.

The indirect results had been obtained by analysing the direct results of the drying box test and they are as follows:

- Cumulative evaporation
- Moisture content
- Void ratio
- Degree of Saturation
- Dry density
- Linear Shrinkage

3.6.1  Cumulative Evaporation

The cumulative evaporation was determined from the amount of water that had evaporated from the drying box. The amount of water evaporated could be determined from the mass of the drying box and the total height in the drying box.

When there was still a layer of water over the tailings, the total height was used to determine the amount of water that had evaporated. The tailings were immersed under
the water and had therefore still been saturated. This was the first stage of evaporation when the rate of evaporation was still constant.

When the excess water had evaporated and the surface of the tailings was exposed, the mass of the drying box was used to determine the amount of water evaporated. The transition from first stage to second stage of evaporation started to take place. This meant that the rate of evaporation was starting to change and was no longer constant anymore.

The amount of water evaporated was determined using the mass of the drying box at that specific time. The initial mass of tailings and the mass of the empty drying box was known. The following equation gives the mass of water left in the drying box:

$$M_w = M_{DB} - M_T - M_B$$ \hspace{1cm} (3-2)

Where:

- $M_w$ = Mass of water (kg)
- $M_{DB}$ = Mass of drying box (kg)
- $M_T$ = Initial mass of tailings (kg)
- $M_B$ = Mass of empty drying box (kg)

The amount of water that had evaporated from the drying box is then:

$$e_w = M_{wi} - M_w$$ \hspace{1cm} (3-3)

Where:

- $e_w$ = Amount of water evaporated (kg)
- $M_{wi}$ = Initial mass of water (kg)
- $M_w$ = Mass of water (kg)

The amount of water evaporated was converted from kilograms to mm by dividing by the surface area of the drying box. The two results of the amount of water evaporated were then combined to give a single result.

The cumulative evaporation is the sum of all the previous amounts of water evaporated up to the current amount of water evaporated. The unit of cumulative evaporation is mm.
3.6.2 **Moisture Content**

The moisture content is expressed as the ratio of the mass of water to the mass of tailings as shown in *Equation (3-4)* below.

\[ w = \frac{M_w}{M_T} \]  

(3-4)

Where:

- \( w \) = Moisture content
- \( M_w \) = Mass of water (kg)
- \( M_T \) = Mass of tailings (kg)

Moisture content is a ratio and has no units; it is expressed as a ratio or a percentage. The mass of the tailings was constant and was the initial mass; i.e. 55.2 kg. The mass of the water changed because water had continually been evaporating from the drying box. The mass of water was calculated using *Equation (3-2)*.

Tailings samples were taken during the first and second stage of evaporation when all the water has evaporated from the surface of the tailings. The moisture content was determined using *Equation (3-4)* for the samples. The final moisture content was determined using both the drying box and tailings sample results.

3.6.3 **Void Ratio**

Void ratio is the ratio of the volume of voids to the volume of tailings solids. The equation for void ratio is:

\[ e = \frac{V_v}{V_s} \]  

(3-5)

Where:

- \( e \) = Void ratio
- \( V_v \) = Volume of voids
- \( V_s \) = Volume of tailings

When the tailings had still been saturated, before the second stage of evaporation had occurred, *Equation (3-6)* was used to determine the void ratio. This equation is only valid when \( S = 1 \), i.e. the tailings are fully saturated.
\[ e = wG_s \]  \hspace{1cm} (3-6)

Where:
- \( e \) = Void ratio
- \( w \) = Moisture content
- \( G_s \) = Specific Gravity

When the second stage of evaporation occurred, samples of the tailings were taken. During the second stage of evaporation, the tailings became unsaturated and a new equation was needed to determine void ratio. The following equations together with Equation (3-11) can be combined to give Equation (3-9):

\[ \rho_b = G_s(1 + w)(\rho_w)/(1 + e) \]  \hspace{1cm} (3-7)
\[ \rho_b = (1 + w)(\rho_d) \]  \hspace{1cm} (3-8)

The void ratio is therefore:

\[ e = (G_s\rho_w)/(\rho_d) - 1 \]  \hspace{1cm} (3-9)
\[ = (G_sV_T\rho_w)/(M_s) - 1 \]

Where:
- \( e \) = Void ratio
- \( G_s \) = Specific Gravity
- \( \rho_w \) = Density of water (1000 kg/m\(^3\))
- \( \rho_d \) = Dry density = \( M_s/V_T \) (kg/m\(^3\))
- \( \rho_b \) = Bulk density = \( M_T/V_T \) (kg/m\(^3\))
- \( M_s \) = Mass of tailings solids
- \( M_T \) = Total mass of sample
- \( V_T \) = Volume of sample
- \( w \) = Moisture content

This equation was applied to the sample data to determine the void ratio. The final void ratio was determined using both the drying box and the sample results.

3.6.4 Degree of Saturation

The degree of saturation is the ratio of the volume of water to the total volume of void space. The equation for degree of saturation is as follows:

\[ S = V_w/V_v \]  \hspace{1cm} (3-10)
Where:

\[ S = \text{Degree of saturation} \quad V_v = \text{Volume of voids} \]
\[ V_w = \text{Volume of water} \]

The tailings material is saturated during sedimentation and the first stage of evaporation. Once the tailings surface became exposed, there was a transition from the first to the second stage of evaporation and the tailings had become unsaturated. Samples were also taken during this stage. The saturation can then be determined using Equation (3-11).

\[ S = \frac{w \cdot G_s}{e} \quad (3-11) \]

Where:

\[ S = \text{Degree of saturation} \quad w = \text{Moisture content} \]
\[ G_s = \text{Specific gravity} \quad e = \text{Void ratio} \]

Equation (3-11) was generally applied to the sample data and it was found that the degree of saturation started decreasing from 1 after a day or two after the first sample was taken. The final saturation was a combination of the drying box results and the sample results.

### 3.6.5 Dry Density

The dry density of the tailings is the mass of the solids per unit volume of tailings. The basic equation for dry density is:

\[ \rho_d = \frac{M_s}{V_T} \quad (3-12) \]

Where:

\[ \rho_d = \text{Dry density} \quad M_s = \text{Mass of tailings solids} \]
\[ V_T = \text{Total volume of tailings} \]

The bulk density was first calculated for the drying box and then the dry density had been calculated using this and the moisture content. The equation for bulk density is:
\[ \rho_b = \frac{M_T}{V_T} \]  

(3-13)

Where:
\[ \rho_b = \text{Bulk density} \quad M_T = \text{Mass of tailings and water} \]
\[ V_T = \text{Total volume of tailings} \]

The dry density is then:
\[ \rho_d = \frac{\rho_b}{(1 + w)} \]  

(3-14)

Where:
\[ \rho_d = \text{Dry density (kg/m}^3\text{)} \quad \rho_b = \text{Bulk density (kg/m}^3\text{)} \]
\[ w = \text{Moisture content} \]

### 3.6.6 Linear Shrinkage

The crack widths were measured daily to give an idea of the linear shrinkage of the tailings material. The linear shrinkage was determined using the following equation:

\[ LS = (1 - \frac{L_D}{L_i}) \times 100 \]  

(3-15)

Where:
\[ LS = \text{Linear Shrinkage} \quad L_D = \text{Length after drying} \]
\[ L_i = \text{Initial Length} \]

### 3.7 MODEL DETERMINATION

The data that was obtained from the column settling tests and the drying box tests had been used to determine the model parameters for the Swarbrick (1992) model. The model parameters were constants that was used in the equations of the model, these constants are unique to Mispah gold mine tailings. Once the constants were known, the model could then be used to predict the behavior of the gold mine tailings.

The model, as explained in Chapter 2, was used to determine the model parameters by using the data obtained from the column settling tests and the drying box tests. The explicit model procedure from Swarbrick (1992) was used to determine the model parameters.
3.7.1 Explicit Model Procedure

The explicit model procedure was taken from Swarbrick (1992) and is given below:

- **Step 1:** From \( H_i \) (mm), \( w_i \) and \( G_s \), calculate \( H_z \) (Using Equation (2-10) which is given below)

\[
V_s = H_i/(1 + G_s w_i)
\]  \hspace{1cm} (3-16)

- **Step 2:** Using \( H_z \), calculate \( H_f \) (mm) from Equation (2-20).

- **Step 3:** Initiate saturation calculations – Determine upper and lower bounds for \( w_{sat} \) from Equation (2-29) and (2-32). Set \( S_{min} = 1 \).

- **Step 4:** Sedimentation only – \( \Delta H \) is greater than \( e_p \) – Using a time step, \( \Delta t \), of 1 minute, find the drop in height \( \Delta H \) for the current value of \( H \) using Equation (2-11) i.e.

\[
\Delta H = (\Delta t)v_o 10^{(k o V_s H)}
\]  \hspace{1cm} (3-17)

and hence the new height is found from \( H = H - \Delta H \). The new \( w \) is found from

\[
w = w - \Delta H/(G_s V_s)
\]  \hspace{1cm} (3-18)

and saturation, \( S \), equals 1. A time step of 1 min gives the best results in terms of computational effort and accuracy. Repeat step 4 until \( e_p \) exceeds \( \Delta H \) or \( H \) reaches \( H_f \).

Set \( H_s \) and \( w_s \) to the current values of \( H \) and \( w \) and find \( V_{ws} \) using:

\[
V_{ws} = w_s G_s H_z
\]  \hspace{1cm} (3-19)

During steps 5 and 6, a separate variable, \( H_{set} \), is required to independently record the height of settled solids over time due to pure sedimentation. Hence, initially, \( H_{set} k = H_s \).

- **Step 5:** Sedimentation and first-stage evaporation – Using a suggested \( \Delta t \) of 1 hr,
find $\Delta H$ using Equation (3-17), hence $H_{\text{set}} = H_{\text{set}} - \Delta H$. Calculate new $w$ and $w_{\text{sat}}$.

$$w = w - \frac{(e_p \Delta t)/G_s H_z}{(3-20)}$$

$$w_{\text{sat}} = \text{maximum of} \ [\left(\frac{1}{G_s}\right) \times (H_{\text{set}}/H_z - 1)] \text{ and } (w) \quad (3-21)$$

Using Equation (2-28), we obtain an estimate of $S$ and hence height. The true height is found from:

$$H = H_z(wG_s/S + 1) \quad (3-22)$$

This ensures that allowance is made for any layer shrinkage due to evaporation. Repeat step 5 until $w$ is less than $w_1$ or $H_{\text{set}}$ reaches $H_f$. Once this occurs, stage one ends so $t_1$ is known. Then find $t_0$ using Equation (2-26) and parameter $b_s$.

- **Step 6:** Sedimentation and second-stage evaporation – Using a suggested $\Delta t$ of 1 day, find $\Delta H$ using Equation (3-17) hence, $H_{\text{set}} = H_{\text{set}} - \Delta H$. Calculate $w_{\text{sat}}$ from Equation (3-21) and new $w$ from:

$$w = w - \frac{(w_s b_s \Delta t)/(2\sqrt{t - t_0})}{(3-23)}$$

Determine $H$ using Equation (3-22). Repeat step 6 until desired final water content is reached or $H_{\text{set}}$ reaches $H_f$.

- **Step 7:** Once $H_{\text{set}}$ reaches $H_f$ in steps 4, 5 and 6, sedimentation ceases. Steps 5, then 6 are repeated ignoring the use of Equation (3-17), (3-21) and (3-22). The value of $w_{\text{sat}}$ is found by linear interpolation with respect to $S_{\text{min}}$.

$$w_{\text{sat}} = \text{maximum of} \ [w_1 + (w_r - w_1) \times S_{\text{min}}] \text{ and } [w] \quad (3-24)$$

and $S$ is found by Equation (2-28). A time step of one day is suggested.

- **Step 8:** Having obtained water content and saturation, calculate other parameters as required, using:

$$\rho_d = \frac{(SG_s \rho_w)}{(S + G_s w)} \quad (3-25)$$
and the corresponding estimated height is:

\[ H = \frac{G_s h z\rho_w}{\rho_d} \quad (3-26) \]

3.8 FIELD MEASUREMENTS

Mispah tailings dam was chosen for all field measurements because previous work had been done on the dam. Readings and measurements were taken from the daywall of the dam. These measurements were compared to the results and analysis from the laboratory experiments. This then determined whether the parameters in the laboratory were realistic or not.

The model by Swarbrick (1992) was one of the main components of the research that needed to be compared to real data from the tailings dam. The other main component that needed to be compared was the results of the laboratory experiments.

The following are the field measurements necessary for comparison:

- Height of tailings as sedimentation and desiccation takes place
- Moisture content of tailings
- Bulk density of tailings
- Suction pressures of tailings

3.8.1 Height

The height of the tailings, in the daywall, as sedimentation and desiccation took place was recorded against time. Wooden doweling rods were used for the purpose of height measurement. The rods were 1.5 m in length and markings in centimeters started after 0.5 m. The 0.5 m unmarked part of the rod was planted into the old tailings layers.

The rod was planted before the pouring of the tailings slurry occurred. The surface of the tailings was at zero centimeters on the rod. The slurry was then poured and the initial time and height of the tailings were recorded. A sample of the slurry was taken on site to determine the moisture content. The height of the tailings was monitored as the tailings settled and eventually desiccated. Figure 3-16 (a) shows the rod after pouring of the tailings slurry and (b) once the tailings have desiccated.
Due to the fact that the tailings dam had been relatively far away, only a few site visits could be made and proper monitoring of the tailings was difficult.
3.8.2 Moisture Content

Samples were taken on site to be able to determine the moisture content. Sampling started from the beginning of the tailings site measurements, i.e. when the tailings slurry had been poured. When the material was still soft, bulk samples were taken in containers. When the material became hard enough to sample, in the daywall, the tube sampler was used to extract samples.

The samples were taken back to the soil laboratory and weighed. They then were put in the oven overnight at a temperature of 60 to 100°C. The next day they were removed and are weighed again. From these measurements the moisture content (w) could be determined as follows:

\[ w = \frac{M_w}{M_T} \quad (3-27) \]

Where:
\[ M_w = \text{Mass of water} \quad M_T = \text{Mass of tailings} \]

Moisture content is a ratio and has no units; it is expressed as a ratio or a percentage.

3.8.3 Bulk Density

Bulk density was difficult to measure on site especially when the tailings were very soft. The bulk density could be obtained from a sample of the tailings slurry as it got poured but once settlement occurred, it was a very difficult parameter to determine. Only when samples were taken using the tube sampler, could the density be determined once again.

The samples were used to determine moisture content as well as bulk density because the volume as well as the amount of tailings and water was determined. Once the sample was extruded from the tailings, it then was taken out of the sampler by opening the valve and blowing. It was placed on a glass plate and the height and diameter of the sample was measured at various points. The sample was then covered in alternating layers of clingwrap and foil. It was then taken to the laboratory to be weighed and dried to determine the moisture content.

The volume (V) of the sample is:
\[ V = (\pi D^2/4) \times H \quad (3-28) \]

Where:
\[ D = \text{Average diameter} \quad H = \text{Average height} \]

The bulk density \( (\rho_b) \) of the sample is:
\[ \rho_b = M/V \quad (3-29) \]

Where:
\[ M = \text{Mass of tailings sample} \quad V = \text{Volume of sample} \]

The units for volume and bulk density are m\(^3\) and kg/m\(^3\), respectively.

### 3.8.4 Suctions

Suctions were taken once the tailings material had started to desiccate. The suction probe connected to the amplifier was used to measure suctions on site. The same suction probe was used in the laboratory and in the field.
CHAPTER 4
SEDIMENTATION AND DESICCATION OF GOLD MINE TAILINGS

4.1 INTRODUCTION

The aim of this chapter is to present the raw data obtained from the column settling and drying box tests explained in Chapter 3. The discussion of the presented data will follow in Chapter 5. The results of the column settling tests and drying box tests are presented in the form of tables and graphs.

This chapter also gives the data obtained from the sedimentation and desiccation model, which was discussed in Chapter 2 and Chapter 3.

Chapter 4 is divided into three sections. Section one deals with the column settling test results, section two deals with the drying box test results and section three deals with the sedimentation and desiccation model. In section two, the notation used on the graph pertains to the specific drying box test, for e.g. DB3 would indicate that the results are from Drying Box test 3.

The raw data obtained from the column settling tests and drying box tests are tabulated in the Appendices.

4.2 COLUMN SETTLING TEST RESULTS

4.2.1 Introduction
In this section, of the column settling tests, the results are summarized in graph and table format. These results show the behaviour of the tailings during sedimentation and are used to determine various model parameters.

4.2.2 Tailings Sedimentation
The height of the tailings was recorded as sedimentation occurred in the settling columns. The time was noted each time a height reading was taken. The height of the tailings was then plotted against time.

The terminology used in the legend for the column settling tests had to do with the material used for the tests.
The graphs of the tailings height versus time are plotted in Figure 4-1 to Figure 4-3 for the 250 ml, 500 ml and 1000 ml column settling tests. There is a range of values in each graph due to the material grading, i.e. coarse, fine or a mix.

In Figure 4-1 to Figure 4-6 the height of the tailings is given in centimetres and the time is in hours.

![Graph of tailings height versus time for the 250 ml column settling test.](image)

**Figure 4-1:** Height versus time for the 250 ml column test.
**Figure 4-2:** Height versus time for the 500 ml column test.

**Figure 4-3:** Height versus time for the 1000 ml column test.
**Figure 4-4** to **Figure 4-6** shows the height of the tailings plotted against the logarithm of the time for the 250 ml, 500 ml and 1000 ml column settling tests.

The initial and final heights and corresponding times were determined from **Figure 4-4** to **Figure 4-6** using the principles of **Figure 3-15** on page 3-18, which was taken from Swarbrick and Fell, 1992. These values were used to determine various model parameters and are given in **Table 4-1**, which follows after **Figure 4-4**.

The tailings settling behaviour as shown in **Figure 4-4**, **4-5** and **4-6** is similar to the idealised behaviour as shown in **Figure 3-15**.

**Figure 4-4**: Height versus log time for the 250 ml column test.

$H_i$ and $H_f$ in **Table 4-1**, are the initial and final height, respectively. The initial and final times are $t_i$ and $t_f$, respectively.
Table 4-1: Initial and final heights and times for the column tests.

<table>
<thead>
<tr>
<th>Column</th>
<th>Test</th>
<th>$H_i$</th>
<th>$H_f$</th>
<th>$t_i$</th>
<th>$t_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>fine</td>
<td>21.91</td>
<td>16.48</td>
<td>0.09</td>
<td>8.13</td>
</tr>
<tr>
<td>250</td>
<td>mix</td>
<td>22.45</td>
<td>13.76</td>
<td>0.13</td>
<td>1.52</td>
</tr>
<tr>
<td>250</td>
<td>mix2</td>
<td>22.82</td>
<td>16.12</td>
<td>0.00</td>
<td>3.32</td>
</tr>
<tr>
<td>250</td>
<td>fine2</td>
<td>22.45</td>
<td>17.29</td>
<td>0.36</td>
<td>7.82</td>
</tr>
<tr>
<td>500</td>
<td>fine</td>
<td>30.48</td>
<td>24.39</td>
<td>0.00</td>
<td>8.93</td>
</tr>
<tr>
<td>500</td>
<td>mix</td>
<td>30.36</td>
<td>20.42</td>
<td>0.00</td>
<td>1.23</td>
</tr>
<tr>
<td>500</td>
<td>mix 2</td>
<td>30.48</td>
<td>20.67</td>
<td>0.09</td>
<td>0.94</td>
</tr>
<tr>
<td>500</td>
<td>mix 3</td>
<td>28.20</td>
<td>21.64</td>
<td>0.21</td>
<td>2.50</td>
</tr>
<tr>
<td>1000</td>
<td>fine</td>
<td>35.62</td>
<td>26.49</td>
<td>0.00</td>
<td>6.14</td>
</tr>
<tr>
<td>1000</td>
<td>mix</td>
<td>35.37</td>
<td>24.76</td>
<td>0.00</td>
<td>2.35</td>
</tr>
<tr>
<td>1000</td>
<td>coarse</td>
<td>35.79</td>
<td>22.53</td>
<td>0.31</td>
<td>1.85</td>
</tr>
</tbody>
</table>

The initial and final heights in Table 4-1 are given in centimetres and the initial and final times are in hours. The original column settling data is given in Appendix A.

![500 ml COLUMN SETTLING TEST](image)

Figure 4-5: Height versus log time for the 500 ml column test.
In Figure 4-7 below, the height of the tailings is normalised, i.e. it is taken as a percentage of the initial height for each column. This percentage height of initial height was plotted against the logarithm of the time for the 250 ml, 500 ml and 1000 ml column settling tests. All the column settling test results are plotted on this graph for comparison.

In Figure 4-7, the results of the 250 ml column tests are plotted in blue, the results of the 500 ml column tests are plotted in red and those of the 1000 ml column tests are plotted in green.
Figure 4-7: Height as a percentage of the initial height versus log time for the 250ml, 500ml and 1000 ml column test.

4.2.2 Initial Moisture Content

The initial moisture content for each column test was calculated using Equation (3-1) and is tabulated below in Table 4-2. The moisture content is expressed as a ratio of mass of water to mass of tailings. This initial moisture content is needed for the determination of various model parameters.

The mass of water and mass of tailings was measured before the start of the column settling tests, i.e. before the water and tailings were mixed together for the test.
Table 4-2: The initial moisture content for the column tests.

<table>
<thead>
<tr>
<th>Column</th>
<th>Test</th>
<th>wi</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>fine</td>
<td>1.28</td>
</tr>
<tr>
<td>250</td>
<td>mix</td>
<td>1.25</td>
</tr>
<tr>
<td>250</td>
<td>mix2</td>
<td>1.31</td>
</tr>
<tr>
<td>250</td>
<td>fine2</td>
<td>1.32</td>
</tr>
<tr>
<td>500</td>
<td>fine</td>
<td>1.27</td>
</tr>
<tr>
<td>500</td>
<td>mix</td>
<td>1.22</td>
</tr>
<tr>
<td>500</td>
<td>mix2</td>
<td>1.32</td>
</tr>
<tr>
<td>500</td>
<td>mix3</td>
<td>1.31</td>
</tr>
<tr>
<td>1000</td>
<td>fine</td>
<td>1.31</td>
</tr>
<tr>
<td>1000</td>
<td>mix</td>
<td>1.30</td>
</tr>
<tr>
<td>1000</td>
<td>coarse</td>
<td>1.31</td>
</tr>
</tbody>
</table>

4.3 DRYING BOX TEST RESULTS

4.3.1 Tailings Sedimentation and Desiccation

Five drying box tests were conducted and the results are given in this chapter in the form of tables and graphs. These results are discussed in more detail in Chapter 5.

As has been stated previously, the terminology used in the legend for the drying box test graphs is as follows:

- **DB1** – Drying Box test no 1
- **DB2** – Drying Box test no 2
- **DB3** – Drying Box test no 3
- **DB4** – Drying Box test no 4
- **DB5** – Drying Box test no 5

Drying Box test no 1 was a trial run and the only proper data obtained from this test was the height of the tailings versus time and the air and soil temperatures. From Drying Box test no 2 to 5, proper data was obtained; and the results of which are plotted on the graphs that follow.
Figure 4-8: Height versus time for the drying box tests.

Figure 4-9: Height versus time (on Logarithmic scale) for the drying box tests.
The height of the tailings, is recorded against time as sedimentation and desiccation occur in each drying box test, see Figure 4-8. Figure 4-9 gives the height of the tailings plotted against the logarithmic of time. These graphs are very similar in shape to those for the column settling tests.

The process of sedimentation and desiccation is discussed in Chapter 2 and Chapter 3. The data that was obtained from each drying box test carried out on Mispah tailings is given in Appendix B.

The height of the tailings was divided by the initial height and multiplied by 100 to determine the height as a percentage of initial height, i.e. the height was normalised. This was plotted against the logarithm of time in Figure 4-10 below. The final height of the tailings ranges between 40 and 60% of the initial height of the tailings.

![Figure 4-10: Height as a percentage of initial height versus time (on Logarithmic scale) for the drying box tests.](image)

4.3.2 Air and Soil Temperatures

The air temperatures that were measured ranged from approximately 19 to 29 degrees Celsius and the soil temperatures ranged from approximately 18 to 27 degrees Celsius.
The soil temperatures generally increased as the tailings became dryer. The average temperatures for the air and soil are given in Table 4-3 below.

**Table 4-3:** Average air and soil temperatures.

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Temperature</th>
<th>Soil Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB1</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>DB2</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>DB3</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>DB4</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>DB5</td>
<td>25</td>
<td>24</td>
</tr>
</tbody>
</table>

4.3.3 Suction

The suctions in the drying box were measured using the suction probe, as discussed in Chapter 3. The suctions that were measured, ranged from 0 kPa to just over 200 kPa for the various drying box tests.

The suctions were measured on the surface of the tailings in the drying box, and 3 or 4 suction readings were taken on various positions on the tailings surface. This was done to ensure that accurate readings were taken, i.e. that there were no anomalies on the surface of the tailings that could cause a distortion to the suction readings. The average of these readings was used as the final suction value. This average value of suction is plotted on the graphs that follow in this section.

The suctions in the tailings are plotted against time. Figure 4-11 represents the suctions for four drying box tests; i.e. Drying Box Test 2 to 5. The suctions are in kPa and the time is in days. Figure 4-12 gives the suction on a logarithmic scale.
Figure 4-11: Suction versus time.

Figure 4-12: Suction (on logarithmic scale) versus time for the drying box tests.
The suctions are plotted against various soil parameters, i.e. degree of saturation, moisture content, void ratio and linear shrinkage.

In **Figure 4-13** the degree of saturation is plotted against suction and in **Figure 4-14**, the degree of saturation is plotted against suction on a logarithmic scale for the drying box test results.

**Figure 4-15** gives the moisture content plotted against suction and **Figure 4-16** represents moisture content versus suction (on a logarithmic scale) for the drying box test results. The graphs in **Figure 4-14** and **Figure 4-16** are known as soil-water characteristics curves.

The void ratio is plotted against suction in **Figure 4-17**. The linear shrinkage is plotted against the logarithm of suction in **Figure 4-18** and **Figure 4-19**. In **Figure 4-18** the linear shrinkage is along the length of the drying box and in **Figure 4-19** it is along the width.

**Figure 4-13**: Degree of saturation versus suction.
Figure 4-14: Degree of saturation versus suction (logarithmic scale).

Figure 4-15: Moisture content versus suction.
Figure 4-16: Moisture content versus suction (logarithmic scale).

Figure 4-17: Void ratio versus suction.
Figure 4-18: Linear Shrinkage (along length of drying box) versus suction (log scale).

Figure 4-19: Linear Shrinkage (along width of drying box) versus suction (log scale).
The moisture content is the ratio of the mass of water to the mass of tailings. The mass of the tailings is constant and is known, the mass of the drying box is known and the mass of water can be determined by weighing the drying box as the tailings dry out.

In determining all the parameters using the data obtained from the drying box tests, a value of 2.74 was assumed for \( G_s \). Vermeulen (2001) determined this value of \( G_s \), which was obtained by research on gold mine tailings from Mispah tailings dam. Other researchers have obtained values of \( G_s \) for gold mine tailings, these values are given in Table 2-1. They range from 2.6 to 3.1, so in assuming that the specific gravity, \( G_s \), is 2.74, is a good assumption as it is almost the average of this range of \( G_s \). Also, the tailings from Vermeulen’s research and this research originate from the same mine, so they will have been produced using the same or similar processes and will, therefore, have similar characteristics.

While the tailings were still saturated in the drying box, i.e. during sedimentation and the first stage of evaporation, the void ratio was calculated using Equation (3-6) \[ e = w G_s \]. Once the second stage of evaporation begins, and the tailings are no longer fully saturated, i.e. \( S < 1 \), Equation (3-9) \[ e = (G_s V p_w)/(M_s) - 1 \] is used to calculate the void ratio. This equation was used to determine the void ratio using values obtained from the drying box tests. This can only be done until cracks start to appear in the tailings as the tailings desiccate. Once cracks have started to appear, samples of the tailings were taken using the modified sampler (described in Chapter 2), and the void ratio was determined for these samples. It was assumed that the void ratio of this sample is representative of the void ratio of the tailings in the drying box. It was also assumed that the disturbance due to the sampler was minimal.

The void ratio that was determined using the samples, as stated in the paragraph above, was assumed to be representative of the tailings in the drying box. It does not take into account the cracks that form, and thus the void ratio is only representative of the intake tailings material between the cracks.

The degree of saturation was calculated using Equation (3-11) \[ S = (w G_s)/e \]. The moisture content and void ratio is determined as discussed above, and is then used in Equation (3-11) to determine the degree of saturation. It is assumed the saturation,
which was determined using the samples, is representative of the saturation throughout the drying box.

4.3.4 Cumulative Evaporation

The cumulative evaporation is determined from the amount of water that is evaporated from the drying box. The cumulative evaporation is the sum of all the previous amounts of water evaporated up to the current amount of water evaporated.

The cumulative evaporation of all the drying box tests is plotted against time on the graph in Figure 4-20. The cumulative evaporation is used to determine the evaporation potential for each drying box test.

![Cumulative Evaporation Graph](image)

**Figure 4-20:** Cumulative evaporation versus time.

4.3.5 Moisture Content

The moisture content is expressed as the ratio of the mass of water to the mass of tailings. Figure 4-21 gives the moisture content versus time for four drying box tests; namely Drying Box Test 2 to Drying Box Test 5.
In **Section 4.3.3**, the moisture content has already been compared to the suction for the drying box tests, see **Figure 4-15**. The moisture content determination is discussed in **Section 3.6.2** and **4.3.3**.

![Moisture Content Graph](image)

**Figure 4-21**: Moisture content versus time.

### 4.3.6 Void Ratio

Void ratio is the ratio of the volume of voids to the volume of tailings solids. **Figure 4-22** gives the void ratio against time for four drying box tests.

In **Section 4.3.3**, the void ratio has already been compared to the suction for the drying box tests, see **Figure 4-17**. Void ratio determination has already been discussed in **Section 3.6.3** and **4.3.3**.

The void ratio is plotted against moisture content on the graph in **Figure 4-23**.
Figure 4-22: Void ratio versus time.

Figure 4-23: Void ratio versus moisture content.
4.3.7 Degree of Saturation

The degree of saturation is the ratio of the volume of water to the total volume of void space. The degree of saturation is plotted against time in Figure 4-24.

In Section 4.3.3, the degree of saturation has already been compared to the suction for the drying box tests, see Figure 4-13. The determination of the degree of saturation is discussed in Section 3.6.4 and 4.3.3.

![Figure 4-24: Degree of saturation versus time.](image)

4.3.8 Dry Density

The dry density of the tailings is the mass of the solids per unit volume of tailings. The dry density is plotted against time in Figure 4-25 for all the drying box tests. The dry density is calculated from the bulk density and the moisture content. The dry density is calculated using Equation (3-14), which uses the bulk density to determine the dry density using the moisture content.

The bulk density is the total mass over the total volume. The total mass was determined by adding the mass of the tailings and the mass of the water. The mass of the tailings is constant and was measured before the start of the drying box test. The mass of the
water was determined by subtracting the mass of the tailings and the mass of the drying box from the total mass of the drying box. The volume of the material was determined by multiplying the internal plan area of the box with the height of the tailings in the box.

The bulk density was calculated in this fashion until cracks start to form on the surface of the tailings in the drying box. The bulk density was then calculated using the samples that were taken in the drying box. The dimensions of the sample were measured and the volume determined. The mass of the water and the mass of the solids were determined by weighing the sample before and after drying of the tailings sample.

It is assumed that the bulk and dry density of the sample is representative of the tailing the drying box.

Figure 4-25: Dry density versus time for the drying box tests.

4.3.9 Linear Shrinkage

The linear shrinkage is measured along the width and the length of the drying box. Table 4-4 gives the linear shrinkage for Drying Box test 3 to 5.
Table 4-4: Linear shrinkage in drying box tests.

<table>
<thead>
<tr>
<th></th>
<th>Length (%)</th>
<th>Width (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB3</td>
<td>5.26</td>
<td>5.25</td>
</tr>
<tr>
<td></td>
<td>5.75</td>
<td>4.45</td>
</tr>
<tr>
<td>DB4</td>
<td>5.36</td>
<td>6.35</td>
</tr>
<tr>
<td></td>
<td>6.24</td>
<td>7.22</td>
</tr>
<tr>
<td></td>
<td>6.63</td>
<td>7.22</td>
</tr>
<tr>
<td></td>
<td>6.73</td>
<td>6.31</td>
</tr>
<tr>
<td>DB5</td>
<td>5.71</td>
<td>7.11</td>
</tr>
<tr>
<td></td>
<td>5.48</td>
<td>6.63</td>
</tr>
<tr>
<td>Average</td>
<td>5.90</td>
<td>6.21</td>
</tr>
</tbody>
</table>

The linear shrinkage is plotted against time in Figure 4-26 and Figure 4-27. In Figure 4-25 the linear shrinkage is along the length of the drying box and in Figure 4-27 it is along the width. In Section 4.3.3, the linear shrinkage has already been compared to the suction for the drying box tests; see Figure 4-18 and Figure 4-19.
4.4 THE SEDIMENTATION AND DESICCATION MODEL

4.4.1 Tailings Model Parameters

The tailings model parameters were calculated using the information obtained from the column settling tests and the drying box tests. These model parameters are the constants in the equations of the model, which is used to predict the behaviour of the tailings. The tailings model parameters of Mispah Tailings Dam are given below in Table 4-5.
Table 4-5: Tailings Model Parameters.

<table>
<thead>
<tr>
<th>Tailings Dam</th>
<th>Mispah</th>
</tr>
</thead>
<tbody>
<tr>
<td>G_s</td>
<td>2.74</td>
</tr>
<tr>
<td>v_o</td>
<td>30</td>
</tr>
<tr>
<td>K_o</td>
<td>-19</td>
</tr>
<tr>
<td>A</td>
<td>2.95</td>
</tr>
<tr>
<td>B</td>
<td>-0.14</td>
</tr>
<tr>
<td>k_l</td>
<td>10.8</td>
</tr>
<tr>
<td>D_o</td>
<td>127</td>
</tr>
<tr>
<td>b_s</td>
<td>0.0462</td>
</tr>
<tr>
<td>ρ_dmax</td>
<td>1.217</td>
</tr>
</tbody>
</table>

4.4.2 Model Prediction

The model using the calculated model parameters was used to predict the behaviour of various tailings properties in the daywall of Mispah Tailings dam. The properties that are predicted are compared to field test results in Chapter 5 to determine if the model is realistic.

The model was also used to predict the behaviour of the tailings in the drying box, to determine the accuracy of the predictions.

The tailings properties that are predicted are:

- **Height**
- **Moisture Content**
- **Degree of Saturation**
- **Dry Density**
- **Void Ratio**

(a) **Height**

The height of the tailings layer in the daywall is predicted using the model. In Figure 4-28, the predicted height is plotted against time for Mispah Tailings dam. **Figure 4-29** gives the predicted height against the logarithmic of time.
Figure 4-28: Predicted height versus time for daywall.

Figure 4-29: Predicted height versus time (on Logarithmic scale) for the daywall.
The height of the tailings was predicted for the drying box using the model. **Figure 4-30** shows the predicted height of the tailings in the drying box versus time and **Figure 4-31** shows the predicted height versus time, with time on a logarithmic scale.

**Figure 4-30**: Predicted height versus time for the drying box.
Figure 4-31: Predicted height versus time (log scale) for the drying box.

(b) **Moisture Content**

The moisture content of the tailings in the daywall is predicted using the model and is plotted against time on the graph in Figure 4-32. Similarly, the moisture content of the tailings is predicted for the drying box experiment. The predicted moisture content in the drying box is plotted against time in Figure 4-33.

(c) **Degree of Saturation**

The model is used to predict the degree of saturation of the tailings against time. The degree of saturation is plotted against time on the graph in Figure 4-34. Figure 4-35 gives the predicted degree of saturation for the tailings in the drying box against time.
**Figure 4-32:** Predicted moisture content for daywall versus time.

**Figure 4-33:** Predicted moisture content for drying box versus time.
Figure 4-34: The predicted degree of saturation for the daywall plotted against time.

Figure 4-35: The predicted degree of saturation for the drying box plotted against time.
(d) **Dry density**

The dry density of the tailings is the ratio of mass of dry tailings to total volume. The predicted dry density is plotted against time on the graph in Figure 4-36. The predicted dry density for the tailings in the drying box is predicted using the model and plotted against time in Figure 4-37.

![Graph showing dry density over time](image-url)

**Figure 4-36:** Predicted dry density for the daywall versus time.
Figure 4-37: Predicted dry density for the drying box versus time.

(e) Void Ratio
The void ratio is the volume of voids to the volume of solids. The void ratio of the tailings can be determined from the predicted values of saturation and moisture content. Thus, the predicted void ratio is plotted against time in Figure 4-38. The void ratio is predicted for the tailings in the drying box and is plotted against time in Figure 4-39.
Figure 4-38: The predicted void ratio for the daywall plotted against time.

Figure 4-39: The predicted void ratio for the drying box plotted against time.
4.5 FIELD TEST RESULTS

Field tests were conducted on the daywall of Mispah Tailings Dam. The comparison of the field test results and the predicted properties for Mispah tailings are discussed in Chapter 5. Various tailings properties were obtained from the field tests.

The tailings properties that were obtained are:

- Height
- Moisture Content
- Degree of Saturation
- Dry Density
- Void Ratio
- Suctions

4.5.1 Height

Various measurements of height were taken during the field tests on different occasions. The height is plotted against its relative age in Figure 4-40. The graph only comprises of a few points and not a continuous line from constant measurements.
4.5.2 Moisture Content

The moisture content was not constantly measured and only a few samples at different times were taken. The moisture content at these times is plotted on a graph against time in Figure 4-41.
4.5.3 Degree of Saturation

The degree of saturation is plotted against time on the graph in Figure 4-42. The degree of saturation is also determined at different times; therefore Figure 4-42 is not a continuous plot but only a few points on the graph.

4.5.4 Dry Density

The dry density that was obtained from field measurements is plotted against time for the Mispah tailings in Figure 4-43. As mentioned for the properties above, only a few points on the graph were determined.

**Figure 4-41:** Field measurements of moisture content against time.
**Figure 4-42:** Field measurement of degree of saturation plotted against time.

**Figure 4-43:** Field measurement of dry density plotted against time.
4.5.5 Void Ratio

The void ratio is plotted against time in Figure 4-44. The void ratio was not constantly measured and therefore only a few points on the graph were obtained.

![VOID RATIO](image)

**Figure 4-44:** Field measurement of void ratio plotted against time.

4.5.6 Suctions

Suction measurements were also taken during the field tests. The suctions are plotted against degree of saturation in Figure 4-45. The moisture content is plotted against suction on the graph in Figure 4-46. **Figure 4-47** gives the moisture content plotted against suction, where the suction is plotted on a logarithmic scale. In **Figure 4-48**, the void ratio versus suction is plotted on the graph.
Figure 4-45: Suction versus degree of saturation for the field tests.

Figure 4-46: Field measurements of moisture content plotted against suction.
Figure 4-47: Moisture content plotted against suction (on Logarithmic scale).

Figure 4-48: Field measurement of void ratio versus suction.
4.6 CONCLUSIONS

The results from the laboratory and field experiments are presented in table and graph format in this chapter. The model parameters and predictions are also presented in this chapter. The next chapter, Chapter 5, is a discussion of the results presented in this chapter.

--oOo--
CHAPTER 4

SEDIMENTATION AND DESICCATION OF GOLD MINE TAILINGS

4.1 INTRODUCTION

The aim of this chapter is to present the raw data obtained from the column settling and drying box tests explained in Chapter 3. The discussion of the presented data will follow in Chapter 5. The results of the column settling tests and drying box tests are presented in the form of tables and graphs.

This chapter also gives the data obtained from the sedimentation and desiccation model, which was discussed in Chapter 2 and Chapter 3.

Chapter 4 is divided into three sections. Section one deals with the column settling test results, section two deals with the drying box test results and section three deals with the sedimentation and desiccation model. In section two, the notation used on the graph pertains to the specific drying box test, for e.g. DB3 would indicate that the results are from Drying Box test 3.

The raw data obtained from the column settling tests and drying box tests are tabulated in the Appendices.

4.2 COLUMN SETTLING TEST RESULTS

4.2.1 Introduction

In this section, of the column settling tests, the results are summarized in graph and table format. These results show the behaviour of the tailings during sedimentation and are used to determine various model parameters.

4.2.2 Tailings Sedimentation

The height of the tailings was recorded as sedimentation occurred in the settling columns. The time was noted each time a height reading was taken. The height of the tailings was then plotted against time.

The terminology used in the legend for the column settling tests had to do with the material used for the tests.
The graphs of the tailings height versus time are plotted in Figure 4-1 to Figure 4-3 for the 250 ml, 500 ml and 1000 ml column settling tests. There is a range of values in each graph due to the material grading, i.e. coarse, fine or a mix.

In Figure 4-1 to Figure 4-6 the height of the tailings is given in centimetres and the time is in hours.

![Figure 4-1](image)

**Figure 4-1:** Height versus time for the 250 ml column test.
Figure 4-2: Height versus time for the 500 ml column test.

Figure 4-3: Height versus time for the 1000 ml column test.
Figure 4-4 to Figure 4-6 shows the height of the tailings plotted against the logarithm of the time for the 250 ml, 500 ml and 1000 ml column settling tests.

The initial and final heights and corresponding times were determined from Figure 4-4 to Figure 4-6 using the principles of Figure 3-15 on page 3-18, which was taken from Swarbrick and Fell, 1992. These values were used to determine various model parameters and are given in Table 4-1, which follows after Figure 4-4.

The tailings settling behaviour as shown in Figure 4-4, 4-5 and 4-6 is similar to the idealised behaviour as shown in Figure 3-15.

Figure 4-4: Height versus log time for the 250 ml column test.

$H_i$ and $H_f$ in Table 4-1, are the initial and final height, respectively. The initial and final times are $t_i$ and $t_f$, respectively.
Table 4-1: Initial and final heights and times for the column tests.

<table>
<thead>
<tr>
<th>Column</th>
<th>Test</th>
<th>$H_i$</th>
<th>$H_f$</th>
<th>$t_i$</th>
<th>$t_f$</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>fine</td>
<td>21.91</td>
<td>16.48</td>
<td>0.09</td>
<td>8.13</td>
</tr>
<tr>
<td>250</td>
<td>mix</td>
<td>22.45</td>
<td>13.76</td>
<td>0.13</td>
<td>1.52</td>
</tr>
<tr>
<td>250</td>
<td>mix2</td>
<td>22.82</td>
<td>16.12</td>
<td>0.00</td>
<td>3.32</td>
</tr>
<tr>
<td>250</td>
<td>fine2</td>
<td>22.45</td>
<td>17.29</td>
<td>0.36</td>
<td>7.82</td>
</tr>
<tr>
<td>500</td>
<td>fine</td>
<td>30.48</td>
<td>24.39</td>
<td>0.00</td>
<td>8.93</td>
</tr>
<tr>
<td>500</td>
<td>mix</td>
<td>30.36</td>
<td>20.42</td>
<td>0.00</td>
<td>1.23</td>
</tr>
<tr>
<td>500</td>
<td>mix 2</td>
<td>30.48</td>
<td>20.67</td>
<td>0.09</td>
<td>0.94</td>
</tr>
<tr>
<td>500</td>
<td>mix 3</td>
<td>28.20</td>
<td>21.64</td>
<td>0.21</td>
<td>2.50</td>
</tr>
<tr>
<td>1000</td>
<td>fine</td>
<td>35.62</td>
<td>26.49</td>
<td>0.00</td>
<td>6.14</td>
</tr>
<tr>
<td>1000</td>
<td>mix</td>
<td>35.37</td>
<td>24.76</td>
<td>0.00</td>
<td>2.35</td>
</tr>
<tr>
<td>1000</td>
<td>coarse</td>
<td>35.79</td>
<td>22.53</td>
<td>0.31</td>
<td>1.85</td>
</tr>
</tbody>
</table>

The initial and final heights in Table 4-1 are given in centimetres and the initial and final times are in hours. The original column settling data is given in Appendix A.

Figure 4-5: Height versus log time for the 500 ml column test.
In **Figure 4-7** below, the height of the tailings is normalised, i.e. it is taken as a percentage of the initial height for each column. This percentage height of initial height was plotted against the logarithm of the time for the 250 ml, 500 ml and 1000 ml column settling tests. All the column settling test results are plotted on this graph for comparison.

In **Figure 4-7**, the results of the 250 ml column tests are plotted in blue, the results of the 500 ml column tests are plotted in red and those of the 1000 ml column tests are plotted in green.
Figure 4-7: Height as a percentage of the initial height versus log time for the 250ml, 500ml and 1000 ml column test.

4.2.2 Initial Moisture Content

The initial moisture content for each column test was calculated using Equation (3-1) and is tabulated below in Table 4-2. The moisture content is expressed as a ratio of mass of water to mass of tailings. This initial moisture content is needed for the determination of various model parameters.

The mass of water and mass of tailings was measured before the start of the column settling tests, i.e. before the water and tailings were mixed together for the test.
Table 4-2: The initial moisture content for the column tests.

<table>
<thead>
<tr>
<th>Column</th>
<th>Test</th>
<th>wi</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>fine</td>
<td>1.28</td>
</tr>
<tr>
<td>250</td>
<td>mix</td>
<td>1.25</td>
</tr>
<tr>
<td>250</td>
<td>mix2</td>
<td>1.31</td>
</tr>
<tr>
<td>250</td>
<td>fine2</td>
<td>1.32</td>
</tr>
<tr>
<td>500</td>
<td>fine</td>
<td>1.27</td>
</tr>
<tr>
<td>500</td>
<td>mix</td>
<td>1.22</td>
</tr>
<tr>
<td>500</td>
<td>mix2</td>
<td>1.32</td>
</tr>
<tr>
<td>500</td>
<td>mix3</td>
<td>1.31</td>
</tr>
<tr>
<td>1000</td>
<td>fine</td>
<td>1.31</td>
</tr>
<tr>
<td>1000</td>
<td>mix</td>
<td>1.30</td>
</tr>
<tr>
<td>1000</td>
<td>coarse</td>
<td>1.31</td>
</tr>
</tbody>
</table>

4.3 DRYING BOX TEST RESULTS

4.3.1 Tailings Sedimentation and Desiccation

Five drying box tests were conducted and the results are given in this chapter in the form of tables and graphs. These results are discussed in more detail in Chapter 5.

As has been stated previously, the terminology used in the legend for the drying box test graphs is as follows:

- **DB1** – Drying Box test no 1
- **DB2** – Drying Box test no 2
- **DB3** – Drying Box test no 3
- **DB4** – Drying Box test no 4
- **DB5** – Drying Box test no 5

Drying Box test no 1 was a trial run and the only proper data obtained from this test was the height of the tailings versus time and the air and soil temperatures. From Drying Box test no 2 to 5, proper data was obtained; and the results of which are plotted on the graphs that follow.
Figure 4-8: Height versus time for the drying box tests.

Figure 4-9: Height versus time (on Logarithmic scale) for the drying box tests.
The height of the tailings, is recorded against time as sedimentation and desiccation occur in each drying box test, see **Figure 4-8. Figure 4-9** gives the height of the tailings plotted against the logarithmic of time. These graphs are very similar in shape to those for the column settling tests.

The process of sedimentation and desiccation is discussed in **Chapter 2** and **Chapter 3**. The data that was obtained from each drying box test carried out on Mispah tailings is given in **Appendix B**.

The height of the tailings was divided by the initial height and multiplied by 100 to determine the height as a percentage of initial height, i.e. the height was normalised. This was plotted against the logarithm of time in **Figure 4-10** below. The final height of the tailings ranges between 40 and 60% of the initial height of the tailings.

![Figure 4-10: Height as a percentage of initial height versus time (on Logarithmic scale) for the drying box tests.](image)

**4.3.2 Air and Soil Temperatures**

The air temperatures that were measured ranged from approximately 19 to 29 degrees Celsius and the soil temperatures ranged from approximately 18 to 27 degrees Celsius.
The soil temperatures generally increased as the tailings became dryer. The average temperatures for the air and soil are given in Table 4-3 below.

Table 4-3: Average air and soil temperatures.

<table>
<thead>
<tr>
<th>Test</th>
<th>Air Temperature</th>
<th>Soil Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB1</td>
<td>28</td>
<td>24</td>
</tr>
<tr>
<td>DB2</td>
<td>26</td>
<td>19</td>
</tr>
<tr>
<td>DB3</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>DB4</td>
<td>24</td>
<td>24</td>
</tr>
<tr>
<td>DB5</td>
<td>25</td>
<td>24</td>
</tr>
</tbody>
</table>

4.3.3 Suction

The suctions in the drying box were measured using the suction probe, as discussed in Chapter 3. The suctions that were measured, ranged from 0 kPa to just over 200 kPa for the various drying box tests.

The suctions were measured on the surface of the tailings in the drying box, and 3 or 4 suction readings were taken on various positions on the tailings surface. This was done to ensure that accurate readings were taken, i.e. that there were no anomalies on the surface of the tailings that could cause a distortion to the suction readings. The average of these readings was used as the final suction value. This average value of suction is plotted on the graphs that follow in this section.

The suctions in the tailings are plotted against time. Figure 4-11 represents the suctions for four drying box tests; i.e. Drying Box Test 2 to 5. The suctions are in kPa and the time is in days. Figure 4-12 gives the suction on a logarithmic scale.
Figure 4-11: Suction versus time.

Figure 4-12: Suction (on logarithmic scale) versus time for the drying box tests.
The suctions are plotted against various soil parameters, i.e. degree of saturation, moisture content, void ratio and linear shrinkage.

In Figure 4-13 the degree of saturation is plotted against suction and in Figure 4-14, the degree of saturation is plotted against suction on a logarithmic scale for the drying box test results.

Figure 4-15 gives the moisture content plotted against suction and Figure 4-16 represents moisture content versus suction (on a logarithmic scale) for the drying box test results. The graphs in Figure 4-14 and Figure 4-16 are known as soil-water characteristics curves.

The void ratio is plotted against suction in Figure 4-17. The linear shrinkage is plotted against the logarithm of suction in Figure 4-18 and Figure 4-19. In Figure 4-18 the linear shrinkage is along the length of the drying box and in Figure 4-19 it is along the width.

Figure 4-13: Degree of saturation versus suction.
Figure 4-14: Degree of saturation versus suction (logarithmic scale).

Figure 4-15: Moisture content versus suction.
Figure 4-16: Moisture content versus suction (logarithmic scale).

Figure 4-17: Void ratio versus suction.
Figure 4-18: Linear Shrinkage (along length of drying box) versus suction (log scale).

Figure 4-19: Linear Shrinkage (along width of drying box) versus suction (log scale).
The moisture content is the ratio of the mass of water to the mass of tailings. The mass of the tailings is constant and is known, the mass of the drying box is known and the mass of water can be determined by weighing the drying box as the tailings dry out.

In determining all the parameters using the data obtained from the drying box tests, a value of 2.74 was assumed for $G_s$. Vermeulen (2001) determined this value of $G_s$, which was obtained by research on gold mine tailings from Mispah tailings dam. Other researchers have obtained values of $G_s$ for gold mine tailings, these values are given in Table 2-1. They range from 2.6 to 3.1, so in assuming that the specific gravity, $G_s$, is 2.74, is a good assumption as it is almost the average of this range of $G_s$. Also, the tailings from Vermeulen’s research and this research originate from the same mine, so they will have been produced using the same or similar processes and will, therefore, have similar characteristics.

While the tailings were still saturated in the drying box, i.e. during sedimentation and the first stage of evaporation, the void ratio was calculated using Equation (3-6) $[e = wG_s]$. Once the second stage of evaporation begins, and the tailings are no longer fully saturated, i.e. $S<1$, Equation (3-9) $[e=(G_s V_T p_w)/(M_s) – 1]$ is used to calculate the void ratio. This equation was used to determine the void ratio using values obtained from the drying box tests. This can only be done until cracks start to appear in the tailings as the tailings desiccate. Once cracks have started to appear, samples of the tailings were taken using the modified sampler (described in Chapter 2), and the void ratio was determined for these samples. It was assumed that the void ratio of this sample is representative of the void ratio of the tailings in the drying box. It was also assumed that the disturbance due the sampler was minimal.

The void ratio that was determined using the samples, as stated in the paragraph above, was assumed to be representative of the tailings in the drying box. It does not take into account the cracks that form, and thus the void ratio is only representative of the intake tailings material between the cracks.

The degree of saturation was calculated using Equation (3-11) $[S = (wG_s)/e]$. The moisture content and void ratio is determined as discussed above, and is then used in Equation (3-11) to determine the degree of saturation. It is assumed the saturation,
which was determined using the samples, is representative of the saturation throughout the drying box.

4.3.4 Cumulative Evaporation

The cumulative evaporation is determined from the amount of water that is evaporated from the drying box. The cumulative evaporation is the sum of all the previous amounts of water evaporated up to the current amount of water evaporated.

The cumulative evaporation of all the drying box tests is plotted against time on the graph in Figure 4-20. The cumulative evaporation is used to determine the evaporation potential for each drying box test.

![Cumulative Evaporation Graph](image)

Figure 4-20: Cumulative evaporation versus time.

4.3.5 Moisture Content

The moisture content is expressed as the ratio of the mass of water to the mass of tailings. Figure 4-21 gives the moisture content versus time for four drying box tests; namely Drying Box Test 2 to Drying Box Test 5.
In **Section 4.3.3**, the moisture content has already been compared to the suction for the drying box tests, see **Figure 4-15**. The moisture content determination is discussed in **Section 3.6.2** and **4.3.3**.

**Figure 4-21**: Moisture content versus time.

### 4.3.6 Void Ratio

Void ratio is the ratio of the volume of voids to the volume of tailings solids. **Figure 4-22** gives the void ratio against time for four drying box tests.

In **Section 4.3.3**, the void ratio has already been compared to the suction for the drying box tests, see **Figure 4-17**. Void ratio determination has already been discussed in **Section 3.6.3** and **4.3.3**.

The void ratio is plotted against moisture content on the graph in **Figure 4-23**.
Figure 4-22: Void ratio versus time.

Figure 4-23: Void ratio versus moisture content.
4.3.7 Degree of Saturation

The degree of saturation is the ratio of the volume of water to the total volume of void space. The degree of saturation is plotted against time in Figure 4-24.

In Section 4.3.3, the degree of saturation has already been compared to the suction for the drying box tests, see Figure 4-13. The determination of the degree of saturation is discussed in Section 3.6.4 and 4.3.3.

![Graph of Degree of Saturation vs. Time](image)

**Figure 4-24:** Degree of saturation versus time.

4.3.8 Dry Density

The dry density of the tailings is the mass of the solids per unit volume of tailings. The dry density is plotted against time in Figure 4-25 for all the drying box tests. The dry density is calculated from the bulk density and the moisture content. The dry density is calculated using Equation (3-14), which uses the bulk density to determine the dry density using the moisture content.

The bulk density is the total mass over the total volume. The total mass was determined by adding the mass of the tailings and the mass of the water. The mass of the tailings is constant and was measured before the start of the drying box test. The mass of the
water was determined by subtracting the mass of the tailings and the mass of the drying box from the total mass of the drying box. The volume of the material was determined by multiplying the internal plan area of the box with the height of the tailings in the box.

The bulk density was calculated in this fashion until cracks start to form on the surface of the tailings in the drying box. The bulk density was then calculated using the samples that were taken in the drying box. The dimensions of the sample were measured and the volume determined. The mass of the water and the mass of the solids were determined by weighing the sample before and after drying of the tailings sample.

It is assumed that the bulk and dry density of the sample is representative of the tailing the drying box.

![Dry density versus time for the drying box tests.](image)

Figure 4-25: Dry density versus time for the drying box tests.

### 4.3.9 Linear Shrinkage

The linear shrinkage is measured along the width and the length of the drying box. Table 4-4 gives the linear shrinkage for Drying Box test 3 to 5.
Table 4-4: Linear shrinkage in drying box tests.

<table>
<thead>
<tr>
<th></th>
<th>Length (%)</th>
<th>Width (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DB3</td>
<td>5.26</td>
<td>5.25</td>
</tr>
<tr>
<td></td>
<td>5.75</td>
<td>4.45</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.33</td>
</tr>
<tr>
<td>DB4</td>
<td>5.36</td>
<td>6.35</td>
</tr>
<tr>
<td></td>
<td>6.24</td>
<td>7.22</td>
</tr>
<tr>
<td></td>
<td>6.63</td>
<td>7.22</td>
</tr>
<tr>
<td></td>
<td>6.73</td>
<td>6.31</td>
</tr>
<tr>
<td>DB5</td>
<td>5.71</td>
<td>7.11</td>
</tr>
<tr>
<td></td>
<td>5.48</td>
<td>6.63</td>
</tr>
<tr>
<td>Average</td>
<td>5.90</td>
<td>6.21</td>
</tr>
</tbody>
</table>

The linear shrinkage is plotted against time in Figure 4-26 and Figure 4-27. In Figure 4-25 the linear shrinkage is along the length of the drying box and in Figure 4-27 it is along the width. In Section 4.3.3, the linear shrinkage has already been compared to the suction for the drying box tests; see Figure 4-18 and Figure 4-19.

Figure 4-26: Linear shrinkage (along length of drying box) versus time.
4.4 THE SEDIMENTATION AND DESICCATION MODEL

4.4.1 Tailings Model Parameters
The tailings model parameters were calculated using the information obtained from the column settling tests and the drying box tests. These model parameters are the constants in the equations of the model, which is used to predict the behaviour of the tailings. The tailings model parameters of Mispah Tailings Dam are given below in Table 4-5.
Table 4-5: Tailings Model Parameters.

<table>
<thead>
<tr>
<th>Tailings Dam</th>
<th>Mispah</th>
</tr>
</thead>
<tbody>
<tr>
<td>G_s</td>
<td>2.74</td>
</tr>
<tr>
<td>V_o</td>
<td>30</td>
</tr>
<tr>
<td>K_o</td>
<td>-19</td>
</tr>
<tr>
<td>A</td>
<td>2.95</td>
</tr>
<tr>
<td>B</td>
<td>-0.14</td>
</tr>
<tr>
<td>k_t</td>
<td>10.8</td>
</tr>
<tr>
<td>D_o</td>
<td>127</td>
</tr>
<tr>
<td>b_s</td>
<td>0.0462</td>
</tr>
<tr>
<td>$\rho_{d_{\text{max}}}$</td>
<td>1.217</td>
</tr>
</tbody>
</table>

4.4.2 Model Prediction

The model using the calculated model parameters was used to predict the behaviour of various tailings properties in the daywall of Mispah Tailings dam. The properties that are predicted are compared to field test results in Chapter 5 to determine if the model is realistic.

The model was also used to predict the behaviour of the tailings in the drying box, to determine the accuracy of the predictions.

The tailings properties that are predicted are:

- Height
- Moisture Content
- Degree of Saturation
- Dry Density
- Void Ratio

(a) Height

The height of the tailings layer in the daywall is predicted using the model. In Figure 4-28, the predicted height is plotted against time for Mispah Tailings dam. Figure 4-29 gives the predicted height against the logarithmic of time.
Figure 4-28: Predicted height versus time for daywall.

Figure 4-29: Predicted height versus time (on Logarithmic scale) for the daywall.
The height of the tailings was predicted for the drying box using the model. Figure 4-30 shows the predicted height of the tailings in the drying box versus time and Figure 4-31 shows the predicted height versus time, with time on a logarithmic scale.

**Figure 4-30**: Predicted height versus time for the drying box.
Figure 4-31: Predicted height versus time (log scale) for the drying box.

(b) **Moisture Content**

The moisture content of the tailings in the daywall is predicted using the model and is plotted against time on the graph in Figure 4-32. Similarly, the moisture content of the tailings is predicted for the drying box experiment. The predicted moisture content in the drying box is plotted against time in Figure 4-33.

(c) **Degree of Saturation**

The model is used to predict the degree of saturation of the tailings against time. The degree of saturation is plotted against time on the graph in Figure 4-34. Figure 4-35 gives the predicted degree of saturation for the tailings in the drying box against time.
Figure 4-32: Predicted moisture content for daywall versus time.

Figure 4-33: Predicted moisture content for drying box versus time.
Figure 4-34: The predicted degree of saturation for the daywall plotted against time.

Figure 4-35: The predicted degree of saturation for the drying box plotted against time.
(d) **Dry density**

The dry density of the tailings is the ratio of mass of dry tailings to total volume. The predicted dry density is plotted against time on the graph in **Figure 4-36**. The predicted dry density for the tailings in the drying box is predicted using the model and plotted against time in **Figure 4-37**.

![Dry Density Graph](image)

**Figure 4-36**: Predicted dry density for the daywall versus time.
Figure 4-37: Predicted dry density for the drying box versus time.

(e) Void Ratio
The void ratio is the volume of voids to the volume of solids. The void ratio of the tailings can be determined from the predicted values of saturation and moisture content. Thus, the predicted void ratio is plotted against time in Figure 4-38. The void ratio is predicted for the tailings in the drying box and is plotted against time in Figure 4-39.
Figure 4-38: The predicted void ratio for the daywall plotted against time.

Figure 4-39: The predicted void ratio for the drying box plotted against time.
4.5 FIELD TEST RESULTS

Field tests were conducted on the daywall of Mispah Tailings Dam. The comparison of the field test results and the predicted properties for Mispah tailings are discussed in Chapter 5. Various tailings properties were obtained from the field tests.

The tailings properties that were obtained are:

- Height
- Moisture Content
- Degree of Saturation
- Dry Density
- Void Ratio
- Suctions

4.5.1 Height

Various measurements of height were taken during the field tests on different occasions. The height is plotted against its relative age in Figure 4-40. The graph only comprises of a few points and not a continuous line from constant measurements.
4.5.2 Moisture Content

The moisture content was not constantly measured and only a few samples at different times were taken. The moisture content at these times is plotted on a graph against time in Figure 4-41.
Figure 4-41: Field measurements of moisture content against time.

4.5.3 Degree of Saturation
The degree of saturation is plotted against time on the graph in Figure 4-42. The degree of saturation is also determined at different times; therefore Figure 4-42 is not a continuous plot but only a few points on the graph.

4.5.4 Dry Density
The dry density that was obtained from field measurements is plotted against time for the Mispah tailings in Figure 4-43. As mentioned for the properties above, only a few points on the graph were determined.
Figure 4-42: Field measurement of degree of saturation plotted against time.

Figure 4-43: Field measurement of dry density plotted against time.
4.5.5 Void Ratio

The void ratio is plotted against time in Figure 4-44. The void ratio was not constantly measured and therefore only a few points on the graph were obtained.

![VOID RATIO](image)

**Figure 4-44:** Field measurement of void ratio plotted against time.

4.5.6 Suctions

Suction measurements were also taken during the field tests. The suctions are plotted against degree of saturation in Figure 4-45. The moisture content is plotted against suction on the graph in Figure 4-46. Figure 4-47 gives the moisture content plotted against suction, where the suction is plotted on a logarithmic scale. In Figure 4-48, the void ratio versus suction is plotted on the graph.
**Figure 4-45:** Suction versus degree of saturation for the field tests.

**Figure 4-46:** Field measurements of moisture content plotted against suction.
Figure 4-47: Moisture content plotted against suction (on Logarithmic scale).

Figure 4-48: Field measurement of void ratio versus suction.
4.6 CONCLUSIONS

The results from the laboratory and field experiments are presented in table and graph format in this chapter. The model parameters and predictions are also presented in this chapter. The next chapter, Chapter 5, is a discussion of the results presented in this chapter.

--oOo--
CHAPTER 5
DISCUSSION

5.1 INTRODUCTION

The aim of this chapter is to present the raw data obtained from the column settling and drying box tests explained in Chapter 3, as well as to discuss the suitability of the sedimentation and desiccation semi-empirical model that was proposed by Swarbrick (1992) to gold mine tailings.

There are shortcomings with the research that had been conducted for this dissertation. The first shortcoming is the fact that not enough field measurements were taken during this research period. One reason for this was that the field measurements were conducted on Mispah Tailings Dam, which was quite a distance away and could not be visited very often. For this reason the field measurements could not be measured on a day to day basis and are very erratic. The reason Mispah Tailings Dam was chosen as the field test site was because previous research had been conducted by Dr NJ Vermeulen on Mispah tailings.

The second shortcoming is the inaccuracies that resulted from sampling in the drying box. Sampling caused some disturbance in the drying box as well as with the sample itself, especially when the tailings were becoming dry. The sampling disturbance caused some inaccuracies with some soil parameters that were measured with the drying box test. The linear shrinkage, void ratio and dry density were some of the soil parameters affected by this. The inaccuracies from sampling disturbance are evident from the graphs of these parameters against time; the inaccuracies caused the graphs to display a wave motion towards the end of the drying box test.

Another shortcoming is the fact that the drying box did not allow for any excess or bleed water to be drained away. This is due to the design of the drying box. One assumption that is made by Swarbrick, 1992, in their model is that all bleed water becomes runoff and is reclaimed. This is true for Mispah Tailings Dam, which is operated with subaerial deposition.
5.2 COLUMN SETTLING TEST RESULTS

5.2.1 Tailings Sedimentation

The height of tailings is recorded as sedimentation occurs in the column. The graphs of tailings height versus time is given in Figure 4-1 to Figure 4-3 for the 250 ml, 500 ml and 1000 ml column settling tests. There is a range of values in each graph due to the material grading, i.e. coarse, fine or a mix. A summary of the entire column settling tests results is shown in Figure 5-1.

Figure 5-1: Height versus time for the column settling tests.

From Figure 5-1 it can be seen that all the graphs have a similar shape. These graphs can all be divided into three sections or stages. During the first stage, the rate of settlement is high and also constant. The graph during stage one is, therefore, linear or very nearly linear. As the rate of settlement starts to change, there is a transition from the first stage to the second stage. During the second stage of sedimentation, the graph is no longer linear because the rate of settlement is no longer constant. The rate of settlement of the tailings particles is becoming less. During the last stage or third
section of sedimentation, the graph is once again linear. The rate of settlement has become very low, and settlement eventually ceases.

An explanation of the behaviour of the tailings could be as follows. Initially the tailings particles are hardly touching one another and their behaviour is governed by stokes law. As settlement occurs, the particles will eventually start coming into contact with one another and start becoming packed on one another. This is usually when stage two starts to occur and the rate of settlement starts to decrease. The tailings will then start to settle as a whole until the maximum packing density is reached. This takes place during the third stage of sedimentation.

From these graphs it is also evident that finer tailings particles have a lower initial rate of settlement than coarser tailings particles. The final settled height of the finer tailings is also higher than that of the coarser tailings particles. This could be due to the fact that the larger the particle is, the heavier it is and the faster it settles. The coarser particles tend to form a tighter packing arrangement.

The dry density of the fine tailings is low and the void ratio is high. The opposite is true for coarse tailings, i.e. the dry density is high and the void ratio is low.

From Figure 5-1 it is also evident that most of the settlement occurs within the first few hours from commencement of sedimentation.

Figure 4-4 to Figure 4-6 shows the height of the tailings plotted against the logarithm of the time for the 250 ml, 500 ml and 1000 ml column settling tests. These graphs all have a similar backward ‘S’ shape. All these graphs for the column settling tests are summarised in Figure 5-2. They are all consistent with Figure 3-6, which is a general sedimentation curve from Swarbrick and Fell (1991). From this curve, the initial and final heights, as well as the initial and final time for settlement for all the tests were determined. These parameters are tabulated in Table 4-1.

The parameters in Table 4-1 were used to determine various model parameters. These parameters also gave some idea of the behaviour of the tailings during sedimentation. From Table 4-1, it is evident that sedimentation occurs quite rapidly, i.e. within a few hours most of the sedimentation is completed.
Figure 5-2: Height versus time (on logarithmic scale) for the column settling tests.

For each column test size in Figure 5-2, there is a range of different curves. This is due to the different size tailings particles used during the test, i.e. fine, coarse or a mix.

Initially the rate of settlement is high, but as time passes, the rate of settlement starts to decrease and eventually cease, giving a maximum dry density for the tailings material. For the 250 ml column settling tests, most of the tailings settlement has occurred before 3 hours from the commencement of the tests; for the 500 ml it is 2 hours and for the 1000 ml it is also 2 hours.

Figure 5-3 gives the normalised height, i.e. the height as a percentage of the initial height, versus time (on a logarithmic scale) for all the column settling tests that were conducted. The rate of settlement for the fine tailings is much less than that for the coarser tailings. It is also evident from Figure 5-3 that the finer tailings will settling in a much looser packing and thus have a higher void ratio than for the coarser tailings, which will have a denser packing, and therefore a smaller void ratio.
Figure 5-3: Height as a percentage of initial height versus time (on logarithmic scale) for the column settling tests.

The finer tailings settled at a height of between 75 to 80% of initial height. While the coarser tailings the range was between 60 and 72%. It can thus be said, that the final settled height of the tailings should range between 60 to 80% of the initial height after settlement has taken place. The coarser material will tend to the lower value of 60% while the finer material will tend to the higher value of 80%.

5.2.2 Initial Moisture Content
The initial moisture content for each column test is tabulated in Table 4-2, and this table is repeated below in Table 5-1. The moisture content is expressed as a ratio of mass of water to mass of tailings. This initial moisture content is needed for the determination of various model parameters.

These initial moisture contents were determined from field test results. The moisture content of the tailings slurry was determined by taking samples. The samples were taken directly from the delivery stations on the daywall. The moisture content was found to be approximately 1.3 for the tailings slurry from Mispah tailings dam.
The initial moisture contents given in Table 5-1 are based on these field test results in order to obtain realistic answers for the column settling and drying box tests.

Table 5-1: The initial moisture content for the column tests.

<table>
<thead>
<tr>
<th>Column</th>
<th>Test</th>
<th>wi</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>fine</td>
<td>1.28</td>
</tr>
<tr>
<td>250</td>
<td>mix</td>
<td>1.25</td>
</tr>
<tr>
<td>250</td>
<td>mix2</td>
<td>1.31</td>
</tr>
<tr>
<td>250</td>
<td>fine2</td>
<td>1.32</td>
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<tr>
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<td>1.32</td>
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<tr>
<td>500</td>
<td>mix3</td>
<td>1.31</td>
</tr>
<tr>
<td>1000</td>
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<td>1000</td>
<td>mix</td>
<td>1.30</td>
</tr>
<tr>
<td>1000</td>
<td>coarse</td>
<td>1.31</td>
</tr>
</tbody>
</table>

5.3 DRYING BOX TEST RESULTS

5.3.1 Tailings Sedimentation and Desiccation

The height of the tailings is recorded against time as sedimentation and desiccation occur in each drying box test. The height against time plot is given in Figure 5-4. This plot has a similar shape to the sedimentation curves that are discussed in Section 5.2, and is shown in Figure 5-1.

The sedimentation and desiccation graph consists of the results from the drying box tests. From the graph it is evident that the results from Drying Box Test 2 and Drying Box Test 5 (group A) are very similar, as is the results from Drying Box Test 3 and Drying Box Test 4 (group B). The results from Drying Box Test 1 are in the middle of these two groups. Group A and Group B is an arbitrary group name given to each of the two drying box test results that are similar in nature.

The sedimentation and desiccation graph can be divided into three sections, two linear sections and one curved section. Section one is linear, where the rate of change of height against time is constant. During this section, sedimentation and the first stage of
evaporation occurs. The second section is a curved section, where the rate of change of the height is no longer constant. This section is the transition of the first stage of evaporation to the second stage of evaporation. The third section on the graph is once again linear, where the rate of change of the height with time is once again constant. This section is synonymous with the second stage of evaporation. There is no more decrease in height during this section, shrinkage of the tailings material now occurs along the width and length of the drying box. This shrinkage results in cracking of the tailings.

The tailings consolidate as time passes due to sedimentation and desiccation. The sedimentation is due to the self weight of the particles and the desiccation is due to evaporation. From Figure 5-4, it is evident that consolidation of the sample occurs up to between 10 and 15 days depending on the grading of the tailings used in the test. Consolidation of tailings is not due to loading of the material but due to itself and external factors such as evaporation.

**Figure 5-4:** Height versus time for the drying box tests.
Evaporation from the tailings, results in a water loss, and a build up of negative pore pressures or suctions between the tailings particles. This suction, causes the particles to move closer and therefore, the tailings compress and consolidation occurs. This happens until the tailings particles are in a tightly packed state and no more compression can occur in the vertical direction. The tailing start to compress in the horizontal direction and eventually cracks start to form.

**Figure 5-5** gives the height of the tailings in the drying box, plotted against the logarithmic of time. The shape of the graph is similar to the graphs from the column settling tests, i.e. **Figure 5-2**. From **Figure 5-5** it is evident that by 10 days after the commencement of the drying box test, most of the sedimentation and desiccation along the height of the drying box has occurred.

![SEDIMENTATION AND DESICCATION](image)

**Figure 5-5:** Height versus time (on Logarithmic scale) for the drying box tests.

The height as a percentage of the initial height is plotted against the logarithm of time in **Figure 5-6**. The height has been normalised and is expressed as a percentage. The final height ranges from 45 to 55% of the initial height of the tailings in the drying box. The decrease in height of the tailings is due to sedimentation and desiccation.
In Figure 5-3, the height as a percentage of the initial height was plotted for the column settling tests. There the final height due only to sedimentation ranged between 60 and 80% of the initial height. So the decrease in final height from this range (60 – 80%) to between 45 and 55% of the initial height can be attributed to desiccation of the tailings material.

![SEDIMENTATION AND DESICCATION](image)

**Figure 5-6:** Height as a percentage of initial height versus time (on Logarithmic scale) for the drying box tests.

5.3.2 **Air and Soil Temperatures**

The air temperatures that were measured ranged from approximately 19 to 29 degrees Celsius and the soil temperatures ranged from approximately 18 to 27 degrees Celsius. The soil temperatures generally increased as the tailings became dryer. The average temperatures for the air and soil are given in Table 4-3. The air and soil temperatures were used to monitor the drying box during the tests.

5.3.3 **Suctions**

The suctions are plotted against various parameters, and are:
- **Time**
- **Degree of Saturation**
- **Moisture Content**
- **Void Ratio**
- **Linear Shrinkage**

(a) **Time**

The suctions that were measured in the tailings are plotted against time. This graph is plotted in Figure 4-11. The suctions during the drying box tests were only measured to around 200 kPa because this roughly corresponds to the age of the tailings at which the next tailings layer is poured onto the daywall.

The suction versus time graphs can be divided into three sections. The first section is linear, where there are no suctions. This occurs during sedimentation and the first stage of evaporation. The second section is curved, where the suctions start to increase from zero as time passes, and the increase in suctions is not constant. The second section occurs as there is a transition from first stage to second stage of evaporation. The third section of the graph is very nearly linear, when the increase in suction is constant with time.

From this figure it is once again evident that Drying Box Test 2 and Test 5 (group A) furnish similar results. The same is true for the results from Drying Box Test 3 and Test 4 (group B). This can be due to the fact that Drying Box Test 2 and Test 5 (group A) were conducted under similar conditions. The same can be said for Drying Box Test 3 and Test 4 (group B).

The suctions can also be plotted on a logarithmic scale. **Figure 5-7** shows these suctions plotted against time. The graph shows a roughly linear increase of suction against time. The similarity of Drying Box Test 2 and Test 5 (group A), and Drying Box Test 3 and Test 4 (group B) is once again evident.

**Figure 5-7** can be compared with results obtained from Van Heerden (2002) presented in **Figure 5-8**. The figure shows the suctions for Pay Dam, which is also a gold tailings dam. The work done by Van Heerden (2002) was on a much smaller scale than that from this research. He used a small drying trough where, in this research, a large drying box was used. That is why **Figure 5-8** is in terms of hours...
and Figure 5-7 is in terms of days. Both these figures, however, show a similar shape; Figure 5-7 is just less accurate due to the size of the drying box. The suctions in Figure 5-8 are higher than the suctions in Figure 5-7.

![Figure 5-7: Suction (on logarithmic scale) versus time for the drying box tests.](image)

It is evident from Figure 5-7 and 5-8, that the gold tailings material exhibits similar behaviour with regard to suctions. The suctions increase linearly with time when the suctions are plotted on a log scale.
Figure 5-8: Suction versus time (on logarithmic scale) (after Van Heerden, 2002).

The graph of the suctions plotted against time in Figure 5-8 (Van Heerden, 2002) shows a kink for each of the plots. This kink is not clearly defined in Figure 5-7. The reason for this could be that the kink could only occur for suction readings greater than those taken or due to the size of the drying box compared with the drying trough. The suctions plotted in Figure 5-8 were taken in a small trough, where the suction probe was kept on the same position. This is not the case for the suction plotted in Figure 5-7.

(b) Degree of Saturation

Figure 4-13 and 4-14 gives the suction of the tailings plotted against the degree of saturation. The graph shows that as the degree of saturation decreases, the suction increases. In Figure 4-13, the graph is curves very slightly and is very close to linear. The results from all the drying box tests give very similar values; their plotted graphs have very similar shapes. The suction measurements have a maximum value somewhere around 200 kPa.
**Figure 4-14**, is given below in **Figure 5-9**. This is a soil-water characteristics (SWCC) curve and it exhibits similar behaviour to the typical SWCC in **Figure 2-9**. The curves plotted in **Figure 5-9**, are part of the desorption curve which are beyond the air entry value. At the air entry value, the position is indicated in **Figure 2-9**, desaturation of the tailings begins.

As water evaporates from the surface of the tailings, the tailings start to desaturate. As the tailings desaturate, the moisture content of the tailings decreases. As the water between the soil particles become less, the negative pore water pressure or suction increases

![Suction vs Degree of Saturation](image)

**Figure 5-9**: Degree of saturation versus suction (logarithmic scale).

(c) **Moisture Content**

The moisture content is plotted against the suction of the tailings in **Figure 4-15**. The graph is vertical at first, when there are no suctions in the tailings yet. This occurs during sedimentation and the first stage of evaporation. Once the second stage of evaporation starts, the suctions start to increase. The moisture content, at which the suctions start to increase from zero, is around 50%.
Once the suctions start to increase, the graph curves slightly. The graph eventually becomes horizontal at suction values greater than about 140 kPa. All the drying box test results, except Drying Box Test 2, which is slightly higher up, lie very close together on the graph and have the same basic shape.

The moisture content is plotted against suctions on a logarithmic scale. This graph is given in Figure 5-10. The graph shows a roughly linear decrease of moisture content with suction. The results from Drying Box Test 2 are slightly higher than the other results, but they all have the same basic shape.

![Figure 5-10: Moisture content versus suction (logarithmic scale).](image)

The graphs in Figure 5-10 form part of a soil-water characteristic curve and can be compared to graphs from Van Heerden (2002), which is also on Figure 5-10. The graphs of Van Heerden came from the results of the tests on Pay Dam tailings. The moisture content versus suction for this research compares well to the previous research conducted by Van Heerden (2002). The graphs of Drying Box 3, 4 and 5 are very close to the graphs of Van Heerden. They differ slightly at low suctions up
to about 50 kPa. After 50 kPa, however, the results of Drying Box 4 and 5 are almost identical to the results from Van Heerden (2002).

(d) **Void Ratio**

The suctions are plotted against the void ratio of the tailings, as is shown in Figure 4-17 and is repeated below in Figure 5-11. The void ratios first decrease vertically down the vertical axis because there are no suctions present in the tailings yet. This occurs during sedimentation and the first stage of evaporation. Once the suctions start to increase from zero, the void ratios continue to decrease.

![VOID RATIO VS SUCTION](image)

**Figure 5-11**: Void ratio versus suction.

The void ratios decrease to a certain value and then remain constant or start to increase slightly again. The void ratios from Drying Box Test 2 and Drying Box Test 4 first decrease and then become constant as the suctions decrease. The graph of Drying Box Test 2 is slightly higher than the rest of the graphs for the other drying box tests. The void ratios from Drying Box Test 3 and Drying Box Test 5 first decrease to a value of around 1.1 and then start to increase again to a value of 1.3.
The reason that the void ratio results from Drying Box Test 3 and Drying Box Test 5 increase from a maximum value and exhibit a wave motion while doing so, is that sampling inaccuracies and errors have occurred. The void ratio is determined from samples that are taken from the drying box once the suctions start to increase from zero, i.e. during the second stage of evaporation. Initially when samples are taken, the tailings material is wet and soft and accurate samples are very hard to achieve. Once the tailings become dryer it is difficult to push the sampler into the tailings material, this also causes disturbance during sampling. The samples also have a tendency to shatter when the tailings become too dry and accurate volume, mass and moisture measurements are difficult to achieve.

The void ratio from Drying Box Tests 3, 4 and 5 all have a value of around 1.3 when the maximum suction value of 200 kPa is reached. The void ratio from Drying Box Test 2 has a value of 1.5 at its maximum suction of around 50 kPa.

(e) **Linear Shrinkage**

The linear shrinkage is determined along the length and the width of the drying box. This linear shrinkage is plotted in both directions against suction. The suctions are plotted on a logarithmic scale. These two plots are shown in Figure 5-12 and 5-13, respectively.
Figure 5-12: Linear Shrinkage (along length of drying box) versus suction (log scale).

Figure 5-13: Linear Shrinkage (along width of drying box) versus suction (log scale).
The linear shrinkage along the length of the drying box increases linearly with suction. Figure 5-12 can be compared with results obtained from Van Heerden (2002) presented in Figure 5-14. The difference between Figure 5-12 and Figure 5-14 is that the maximum linear shrinkage from the results of this work is 6% compared to Van Heerden (2002), which is 2.44%. The difference in linear shrinkage could be the size difference of experimental equipment. Van Heerden (2002) used a small trough while this dissertation used a large drying box. Another difference between the two dissertations is that this work used a tailings slurry while Van Heerden (2002) used a thickened tailings paste which is at a much higher initial density. The thickened tailings paste is homogeneous and no sedimentation and material layering occurs. In this work, however, the tailings material becomes non-homogeneous once sedimentation and desiccation of the slurry occurs. The settled and desiccated tailings are layered with a clay layer situated on top of the rest of the tailings. This clay layer has a greater shrinkage limit than if the tailings material was to be mixed and homogeneous. The shape of Figure 5-12 and 5-14 is, however, almost the same.

Figure 5-14 from Van Heerden (2002) was based on gold tailings but they are not from Mispah Tailings Dam, they are from Pay Tailings Dam which is a tailings dam from the same operation. No data on Mispah whole tailings was available, so results from Pay tailings were used. This was done just to show that the behaviour in the drying box test is realistic and consistent with the behaviour of gold mine tailings.
Figure 5-14: Linear Shrinkage versus suction (logarithmic scale), (after Van Heerden, 2002).

The linear shrinkage along the width of the dying box is not as linear as along the length. The linear shrinkage does not increase smoothly with suction when the suctions reach a value around 100 kPa. This is due to the accuracy of measurements as a result of sample disturbance in the box and the fact that for linear shrinkage, the linear shrinkage should be taken along the length of a container, not the width. This container should be much longer than it is wide.

5.3.4 Cumulative Evaporation

The cumulative evaporation is determined from the amount of water that is evaporated from the drying box. The cumulative evaporation of all the drying box tests is plotted against time on the graph in Figure 4-20. The cumulative evaporation is used to determine the evaporation potential for each drying box test. This evaporation potential is used in the determination of the model parameters.

The graph of cumulative evaporation versus time looks similar to that obtained from Swarbrick and Fell, 1992. There is first a linear increase in evaporation with time; this is
the first stage of evaporation where the evaporation potential is constant. The graph starts becoming non-linear later on; this is the second stage of evaporation where the evaporation potential is no longer constant.

5.3.5 Moisture Content

The moisture content is expressed as the ratio of the mass of water to the mass of tailings. Figure 5-15 gives the moisture content versus time for four drying box tests. In Section 5.3.3, the moisture content has already been compared to the suction for the drying box tests; see Figure 4-16 and Figure 5-10.

![Figure 5-15: Moisture content versus time.](image)

The graph of moisture content versus time is linear or very close to linear. There is a constant decrease of moisture content with time. Drying Box Test 2 and Test 5 (group A) deliver similar results, and Drying Box Test 3 and Test 4 (group B) deliver similar results. This could be due to the fact that the conditions for these drying box tests are similar.
Figure 5-15 can be compared with results obtained from Van Heerden (2002) presented in Figure 5-16. This comparison is just to show that in both figures the moisture content decreases linearly with time, i.e. decrease in the moisture content with the increase in time, is constant.

![Graph showing moisture content versus time](image)

**Figure 5-16:** Moisture content versus time (after Van Heerden, 2002).

### 5.3.6 Void Ratio

Void ratio is the ratio of the volume of voids to the volume of tailings solids. Figure 4-22 gives the void ratio against time for four drying box tests. In Section 5.3.3, the void ratio has already been compared to the suction for the drying box tests; see Figure 5-11.

The graph of void ratio against time can be divided into two sections. The first section is linear, where there is a constant decrease in void ratio with time. This usually occurs during sedimentation and the first stage of evaporation. The second section of the graph is no longer linear. The graph becomes horizontal and displays a wave motion. This occurs during the second stage of evaporation when cracks start to form.
The wave motion which occurs later on in the drying box tests is a result of inaccuracies due to sampling. As discussed in Section 5.3.3 (d), the errors in void ratio are caused by inaccurate measurements of volume, mass and moisture of the tailings sample. The void ratios are based on the results of the samples once the tailings start to become dry and suctions start to increase from zero.

The void ratios from Drying Box Test 2 and 5 (group A) are nearly the same; the same can be said for the void ratios from Drying Box Test 3 and 4 (group B).

![Void Ratio vs Moisture Content](image)

**Figure 5-17:** Void ratio versus moisture content.

Void ratio is also plotted against moisture content; see **Figure 5-17**. This graph shows that there is a good correlation between the void ratio and moisture content for all the drying box tests. There are two sections on this graph. Section one is linear; the decrease in void ratio is constant as the moisture content decreases. Section two is no longer linear. In this section the graph becomes horizontal, and displays a wave motion again. This wave motion is a result of inaccuracies from sampling disturbance and inaccurate measurements. During section two there is no more shrinkage that occurs. This graph is a shrinkage curve and from it the shrinkage limit can be determined.
Using the method described by Van Heerden (2002), the shrinkage limit was found to be at a moisture content of roughly 35%.

5.3.7 Degree of Saturation
The degree of saturation is the ratio of the volume of water to the total volume of void space. The degree of saturation is plotted against time in Figure 4-24. In Section 5.3.3, the void ratio has already been compared to the suction for the drying box tests; see Figure 5-9.

In Figure 4-24, all the drying box tests give similar results. The degree of saturation graph is initially horizontal when the tailings are still fully saturated. This is usually the case during sedimentation and the first stage of evaporation. When the second stage of evaporation starts, the tailings start to desiccate and eventually become unsaturated. The graph is slightly curved, nearly linear when there is a decrease in the degree of saturation with time.

The results from Drying Box Test 2 and 5 (group A) are close together and exhibit similar behaviour. The same is true for the results from Drying Box Test 3 and 4 (group B).

5.3.8 Dry Density
The dry density of the tailings is the mass of the solids per unit volume of tailings. The dry density is plotted against time in Figure 4-25 for all the drying box tests. The dry density is calculated from the bulk density and the moisture content.

The dry density for the drying box tests generally increases as time lapses. The dryer the tailings, the lower the void ratio and the higher the dry density. The graphs in Figure 4-25 can be divided into two sections. The first section is a region that is very close to linear where the rate of increase of dry density is constant with time. This is usually when sedimentation and the first stage of evaporation occur. The second section of the graphs is not linear anymore. The graphs exhibit wave behaviour and are moving more horizontal than vertical. This is usually when the second stage of evaporation occurs.

The reason for the wave behaviour in the graph after about 11 days is once again the result from inaccurate measurements during sampling and sampling disturbance. The
dry density is calculated using the void ratio and the specific gravity of the tailings. The void ratios are obtained from the tailings samples. The reason for the inaccuracies has been discussed in Section 5.3.3 (d) and 5.3.6. Another reason for the wave behaviour could be the light cycle where the lights are switched on and off continuously due to the overheating of the lights.

The maximum dry density that is obtained is in the range of 1100 to 1300 kg/m².

5.3.9 Linear Shrinkage

The linear shrinkage is measured along the width and the length of the drying box. Table 4-4 gives the linear shrinkage for Drying Box test 3 to 5.

The average linear shrinkage, which is given in Table 4-4, is 5.9% in the length and 6.21% in the width of the drying box. Table 3-1 in Chapter 3 gives previous values of linear shrinkage, which are much lower. Table 3-1 gives the maximum linear shrinkage as 2%. These values do not compare well with each other because they were determined using different experimental equipment, which are of different size magnitudes. There are also other reasons for the difference, one being that the linear shrinkage of 2% was determined on homogeneous tailings material while the 6.21% was determined on non-homogeneous layered tailings. The tailings in the drying box test are layered because of sedimentation and desiccation which results in the finer tailings being deposited in the upper layer. The shrinkage of this finer tailings layer is a lot higher that the shrinkage of the tailings material as a whole.

The linear shrinkage for the drying box tests is plotted against time in Figure 4-26 and Figure 4-27. In Figure 4-26 the linear shrinkage is along the length of the drying box and in Figure 4-27 it is along the width. In Section 5.3.3, the linear shrinkage has already been compared to the suction for the drying box tests; see Figure 5-12 and Figure 5-13.

The linear shrinkage along the length of the drying box versus time is not very linear as was the case for the linear shrinkage versus suction. Most of the graphs are very close to linear, an exception being the linear shrinkage from Drying Box 3. The linear shrinkage generally increases at a near constant rate as the time passes. The linear shrinkage along the width of the drying box versus time is also not very linear. The linear shrinkage generally increases as time passes.
The reason for the non-linearity could be due to inaccuracies due to sampling in the drying box tests, as well as inaccuracies during measurement of the crack widths.

5.4 THE SEDIMENTATION AND DESICCATION MODEL

5.4.1 Tailings Model Parameters

The tailings model parameters were calculated using the information obtained from the column settling tests and the drying box tests. These model parameters are the constants in the equations of the model, which is used to predict the behaviour of the tailings. The tailings model parameters are given below in Table 5-2, along with the tailings model parameters from Swarbrick (1992). Table 5-2 is given to compare the results from this work to previous work by Swarbrick (1992).

Table 5-2: Tailings Model Parameters.

<table>
<thead>
<tr>
<th>Tailings Dam</th>
<th>Mispah</th>
<th>Swarbrick and Fell (1992)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Hamersley</td>
</tr>
<tr>
<td>Gs</td>
<td>2.74</td>
<td>3.76</td>
</tr>
<tr>
<td>vo</td>
<td>30</td>
<td>4.4</td>
</tr>
<tr>
<td>Ko</td>
<td>-19</td>
<td>-13</td>
</tr>
<tr>
<td>A</td>
<td>2.95</td>
<td>2.08</td>
</tr>
<tr>
<td>B</td>
<td>-0.14</td>
<td>-0.253</td>
</tr>
<tr>
<td>ki</td>
<td>10.8</td>
<td>9.1</td>
</tr>
<tr>
<td>Do</td>
<td>127</td>
<td>558</td>
</tr>
<tr>
<td>bs</td>
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<td>0.032</td>
</tr>
<tr>
<td>\rho_{dmax}</td>
<td>1.217</td>
<td>1.86</td>
</tr>
</tbody>
</table>

The values of the model parameters for Mispah Tailings Dam are in the same order of magnitude as for the model parameters for the other tailings dams. The values will, however, be different because the model parameters from Swarbrick (1992) were determined for iron ore, coal and bauxite tailings.

5.4.2 Comparison of Model with Field Test Results

The model using the calculated model parameters was used to predict the behaviour of various tailings properties in the daywall of Mispah Tailings dam. The properties that are predicted are compared to field test results in this section to determine if the model is realistic.

The graphs that follow all have a 14-day time limit because this is the rough age of the tailings on Mispah Tailings Dam before the next layer is poured.
The tailings properties discussed are:

- Height
- Moisture Content
- Degree of Saturation
- Dry Density
- Void Ratio

(a) **Height**

The height of the tailings layer in the daywall is predicted using the model. In **Figure 5-18**, the predicted height is plotted against time for Mispah Tailings dam. Also in this figure are the results from the field tests that were conducted.

The graph of the predicted height against time shows a relatively linear decrease of height with time up to day 4. From day 4 to day 6 the graph is no longer linear, i.e. the decrease in height is not constant with time anymore. After day 6 the graph is linear again but the rate of decrease in height is much lower than for the initial linear section.

**Figure 5-18:** Height versus time for model and field test results.
The field test results are not a continuous curve but a few points are plotted on the graph. The field test results do not compare favourably with the model prediction of the height versus time. Initially the model predicts the height of the tailings too high and later on the model predicts the height too low. The model prediction should have a steeper gradient initially and then flatten out sooner.

**Figure 5-19** gives the height against the logarithmic of time for the model prediction and the field test results. The predicted height versus time graph has a backward ‘S’ shape. From this graph, it is predicted that most of the sedimentation and desiccation will have occurred by day 7.

Once again it is evident that the field test results and model prediction do not compare well. There is a maximum difference of 30 mm and a minimum difference of 5 mm between the predicted and actual values of height.

**Figure 5-19:** Height versus time (logarithmic scale) for model prediction and field test results.
The test results from the field are not conclusive and more testing is necessary to determine accurately whether the model can be used for prediction of height versus time or a new model must be setup.

(b) Moisture Content

The moisture content of the tailings is predicted using the model and is plotted against time on the graph in Figure 5-20. Figure 5-20 also contains the field test results.

The predicted moisture content initially decreases linearly with time, i.e. the loss of moisture is occurring at a constant rate. At around day 5 there is a slight curve in the graph where the decrease in moisture content with time is no longer constant anymore. After this section, there is once again a linear decrease of moisture content with time but the rate of decrease is much lower than the initial linear section.

The field test results compare better with moisture content than with height to the model prediction. There is a maximum difference of 0.75 and a minimum difference of 0.05 between the predicted and actual values of the moisture content. There are, however, not enough field test results to make an accurate conclusion about the model prediction for moisture content. More field tests will need to be conducted to determine this accurately.
Figure 5-20: Moisture content versus time for model and field test results.

(c) **Degree of Saturation**

The degree of saturation is plotted against time on the graph in Figure 5-21; this figure contains the prediction of the degree of saturation from the model and the field test results.

Initially the predicted degree of saturation graph is horizontal with time, i.e. the tailings material is still saturated. The graph starts to become linear just before day 4, where the degree of saturation starts to decrease with time at a constant rate. At day 5 there is a slight curve in the graph where the decrease in degree of saturation is not constant with time anymore. After the curved section, the graph becomes linear again but the rate of decrease of degree of saturation with time is lower than before.

The field test results follow the same kind of trend as the predicted degree of saturation graph, but the difference between the two is still too great. There is a maximum difference of 0.25 and a minimum difference of 0 between the predicted and actual values of saturation. More field tests have to be conducted to conclude
accurately whether the model can be used or if a new model should be created. From these results it is so far evident that the model is not suited for these conditions.

![Degree of Saturation vs Time](image)

**Figure 5-21**: Degree of saturation versus time for model and field test results.

(d) **Dry density**

The dry density of the tailings is the ratio of mass of dry tailings to total volume. The predicted dry density is plotted against time along with the field test results in **Figure 5-22**.

The predicted dry density graph is initially linear when plotted against time. At day 4 the graph becomes non-linear and starts to curve to roughly day 6. From day 6 it is again linear but the rate of increase in dry density is now lower. The predicted maximum dry density is close to 1100 kg/m³.
The field test results are higher than the predicted values of dry density especially after day 6 when the tailings are relatively dry and desiccated. Initially the model and field test results are quite similar but as time passes, the difference between the two becomes a lot greater. The maximum dry density from the field test results is close to 1400 kg/m$^3$. The difference is, therefore, 300 kg/m$^3$ in dry density between predicted and actual values.

More field tests need to be conducted to conclude accurately whether the model is suited for gold tailings or if a new model should be setup.

(e) **Void Ratio**

The void ratio is the volume of voids to the volume of solids. The void ratio of the tailings can be determined from the predicted values of saturation and moisture content. Thus, the predicted void ratio is plotted against time in **Figure 5-23**. **Figure 5-23** also contains the field test results.
The predicted void ratio decreases linearly with time for the first section of the graph. At about day 4 the graph starts to curve and the decrease in void ratio with time is no longer constant. After day 6 the graph is once again linear but the rate of decrease of void ratio with time is now lower than it was initially.

The field test results for void ratio are lower than what is predicted by the model. The model predicts a final void ratio of 1.6 while the void ratio from the field results at 13 days is 1. This is quite a large difference and therefore, the model does not compare favourably with actual values.

![Graph showing void ratio vs time](image)

**Figure 5-23:** Void versus time for model prediction and field test results.

### 5.4.3 Comparison of Model with Drying Box Test Results

The model is used to predict values for height, moisture content, degree of saturation, dry density and void ratio for the tailings in the drying box. This was done to check the accuracy of the prediction of the model and to determine whether the model could be used to predict the various parameters.
The following sections deals with the prediction of the tailings as sedimentation and desiccation occur in the drying box.

(a) **Height**

The height of the tailings as sedimentation and desiccation were predicted for the tailings in the drying box. The predicted height is compared to the results obtained from the drying box experiments that were conducted. This comparison is shown in Figure 5-24 below.

![SEDIMENTATION AND DESICCATION](image)

**Figure 5-24:** Height versus time for model prediction and drying box test results.

The model seems to compare well with the drying box results, especially the initial section of the curve. The model prediction has the same shape as the drying box results, except at the end where it seems to under estimate the height and the rate at which it takes to get to the final height.

Initially the model prediction appears to be the average of all the drying box test results for height versus time. But as the rate of sedimentation and desiccation decreases, the model prediction no longer appears to be the average.
(b) **Moisture Content**

The moisture content of the tailings is predicted using the model and is plotted against time on the graph in **Figure 5-25**. **Figure 5-25** also contains the drying box test results.

![Moisture Content Graph](image)

**Figure 5-25**: Moisture content versus time for model prediction and drying box test results.

The model prediction compares well initially with the drying box test results for the moisture content versus time. The initial linear section of the model prediction for moisture content appears to be the average of the results but towards the end of the graph, the difference between measured and predicted becomes larger. The model prediction starts to become non-linear after 12 days.

(c) **Degree of Saturation**

The degree of saturation is plotted against time on the graph in **Figure 5-26**; this figure contains the prediction of the degree of saturation from the model and the drying box test results.
Initially, up to approximately 12 days, the graph of the model prediction for the degree of saturation is similar in shape to the graphs for the measured values from the drying box tests. After 12 days, the predicted degree of saturation deviates and is no longer similar to the measured values.

(d) **Dry density**

The dry density of the tailings is the ratio of mass of dry tailings to total volume. The predicted dry density is plotted against time along with the drying box test results in Figure 5-27.
Figure 5-27: Dry density versus time for model prediction and drying box test results.

The graph for the predicted dry density under estimates the dry density, making the prediction conservative. The shape of the curve, however, compares well with the measured dry densities from the drying box tests.

(e) Void Ratio

The void ratio is the volume of voids to the volume of solids. The void ratio of the tailings can be determined from the predicted values of saturation and moisture content. Thus, the predicted void ratio is plotted against time in Figure 5-28. Figure 5-28 also contains the drying box test results.
The predicted void ratio appears to be the average of the measured void ratios from the drying box up to approximately 12 days. After 12 days the predicted value of void ratio appears to under estimate the void ratio, making it conservative. On a whole, the predicted void ratio compares well with the measured values, especially up to 12 days.

### 5.4.4 Discussion of Model
The semi-empirical model that was setup by Swarbrick (1992) was used to predict various parameters for Mispah Tailings Dam. Each parameter was plotted against time and has been discussed in Section 5.4.2 above.

The poor results of the model to predict the height as sedimentation and desiccation of the tailings occur could be the result of a number of factors. These factors may be:

- There were not enough field tests conducted. The field tests that were conducted, did not capture the field conditions properly.
- The material that was tested in the laboratory is not representative of the material in the dam wall.
The way in which the laboratory tests were conducted do not properly resemble the field conditions.

The conclusion that was made from all the results is that the model either overestimates or underestimates the values of the parameters from the field experiments.

The model prediction from Swarbrick (1992) was for tailings slurry with an initial height of 450 mm and the duration of sedimentation and desiccation was roughly 70 days. This work was based on a tailings slurry with an initial height of 150 mm and a duration of 14 days. That is a difference of 300 mm for the initial height and 56 days for the duration of the sedimentation and desiccation of the tailings. This difference is one reason why the model did not accurately predict the tailings properties.

When the semi-empirical model was compared to the measured values from the drying box tests, there was a better correspondence between the predicted and measured values, especially for the first 10 days. The comparison between the predicted model and the drying box test results are discussed in Section 5.4.3.

The Swarbrick (1992) semi-empirical model is very difficult to use and it is therefore, not very user friendly. Mistakes can easily be made with the model parameters, which may also result in predictions that are not very accurate.

It is recommended that:

- More extensive field tests are conducted in order to have a better set of results for comparison. Also to better understand the sedimentation and desiccation of the tailings in the field, and therefore, determine how accurately the drying box tests model field conditions.

- Make sure that the material that is tested is more representative of the field conditions. Have a more even grading of material, not just coarse or not just fine material. This could be done by, for example, taking more samples over a wider area.

It is felt that the model has potential, this can be seen when it was compared to the results from the drying box tests. More research is required to fine tune the model and to get better representative field test results.
5.5 FIELD TEST RESULTS

Field tests were conducted on the daywall of Mispah Tailings Dam. The comparison of the field test results with the predicted properties from the model for Mispah tailings are discussed in Section 5.4. This section contains the comparison of various field test results with the drying box test results.

The following graphs are used to compare field test and drying box test results:

- Moisture Content versus Suction
- Degree of Saturation versus Suction
- Void Ratio versus Suction

5.5.1 Moisture Content versus Suction

The moisture content is plotted against suction for the field and drying box test results. Figure 5-29 shows this comparison of the field and drying box test results.

The drying box test results, shows that the suctions start to increase from zero at a moisture content of roughly 50%. From here the graph curves as the suctions increase, indicating that the decrease in moisture content with increase in suction is not constant. A few points of the field test results are plotted on Figure 5-29 and range between a suction of 20 kPa and 140 kPa.
Figure 5-29: Moisture content versus suction for field and drying box test results.

The field test and drying box test results compare very well. This shows that the drying box test results for moisture content versus suction are realistic.

Figure 5-30 gives the moisture content plotted against suction on a logarithmic scale for the field test and drying box test results. This graph is part of a soil-water characteristic curve where the moisture content is plotted against suction. Once again it is evident from this graph that the drying box results compare well with the field test results.
Figure 5-30: Moisture content versus suction (logarithmic scale) for field and drying box tests.

5.5.2 Degree of Saturation versus Suction

The saturation is plotted against suction on the graph in Figure 5-31 for the field and drying box test results.

The drying box test results give a graph that curves as the degree of saturation decreases as suction increases. A few points of the field test results are plotted on this graph.

The comparison between the field and drying box test results is relatively good. There are a few places where there is a large difference between the two but generally the comparison is good. The drying box test graphs run through the middle of all the field test results, so the drying box test graphs are about the average of the field test results.
5.5.3 Void Ratio versus Suction

The void ratio is plotted against suction in Figure 5-32 for the field test and drying box test results.

The void ratio for the drying box tests is higher than for the field test results. The average void ratio from the field test results is 1.1 which is lower than that for the drying box test results. The problem with the inaccuracies due to sampling disturbance, discussed in Section 5.3.3 (d) and 5.3.6, result in the accurate comparison between the field and drying box tests reasonably difficult.
Figure 5-31: Void ratio versus suction for field test and drying box test results.
CHAPTER 6
CONCLUSIONS

6.1 CONCLUSIONS AND RECOMMENDATIONS

- The aim of the study was to investigate a semi-empirical model that predicts various tailings properties during sedimentation and desiccation by Swarbrick (1992). Another aim that this study investigated is the general behaviour of the tailings during sedimentation and desiccation.

- Sedimentation of tailings was observed using column settling tests, where three different size columns were used. This provided information about the general settling behaviour of tailings.

- The desiccating behaviour of tailings was observed with the use of a drying box. The drying box had to be constructed specifically for the purpose of these experiments.

- The tailings material used for the research was obtained from Mispah tailings dam. Mispah tailings dam was chosen because previous research has been done by Dr NJ Vermeulen on the tailings material from this dam.

- From the column settling tests it is evident that finer tailings particles have a lower initial rate of settlement than coarser tailings particles. The final settled height of the finer tailings is also higher than that of the coarser tailings particles. The dry density of the fine tailings is low and the void ratio is high. The opposite is true for coarse tailings, i.e. the dry density is high and the void ratio is low.

- The drying box test produced direct and indirect results. The direct results were measured against time and are height, temperature, suction and the mass of the drying box. The indirect results were obtained by analysing the direct results of the drying box test and they are the cumulative evaporation, moisture content, void ratio, degree of saturation, dry density and linear shrinkage.

- The plot of height versus time for the drying box tests has a similar shape to the sedimentation curves from the column settling tests.
The conclusion that was made from all the results is that the model from Swarbrick (1992) either overestimates or underestimates the values of the parameters. The Swarbrick (1992) model is also very difficult to use and it is therefore, not very user friendly.

The semi-empirical model from Swarbrick (1992) has potential because when it was compared with results from the drying box tests, there was a better correlation between the measured and predicted values. It is recommended that more extensive field tests are conducted and the semi-empirical model is further researched.

The field test and drying box test results compare very well when moisture content is plotted against time. This shows that the drying box test results, for moisture content versus suction, are realistic. These graphs are part of soil-water characteristic curves when the moisture content is plotted against the logarithmic of suction.

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REFERENCES


