SOIL SUCTION IN MINE TAILINGS

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A thesis submitted in partial fulfillment of the requirements for the degree of

MASTER OF ENGINEERING (GEOTECHNICAL ENGINEERING)

in the

FACULTY OF ENGINEERING

UNIVERSITY OF PRETORIA

November 2000

UNIVERSITEIT VAN PRETORIA
UNIVERSITY OF PRETORIA
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THESIS SUMMARY

SOIL SUCTION IN MINE TAILINGS

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The failure of the tailings dam at Merriespruit highlighted the uncertainties concerning the strength and stability of such dams. Owing to the theory, a tailings dam would remain stable at a slope equal to the material's internal angle of friction and is thus designed accordingly. In practice however, it was found that these structures remain stable at slopes greater than this specified angle. It was also found that, irrespective of sufficient freeboard, failures often occur after prolonged rainfall. Negative pore or suction pressures present in the tailings, especially in the upper regions, increases the effective stress and hence the stability of the structure. Currently the friction properties of tailings can be measured with relative accuracy whereas the opposite is true for the suction pressures. Measurement of these pressures would result in the economical design and risk assessment of tailings dams.

The aim of the thesis is therefore to design, calibrate and test an instrument that is able to measure the suction pressures in gold mine tailings.

A literature survey was conducted to assess the advantages and disadvantages of the available suction measurement devices. Attention was paid to the specific characteristics of suction pressures in mine tailings. This study showed that the tailings environment is harsh with varying moisture contents and temperatures as well as high salinity. The instrument required for measuring the suction pressures in gold mine tailings would have to be able to operate under these conditions. The literature survey however, indicated that most of the instruments, with the exception of the Imperial College suction probe, would not comply with these criteria. Limitations such as suction range, long response time and their susceptibility to salinity and other environmental influences made them unsuitable.

A suction probe was designed and built based on the Imperial College suction probe but using a lower air entry ceramic. Laboratory desorption tests were conducted on two samples of gold mine tailing. These tests indicated some design flaws of the instrument but none the less gave an indication of the suction characteristics of the material. The instrument was however discarded after some period of time due these design flaws and a new instrument, namely the mid-plane suction probe, was designed and built. This probe incorporated a Kyowa PS-2KA pressure transducer and the overall size was reduced to the dimensions generally used for a mid-plane triaxial pore pressure sensor (hence the name). Desorption tests were carried out on the same tailings using the mid-plane suction probe. These tests were successful demonstrating that the goals set out in this thesis were met.

ACKNOWLEDGEMENTS

I wish to express my appreciation to the following organisations and individuals that made this thesis possible:

- Wates Meiring and Barnard for their moral and financial support during the course of the study.
- Fraser Alexsander Tailings Ltd (Pty) for the financial support.
- Jan Brand and Jaap Peens for their technical support.
- Nico Vermeulen for his views and samples.
- Professor E. Rust, my supervisor for his guidance and support.
- My family for their encouragement, support and coffee during the study.
- Martin for his motivation and confidence in my abilities.

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a, m, n	fitting parameters
C_s	the concentration of the solute
C_ψ	correction factor introduced by Fredlund and Xing (1994) to ensure that θ reach zero as ψ reach a limiting value (ψ_0) equal to 10^7 cm of water.
c′	intercept of the "extended" Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero: it is also referred to as the "effective cohesion"
h	pressure head
h_{oc}	corresponding water head which is linear to the suction
m	undetermined parameter with m = 1- (1/n)
n	porosity
π	osmotic suction
p	slope of linear part of SWCC
q	intercept of linear part of SWCC
R	universal (molar) gas constant i.e. 8.31432J/ mol K
R_s	radius of curvature
S	degree of saturation
T	absolute temperature i.e. T = (273.16+t°) (K)
T_s	tensile pressure
t°	temperature (°C)
$(u_a - u_w)$	matric suction
$(u_a - u_w)_f$	matric suction on the failure plane at failure
u_a	pore-air pressure
u_{af}	pore-air pressure on the failure plane at failure
u_{vo}	saturated pressure of water vapour over a flat surface of pure water at the same temperature (kPa)
v_{wo}	specific volume of water or the inverse of the density of water i.e. $1/\rho w$ (m^3/kg)
Δu	u_a-u_w
Ω	the molar osmotic coefficient of the solute
Ψ	soil suction or total suction (kPa)

$\bar{u}_v$	partial pressure of the water vapour (kPa)
α	undetermined parameter
χ	a parameter related to the degree of saturation of the soil
ϕb	angle indicating the rate of increase in shear strength relative to the matric suction, $(u_a - u_w)_f$
ϕ'	angle of internal friction associated with the net normal stress state variable, $(\sigma_f - u_a)f$
θ	volumetric water content
θ_r	residual water content
θ_r	residual volumetric water content
θ_s	saturated volumetric water content
$(\sigma f - u_a)_f$	net normal stress state on the failure plane at failure
ρ_w	density of water i.e. 998kg/ m³ at t° = 20 °C
ω_v	molecular mass of water vapour i.e. 18.016 kg/kmol
ψ	soil suction
ψ_r	soil suction corresponding to the residual volumetric water content

1 INTRODUCTION

1.1 Background

A large percentage of the earth's surface is subjected to arid and semi-arid climatic conditions. In these regions the evaporation rate mostly exceeds that of precipitation with the result that an unsaturated zone with suction pressures is established in the upper section of a soil profile. Classical soil mechanics is based on the assumption of saturation and is therefore not generally applicable to the material found in these regions. The negative pressures generated by suction in these soils govern their engineering behaviour and are therefore of great importance. Little has been done thus far to incorporate these negative pressures in soil mechanical principles and even more unfortunate is the fact that the little development that has been gained is not put into practice.

Special reference can be made to this effect in mine tailings. The extraction and processing of most mineral ores result in the generation of large volumes of fine-grained residue or tailings. The safe disposal of such material, which generally exhibit slow rates of sedimentation and consolidation, is of prime concern in the management of mining operations (Concoli and Sills, 2000). This is in particular true in South Africa, being one of the world's largest mineral producing countries. The country's climatic condition could best be defined as semi-arid and in some parts of the country even as arid. Due to these conditions water evaporates from the deposited slurry resulting in the generation of suction pressures. It is believed that the suction pressures in the mine tailings contribute largely to its stability. The measurement of these pressures and application to stability calculations have been neglected and disregarded in the past. This could have a significant influence on the understanding of the true failure mechanism of a tailings dam. This could also be incorporated in risk analysis and used as criteria for the economic design of these structures.

1.2 Objectives

The objectives of the thesis can be summarised as follows:

- Carry out a literature survey of the suction measurement devices currently available and

assess their advantages and limitations.

- Select a prototype instrument that would be able to measure suction pressures according to a set of design criteria. These will be based on conditions expected in mine tailing .
- Design, manufacture and calibrate such an instrument successfully.
- Carry out laboratory tests on samples of gold mine tailing to assess whether the instrument meets the desired performance criteria.

1.3 Scope

The thesis aims at designing and manufacturing an instrument that is able to measure the suction pressure in gold mine tailings according to an established set of design criteria. The research is commenced by a literature review on the definition of suction, the relevance of it to the tailings industry and the various suction measurement devices available. The applicability of each instrument is quantified by firstly establishing whether it is appropriate for use in the tailing environment and secondly whether its suction range coincides with that specified, i.e. the design criteria. This is followed by the design and manufacture of the instrument. Lastly the calibration and laboratory testing will be conducted to assess and demonstrate the performance of the instrument.

1.4 Methodology

The methodology of developing an instrument to measure suction pressures in mine tailing is as follows:

- Carry out a literature survey of publications on the principles of suction pressures and suction measuring devices.
- Selection of a prototype instrument.
- Design of the suction probe based on the selected prototype.
- Machining and assembly of the probe.
- Saturation of the probe.
- Calibration of the probe.
- Laboratory trials on mine tailings.
- Analysis, interpretation and discussion of laboratory trials.

1.5 Organisation

The thesis consist of the following chapters:

Chapter 1 serves as an introduction to the thesis.

Chapter 2 entails the literature review and serves as a basis from which the development of the instrument was carried out.

Chapter 3 discusses the development of the suction probe.

Chapter 4 deals with both the calibration and laboratory testing procedure. It also includes the results obtained from the testing.

Chapter 5 discusses the development of a mid-plane suction probe.

Chapter 6 consists of a discussion on the development of both the suction probe and mid-plane suction probe including laboratory test results.

Chapter 6 draws some conclusions on the development of the instruments and tests.

Chapter 7 contains the references for this thesis.

2 LITERATURE REVIEW: INVESTIGATION OF SUCTION MEASUREMENT

2.1 Definition of Suction

In order to understand the mechanism involving suction measurement devices, one has to be familiar with the concept of suction. Suction is commonly referred to as the free energy state of soil water and is measured as partial vapour pressure of soil water (Richards, 1965). Vapour pressure of soil can best be explained in terms of the kinetic theory. Molecules in liquid state are in constant motion of movement and collide into each other. At the free surface of the liquid a molecule can absorb enough energy by this action to change phase i.e. liquid to gas. Molecules changing from liquid to gaseous phase result in the development of vapour pressure of which the magnitude depends on the rate that molecules leave the liquid phase. On the other hand some molecule may return to the liquid phase causing partial pressure to develop. When the rate of the two opposing processes are equal the gas above the liquid is saturated with vapour and is termed the saturation pressure. The equilibrium vapour pressure is a function of the water temperature and pressure as well as the concentration of solubles.

Soil suction that is the free energy of soil is thermodynamically related to the partial pressure of the pore water (Equation 2.1). The calculation is made relative to a flat surface of pure water.

$$\psi = -\frac{RT}{v_{wo}\omega_v}\ln\left(\frac{\bar{u}_v}{u_{vo}}\right) \qquad 2.1$$

where:

ψ soil suction or total suction (kPa)

R universal (molar) gas constant i.e. 8.31432J/ mol K

T absolute temperature i.e. T = (273.16+t°) (K) where t^o = temperature (°C)

v_{wo} specific volume of water or the inverse of the density of water i.e. 1/ρw (m³/kg) where ρ_w = density of water i.e. 998kg/ m³ at t° = 20 °C

ω_v molecular mass of water vapour i.e. 18.016 kg/kmol

$\bar{u}_v$ partial pressure of the water vapour (kPa)

u_{vo} saturated pressure of water vapour over a flat surface of pure water at the same

temperature (kPa)

The Review Panel (1965) at the symposium "Moisture Equilibria and Moisture Changes in Soils" formally defines suction as:

> "In suction terms, it is the equivalent suction derived from the measurement of the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapour in equilibrium with free pure water."

Both of the previous definitions are related to the total soil suction. It has been postulated and proved to some extend by various researches such as Krahn and Fredlund (1972) (Figure 2.1) that the total suction of the soil consist of two components namely matric and osmotic suction (Equation 2.2). Each of these will now be discussed separately in the following section.

$$\psi = (u_a - u_w) + \pi \qquad 2.2$$

where:

$(u_a - u_w)$ matric suction

π osmotic suction

2.1.1. Matric Suction

According to Aitchison (1965) matric suction can be defined as:

> "In suction terms, it is the equivalent suction derived from the measurement of partial pressure of the water vapour in equilibrium with the soil water, relative to the partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water."

Matric suction is commonly associated with the capillary phenomenon resulting from surface tension. This association seems valid, as the radii of the pores between the soil particle are so small that it in fact acts as capillary tubes. Surface tension is the result of intermolecular forces acting on the molecules at the interface between air and water. These forces differ from

that experienced by molecules in the interior of the water, as a molecule in the interior experience isotropic pressure while one at the boundary experience an unbalanced force towards the interior (Figure 2.2). In order for the water at the interface to remain in equilibrium, a tensile pull is generated. The meniscus formed by the pull is such that it is concave towards the higher pressure. The pressure difference across the interface is related to the tensile pressure (T_S) and radius of curvature (R_S). The pressures acting on the interface are u and $u + \Delta u$ as illustrated in Figure 2.2. By taking vertical force equilibrium, it can be seen that:

$$2T_s \sin\beta = 2\Delta u R_s \sin\beta \qquad 2.3$$

where:

$2R_S sin\beta$ length of membrane projected onto horizontal plane

If Equation 2.3 is re-arranged:

$$\Delta u = \frac{T_s}{R_s} \qquad 2.4$$

where:

Δu u_a-u_w

Taylor (1948) demonstrated that incorrect suction measurements were often related to the height and radius of the capillary rise. This was achieved by considering a capillary tube of varying height and radius. As mentioned previously the capillary model is simony to the pore between soil particles. In the event of the capillary height being too short water will only rise up to the top of the capillary, but the radius of curvature would be greater than of full rise was achieved. In this case the measurement will overestimate the true suction pressure. On the other hand, if the radius of the capillary suddenly increase, water would only rise up to the bottom of the increased radius and not the full capillary height. Full capillary height however, could be achieved by means of submersion i.e. the drying of the tube. It is thus evident that varying pore radii result in hysteresis of suction measurements.

The capillary model, however can not justify the extremely high suction pressure often encountered in soils such as clays (Harrison, 1998). These high pressures are attributed to absorption. Absorption pressures are caused by the attraction of water molecules to the double diffuse layer surrounding soil particles. In sandy and silty soils these forces are almost non-existing whereas in clayey soils these forces primary contributes to the measured matric suction.

2.1.2. Osmotic Suction

Aitchison (1965) defined osmotic suction as:

> "In suction terms, is it the equivalent suction derives from the measurement of partial pressure of the water vapour in equilibrium with a solution identical in composition with the soil water, relative to the partial pressure of water vapour in equilibrium with free water."

Osmotic suction is generated by the osmotic repulsion mechanism, arising from the presence of soluble salts in the pore water of soil. These forces are identical in context to the osmotic attractive forces (Snethen, 1980). Osmotic suction could best be explained by considering a scenario where pure water is placed in contact with a solution through a semi-permeable membrane. The membrane allows water to move through it while at the same time preventing the solution from doing so. The concentration of solubles creates the potential for water to flow through the semi-permeable membrane to the solution. If the flow of water is restricted, a differential pressure namely osmotic suction (π) is created between the two. Osmotic suction can be expressed mathematically as follows:

$$\pi = \Omega RTC_s \qquad 2.5$$

where:

- Ω the molar osmotic coefficient of the solute
- R the universal gas constant
- T the absolute temperature
- C_S the concentration of the solute

The double layer surrounding clay particles (Figure 2.3) acts as such a semi-permeable membrane, giving rise to osmotic suction. The double layer entails cations absorbed to the negative charge particle surfaces. This strong attractive force prevents ions in concentration to move away from the double layer giving rise to high water pressure (u_{bound}). The bulk pore water pressure (u_{free}) is considerably less than that of the double layer (u_{bound}) and hence is free dilute the concentration of ions (Chen, 1975). Osmotic pressure or suction is thus the pressure difference between the bulk pore water and the fluid between clay particles and is equivalent to the repulsive pressure between the particles (Childs, 1969). It could only be altered by adding or subtracting solubles to or from the soil (Barbour and Fredlund, 1989). As the solubles is present irrespective of the degree of saturation of the soil, osmotic suctions is present in both saturated and unsaturated soil.

The importance and relevance of the three suction terms define above were investigated to determine which of them are applicable to unsaturated soils such as mine tailings. Geotechnical problems relating to such soils are mostly caused by environmental changes such as changes in the pore pressure regime. These environmental changes alter the matric suction of the soil and consequently the overall equilibrium of the soil. There was thus no doubt that matric suction was an important component of total suction that could not be neglected. Referring to Figure 2.1 it can be seen that the matric and total suction of soil are closely related to each other, especially in the higher suction range. Osmotic suction on the other hand is considerably removed from both the matric and total suction curves. Based on this figure it can be concluded that osmotic suction remain extremely low and may be neglected. Following remarks supports this statement:

- Osmotic suction can only be altered by changing the amount of the solvents present and thus remains constant irrespective of environmental and pore water changes. This greatly reduce the relevance of the implementing of the component to geotechnical unsaturated soil problems.
- Laboratory tests performed on unsaturated samples mostly simulate the field conditions with regards to osmotic suctions as the solubles are neither removed nor added. The component is thus already taken into account even at the early stage of testing.

If the above mentioned factors are taken into account it can be concluded that matric suction

and hence total suction is of great importance in unsaturated soil whilst osmotic suction can often be neglected.

The importance of matric suction in unsaturated soil mechanics is highlighted even further by the soil-water characteristic curve (Figure 2.4) or alternatively known as the water retention, capillary pressure saturation curve or soil moisture characteristic curve. For the purpose of this thesis it will be referred to as the soil water characteristic curve (SWCC). The curve is a function of the initial water content, dry density, stress history and state and can thus be used to describe the unsaturated behaviour of the soil. This is done by relating the volumetric water content (θ) (Equation 2.6) to the matric suction (ψ). The matric suction is physically measured with suction measurement instruments as will discussed in preceding sections whilst the volumetric water content is obtained mathematically (Muraleetharan and Granger, 1999).

$$\theta = nS \qquad 2.6$$

where:

n porosity
S degree of saturation

The curve can be used to establish both the air entry value and the residual water content of the soil. The air entry value or bubbling pressure is the matric suction at which air starts to enter the largest pores near the boundary of the soil mass. In general this value will fall within the following range (Kovacs, 1981):

coarse sands:	2 to 10cm of water
medium sands:	10 to 35 cm of water
fine sands:	35 to 70cm of water
silts:	70 to 250cm of water
clays:	greater than 250cm of water

The residual water content (θ_r) on the other hand can be defined as the water content where large suction pressures is required to remove addition water from the soil (Chenggang et al,

1998). The numerical value of both can be determined by adopting the graphical method illustrated in Figure 2.4. Inadequate matric suction measurements influence the accuracy of the residual water content in that it is no longer clearly defined. This problem can be overcome by adopting procedures proposed by Van Genuchten (1980) where the residual water content is estimated by extrapolation. Extrapolation is achieved by one of two methods namely best fit where several values for θ_r is assumed or least square curve fitting where simultaneous estimates of θ_r, n and α (Equation 2.7) is made. The entire range of measurements were employed for the procedures.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha h)^n\right]^m} \qquad 2.7$$

where:

θ_r	residual water content
θ_S	saturated water content
α	undetermined parameter
h	pressure head
n	porosity
m	undetermined parameter with m = 1- (1/n)

As discussed previously the soil pore network consist of tubes of varying cross section where both the distribution of pore size in the horizontal section and vertical change of pore diameters influence the capillary height. The degree of saturation is thus highly hysteretic with regards to the sorption and desorption process (Fredlund et al, 1994). Based on this fact the SWCC is not unique for a specific soil, but can be defined in terms of an upper and lower bound. Several researchers such as Van Genuchten, Brooks and Corey and Kovacs proposed methods of obtaining the SWCC but most of these are only applicable to certain suction ranges, soil or sample preparation i.e. sorption or desorption. The methods are further based on the assumption of the water content either being non-zero or zero at infinite suction (Rossi and Nimmo, 1994). Since then much have been done to overcome these disadvantages. Fredlund et al (1994) proposed Equation 2.8 that is based on the assumption that the shape of the SWCC is governed by the pore-size distribution of the soil. The equation is applicable to

the entire suction range and provides a good fit for soil types such as sand, silt and clays.

$$\theta = C(\psi)\frac{\theta_s}{\left\{\ln\left[e+\left(\psi/a\right)^n\right]\right\}^m} \qquad 2.8$$

$$C(\psi) = 1-\frac{\ln\left(1+\psi/\psi_r\right)}{\ln\left(1+10^6/\psi_r\right)} \qquad 2.9$$

where:

a, m, n fitting parameters

ψ soil suction

θ volumetric water content

θ_S saturated volumetric water content

ψ_r soil suction corresponding to the residual volumetric water content

$C(\psi)$ correcting function

Recently Aubertin et al (1998) proposed a modified Kovacs model that takes into account some of the aspects of Fredlund and Xing approach. Good agreement was achieved between observed and calculated results. Similar to Kovacs, it make use of a saturation ratio (θ/θ_S) that incorporates both the capillary (S_C) and absorption (S_a) forces (Equation 2.10).

$$S_r = S_c + S_a(1 - S_c) \qquad 2.10$$

The respective parameters are defined by the following equations:

$$S_c = 1-\left[\left(h_\infty/\psi\right)^2+1\right]e^{\left[-n\left(h_\infty/\psi\right)^2\right]} \qquad 2.11$$

$$S_a = C_\psi \frac{a}{e^{1/3}\psi^{1/6}}\psi^{2/3}_{90} \qquad 2.12$$

$$C_\psi = 1 - \frac{\ln\left(1 + \psi/\psi_0\right)}{\ln\left(1 + \psi_0/\psi_r\right)} \qquad 2.13$$

where:

C_ψ correction factor introduced by Fredlund and Xing (1994) to ensure that θ reach zero as ψ reach a limiting value (ψ_0) equal to 10^7 cm of water.

ψ_r suction corresponding to the residual volumetric water content

h_{oc} corresponding water head which is linear to the suction

2.2 Construction of a Tailings Dam

Tailings can be defined as the waste product of mining, industrial and chemical processes. Mine tailings in specific consist of ground up rock of which the mineral value has been removed. The grain size distribution of the tailings varies from fine sands to clay-sized particles depending on the characteristics of the ore and mill process used (Messrs et al, 1989).

Essentially tailings dams are constructed in two phases namely the initial starter dyke and secondly the remaining tailings dam structure (Messrs et al, 1989). The initial starter dyke provides a starting point from which further construction takes place. The type is governed by the construction method of the remaining dam. The second phase (the remaining dam) is a lengthy and continuos operation that requires proper planning and management. It consists of increasing both the wall and beach height by means of deposition. Tailings is deposited onto the dam by one of three methods namely cycloning, spigotting or paddocking.

Cycloning aims at segregating the tailings into two grading types i.e. the cyclone underflow and overflow (Messrs et al, 1982). The underflow consist of coarse particles with a relative low water content while that of the overflow is fine particles of low permeability, good flow characteristics and high water content. The tailings is then placed in such a way that the underflow is deposited on the outer perimeter to increase wall height and the overflow is discharged into the pool area. Care should be taken to ensure that the increase in wall height remains superior to that of the beach. The technique is dependent of consistent cyclone

performance and planned positioning of the cyclones.

Similar to cycloning, spigotting segregates the tailing particles according to grain size (Messrs et al, 1982). The tailings are segregated by means of multiple outlets of reduced volume along the delivery line, causing an increase in the discharge velocity. Coarser particles then settles out under gravitation while the finer particles are carried in the stream until it is deposited in the tailing pond. Segregation is thus naturally achieved making it an economical method with low capital and operational cost. The method however has the disadvantage that particle segregation can not be controlled and as a result horizontal layering is almost always encountered. This reduces the vertical permeability of the tailings and encourages horizontal seepage. Other characteristic features of the method are the limited application to upstream wall building and the pheatric surface that is governed by the freeboard that is a function of the containment wall and spigotted beach.

The paddock system is a common method for the deposition gold mine tailings. It consists of a grid of paddocks along the outer perimeter of the dam (Messrs et al, 1982). Unlike the previous two methods, tailings are not segregated into two different particle sized sections. It is simply deposited in layers of 100 to 150 mm and left to settle and dry out by means of evaporation and drainage. The deposition cycle is governed by the rate of rise of the dam and the period required for the drying of the previous layer. The wall height is increased by mechanically scraping dried tailings and placing it on the outer perimeter of the dam. It is clear that the method is dependent on the drying out of the tailings and for this reason it is only suitable for countries with arid and semi-arid climatic conditions where the evaporation rate is relatively high. The method is also restricted to single grained material as graded material would result in the gravitational sorting of the particles, horizontal layering and a high k_h:k_v ratio. Another disadvantage of the method is improper compaction of the wall, but this could be limited to some extend by the traffic on it.

The wall is constructed by one of three methods namely upstream, downstream and centreline. The method refers to the direction that the wall moves relative to the starter dyke as the height is increased. Common to all three methods a starter dyke of 3 to 6 m in height is constructed from local borrow material.

The upstream method (Figure 2.5) initiates from deposition of tailings onto the starter dyke (Messrs et al, 1989). As mentioned previously, the wall progress upstream with increasing height such that each new dyke is underlain by soft pervious deposited tailings. Due to this fact management of the pheatric surface is prudent for stability. The pheatric surface of the dam is governed by several factors such as the relationship between the permeability of the foundation and deposited tailings, the degree of grain size segregation, horizontal permeability layering and the position of ponded water relative to the dam crest (Vick, 1983). Unfortunately the only controlling factor that can be manipulated is the position of the ponded water that is achieved by under drainage, cycloning or spigotting and decant procedures. The rate of rise of the wall is a function of the rate of mill tailings production, the topographical configuration of the site and the excess pore pressures generated during deposition. The method is only feasible for countries of arid climatic conditions in which case it proves to be simplistic with both low capital and operational cost.

The downstream method (Figure 2.6) involves discharging of tailings behind the starter dyke and thus the downstream movement of further dykes. Unlike the previous method, each new dyke is founded on a carefully prepared base (Messrs et al, 1989). Tailings are discharged onto the dam by either spigotting or cycloning as to provide sandy material for the wall and clayey material for the pond. Water can be stored directly against the inner face of the wall since the well controlled beach, inner drains and pervious wall prevents the build up of excess pore pressures. The method suffers from two disadvantages namely high cost and large fill volumes required for wall building (Vick, 1983). The volume of fill required is a function of the topography of the site and increase exponentially as the height of the wall increase.

The centreline method (Figure 2.7) is a combination of the two methods discussed previously and hence shares the advantages while mitigates the disadvantages. Tailings are discharged peripherally from the crest of the starter dyke onto the beach. The wall is raised by the placement of fill on both the beach and downstream slope. Spigotting is mainly used for deposition as it provides a competent beach for the further placement of fill. Internal drains can be installed as to ensure proper drainage. Unlike the downstream method, water can not be stored at great depths for long periods. However, in the event of a flood the dam would be able to store the additional water for a short period without affecting the slope stability. The overall rate of rise of the dam is not restricted by the pore pressure dissipation of the tailings

but could occasionally be affected by the undrained shear strength of the beach (Vick, 1983). The volume of fill required for raising of the wall is intermediate of the two methods. A disadvantage that is exclusive to the centreline method is compatibility problems between the fill requirements and the production rates.

2.3 Suctions in a Tailings Dam

The study of saturated soil mechanics is founded on the effective stress concept (Fredlund and Rehardjo, 1998). All mechanical aspects of saturated soil are related to effective stress and as a result of it, the equilibrium state of the soil. Tezaghi (1936) define the stress state variable that control the behaviour of the soil as follows:

> "The stresses in any point of a section through a mass of soil can be computed from the total principle stresses σ_1, σ_2 and σ_3 which act at this point. If the voids of the soil are filled with water under a stress u_W, the total principle tress consist of two parts. One part, u_W, acts in the water and in the solid in every direction with equal intensity. It is called the neutral (or the pore-water) pressure. The balance $\sigma_1'=\sigma_1-u_W$, $\sigma_2'=\sigma_2-u_W$ and $\sigma_3'=\sigma_3-u_W$ represents an excess over the neutral stress, u_w, and it has its seat exclusively in the solid phase of the soil. All the measurable effects of the change in stress, such as compression, distortion, and a change in the shearing resistance, are exclusively due to changes in the effective stresses σ_1', σ_2' and σ_3'."

The number of stress state variables required to describe the mechanical behaviour of soil is a function of the phases of which soil consists (Fredlund and Rehardjo, 1998). Saturated soil consist of three phases namely soil grains, water and air and hence require only a single stress state variable (Equation 2.14).

$$\sigma' = \sigma - u_W \qquad 2.14$$

On the other hand, the behaviour of unsaturated soil is more complex than that of saturated soil as it consists of four phases as opposed to the mentioned three of saturated soil. These include water, soil particles, air and the air-water interface. The concept of effective stress is

well established and it is therefore desirable to extend it for the purpose of unsaturated soil. Various researchers attempted to do so. The first attempt was made by Bishop in 1959 (Equation 2.15).

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w) \qquad 2.15$$

where:

u_a pore-air pressure

χ a parameter related to the degree of saturation of the soil

Donald (1961) and Blight (1961) related (Figure 2.8) the degree of saturation to the χ parameter for cohesionless silt and compacted sand respectively.

The relationship was obtained experimentally. Several researchers reported some inaccuracies encountered with the relationship. These are as follows:

- The parameter (χ) is test and stress path dependent (Harrison, 1998).
- A good agreement was obtained for silty sand above the critical saturated value but the contrary was true below it. The critical saturated value can be defined as the point where moisture loss no longer results in a volume decrease. This value was estimated as 20% for silt and sand and 85 to 90% for clay.
- Finally, the most important deficiency of the parameter is that it is obtained via soil properties and not equilibrium conditions, which is normally the case when defining the stress state of the soil.

Following these difficulties with the parameter, Fredlund and Morgenstern (1977) presented a theoretical stress analysis on the basis of multi-phase continuum mechanics. It is assumed that the soil particles are incompressible and chemically inert which is consistent with saturated soil mechanics. The stress state can then be described by making use of any two of the possible three stress states of unsaturated soil:

- $(\sigma - u_a)$ and $(u_a - u_w)$
- $(\sigma - u_w)$ and $(u_a - u_w)$
- $(\sigma - u_a)$ and $(\sigma - u_w)$

The (σ - u_a) and ($u_a - u_w$) combination proves to be the most satisfactory (Fredlund, 1979). If this combination of stress state is assumed the shear stress of the unsaturated soil can be described as follows:

$$\tau_{ff} = c' + (\sigma_f - u_a)_f \tan\phi' + (u_a - u_w)_f \tan\phi_b \qquad 2.16$$

where

c′	intercept of the "extended" Mohr-Coulomb failure envelope on the shear stress axis where the net normal stress and the matric suction at failure are equal to zero: it is also referred to as the "effective cohesion"
$(\sigma f\text{-}u_a)_f$	net normal stress state on the failure plane at failure
u_{af}	pore-air pressure on the failure plane at failure
ϕ'	angle of internal friction associated with the net normal stress state variable, $(\sigma_f\text{-}u_a)f$
$(u_a - u_w)_f$	matric suction on the failure plane at failure
ϕb	angle indicating the rate of increase in shear strength relative to the matric suction, $(u_a - u_w)_f$

Based on previous discussions it is clear that the shear strength of soil is greatly influenced by pore pressures. More so is this relationship of special relevance to unsaturated soil where both the suction pressure and water content of the pores play an important role. In Section 2.1.2 it was demonstrated that a relationship exits between soil suction and water content i.e. the soil-water characteristic curve (SWCC). Following the relationship between the SWCC and the shear strength of soil an alternative method (Equation 2.17) for estimating the shear strength of unsaturated soil is proposed (Vanapalli and Fredlund, 1995). The method mainly incorporates the SWCC and two saturated soil parameters namely cohesion (c') and internal angle of friction (ϕ'). The linear section of the SWCC between the air entry value (ψ_a) and the residual water content (θ_r) are considered for calculations. The shear strength of compacted glacial till and Hong Kong residual soil was measured with a direct shear test in a modified shear strength apparatus. The predicted and measure values were compared to each other and

good agreement between the two was found.

$$\tau_f = c' + (\sigma_n - u_a) tg\varphi' + (u_a - u_w)\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right) tg\varphi' \qquad 2.17$$

where:

θ_r residual volumetric water content

θ_S saturated volumetric water content

The term $\left(\frac{\theta - \theta_r}{\theta_s - \theta_r}\right)$ can be substituted with actual graphical parameters from the SWCC. The point under consideration in this case is the residual water content (θ_r) (Chenggang et al, 1998). If this is done, the following relationship holds.

$$\frac{\theta - \theta_r}{\theta_s - \theta_r} = p - q \lg(u_a - u_w) \qquad 2.18$$

where:

p slope of linear part of SWCC

q intercept of linear part of SWCC

By substituting Equation 2.18 into Equation 2.17, Equation 2.19 can be obtained:

$$\tau_f = c' + (\sigma_n - u_a) tg\varphi' + (u_a - u_w)\left[p - q \lg(u_a - u_w)\right] tg\varphi' \qquad 2.19$$

Matric suction contributes to the shear strength of the soil via the water inter-aggregate contact area (Fredlund et al, 1995). Below the air entry value of the soil (Figure 2.9) little change in the moisture content occurs. Therefore suction as a stress state variable is as effective as the net normal stress in mobilising the shear resistance along all of the contact points hence ϕ_b is equal to ϕ'. The contribution of suction to the shear stress of the soil above the air entry value decreases with increasing resulting in a non-linear relationship between the two. Based on this non-linear relationship it can be concluded that a strong correlation exists between the shear strength behaviour of unsaturated soil and the soil-water characteristic curve.

Referring to Equation 2.19 and Figure 2.9 it can be seen that the degree of saturation is inversely proportional to the matric suction and shear strength of soil. This relationship has specific application for the tailings industry as the moisture content and thus the matric suction of the tailings varies continuously. Rassam and Williams (1999) studied the hydraulic conductivity of mine tailings and found that a loss of strength is mainly due to re-wetting of the tailings caused by rainfall, deposition of fresh tailings and the upward flow of water from consolidation of capped tailing deposits. Several cases (Brazil: Woll and Hachich, 1989, South Africa: Van Schalkwyk and Tomas, 1991) have been reported where failure occurred after prolonged rainfall. The failures occurred at shallow depths of 1 to 1,5 m whilst the ground water level was well below the surface of the slope. Failures could thus only be attributed to a loss of strength resulting from reduce suction pressures. Fourie, Bhana and Blight (1995) studied a coal ash dump of Lethabo Power Station and found that while the internal angle of friction was 34° and the cohesion zero, the tailings remained stable at an angle of 37°. It was postulated that this increased angle of stability is due to the presence of matric suction in the tailings. Figure 2.10 illustrates the relationship between depth, matric suction and factor of safety. The indicated matric suction pressures were selected arbitrary. It is evident from the figure that the factor of safety reduces with reduced matric suction. The following conclusions can thus be drawn (Fourie, Rowe and Blight, 1998):

- While the factor of safety decrease with increasing depth, shallow failures could occur due to a wetting front, i.e. reduced matric suction.
- Failure could occur at suctions greater than zero.

Figure 2.10 is based on the assumption that both the internal angle of friction and the cohesion is independent of the suction. This is not entirely true as the relationship between shear strength and matric suction is non-linear as previously mentioned (Fredlund et al, 1995). If this relationship were taken into account, the graph would be slightly different although the conclusion drawn from it would similar. It is assumed that while the properties of coal tailings differs from that of gold tailings, their behaviour with respect to the matric suction and shear strength would be relatively similar. It is therefore assumed that the results of the above mentioned study is relevant to gold tailings.

Gamso et al (1999) studied a residual soil slope and found that the influence of rainfall and

evaporation decreases with increasing depth. The depth of influence was found to be limited to approximately a depth of 3 m. This observation confirms the results of Figure 2.10 namely that the influence of the pore pressure, i.e. the matric suction in this case reduce with increasing depth and hence the factor of safety reduce with increasing depth. Furthermore, the depth of influence relevant to the case study seems to be fairly deep confirming that the influence of the matric suction on slope stability should not be ignored bluntly. In general, the matric suction of the soil should be taken into account in stability analysis whenever the water table is low or when a shallow failure is expected (Fredlund and Rehardjo, 1998).

In order to obtain an estimate of the matric suction of coal tailings, Fourie et al (1999) measured it with a tensiometer and found it to be in the order of 30 to 40 kPa. It should be bear in mind that the tensiometer (as discussed in great detail in Section 2.6.5) suffer from various limitations of which the limited suction range is the greatest, i.e. between 0 and 90 kPa.

2.4 Suction Measurement Devices

Total suction of soil consists of two components namely matric and osmotic suction (Section 2.2). Currently there are several instruments available that measure these quantities (Table 2.1). Osmotic suction can only be measured directly by using the pore fluid squeezer or indirectly by calculating the difference between measured total and matric suction of the soil. However, neither of them seems to be very reliable. Referring to Section 2.1.2 osmotic suction is relatively small compared to matric suction (especially in sandy and silty soils) and can be neglected. An in depth discussion on osmotic suction measurement devices will therefore not be included in the scope of the thesis.

The aim of the literature study with regards to suction measurement devices was twofold namely:

- To investigate the advantages and limitations of the available suction measuring instruments.
- To identify an instrument that could be used as prototype for the design.

2.5 Total Suction Measurement Devices

Total suction of soil is assessed by measuring the relative humidity of the enclosed environment directly above a soil sample. Measurements are therefore made via the vapour phase. Presently two instruments are available that measures total suction namely the filter paper and psychrometer. The former of the two however is able to measure both total and matric suction of soil.

2.5.1. Psychrometer

Psychrometers measure total soil suction indirectly by measuring the relative humidity of the air in the soil pores or the region directly above the soil. A temperature difference between a non-evaporative surface (dry junction) and an evaporative surface (wet junction) was measured and related to relative humidity (Equation 2.1). Two types of psychrometers are available namely the thermistor and thermocouple. The types utilise different methods for placing the water droplet onto the wetted junction.

In its simplest form the instrument consist of two junctions, namely a wetted and dry junction in a closed environment. Water evaporates from the wetted junction into the adjacent air until equilibrium is reached, i.e. when the environment becomes saturated with water vapour. Evaporation from the wetted junction causes a decrease in temperature, as the water must have energy equal to or greater than the latent heat of evaporation for water. It is assumed that soil water vapour behaves as an ideal gas and consequently has no intermolecular forces and volume. The higher the suction of the soil, the lower the humidity of the surrounding environment and the less water will evaporate from the wetted junction. If it could be assumed that the temperature of the dry junction is similar to that of the environment and the wetted junction prior to evaporation, the suction of the soil can be related to the temperature difference between the junctions. The measurement of this temperature difference is based on the Seebeck effect (Baker et al, 1973). Seebeck (1821) discovered that when two junctions of dissimilar metals are maintained at different temperature, an electromotive force (e.m.f.) is generated in a closed circuit that can be measured with a micro-voltmeter. The relationship between temperature and saturated vapour pressure was exponential in order that small

changes in the ambient temperature results in large changes of the relative humidity and thus the erroneous measurement of soil suction (Fredlund and Rehardjo, 1988). These changes are mainly caused by the following factors (Rawlins and Dalton, 1967):

- The relationship between the water potential of the soil and the relative humidity was temperature dependent.
- The relationship between the decrease in temperature of the wetted bulb and the relative humidity was temperature dependent. Errors of up to 2% per 1°C have been reported.
- The chamber temperature (in which the junctions are enclosed) differs from that of the dry or reference junction. The difference in chamber temperature could be caused by either a change in the ambient temperature or by heat production within the sample itself due to respiration of plant tissue.
- The temperature of the air is directly related to the water vapour capacity of the environment. In turn the water vapour capacity is indirectly related to the relative humidity of the chamber and directly related to the evaporation of the wetted junction. It could thus be seen that an increase in the air temperature of the chamber would result in an increased evaporation from the wetted junction.

2.5.1.1 Thermistor or Transistor Psychrometers

A thermistor psyhrometer (Figure 2.11) consists of two identical thermistors in a closed environment which in this case was a chamber. A thermistor is a temperature sensitive resistor. One of the thermistors was removed from the chamber and a water droplet was placed on it. It was then returned to the chamber and left to come in equilibrium with the closed environment. Evaporation and condensation from the wetted thermistor changes the temperature of the chamber thereby generating an e.m.f. between the thermistors. The e. m. f. is measured and related to the relative humidity and hence suction.

Kay and Low (1970) suggested an alteration (Figure 2.12) to the design in that each thermistor was placed in a separate chamber with the sample and reference solution. The main features of the design include the following:

- Matched thermistors to reduce the differential thermal response.
- The two thermistors are located in separate chambers close to each other to ensure that they are subjected to similar ambient temperatures.

- Identical water drops are placed on both thermistors to eliminate any imbalances in heat dissipation.

Thermistor psychrometers are calibrated against standard sodium chlorine solutions (Woodburn, 1993). The equilibrium output voltage was established by extrapolating the linear portion of the output curve back to the zero time axis (Figure 2.13). This was necessary since evaporation of the water droplet continues with it being more pronounced in a drier environment. The output voltage versus time records indicate that equilibrium for suction greater than 300 kPa can be established after one hour whereas that less than 300 kPa varies between 2 and 24 hours. Several problems are experienced with the calibration of the instrument. The sensitivity of the instrument is poor in the low suction range (Richards, 1965). This phenomenon can probably be attributed to improper ventilation of the chamber resulting in the built-up of humidity around the thermistor and an underestimation of suction. The instrument drifts with both time and temperature (Baker et al, 1973) and requires frequent re-calibration (Woodburn et al, 1993). Hysteresis also occurs but can be prevented by ensuring that measurements are made in an increasing order.

The thermistor psyhrometer was limited to laboratory use since:

- It is a fragile instrument.
- The water droplet must be replaced after each reading.
- A constant temperature is required (temperature variations should be kept at ±0.8°C (Lee and Wray, 1995)).

2.5.1.2. Thermocouple Psychrometers

Thermocouple psychrometers (Figure 2.14) consist of a measuring junction (wet) of chromel and constantan and a reference junction (dry) of copper and constantan. A porous protective cover that is usually made of either a stainless steel mesh or a porous ceramic material surrounds the junctions. Unlike the thermistor psyhrometer, the principle of operation of the thermocouple psyhrometer is based on both the Peltier cooling and Seebeck thermo-electric effects. Peltier discovered that on passing an electrical current across a bi-metallic junction, a temperature difference is generated of which the sign is dependent of the direction of flow of

the current. Spanner employed this principle by placing the junction in a humid atmosphere. The current passing through the junction is sufficient to cool it down and condensation of water takes place. The junction then essentially becomes the wet or measuring junction. Once this has happened the circuit is broken and evaporation from the wet junction takes place. The decrease in temperature of the wet junction causes a temperature difference between the two junctions (Seebeck effect). As a result, an e.m.f. is generated that is measured and related to the relative humidity of the environment.

Calibration of the thermocouple psyhrometer is similar to that of the thermistor psyhrometer (Figure 2.15). The instrument also drift with time, especially in the lower suction ranges (Baker et al, 1973). This was due to oxidation of the wet bulb causing the contact angle between the water drop and thermocouple wire to change. To prevent this from happening, the thermocouple should be covered with a waterproof lacquer during construction and cleaned and dried during the measuring period. In addition, the instrument should be re-calibrated prior to each test, as it was sensitive to temperature fluctuation (Rawlins and Dalton, 1967). Upon cooling of the measuring junction (Peltier effect) heat was generated at the reference junction making it no longer representative of the ambient temperature. This creates a temperature gradient between the two junctions. Errors resulting from this gradient can be prevented if the initial temperature difference between the two was measured. Wescor thermocouple psychrometers recommend that a zero offset greater than 1 μV represents an excessive temperature gradient. Another problem of the instrument is that it is temperature dependent. Adjustments should thus be made relative to the temperature at which the instrument was originally calibrated.

A special application of the thermocouple psyhrometer is the dew-point hygrometer. The temperature of the instrument is maintained at dewpoint temperature. Dewpoint temperature is the temperature where the evaporation and condensation rate is equal to one another. In other words, no heat transfer will occur between the junction and surroundings. By implication the temperature of the wet junction will always be lower than that of the surroundings and heat will always tend to flow from surroundings to the junction. However, if the cooling coefficient of the thermocouple is known, a counter flow of heat can be generated and no net exchange of energy will occur. The cooling coefficient of the thermocouple is defined as the differential e.m.f. that results from the flow of a specific cooling current at a

specified ambient temperature. This coefficient is not unique but is temperature dependent. Suction pressures are measured indirectly, relating the relative humidity to the difference in dewpoint and ambient temperature.

The characteristic output (Figure 2.16) of the thermocouple reaches a plateau voltage as the temperature of the wet junction approaches that of the ambient atmosphere. The plateau is maintained for a short period of time depending on the relative humidity and hence suction of the soil. The useful range of measurement is approximated as 100 to 8 000 kPa (Fredlund and Rehardjo, 1988). Below the lower bound the plateau becomes undetectable while above the upper bound the variability of the output is too large. Campbell et al (1973) employed a dew-point hygrometer for measuring relative humidity. They reported that the advantage of the instrument over a normal thermocouple psyhrometer is that it produces a larger output voltage that remains stable for a longer period (Figure 2.16). This provides the operator with sufficient time to make an accurate reading.

Researchers such as Ridley and Wray (1996) and Dineen (1999) reported several factors that influence its accuracy of measurement. These factors are as follows:

- The permeability of the protective porous material surrounding the psychrometeric junction influences the equilibrium time of the instrument. Brown (1970) illustrated that if a ceramic cup was used instead of a stainless steel mesh, the equilibrium time increase by up to three times. If the protective cover is excluded, the equilibrium time is half of the stainless steel mesh.
- The sensitivity of the instrument deteriorates with continuos usage (Figure 2.17). This could properly be attributed to dust accumulation and corrosion of the measuring junction that alters the heat exchange characteristics of the thermocouple (Zerhouni, 1995).
- Measurements are sensitive to the geometry of the (i.e. the distance between the point of suction generation and suction measurement). Ridley (1993) found that if a space of approximately 1cm is left between the salt solution and stainless steel mesh, the measured output voltage would fall short of that recommended by the manufactures. However, if the level of the salt solution were raised in order that it touched the stainless steel mesh, the calibration of the instrument would be closed to that of the manufacturer.
- The psychrometric potential is influenced by the distance between the instrument is and source. This is illustrated by placing a thermocouple psyhrometer (with no protective

cover) at various distances from known concentrations of PEG solution inside a sealed cylindrical chamber. Adopting the manufacturer's calibration, it was found that the measured suction increases as the psyhrometer is moved away from the solution.

Zollinger et al (1966) compared thermistor and thermocouple psychrometers with each other. This was achieved by mounting both units in a multiple sample holder and measuring the water potential of a sample. On both accounts the measured quantity was changed by the instrument indicating bad conformance. The thermistor psyhrometer continuously added vapour to the system from the water inserted on the junction while the thermocouple psyhrometer subtracted vapour from the system as it requires a small amount of water to be condensed onto it. This hypothesis is proved by Figure 2.18 where higher water potential values where obtained with the thermistor psyhrometer than with the thermocouple psyhrometer. The difference is more pronounced in drier soils. It was found that the influence of the small drop of water inserted on the thermistor was greater than that of the vapour condensed onto the thermocouple psyhrometer.

In conclusion it could thus be said that psychrometers are instruments that are complicated and fragile, making them unsuitable for in-situ use. They are also extremely sensitive to temperature fluctuations and as a result have bad conformance and accuracy.

2.5.2 Filter Paper

The filter paper method is known for its versatility since it is able to measure both total and matric suction in the laboratory or field. The measurable suction range i.e. 10 to 30 000 kPa is fairly large (Conciani et al, 1995). The method is based on the principle that if two porous materials are sealed in a closed environment, moisture exchange will take place until equilibrium is reached (Lee and Wray, 1995 and Al-Khafaf and Hanks, 1974). Moisture exchange can take place either in the vapour or both vapour and liquid phase. Moisture exchange by means of vapour occurs if the sample and filter paper is separated from each other and visa versa.

Matric and total suction measurement can simultaneously be made on a single laboratory

sample. This is accomplished by sandwiching the soil sample between two air-dry filter papers and Perspex discs (Figure 2.19). One of the filter papers is placed in intimate contact with the soil sample while the other is separated by thin wire gauze. The whole assembly is wrapped in a protective seal and left in a temperature-controlled environment for a period of 7 days. At the end of this period both the sample and filter papers is removed and their moisture content is obtained by the weight to the nearest 0.0001 g. It was found that moisture changes of up to 15% can occur due to handling of the filter paper during this procedure (Chandler and Gutterrex, 1986). In order to minimise this error, filter papers should only be handled with tweezers and immediately be placed in plastic bags after weighing (Ridley and Brady, 1997).

Crilly et al (1991) developed an instrument that enables field measurements. The instrument makes use of thin filter paper strips that hangs on a mandrel at the bottom of a borehole. Once equilibrium is reached, the filter papers are sealed in a glass test tube and the whole assembly is removed from the borehole. It is then send to the laboratory for weighing. The advantage of this test is that the system is re-useable and easy to install. However, each set of filter papers requires a unique calibration and sealing of the tube changes the moisture content of the instrument causing the instrument to have bad conformance.

Calibration of the filter paper is normally achieved by either equilibrating it on a pressure plate brought to a known suction or by enclosing it in a sealed container with a salt solution of known vapour pressure (Ridley and Brady, 1997 and Dineen, 1999). In practice the former is associated with in-contact measurements up to 1 500 kPa while the latter is applicable to out-of-contact measurements greater than 1 500 kPa. The filter paper is left to equilibrate for period of 7 days after which the moisture content is determined. Figure 2.20 displays the calibration curves of the two most popular filter papers namely Whatmann No. 42 and Schleiner and Schuell No. 589. The relationship between moisture content of the filter paper and suction is bi-linear with changes in sensitivity occurring at approximately 47 and 54% for Whatmann No. 42 and Schleiner and Schuell No. 589 respectively. Zhao et al (1998) found that the calibration curves of the various filter paper types differ from each other and should therefore be calibrated individually. However, filter papers with the same fibres have similar calibration curves. It is important to note that the calibration curve is time dependent and that the curves of the two methods of measurement i.e. in contact and separation is incompatible (Swarbrick, 1995).

In drier soils the water retreats into the finer pores and direct contact between the filter paper and pore water can no longer be guaranteed. Under these circumstances it is not always evident which suction quantity is being measured. This uncertainty could be clarified to some extend by paying careful attention while removing the filter paper from the sample (Houston, Houston and Wagener, 1994). If it is assumed that the soil surface is relatively flat, matric suction is measured if the filter paper requires pulling away from the sample. The paper is then held in place by the surface tension of the pore water and it can be assumed that absorption mainly took place via the liquid phase. On the other hand, if the filter paper is loose, surface tension is probably negligible and absorption predominantly took place through the vapour phase (total suction). This method however, should only be used as a rule of thumb since it is often difficult to determine which case is being dealt with and exceptions to the rule occurs.

Schreiner (1987) found that precision of measurement is poor. This could be attributed to the fact that the relationship between the moisture content of the filter paper and suction is logarithmic. A slight change in moisture content of the filter paper would result in a relatively large change in measured suction. This has severe implications to the accurate weighing of the filter paper. As mentioned earlier, the filter paper is weighed to the nearest 0.0001 g. Accurate weighing of material to such resolution is impossible since fluctuations in temperature (Woodburn and Lucas, 1995) and movement of air due to air conditioning influences the results radically. At low soil suction, condensation often occurs on the inside of the equilibrium cell since the dew point (i.e. the temperature at which water starts to condense) is reached. The dew point of the equilibrium cell is a function of the relative humidity, which in turn is dependent of the suction of the soil. At 100% humidity (i.e. zero suction) the dew point is approximately 21°C but decreases by about 1°C as the suction increases to 8 000 kPa. Evidently the dewpoint of temperature-controlled laboratory (which is about 20°C) approximately similar to that of the environment and condensation occurs. Contact between the filter paper and condensation droplet will negatively influence the accuracy of the results. Another error that could arise is that of applied contact stress between the filter paper and the soil. Zhao et al (1995) recommend that a contact ratio (which is the ratio of the area of filter paper in contact with the sample to the total area of filter paper) of at least 90% should be maintained when matric suction is measured. However, in an effort to achieve such a high

contact ratio, the contact between the sample and paper could be over-stressed and hence the water is forced out of the sample. This will cause the saturated zero water content to decrease. Problems also arise from contaminated filter papers in that it influences the initial weight and absorbency. Filter papers become contaminated from either soil particles or wax that is used to seal the equilibrium cell. The effect could be minimised by brushing off the soil particles or by disregarding the contaminated section. Hysteresis, as it applies to the filter paper method, is the observed difference in moisture retention characteristic due to the wetting or drying of the filter paper. This should be taken into account by using the filter paper in either a wetting or drying cycles only and calibrates it accordingly.

According to Sibley and Williams (1990) a major drawback of filter paper is that the applicable suction range is influenced by the moisture sensitivity of the filter paper or absorbent. Traditionally filter is adopted for measurement, but they suggest that other absorbents such as cellulose seamless tubing and Millipore MF filtration membranes may be more suitable. This statement was evaluated considering both traditional and non-tradition absorbents with regards to their robustness, uniformity, stability and sensitivity. They found that each absorbent has a limited suction range that governs its applicability. However, they recommended that if a single absorbent is to be used over the entire suction range, the Whatmans Number 42 is the most appropriate.

2.6 Matric Suction Measurement Devices

Matric suction measurements are made via the liquid phase. This is done by allowing water to flow through a porous medium until equilibrium between the medium and soil in contact is established. The measured quantity is then referenced to full saturation. In order to understand these instruments a common problem namely cavitation was also discussed in this section.

2.6.1. Cavitation

Cavitation is the formation and collapse of vapour bubbles in a liquid (Chadwick and Morfet, 1993). Cavitation in a liquid occurs when water is placed under extremely high tension or when it is superheated (Ridley and Brady, 1997). Previously it has been thought that this is

the main reason for the cavitation of water in instruments such as the tensiometer. However, it has been found that neither of these conditions applies to matric suction measurement devices such as the tensiometer.

To support this argument, numerous studies were carried out on Berthelot tubes that proved that neither of these conditions applies. A Berthelot tube (Figure 2.21) is a glass or steel tube, containing the liquid to be tested. The tube is sealed, leaving a small air bubble. The tube is then heated up and the water inside the tube expands, increasing the pressure and forcing the air bubble to dissolve. At this point, the tube is completely filled with water. It is then cooled down at such a rate that the water adheres to the tube, generating negative pressures. Rupture or cavitation of the water is associated with an audible click and at this stage a bubble emerges. The tensile strength of the liquid is then calculated and assumes the following:

- The volume modulus of the expanding liquid is similar to that of the liquid in compression.
- The container is perfectly sealed and maintained at zero pressure.

The tensile strength of water in a Berthelot tube has been the topic of research for quite some time. A characteristic tensile strength could not the appointed to water as the adhesion force between the liquid and the surface of the container varies. Variation in adhesion is the result of cleaning procedures employed as well as the degassing of the system, which in turn is dependent on the container material.

Further research on the topic by various researches such as Harvey et al (1944) has shown that in actual fact bubble formation results from nucleation. Nucleation is the formation of vapour cavities within the liquid itself or at their boundaries (Trevena, 1987). Surface tension prevents the stabilised bubble (or cavitation nuclei) from moving or dissolving. The presence of these cavitation nuclei is best explained by the following theories:

- There are solid particles in the water with gas trapped within the crevices of these particles (Apfel, 1970).
- Gas is trapped in tiny crevices in the water container (Harvey et al, 1944).
- Air bubbles are stabilised by an ionic skin which exist between the gas and the liquid (Akulichev, 1966).
- Bubbles are covered by surface-active substances and are thus stabilised against

dissolution (Yount, 1979).

The most widely accepted model for nuclei stabilisation is the crevice model by Harvey et al (1944). The crevice model states that cavitation will only occur at the walls of the container due to a loss in adhesion, rather than in the body of the liquid due to a loss of cohesion. Undissolved gas nuclei exist as sub-macroscopic bubbles in hydrophobic cracks and interstices of the container walls (Figure 2.22). The surface tension in this case acts to decrease, rather increase the gas pressure and the gas is not forced to dissolve. However, the stabilised nuclei could be forced to dissolve if a high pressure is applied to it. The high pressure reduces the bubble size and increases its solubility. Knapp et al (1970) has shown that if the crevice has an acute angle, an infinite pressure is required to dissolve the bubble. In this case stabilisation is permanent and cavitation could not be avoided. On the other hand, if the crevice is rounded, a finite pressure is required to dissolve the bubble.

The wetability of the ceramic (which acts as a filter between the measuring system and soil) plays an important role in the stability of the instrument. Cavitation inside the filter occurs more easily as it is difficult to eliminate the cavitation nuclei. Another problem that is associated with the use of ceramics is that of the diffusion of air through its wetted pores (Stannard, 1992). This would result in air entering the reservoir even after various efforts have been made to eliminate cavitation nuclei.

In order to avoid cavitation in instruments such as the tensiometer, researchers such as Marinho and Chandler (1995) and Ridley, Patel and Marsland (1998) recommend that the following precautions should be taken:

- Use of de-aired water.
- Water and all surfaces must be extremely clean.
- Surfaces in contact with the water must be as smooth as possible.
- The system must be evacuated with a vacuum pump.
- The system could be cycled between positive and zero pressure or between positive and negative pressures.
- Pre-pressurisation to high pressures will have to the result that all free air will dissolve.
- Limit the reservoir of the instrument to a minimum.

- Make use of material that has naturally low amounts of crevice such as glass or stainless steel.
- Fill the reservoir with de-aired water through the ceramic.

Cavitation within a suction measurement device can easily be detected. It is associated with a sudden drop in suction pressure that can in no way be related to the true suction of the soil.

2.6.2. Suction and Pressure Plate

The suction plate (Figure 2.23) is a laboratory instrument that measures matric soil suction directly. It consists of a flat porous ceramic filter, a water reservoir and a measuring device (Ridley, 1993). The porous ceramic acts as a boundary between the soil and water reservoir. The soil sample is place on top of the ceramic. By implication, soil suction result in a water deficit in the sample, which in turn cause water to flow from the reservoir through the ceramic to the sample. Water will flow from the reservoir to the sample until equilibrium is reached i.e. when the pore pressure of the soil and tension in the reservoir is equal. The tension in the reservoir is then measured by means of a measuring device, normally a manometer. The rate, at which equilibrium is established, is related to the coefficient of consolidation of the soil (Croney and Coleman, 1961). Unfortunately, the suction plate has one rather big disadvantage namely it fails to prevent air from entering the reservoir. Once this has happened the manometer reading would remain less than or equal to one atmosphere. Any further migration of water through the ceramic will only result in an air volume change (Ridley and Wray, 1996). The upper suction range of the instrument is thus limited to atmospheric pressure.

Schofield (1935) recognised this limitation and suggested that by adopting the axis translation technique, the instruments suction range could be extended. The pressure plate (Figure 2.24) was designed to incorporate this technique. It consists of a base plate with a porous ceramic filter cemented to it. The air entry value of the ceramic should be greater than the maximum expected suction. A water reservoir is located beneath the ceramic filter that is connected to a pressure sensor and a drainage system. The airtight chamber is secured to the base plate in such a way that compressed air can be piped to it.

The soil sample is placed on top of the ceramic and the air pressure inside the chamber is raised. Air will fail to pass through the ceramic provided that the displacement pressure of the ceramic remains greater than the applied air pressure (Hanna, 1985). The raised air pressure causes the pore water pressure of the soil to increase to a value that is equal to the difference between the air pressure in the chamber and the original atmospheric pressure. Both the air and pore water pressure of the sample can thus be controlled and hence the stress state of the soil. In order to fully understand the principle of axis translation is necessary to review the definition of matric suction, namely that it is the difference between the pore air and pore water pressure. The definition holds true irrespective of the fact that the pore water pressure may be positive. With the above mentioned definition kept in mind, it can be seen that the matric suction can be measured as a positive value since the reference axis against which the water pressure is measured is translated from zero to a positive value. In this way the cavitation is prevented. Initially the pressure of the water inside the reservoir is atmospheric. However, as soon as the pore water pressure of the sample is raised that of the reservoir is also raised. As mentioned above the unbalanced water potential over the ceramic would cause water to flow from the reservoir to the sample and will continue to done so until the equilibrium is established (Figure 2.25(a)). The suction in the sample would now be equal to the difference between the air pressure in the chamber and the water pressure in the reservoir. Equilibrium that is established in such a way would result in slightly reduced soil suction. The opposite is true when the reservoir pressure is momentarily reduced to zero by venting the system to the atmosphere zero (Figure 2.25(b)). The error that occurs due to the changing reservoir volume could be reduced by ensuring that the volume of the sample is large compared to the volume of water inside the reservoir. An accurate suction measurement can be obtained by ensuring that the reservoir volume remains constant. Dumbleton and West (1968) accomplished just this by connecting a capillary tube to the reservoir. They monitored the meniscus inside the tube by means of a travelling microscope and were thus able to restrict its movement.

Experiments done by Schreiner (1987) with pressure plates indicated that the amount of water on the ceramic have an influence on the measured suctions and thus the conformance of the instrument. It was found that the wetter the ceramic, the longer the response time and the lower the measured suctions and visa versa. A possible explanation for this situation is that the sample takes up the excess water of the ceramic, resulting in a lower suction.

The response time of the pressure plate can be several hours depending on both the size and permeability of the porous filter and sample (Ridley and Brady, 1997). It is the opinion of the student that this fact makes the pressure plate even less accurate than what was initially estimated by other researchers. As discussed previously the suction of the sample is measured once equilibrium is established between the pore water pressure of the sample and the water pressure of the reservoir. However, during the period that the sample is placed in the chamber and equilibrium is established, moisture exchange between the vapour of the enclosed environment and the pore water of the sample takes place and will continue to do so until equilibrium is reached. The amount of moisture exchanged will depend on the humidity of the air above the sample. Applied air pressure reduces the humidity of the enclosed environment (chamber) in order that quite an amount of pore water evaporates into the environment before equilibrium is established. Evidently this will alter the suction of the soil. As mentioned previously, soil suction is measured as pressure changes in the water reservoir. The evaporated water is thus never taken into account in the suction measurement and the suction of the soil can be significantly lower. Furthermore, the effect of the axis translation technique on the soil has not yet been properly assessed (Ridley and Brady, 1997).

2.6.3. Thermal Blocks

Thermal conductivity sensors are associated with in-situ applications and measure the matric suction of soil indirectly. The instrument (Figure 2.26) consists of a porous ceramic block in which a temperature-sensing element and miniature heater is incorporated. The miniature heater generates a controlled heat pulse for each suction measurement (Sattler and Fredlund, 1995). Measurements are made by placing the instrument in a predrilled hole and allowing the water content of the sensor to come in equilibrium with the soil (Sattler and Fredlund, 1989). Once this is accomplished, the heater generates a controlled amount of heat. The soil suction is a measure of the amount of heat dissipated at a fixed point and is expressed as an output voltage. The principle of operation of thermal conductivity sensors is founded on the heat conductivity of water. If the water content of the porous filter is relatively high, heat dissipation will take place at a high rate resulting in a relatively low temperature rise at the centre (Phene et al, 1970). Consequently, the temperature rise in the porous block is inversely

proportional to the water content of the block.

Calibration is conducted by burying the instrument in a pressure plate soil sample. The sample is subjected to a known suction while the temperature change of the thermal conductivity sensor is correlated accordingly. Fredlund and Wong (1989) calibrated an AGWA-II sensor from an initially dry condition and found that the calibration curve (Figure 2.27) is bi-linear with a change in sensitivity occurring at 175 kPa. The slope of the graph is relatively flat for suction less than 175 kPa, indicating a better sensitivity. This phenomenon can be related to the influence that air has on the measurements. If the instrument is placed in contact with a sample of high suctions, air will enter the porous block and replace the water. The remaining film of water inside the pores of the block would become thinner and the path length for heat conduction increases (Phene et al, 1970). It is possible that at this stage the water is not continuos throughout the medium, resulting in improper heat transfer and thus the inaccurate measurement of suction.

Thermal conductivity sensors have numerous limitations and are for this reason not a popular choice. These limitations can be summarised as follows:

- The sensitivity of the instrument restricts the range (0-175 kPa, Fredlund and Wong, 1989) over which accurate measurements can be made.
- The instrument is susceptible to failure, especially if subjected to positive water pressures.
- They are fragile instruments that tend to crumble upon installation.
- The equilibrium time varies between 24 hours to three weeks, depending on the initial moisture content of the block. The equilibrium time of initially dry block tends to be less than that of initially wet blocks.

2.6.4. Gypsum Blocks

Porous or gypsum blocks as it is alternatively known measure the matric suction (100 to 1 000 kPa) of the soil indirectly by relating the electric conductivity of water to suction. The instrument is fairly cheap and simple to use. It (Figure 2.28) consists of two concentric electrodes buried inside a porous medium (Aitchison et al, 1950). The test is conducted by placing the porous block in soil and establishing moisture equilibrium between the two via the

flow of water. Once equilibrium conditions are met the electric conductivity of the block is measured with a Wheatstone bridge. Water is a better electrical conductor than air and thus the higher the water content of the gypsum block, the higher the electrical current measured in the block. However, this in itself pose as a problem, since absorbed salt in the soil could enter the block and affect the electric conductivity of the block severely. A viable medium for measuring the electric resistance under these conditions was investigated. The selection of the material were based on the criteria as set out by Bouyoucos and Mick (1940) namely:

- A hard porous structure that is capable of both rapid absorption and loss of water.
- A large absorption capacity to ensure a useful order of sensitivity.
- A moderate range of solubility to minimise the effects of changes in soil salinity.

Porous materials that complied with the criteria were nylon, fibreglass and gypsum. Aitchison et al (1950) conducted several experiments on the material to determine their behaviour under various soil conditions. These experiments proved that all of the above mentioned porous material indicated:

- A reduction in electrical resistance with increasing temperature especially over a temperature range of 0°C to 35°C.
- Deteriorated under saline effects.

Gypsum was the most desirable medium since it had stable electric properties, a large absorption capacity and saturated the quickest. Aitchison and Richards (1965) found that if gypsum were used as a porous medium, the solute concentration of the block remains constant provided the total soluble salts of the soil water remains less than 0.07%. Although one of the advantages of gypsum above other mediums is its shorter response time, it is still quite lengthily, i.e. 2 to 3 weeks. This makes the instrument unsuitable for the use in soil of relatively rapid changing moisture content. Other drawbacks of the medium are that it softens upon wetting and is adversely affected by soluble salts (Phene et al, 1970).

Calibration of the instrument is similar to that of the thermal conductivity sensors. The calibration curve (Figure 2.29) is generally bi-linear with a change in sensitivity occurring around 100 kPa. The instrument needs to be calibrated for each specific soil type, making it unpractical since one needs to be familiar with the specific soil type prior to testing which is needless to say not always possible (Peck and Rabbidge, 1969). Another limitation is that it

only applicable to soil with a light texture and stable structure (Aitchison et al, 1950). This reduce the application of the instrument even further as the soil encountered often will not comply with the above criteria.

Porous blocks are susceptible to hysteresis, This phenomenon is related to the difference in spacing between the electrodes, the different degrees of contact between the plaster and electrodes and the lack in consistency of plaster porosity (Aitchison. and Richards, 1965). Another cause of error is the large adhesion forces that often exist between the soil and block whenever one of then is relatively dry (Phene et al, 1970). Due to these large adhesion forces water is not free to flow through the interface between the two mediums.

At this stage it is evident that the porous block suffers from several limitations and are thus not appropriate for the accurate measurement of suctions. Despite the obvious limitations to the instrument it is suitable for projects with limited funds where only a first estimate of the suctions is needed.

2.6.5. Tensiometer

The basic design of a tensiometer consists of a porous filter and a measuring device that is separated from each other by means of a water reservoir (Ridley, Patel and Marsland, 1998). The instrument operates by allowing water to be extracted from the reservoir into the soil until the stress holding the water in the tensiometer is equal to that of the soil. Once this condition is reached equilibrium is established and no further exchange of water will take place. The suction will then manifest itself as a tensile stress in the water reservoir that can be assessed with a measuring device. Three types of measuring devices are commonly used namely vacuum gauge, manometer and electronic pressure transducer. The names of the type of tensiometer will normally refer to the measuring device employed.

Commercially available vacuum gauge tensiometers (Figure 2.30) normally consist of a large diameter porous cup that is cemented to a rigid acrylic tube of equal diameter (Stannard, 1992). The vacuum gauge is screwed to the inside of the pipe several centimetres below the top. An air reservoir is located between the vacuum gauge and top of the tube. In the event of

water reaching the vacuum gage inlet, the tube cap is unscrewed and the air space is refilled with water. The advantage of the vacuum-gauge tensiometer is that hydraulic continuity is maintained irrespective of the presence of the occasional air bubbles. However, this advantage results in a decreased resolution and accuracy. The response time of the instrument is relatively rapid though the presence of trapped air bubbles could reduce it to some extend. The construction of the instrument is fairly durable but due to its rigidity it could cause shock and damage to the porous cup. The suction range of the instrument is influenced by the length of tube required for measurement, i.e. a correction in the order of 10 kPa per meter tubing between the tip and the gauge (Ridley and Wray, 1996). To compensate for this inadequacy as well as effects of altitude and changes in the internal characteristic of the gauge with time, the instrument is equipped with an adjustable zero reading. The adjustment is made with the cup immersed in water to its mid-height. Failure to incorporate such an instrument into the vacuum gauge would result in inaccurate readings. The vacuum gauge tensiometer is therefore appropriate for measurements that do not require extreme accuracy.

The manometer tensiometer (Figure 2.31) is referred to as a hybrid tensiometer since it consist of a large diameter cup-tube assembly that is directly connected to a small diameter tube pressure sensor (i.e. a mercury reservoir) (Stannard, 1992). The large diameter porous cup and nylon tube is cemented to each other with an epoxy bond. The instrument's water supply tube is connected to a de-aired water supply via a shutoff valve. Similar to the vacuum-gage tensiometer, the manometer tensiometer has a space at the top of the tube that collects air bubbles. Suction imparted at the porous cup causes the mercury to rise in the tube above the level of the free surface. Using this as a reference, the suction could be calculated as the sum of the height of mercury above it and the depth of the porous cup below it (Ridley and Wray, 1996). The instrument has several advantages such as versatility of on-site applications, accuracy, low cost, no calibration is required and the hysteresis of tensiometer types. The sensitivity and response time can be manipulated as it is indirectly related to the cross-sectional area of the tubing. The mayor drawback of the instrument is related to the epoxy tube bond. Although this type of bond contributes to the simplicity of the design, it is susceptible to rupture caused by the differential movement of the nylon tubes.

The design of the pressure transducer tensiometer (Figure 2.32) is similar to that of the vacuum gauge tensiometer with the exception that the pressure measurements are made

indirectly, measuring the voltage output (Ridley and Wray, 1996). They are suitable to collect large quantities of data as measurements could be made often and be recorded by an automatic data logger or strip-chart recorder (Stannard, 1992). The instrument is extremely sensitive making it susceptible to transient temperature effect cause by thermal expansion and contraction of the water in the tensiometer. The sensing element of a typical pressure transducer consists of semi-conductive resistors that are embedded in a diaphragm. The output of the bridge is a linear function of pressure and is independent of temperature effects. They are prone to zero offset and drift requiring re-calibration. Re-calibration is done relative to hanging column of water or mercury.

Pressure sensors of standard tensiometers are located at the surface of the soil (Ridley and Wray, 1996) to ease the process of measurement. As mentioned previously, each meter of tube required between the porous filter and measuring device reduces the effective range of the tensiometer with 10 kPa. Watson (1967) recognised this fact and developed a tensiometer of which the sensor is located directly behind the porous filter. Unfortunately, its range was limited to –100 kPa at which instant cavitation of reservoir water occurred.

Peck and Rabbidge (1966) introduced a tensiometer (Figure 2.33) that is able to measure suctions well in excess of 100 kPa. Their tensiometer differed from the standard design in that the overall size was reduced, water was replaced with a polyethylene glycol (PEG) solution and the porous filter was lined with a membrane made of cellulose acetate dialysis tubing. The membrane acts as a differential barrier between the larger PEG molecules and water molecules. Water is free to enter the reservoir through the membrane. A positive pressure is induced in the PEG chamber by allowing pure water at atmospheric pressure to flow into it. The instrument is removed from the water and placed in contact with the soil. Suction pressures in the soil will attract water from the PEG chamber through the membrane. It is assumed that the measured suction will not exceed the initial positive pressure induced in the chamber. Failure to comply with this assumption result in the generation of negative pressures in the chamber and hence cavitation. The design is not ideal as several problems were reported during the experimental phase such as:

- Leakage of the PEG concentration under continuous usage. This result in the deterioration of the reference pressure.
- The instrument is temperature dependent.

- Dineen and Burland (1995) studied the use of PEG solutions in the control of suctions. They discovered that the suction resulting from the vapour pressure of PEG solutions is greater than that measured through a semi-permeable membrane. This is due to the percentage of the PEG molecules escaping through the membrane causing a decrease in the concentration of the solution.

An aspect that has not received much attention, but does have an influence on the longevity of the instrument, is that of its removal from the soil. Watson (1967) found that upon the sudden removal of a tensiometer, adhesion forces develop at the soil and ceramic interfaces. This adhesion force may be great enough to exceed the differential overload of the transducer resulting in its destruction. The effect could be minimised by a jetting process that assists in the loosening of the tubing from the surrounding soil.

2.6.6. Imperial College Suction probe

The Imperial College suction probe consists of a stainless steel shroud, a water reservoir, 15 bar ceramic and a pressure sensing system. The water reservoir is formed by a gap between the ceramic that is glued to the top of the probe, and pressure sensing system. The principle of operation of the suction probe is similar to that of a tensiometer since the aim of the design was to improve on the main limitation namely the limited suction range. Initially the instrument was to only applied to laboratory tests but later development extended its use to field measurements, although the latter is not as accurate as the former. This is due to drilling and disturbance to the soil prior to measurement.

During the development of the suction probe, Dr. Ridley experimented with several off-the-shelf pressure transducers such as the Druck PDCR81 and Entran EPX. Problems experienced with the first off-the-shelf pressure transducer (Druck PDCR81) were mainly the concerned with the connection between the diaphragm and the pressure transducer body. The PTV compound connection between the two worked well in compression but came apart once subjected to tensile pressures. Water is then introduced to the strain gauges resulting in erroneous measurements. This problem was already noted during the first couple of measurements. The second off-the-shelf pressure transducer (Entran EPX) differed from the

previous one in that both the diaphragm and connection between the diaphragm and transducer body was of stainless steel. The transducer was kept intact with a threaded connection but this resulted in a mismatch between the threads of the transducer and probe body. Air entered the water reservoir via the mismatched threads resulting in cavitation of the reservoir water. Various attempts were made to prevent this from happening, but with no avail. Based on the experience with off-the-shelf pressure transducers, it was decided to rather make use of a strain-gauged diaphragm that is part of the main body. The design of the probe (Figure 2.34) was slightly altered to incorporate it. Changes include reducing the size of the water reservoir and dividing the main body into two sections as opposed to the initial one.

Ridley (1993) and Monroe (1993) found that the readings would break down after a period at which stage cavitation occurred. Ridley and Brady (1997) ascribed this sudden breakdown to the fact that the water reservoir volume is larger than required. However, upon reducing the volume this phenomenon continued to occur. The only conclusion that they were able to draw with confidence is that the breakdown is not connected to the air entry value of the ceramic. Experimental work indicated that the stable time of the suction probe is related to both the gap between the ceramic and sensing element and ceramic thickness. The longest stable time was obtained with the smallest gap (0.1 mm) and thickest ceramic (5 mm). Monroe (1993) also noted that the suction probe needs to "rest" between successive readings. This resting period is additional to the time required for re-saturate of the ceramic. No explanation has been given as to way this occurs.

As mentioned in Section 2.6 the volume of water on the surface of the ceramic influence the accuracy of the measurements. Monroe (1993) confirmed this observation during her research of the suction probe. It was found that the most accurate results are obtained when the excess water on the ceramic is removed, leaving it glistering. However, it is emphasised that desaturation of the ceramic should be avoided at all times. This is especially a problem directly after the probe is removed from the sample. In order to avoid this, a drop of water should immediately be placed on the ceramic.

The suction probe is calibrated in a modified triaxial cell. It is installed at the base of the cell in such a way that it is in close contact with the sample but at the same time can be easily recovered. An undrained isotropic consolidated triaxial test is then conducted on the clay

sample. Once equilibrium at a known effective stress is established, the cell pressure is reduced to zero thereby generating suction in the sample that is equal to the effective stress prior to unloading. A cross-reference of the effective stress in the sample can be obtained by restoring the cell pressure to its original value. It was found that the suctions measured with the suction probe are in excellent agreement with the subsequent effective stresses.

The equilibrium time of the instrument is in the order of one hour for laboratory testing and three hours for in-situ testing (Ridley and Burland, 1995). It has been found that 90% of the final in-situ suction is reached within a couple of minutes (Figure 2.35). The prolonged equilibrium time is caused by the fact that the reservoir pressure approaches the true suction asymptotically. The rate at which this is done is a function of the time constant and unsaturated hydraulic conductivity of the soil (Stannard, 1992).

2.7 Discussion of the Literature Review

Fatal disasters such as the failure of the tailings dam next to the town of Merriespruit could be prevented if the behaviour of tailings are better understood and the monitoring of these sites improved. The large number of old tailing dams next to densely populated regions is an obvious risk and could lead to the next disaster.

As mentioned in Section 2.3 the unsaturated zone of a tailings profile contributes to the stability of the dam. If the suction pressure can be assessed in some way monitoring of these sites can be improved and the risk reduced. Several suction measurement devises are available, but few of them are applicable to the tailing environment. The tailing environment is harsh with varying moisture contents (especially during deposition of the tailings) and salinity (due to the mining process). This requires that the equilibrium time of the instrument should be fairly rapid to detect changes in the moisture content. The measuring device should also be immune to saline effects. As discussed in Section 2.3 the strength of a tailings dam is influenced by changes in the pore pressure regime caused by environmental factors such as rainfall as well as operational factors such as depositing. The matric suction of coal tailings is estimates to vary between 30 and 40 kPa (Section 2.4). However as the grain size and hence pore radii of coal tailings differ from that of gold tailings it is expected that the matric suction would also differ but would be in the same order.

The suction measurement devices that was considered for measuring the matric suction of gold tailings include the filter paper, psyhrometer, thermal block, gypsum block, suction plate, pressure plate, tensiometer and suction probe. The applicability of each instrument was evaluated by judging whether it will be viable to the tailing environment.

The suction range of filter paper covers the whole spectrum of measurable suction. They are suitable for both laboratory and in-situ applications. On the down side however, is firstly the fact that their equilibrium time is fairly long i.e. 7 days. When considering suction measurement devices in general it is not always clear what quantity is being measured. (Section 2.1.1). However this is especially a problem of the filter paper as it is able to measure both and the total and matric suction and the difference in measurement between the two is not that great (Section 2.5.2). Problems are also experienced with the accuracy of the method. Based on these limitations the filter paper is disregarded for use in the research.

The psyhrometer can reach equilibrium within a couple of minutes. Its suction range is also fairly large, although the lower limit is only at –100 kPa. As mentioned previously the matric suction of coal tailings is in the order of 30 to 40 kPa. It is expected that some of the suction measurement of gold tailings would also be in the same order. This makes the psyhrometer unsuitable for the intended measurements. The instrument is also extremely fragile, has bad conformance and is only able to make laboratory measurements (Section 2.5.1).

Thermal blocks have the advantage that they are able to measure matric suction in-situ. Unfortunately this is the only characteristic that the instrument has for suction measurement is mine tailings. The equilibrium time of it varies from 24 hours to 3 days, making them unsuitable in a rapid moisture changing environment. They are fragile instruments, susceptible to failure and is adversely affected by saline effects (Section 2.5.3).

Gypsum blocks are cheap and simple to use. They are able to measure a large range of suction, but similar to the psyhrometer the lower limit is –100 kPa. They are thus unsuitable for suction measurement of mine tailings for reasons as given in the discussion of the psyhrometer. Their equilibrium time is extremely long i.e. 2 to 3 weeks making them unable to detect any moisture changes. Measurements are also influenced by salinity (Section 2.5.4).

The suction plate reaches equilibrium within a couple of hours, which is not ideal but acceptable to some extend. It is also unaffected by salinity. The instrument is only applicable to laboratory testing. This poses as a problem as the sampling process often alters the moisture content and hence effective stress of the sample. It is thus not able to measure the true in-situ suction pressure. The biggest limitation of the instrument however, is its limited suction range which is from 0 to –90 kPa. Evidently it is unable to measure the expected suction. The pro's and con's of the pressure plate is generally similar to that of the suction plate with the exception that it is able to measure suction up to – 1 500 kPa. This makes it a bit more attractive than the suction plate. On the other hand the technique utilized for suction measurement (axis translation) influences the measurement although the extend of it is not yet determined.

Depending on the type of tensiometer used, it is able to measure the matric suction both in-situ and in the laboratory. It is also unaffected by salinity. Equilibrium is reached in less than two hours which if the previous instruments are taken into account, fairly good. Unfortunately the instrument is only able to measure suction up to –90 kPa. Based on this limitation, the instrument can not be used for the purpose of this research.

Finally the Imperial College suction probe is applicable to both laboratory and in-situ applications. Similar to the previous couple of instrument it is unaffected by salinity. The equilibrium time required for in-situ and laboratory tests varies. Equilibrium is reached within one hour when laboratory test is preformed whilst three hours is required for in-site tests. It should however be noted that 90% of the final in-situ suction pressure is reached within a couple of minutes. The suction range of the instrument is 0 to –1 500 kPa but is a function of the air entry of the ceramic used. Evidently the instrument fully complies with the criteria for functioning in the tailing environment.

The Imperial College suction probe meets the criteria for measuring suction pressure in mine tailings. A few changes however are required. It is assumed that a suction pressure of 300 kPa is adequate for measuring the characteristic suction properties of the tailings. This implies that the 15 bar entry ceramic should be reduced to a 3 bar ceramic. The reduced air entry value improves the instrument response.

Table 2.1: Summary of Suction Measurement Devices

Instrument	**Suction Component**	**Suction Range (kPa)**	**Response Time**
Filter Paper	Total & Matric	10 to 30 000	7 days
Psychrometer	Total	100 to 8 000	minutes
Suction Plate	Matric	0 to 90	Several hours
Pressure Plate	Matric	0 to 1 500	Several hours
Thermal Blocks	Matric	0 to 400	24 hours to 3 weeks
Gypsum Blocks	Matric	100 to 1 000	2 to 3 weeks
Tensiometer	Matric	0 to 90	Up to 2 hours
Imperial College Suction Probe	Matric	0 to 1 800	1 to 3 hours

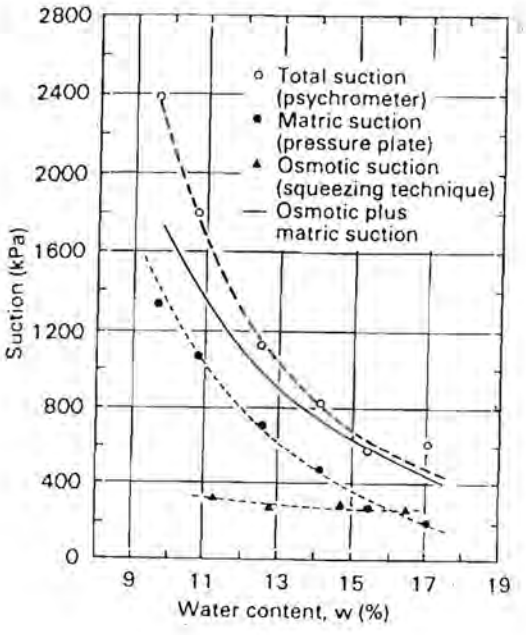


Figure 2.1: Total, matric and osmotic suctions for glacial till (after Krahn and Fredlund, 1972)

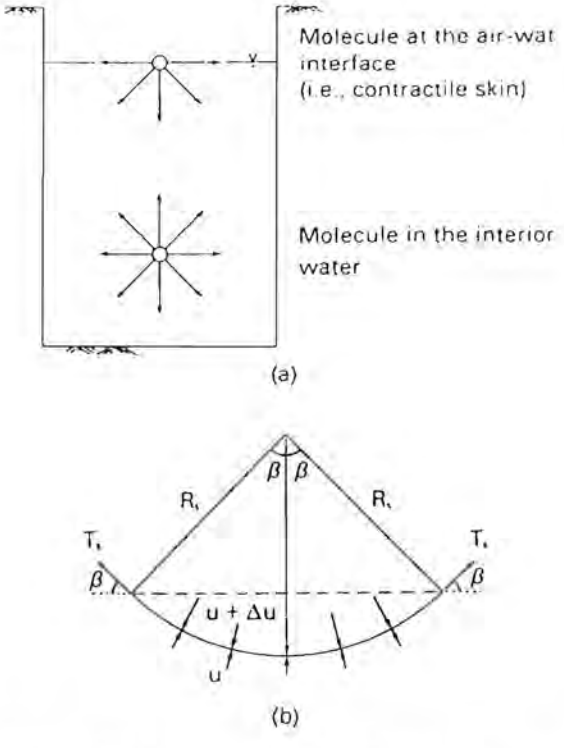


Figure 2.2: The surface tension phenomenon at the air-water interface, a) Intermolecular forces on contractile skin and water b) Pressure and surface tension acting on curve two dimensional surface (after Fredlund and Rehardjo, 1993)

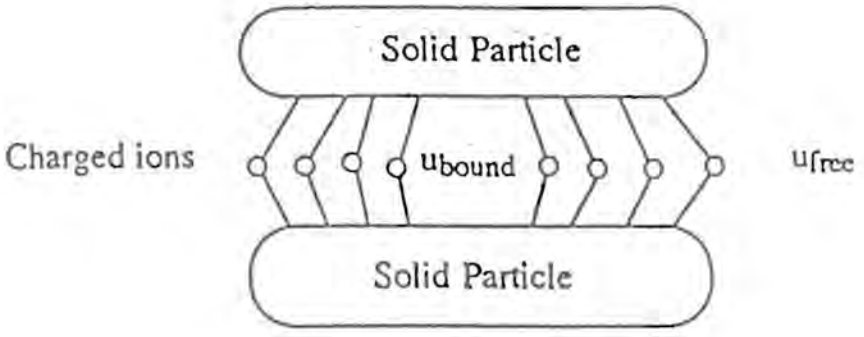


Figure 2.3: Simplified model- Ions attached to rubber-like bands. Salt content is higher at centre than in free water (after Sparks, 1995)

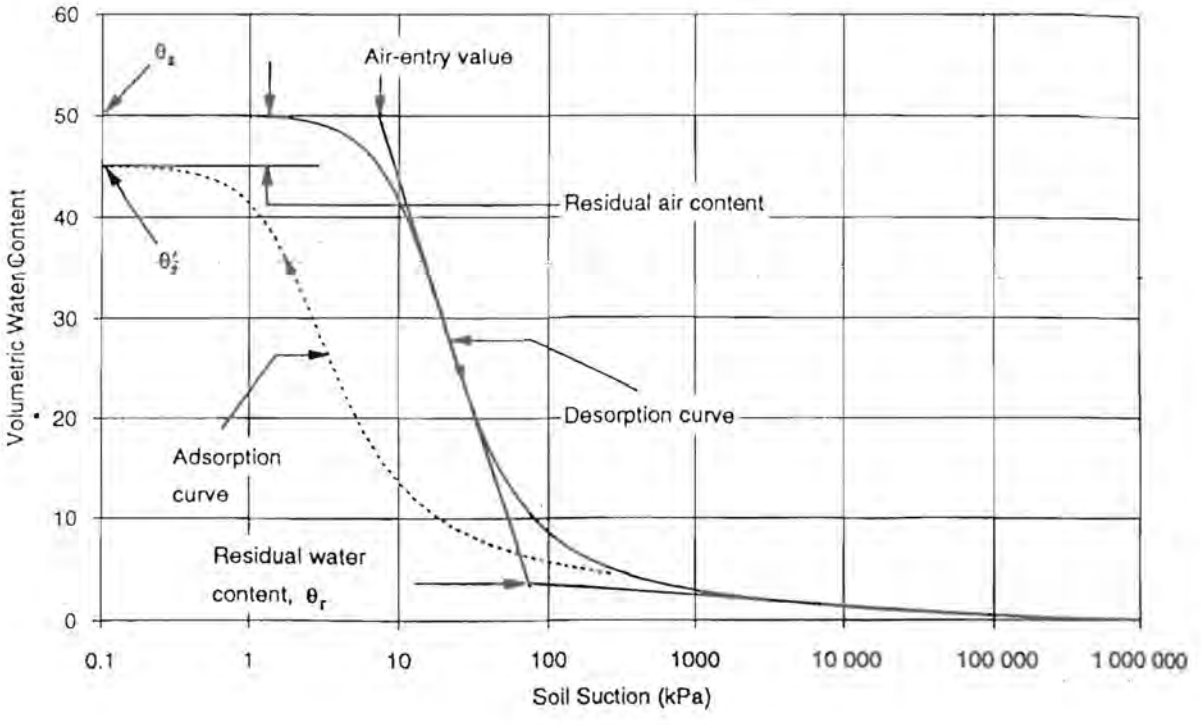


Figure 2.4: Typical desorption and adsorption curves for silty soil (after Aubertin et al, 1998)

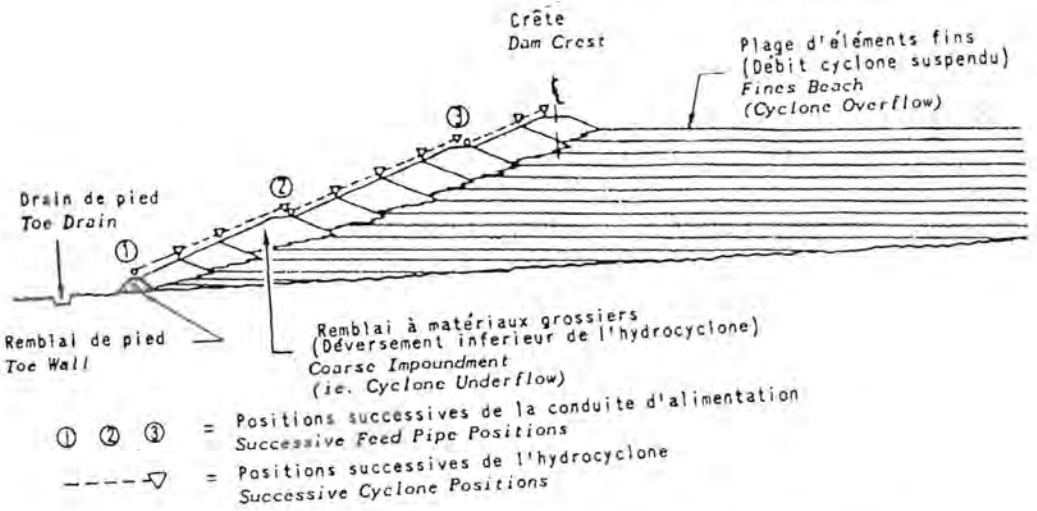


Figure 2.5: Cycloning by upstream method (after Messrs et al, 1989)

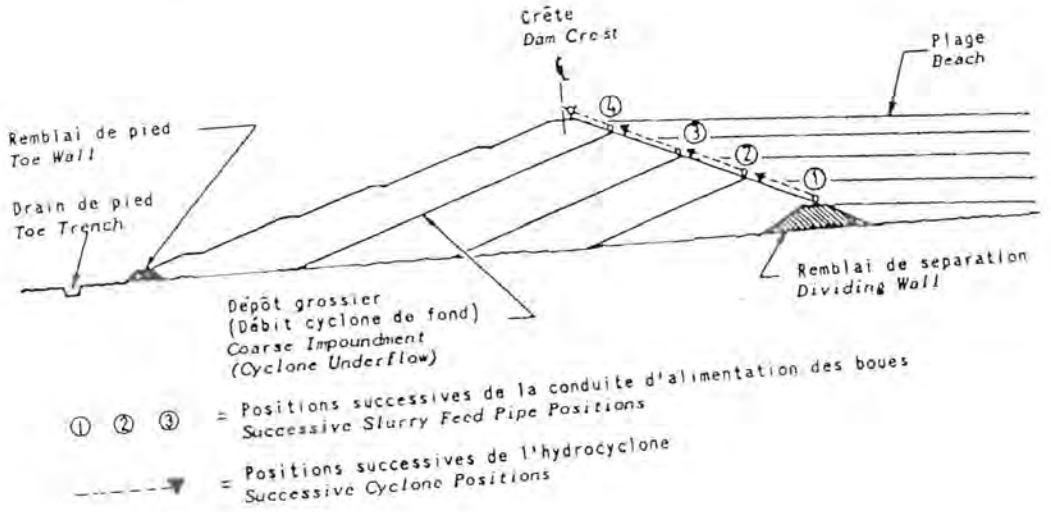


Figure 2.6: Cycloning by downstream method (after Messrs et al, 1989)

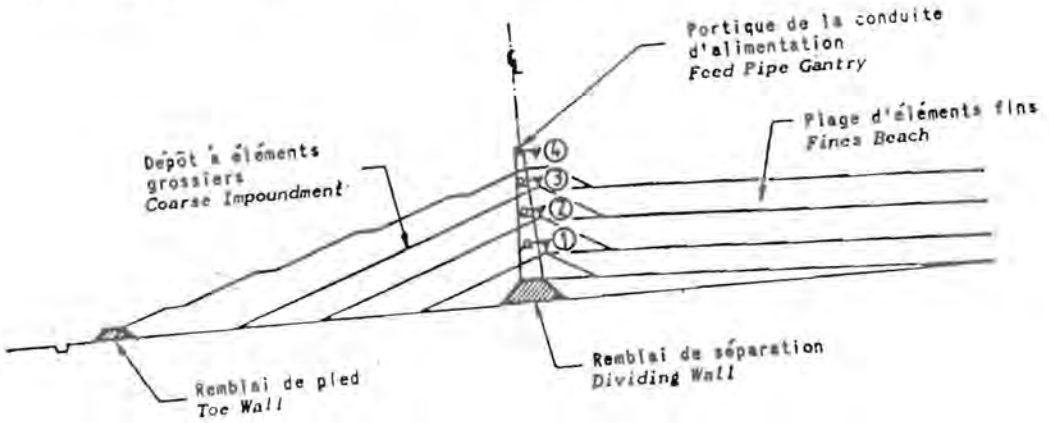


Figure 2.7: Cycloning by centreline method (after Messrs et al, 1989)

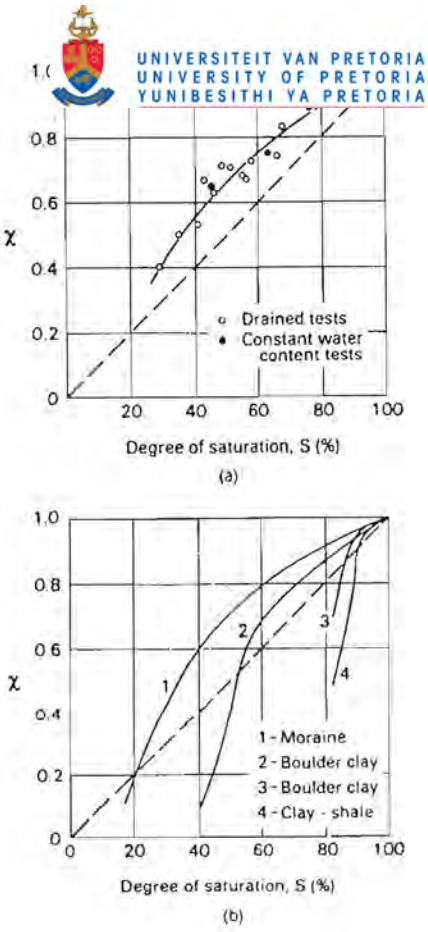
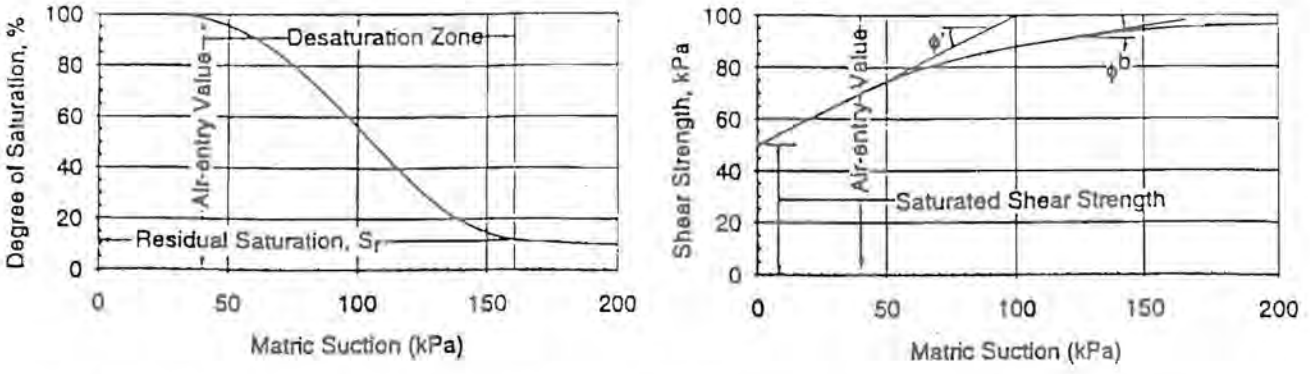


Figure 2.8: The relationship between χ parameter and the degree of saturation (S) a) χ values for a cohesionless silt (after Donald, 1961) and b) χ values for compacted soils (after Blight, 1961)



a) Matric suction versus degree of saturation

b) Matric suction versus shear strength

Figure 2.9: Relationship between the soil water characteristic curve and shear strength (after Fredlund et al, 1995)

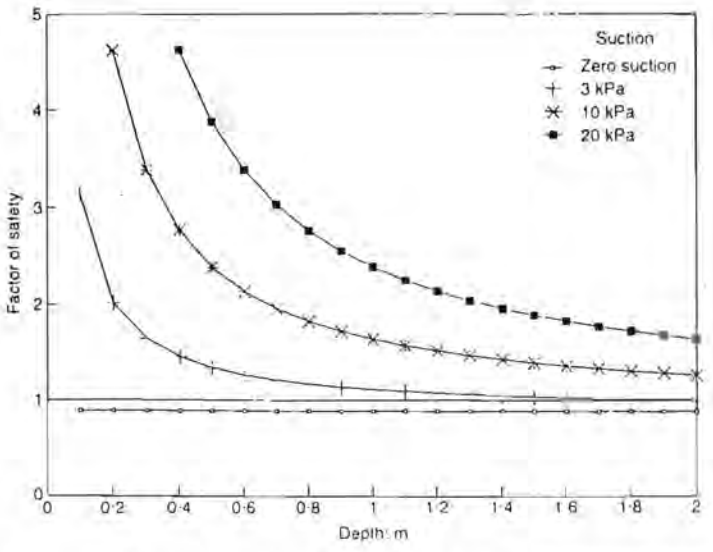


Figure 2.10: The influence of matric suction on the factor of safety of the Lethabo ash dump for shallow, planar failure surfaces (after Fourie et al, 1998)

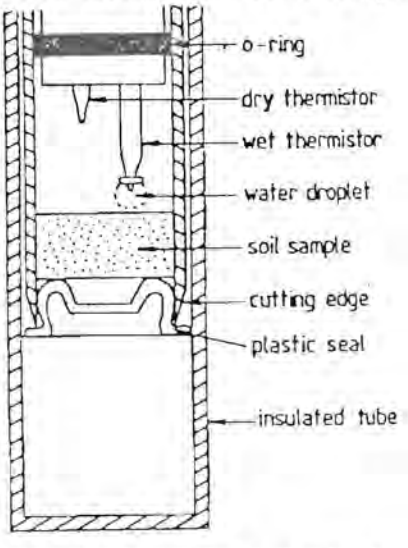


Figure 2.11: A typical thermistor psychrometer (after Richards, 1965)

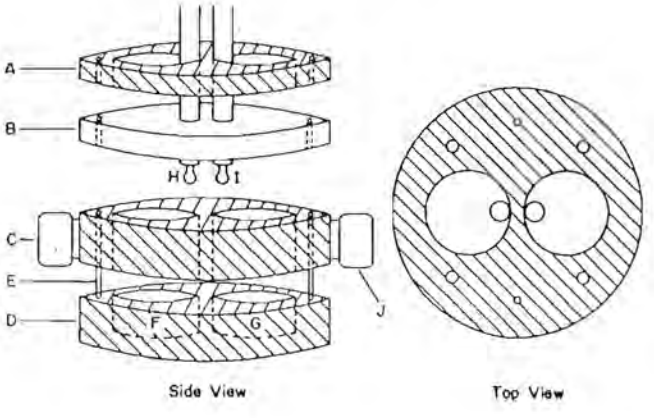


Figure 2.12: Diaphragm of the thermistor transistor (after Kay and Low, 1970)

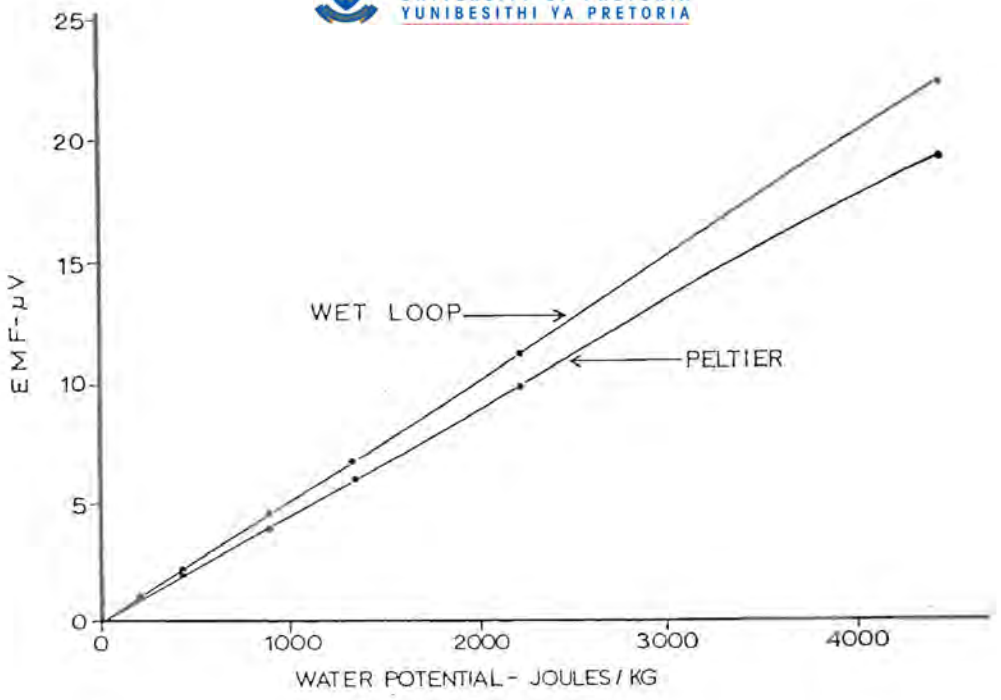


Figure 2.13: Calibration curves for Peltier and wet-loop thermocouple psyhrometer (after Zollinger et al, 1966)

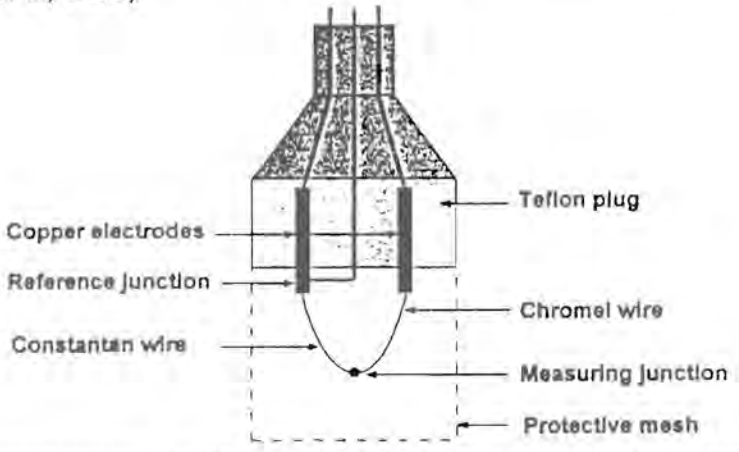


Figure 2.14: Thermocouple psychrometer (after Ridley and Brady, 1997)

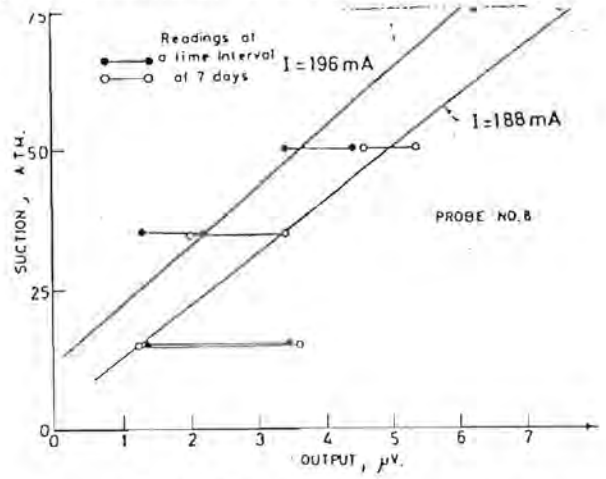


Figure 2.15: Calibration curves of probe No 7 at different cooling currents showing the drift in output for a time interval of 7 days (after Baker at al, 1973)

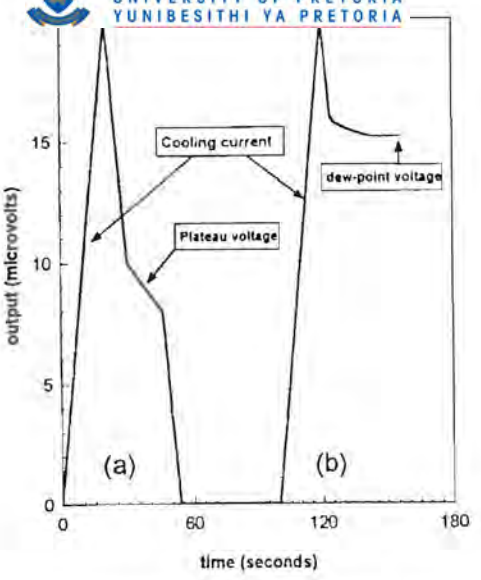


Figure 2.16: Typical output of a psyhrometer (after Ridley and Wray, 1996)

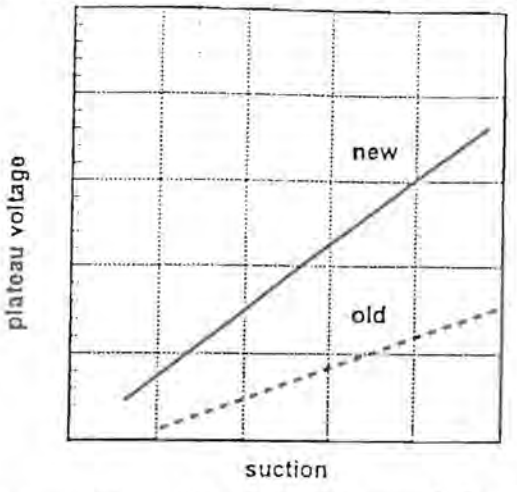


Figure 2.17: Deterioration in sensitivity with continued usage (after Zerhouni, 1995)

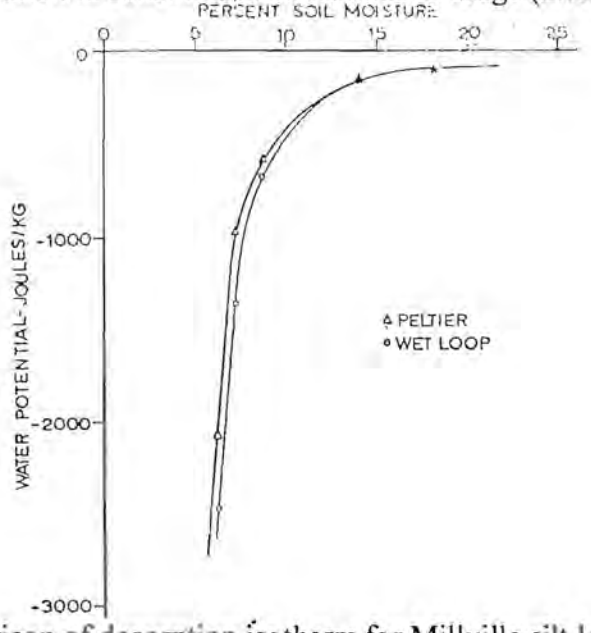


Figure 2.18: Comparison of desorption isotherm for Millville silt loam obtained by two types of thermocouple psychrometers (after Zollinger et al, 1966)

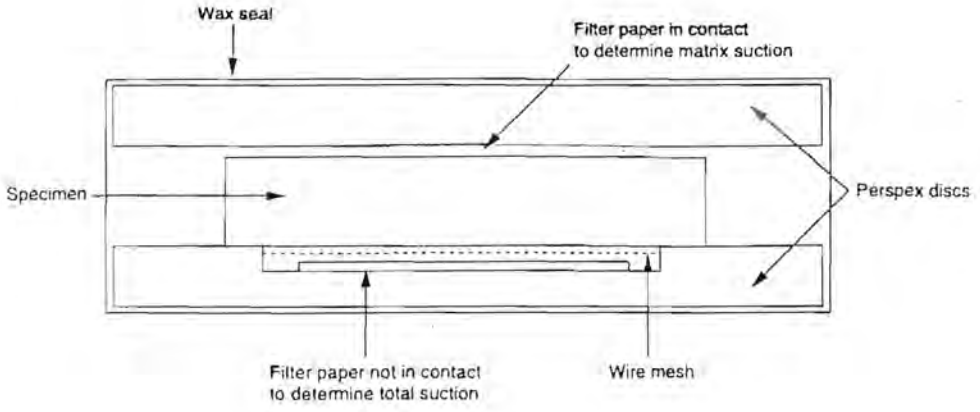


Figure 2.19: Arrangement for measuring suction using filter paper (after Ridley and Brady, 1997)

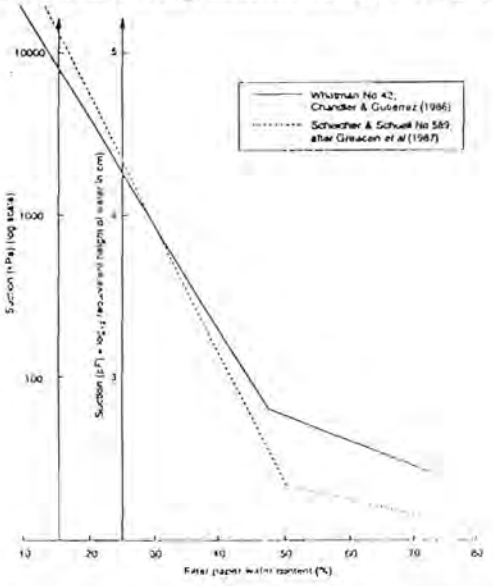


Figure 2.20: Filter paper calibration for papers placed in contact with soil (after Chandler and Gutierriez, 1986)

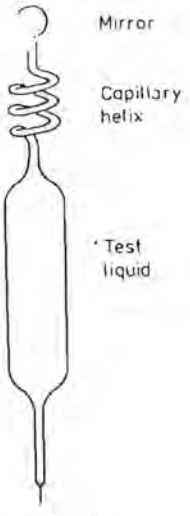


Figure 2.21: Berthelot tube (after Meyer, 1911)

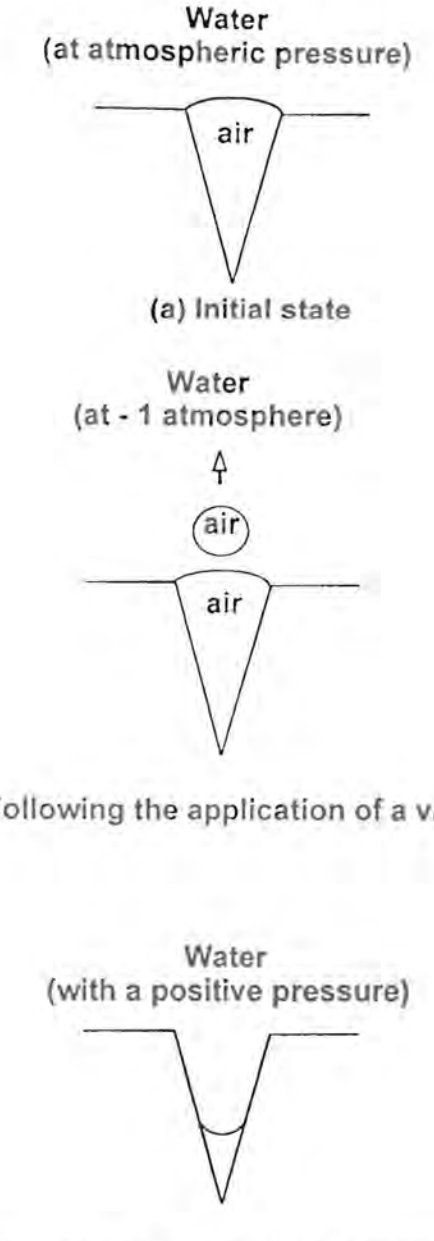


Figure 2.22: Crevice model of tension breakdown (after Harvey et al, 1944)

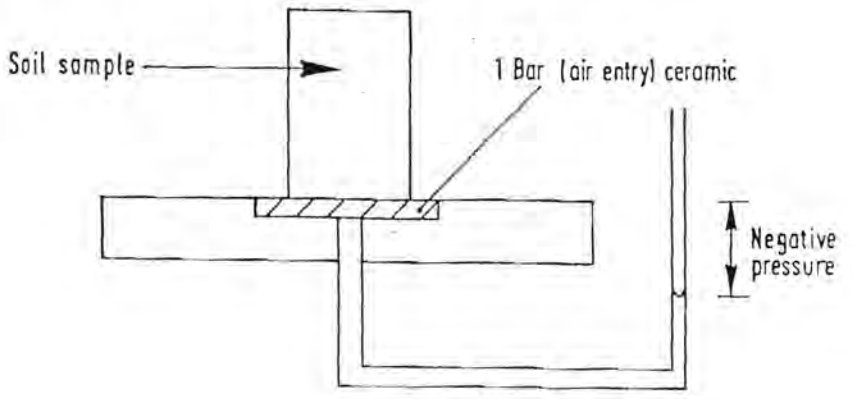


Figure 2.23: Suction plate (after Ridley, 1993)

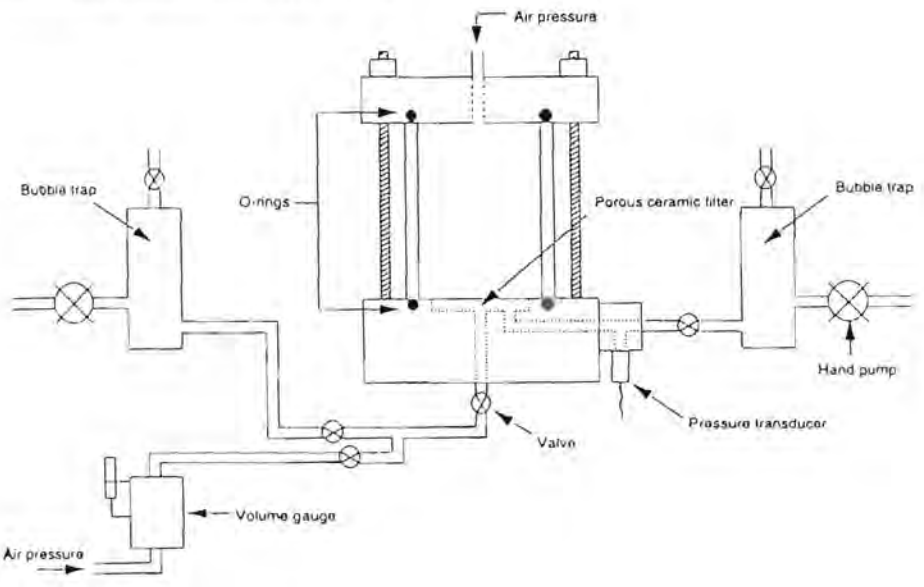


Figure 2.24: Pressure plate (after Ridley and Brady, 1997)

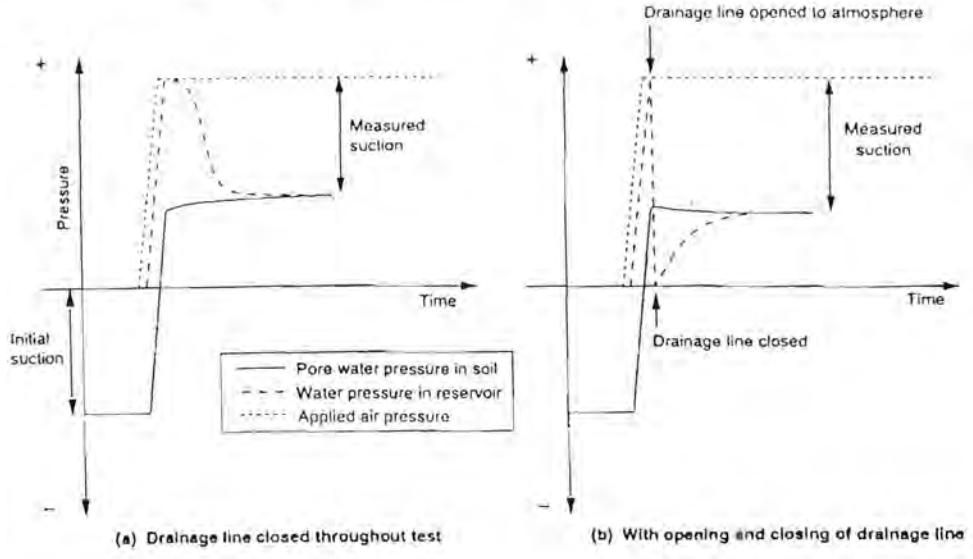


Figure 2.25: Pressure changes in pressure plate (after Ridley and Brady, 1997)

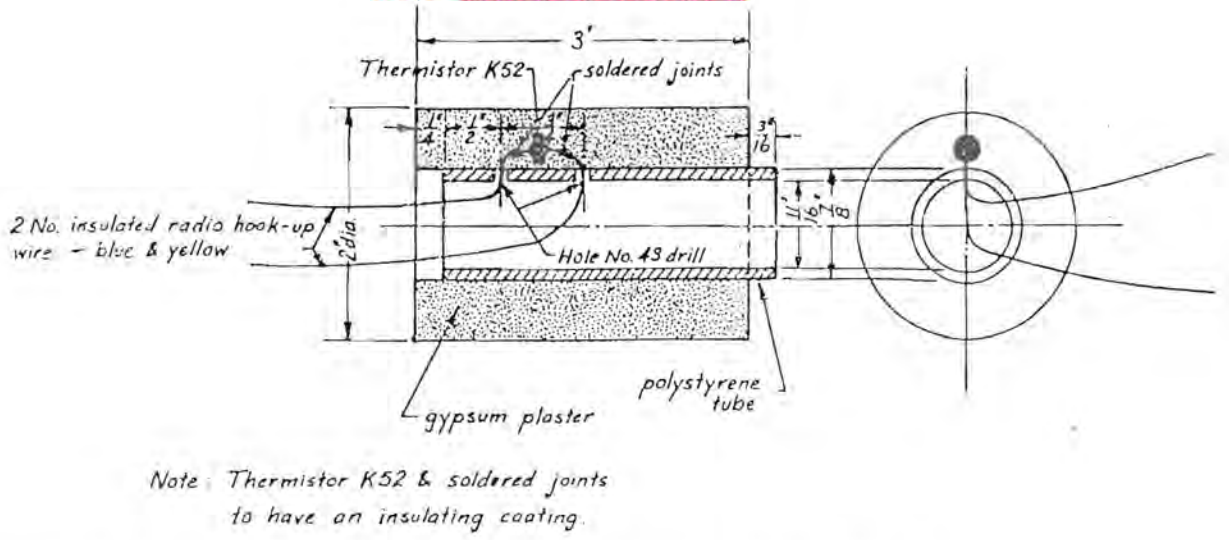


Figure 2.26 (a): Thermistor block details (after Aithison and Richards, 1965)

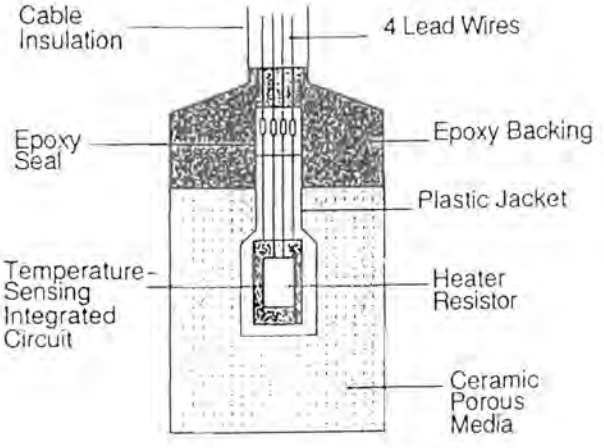


Figure 2.26 (b): Thermal conductivity sensor (after Sattler and Fredlund, 1989)

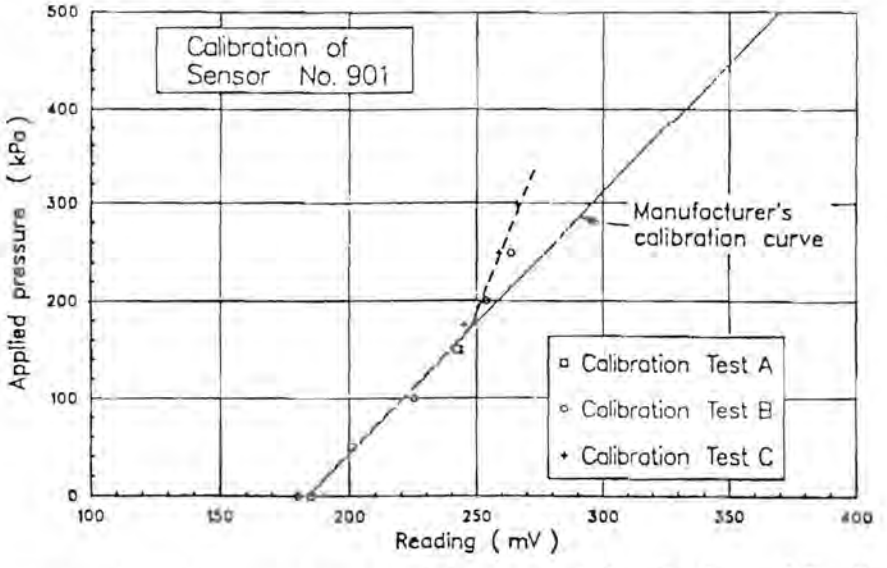


Figure 2.27: Calibration of a typical conductivity sensor (after Sattler and Fredlund, 1989)

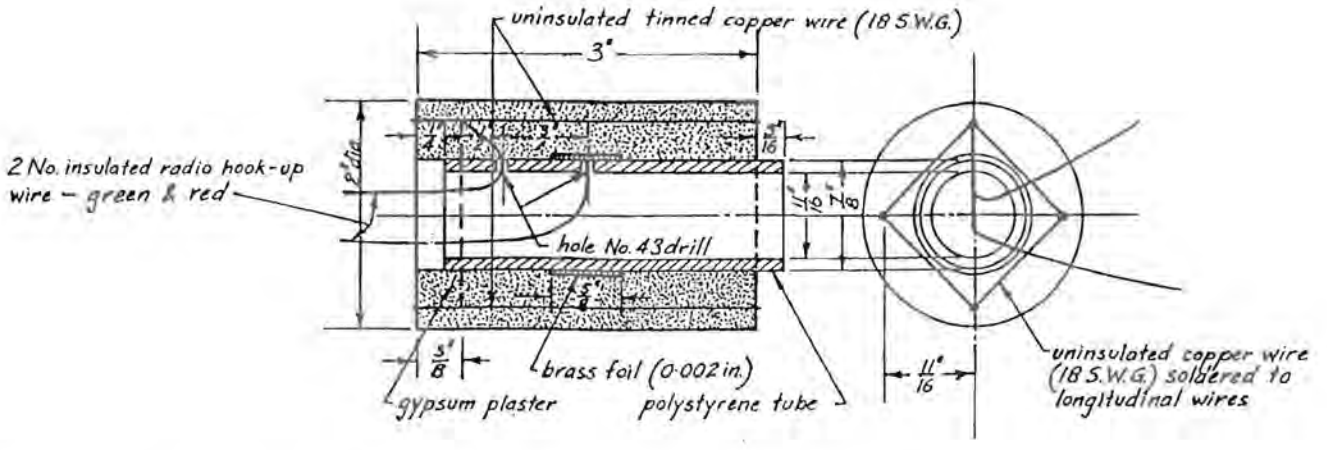


Figure 2.28: Gypsum block details (after Aitchison and Richards, 1965)

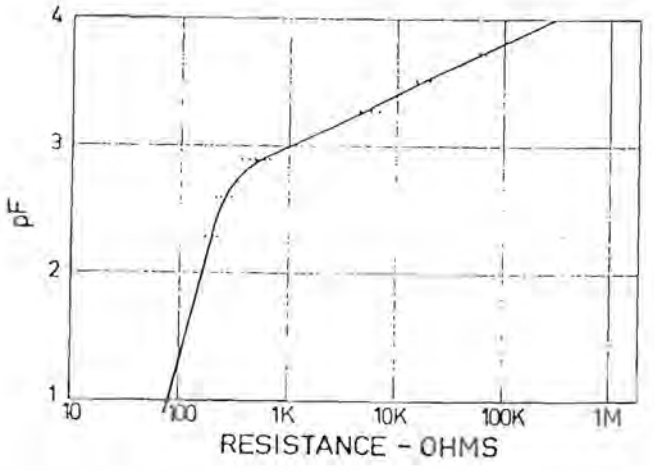


Figure 2.29: Calibration curve for gypsum block (after Aitchison and Richards, 1965)

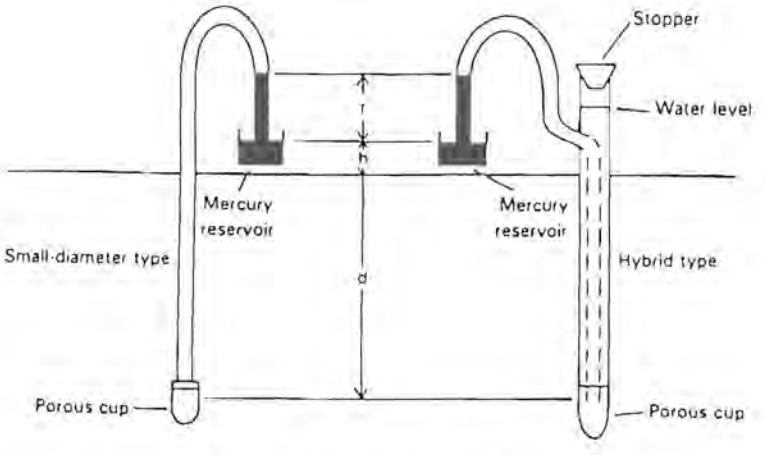


Figure 2.30: Manometer tensiometer (after Stannard, 1992)

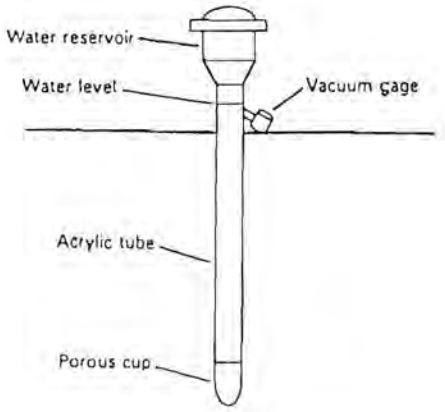


Figure 2.31: Vacuum-gauge tensiometer (after Stannard, 1992)

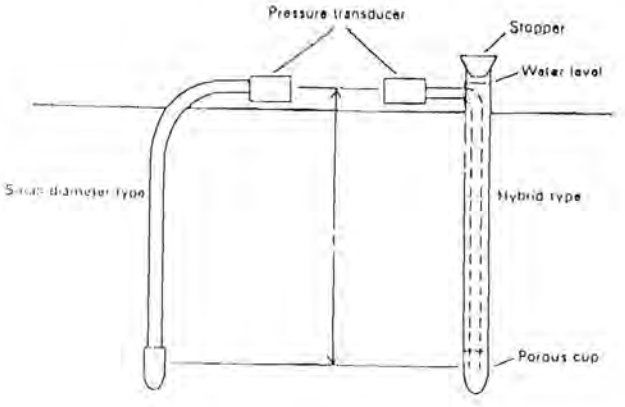


Figure 2.31: Pressure transducer tensiometer (after Stannard, 1992)

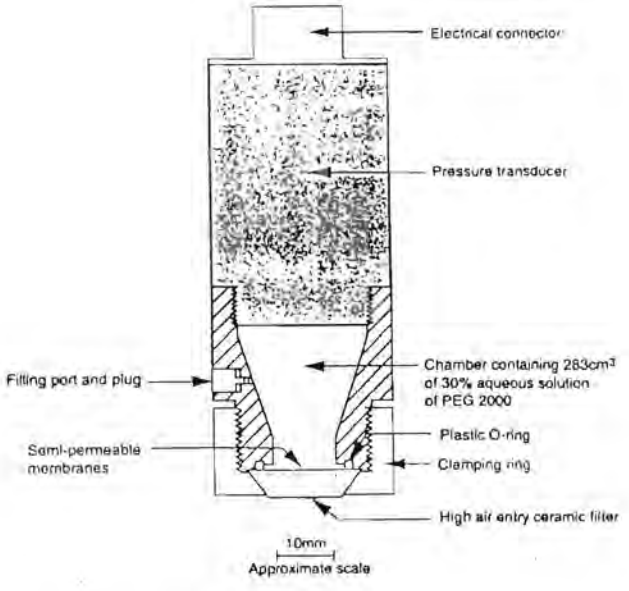


Figure 2.32: Schematic view of an osmotic tensiometer (after Peck and Rabbidge, 1966)

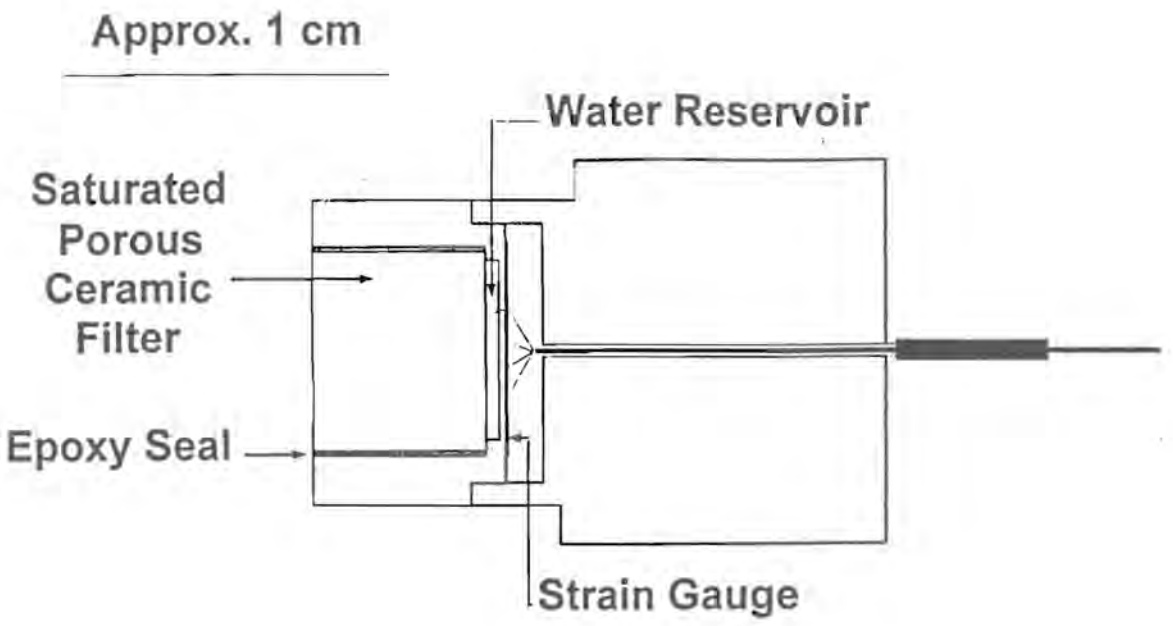


Figure 2.33: Imperial College suction probe (after Ridley, 1993)

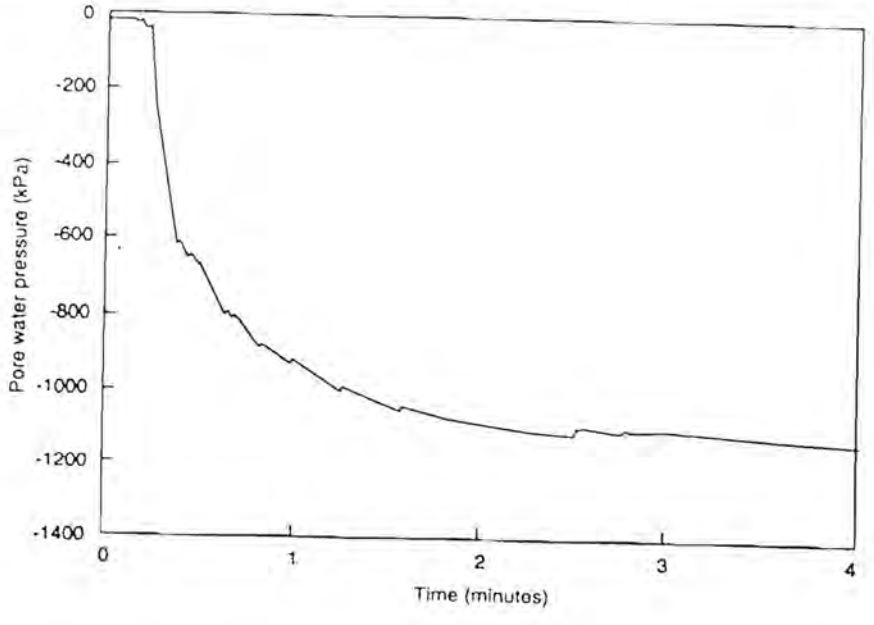


Figure 2.34: Suction measurement (after Ridley and Burland (1995)

3 DESIGN AND DEVELOPMENT OF THE SUCTION PROBE

It is evident from the discussion in Section 2.7 that most of the suction measurement devices currently in use have some limitation making unsuitable for suction measurement in mine tailings. The instrument that proved to be the most viable for this application was the Imperial College suction probe. Some changes to the design had to be made for the application to mine tailings. These changes had to be such that it incorporates the suggested precautionary measures for cavitation (Section 2.6.1) whilst at the same time take note of the limitations of the available transducers.

3.1 Description of Instrument

The suction probe (Figure 3.1) consists of two brass sections. The choice of body material is based on the fact that brass can be considered as an inherently "smooth" material. Referring to Section 2.6.1 this is one of the precautionary measures for preventing cavitation. The front section is the essence of the design as it contains all the vital components necessary for suction measurement. This includes the water reservoir, diaphragm and high air entry porous disk. This makes it possible to remove and replace faulty strain gauges. The back section consists of a housing for the electrical connections.

Special attention was paid to the selection of the correct high air entry porous filter as it governs the suction range of the instrument and plays an important part in the functioning of the instrument. The purpose of the high air entry filter is to separate the air and water phases. The filter normally consists of a porous material of which the pore spaces are extremely small. This ensures that the displacement pressure is greater than the applied suction. This displacement pressure is termed the air entry value or the bubbling pressure of the filter. The choice of ceramic air entry value was governed by several factors such as the suction range, response time and pressure measuring device used. The air entry value should be such that it is equal to or slightly greater than the upper limit of the expected suction range. It is of vital importance that this criterion is met since failure to comply will result in cavitation occurring before the required suction is reached. An air entry value of 300 kPa was adopted for reasons as given in Section 2.7.

Referring to Section 2.6.6 the greatest "stable time" is be obtained when the dimensions of the water reservoir behind the ceramic is minimised combined with the thickest ceramic. For practical reasons the choice was made to use the following dimensions, 0.1 mm for the water reservoir and 5 mm for the ceramic. These dimensions were thus assumed for the design of the suction probe. Due to the problems associated with off-the-shelf pressure transducers (Section 2.6.6), it was decided to rather make use of a strain gauged diaphragm which forms part of the probe body (Figure 3.1). A full bridge strain gauge (HBM 6/120MY 21) was used. These strain gauges measure the curvature of the diaphragm and are fully compensated for temperature changes. Electrical terminals were glued to the backface of both the diaphragm and back section of the suction probe. This ensured that the electrical connection between the suction probe and amplifier could be removed prior to saturation.

The choice of diaphragm thickness is governed by the central deflection (Equation 3.1) as well as machining limitations. If it is assumed that the maximum applied pressure is -300 kPa, the central deflection is in the order of 0.00036 mm provided that the diaphragm is 0.5 mm thick. The calculated deflection is adequate for the strain gauge arrangement and can be achieved by machining processes. The deflection should also be less than the water reservoir depth in order to avoid contact between the diaphragm and the ceramic. According to the calculation the central deflection meets the requirement.

$$Y = \frac{3P(r_0)^4(1-\nu^2)}{16t^3E} \qquad 3.1$$

where:

P is the pressure applied to the diaphragm

r_0 is the radius of the diaphragm

t is the thickness of the diaphragm

ν is the Poisson's ratio of the diaphragm and

E the Young's Modulus of the diaphragm

3.2 Machining and Assembly of Probe

The literature review concerning the Imperial College suction probe highlighted the problems encountered with both the design and successful application of the instrument. Most of these problems are in some way related to cavitation. The prototype great care was taken to prevent this from happening, even at the early stage of machining. As mentioned in Section 2.6.1 this phenomenon can be prevented to some extend by among other things, ensuring that the surfaces in contact with the water, i.e. the water reservoir, is as "smooth" as possible. This can only be accomplished by proper machining techniques and skill. It was therefore decided to allocate the task of machining of the probe to a qualified machine shop. A study of several machine shops was made with the main criteria being capability, quality and relative short manufacturing lead-time. A factor that was also taken into account but received less priority was the cost of manufacturing. Based on these criteria, the task was allocated to the machine shop at the University of Pretoria.

As mentioned in the previous section, the probe comprises of two brass sections. The front section consists of the water reservoir and diaphragm of which the latter is machined as part of the main body. Finer tolerances and finishes were used for the two parts for reasons given above. The back section of the probe contained the wire exits of 1.5 mm. In order to facilitate the volume required for the connection between the wires and strain gauges, it was internally taped towards the front section at an angle of 30.9°.

The suction probe was assembled dry. The first step in the process was to instrument the diaphragm with a HBM 6/120 MY21 strain gauge. The surface of the diaphragm side facing the back section was prepared by burnishing it with extremely fine sandpaper and cleaning it properly. The strain gauge and four terminals were then glued onto the surface with Z70 adhesive glue. The procedure was repeated on the backface of the back section but with the exception that only four terminals were glued to it. The terminals on both sections were connected to each other via four wires. This ensures that the internal connection with the strain gauge remains intact at all times while the external connection (i.e. between the strain gauge the amplifier) can be removed during de-aeration and saturation of the probe.

The machine shop trimmed the ceramic to the correct dimensions so that a tight fit between the ceramic and probe body could be ensured. Epoxy glue was placed on its circumference prior to pushing it into position. Care was taken not to smear the glue onto the rest of the ceramic as it would influence its permeability and hence the functioning of the suction probe. The probe was assembled and sealed.

3.3 Saturation and De-airing of Probe

Correct de-aeration and saturation procedures are important in the prevention of cavitation. Similar to the previous section regarding machining and dimensions, these saturation procedures are important components of the precautionary cavitation measures (Section 2.6.1).

Figure 3.2 schematically illustrates the equipment utilised to de-air the suction probe i.e. the dessicator, vacuum pump, laboratory flask and de-aerator. De-aeration of the suction probe takes place in the dessicator. The probe is slightly elevated by placing a coarse mesh at the bottom of the dessicator. The dessicator is then sealed. A vacuum is generated and maintained in the dessicator for a period of three hours. Thereafter the dessicator was filled with high quality de-aired water and once again put under vacuum for a period of four hours.

The remaining nuclei present in the crevices of the body material could be removed by applying either extremely high positive or cyclic pressures to the water in the reservoir. The latter method was employed to saturate the probe. The probe was placed in a triaxial cell with the ceramic facing upwards. This placement of the probe was practical as a positive meniscus of de-aired water was maintained on top of the ceramic at the end of the process after the cell water was drained. A GDS pressure controller was connected to the cell pressure of the triaxial cell as to apply cyclic pressures of 50 to 350 kPa to the probe. These cyclic pressures were maintained for a period of 24 hours. Theoretically the suction probe should now be fully de-aired and saturated. The probe was removed from the triaxial cell and stored in a container completely filled with de-aired water. Re-saturation may be required from time to time. This consists of placing the probe in the triaxial cell and subjecting it to cyclic pressures for a period of 24 hours.

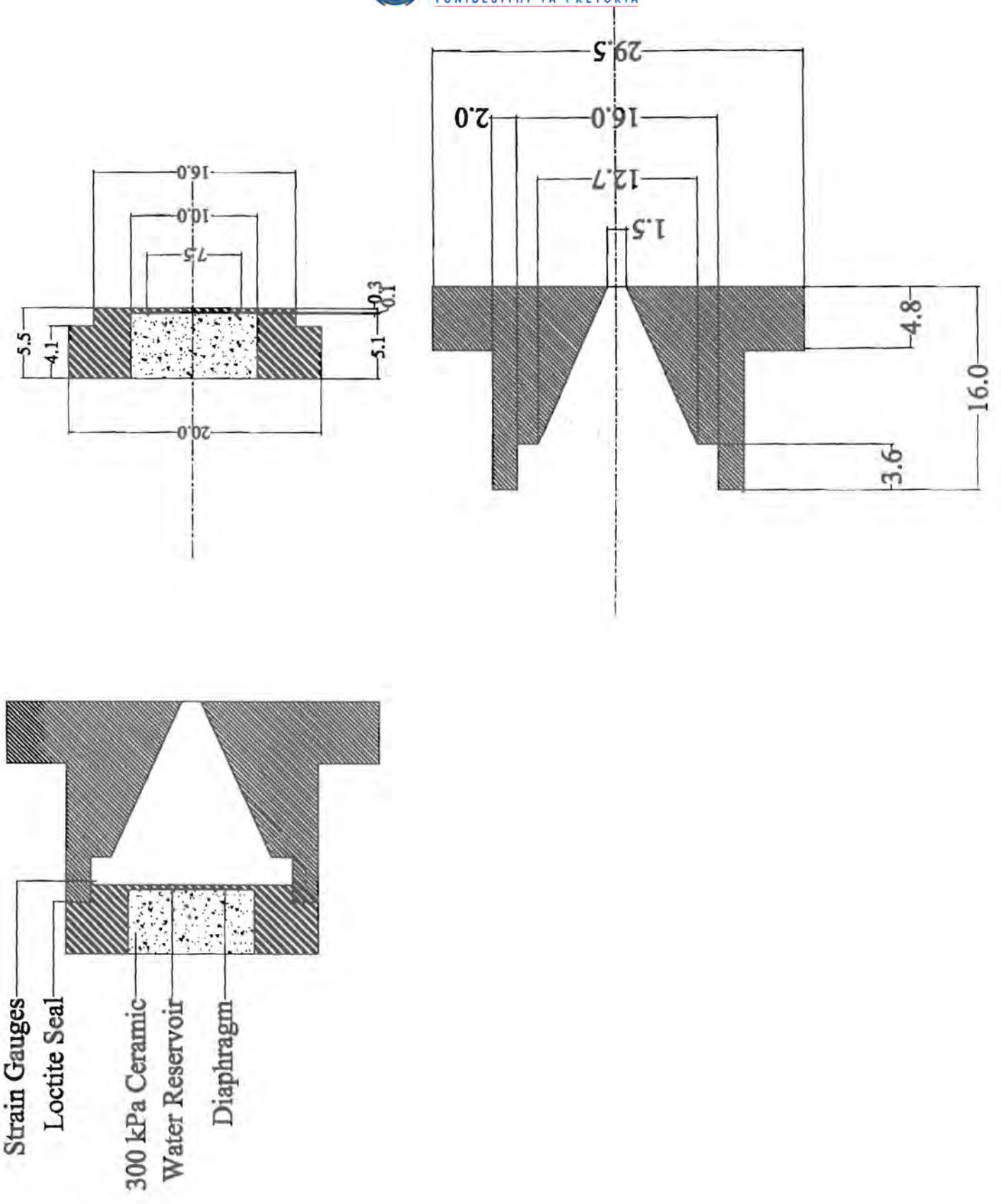


Figure 3.1: Machine drawing of suction probe

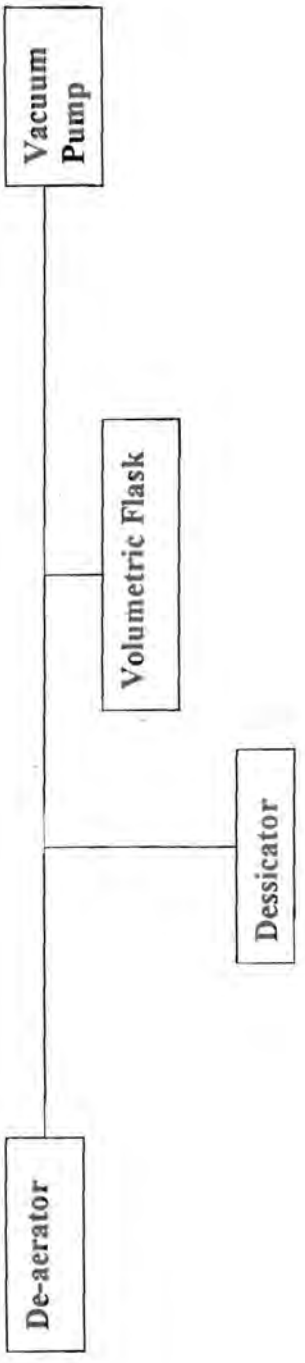


Figure 3.2: Schematic illustration of de-airing equipment

4 TEST PROCEDURE AND CALIBRATION

4.1. Calibration

The suction probe was calibrated separately for the positive and negative range. Theoretically, the material of the diaphragm should obey Hook's law whenever pressurised. This implies that positive and negative deflection should be equal but opposite if the absolute applied pressure is equal. Separate calibration of the two ranges provides the opportunity of proving this fact.

4.1.1. Calibration of the Suction Probe in the Positive Pressure Range

Calibration of the probe in the positive pressure range was achieved by inserting it in a modified triaxial cell. The first attempt at assembling the suction probe was unsuccessful. The probe was placed in the top section of the cell (Figure 4.1) and cell pressure increased in increments of 50 kPa. The output was amplified and displayed by a DMD 20 amplifier. The calibration curve was disappointing as the response was neither linear nor repeatable. The instrument was then removed from the triaxial cell and investigated. It was noted that upon turning it through an angle of 360° the amplified readings would jump from –5 to –1 500. Based on this observation it is assumed that water entered the electronics of the probe. This was confirmed when opening the probe. When re-assembling the probe, greater care was taken to prevent water from entering the electronics. The calibration procedure was repeated and the suction probe responded quickly (i. e. less than one second response time) and in a linear repeatable manner (Figure 4.2).

4.1.2. Calibration of the Probe in the Negative Pressure Range

The first attempt at calibrating the suction probe in the negative pressure range was by means of a modified oedometer apparatus (Figure 4.3). A sample of saturated kaolin clay was placed in the oedometer apparatus and left to consolidate under a pressure of 500 kPa. Thereafter various pressure increments were momentarily removed and the reading from the suction

probe noted. It was assumed that once 100% consolidation was achieved, pressure (equal to or less than the consolidated pressure) could momentarily be removed to induce a negative pore pressure response. The induced pore pressure is numerically equal to the removed pressure at time zero.

This set-up in the oedometer allowed for the probe to be calibrated in the positive range as well (see Section 4.1). All the calibration curves were compared (Figure 4.2). The calibration in the positive range and negative range using the oedometer were different. The negative calibration was approximately 49% higher than the calibration in the positive range. There seemed to be some discontinuity between the positive and negative range as well. The calibration from the modified triaxial cell was vastly different to either of these calibrations i.e. 564%. This immediately placed some doubt on the reliability of the calibration of the suction probe.

The probe was removed form the calibration oedometer and inspected. It then became apparent that whenever the body of the probe was pressurised the pressure reading would respond accordingly without a change in the pore pressure. In hindsight this was a design flaw and this cross-talk should have been expected since the strain gauged diaphragm was machined as a continuous part of the main body (Section 3.1). This probe could not be calibrated in the manner described above. Incorporation of the suction probe in the oedometer cell is such that whist applying pressure to the water reservoir via the sample, the total pressure is also applied to the bottom surface of the probe body, thereby influencing pressure measurements. The probe would therefore only be calibrated reliably if water pressure changes were exclusively applied to the diaphragm via the water reservoir with no change in load to the body of the probe.

This was accomplished by a calibration configuration utilising a modified mercury manometer (Figure 4.4). The connection between the probe body and manometer tube was sealed with Reprosil light body glue. Pressures were calculated by taking into account the geometry of the manometer and the densities of the fluids. Pressures were generated by lowering the unattached end of the manometer tube to different elevations. This allowed positive as well as limited negative pressures to be generated. Calibration was achieved up to –84 kPa at which stage cavitation occurred. Cavitation occurred in the water in the tube

between the suction probe and mercury and could not be prevented. Despite this fact the calibration curve (Figure 4.2) obtained with this method proved to be linear and repeatable with very little hysteresis. The calibration of the manometer set-up also closely resembled that of the triaxial cell calibration (Figure 4.2). This implies that the calibration obtained from the oedometer set-up was incorrect.

4.2. Testing in the Laboratory

The laboratory testing program was carried out to assess the performance of the suction probe on gold mine tailings. As mentioned in the previous section, the probe was only calibrated in the negative pressure range to a value of 84 kPa at which stage cavitation of the water between the mercury and suction probe occurred. It was assumed that the calibration curve (Figure 4.2) was correct and could be extrapolated in the negative range. Up to this stage the successful measurement of suction pressures in excess of 84 kPa with the instrument had not yet been proved. It was expected that laboratory testing of the tailing samples would provide this opportunity. As a secondary outcome of the laboratory testing it might be possible to generate water retention curves as well as air entry and shrinkage properties for the tailings.

The suction properties of the gold mine tailings were measured by allowing samples to dry out. The samples were placed in glass containers and their weights and volumes were measured with time. Further details of the test procedure will follow.

Several assumptions were made during the testing procedure. These include the following:

- The calibration curve was correct and could be extrapolated for suction greater than 84 kPa.
- The density and pore pressure distribution of the sample in the glass container is uniform.
- The degree of saturation of the samples prior to testing is equal to 100%.
- The suction probe is in full hydraulic contact with the sample during suction measurements.
- Any cracks that may develop in the samples during testing are small and can be neglected in volume and density calculations.
- The pore sizes in the tailings are uniform and do not influence measurement.

The equipment employed for the laboratory testing of the tailing samples consist of two laboratory ovens each at a different temperature, the suction probe, DMD 20 amplifier, two tin cups for moisture content measurements and two containers in which the samples is tested. The choice of containers are based on several predetermined criteria such as:

- The height of the containers should be such that it allows for the uniform dissipation of pore pressures. This will ensure that suction measurement on the upper surface of the sample is representative of that of the whole sample. However, it should not be so small that drying of the sample takes place too rapidly and proper monitoring of the suction properties is difficult if impossible.
- The angle between the bottom and sides along the inner perimeter of the container should be sharp and close to 90°. This will ease volume calculations.

Two glass containers were manufactured to above mentioned criteria. The glass containers were of 67.9 mm diameter and 32.4 mm height. The volume of the glass containers was estimated by means of three methods and the average volume was used. The first method consisted of measuring the height and diameter of the glass container and calculating the volume accordingly. The height in the middle of the container differed from that on perimeter and an average height was thus used. The relationship between density, weight and volume was used as the second method of volume calculation. The glass containers were filled with water and the weighted to the nearest 0.00 g. In order to increase the accuracy of measurement the water meniscus was flattened by sliding a glass plate over the edges of the container. The adopted value for the gravitational constant took into account room temperature (ranging from 20 to 25°C) and is in the order of 99.7 kg/m^3 (Head, 1984). The last adopted method consisted of filling the glass containers with mercury. Once again a flat meniscus was established by sliding a glass plate over the edges of the container. The contents of the container was then poured into a measuring cylinder and the volume could be read off.

The gold tailing samples were obtained from the decommissioned Pay Tailings dam of Vaal Reefs in Orkney. Mr N. J. Vermeulen who is currently busy with his PhD on "Composition and State of Gold Tailings", sampled the tailings during the last semester of 1999. The disturbed samples were collected at the penstock of the specified tailing dam. It was divided

into two broad grading categories namely fine and coarse. Figure 4.5 and Table 4.1 presents the grading and fundamental properties of the samples.

Prior to the actual testing, the probe was re-saturated by procedures as outline in Section 3.3. At the same time the samples were prepared in medium sized containers by mixing it with excess water. It was assumed that this action ensures a degree of saturation of 100%. Moisture content samples were taken and dried at 110°C. The manufactured glass containers were filled with the samples and weighed to the nearest 0.00 g. Great care was taken to ensure that any excess material on the outer perimeter of the glass containers was removed as this may affect the weight of the samples and hence calculations. The rate of desorption was increased by oven drying the samples at 28°C. It is assumed that this temperature was representative of the average day temperature on a tailings dam (N. J. Vermeulen). Laboratory testing consisted of taking continuos measurements of weight, height and suction pressure with time during desorption. Between successive measurements the suction probe was stored in a container filled with de-aired water. Occasionally the water in the container was replaced with new de-aired water to ensure that it remains de-aired at all times.

Initially neither of the samples were able to support the weight of the suction probe making it impossible to measure suction. After some period of time enough water evaporated (thereby gaining enough strength) to support it. A suction of zero was measured in both samples. Desorption of the coarse sample took place at a greater rate than that of the fine sample which resulted in a greater suction although the final suction of the fine material was greater. Cracks developed in each of the samples at a later stage in the desorption process. The pattern of the developed cracks differed for each sample. The course sample contained multiple cracks that followed the perimeter of the glass container, approximately one centimetre from its side. On the other hand, a single crack developed through the middle of the fine sample with its width greater than that of the coarse sample. It was noted that the crack width of both samples increased with increasing time. The laboratory tests were repeated several times in order to obtain a continuos spread of suction measurements. The initial moisture content of the samples varied from test to test. It was then noted that the final crack width of the samples are influenced by the initial moisture content in that the higher the initial moisture content the wider the crack width.

Initially suction pressure developed relatively slowly, but increased non-linearly with time. During the first couple of tests, this turning point was reached overnight with the result that only the two extreme values, i. e. low and high suction were measured. In order to obtain a continuous spread of readings, the samples were removed from the oven at night and covered with a glass plate. The connection between the glass containers and plate was sealed off with grease to reduce moisture loss from the enclosed environment. Evaporated water from the samples could be noted as condensed water droplets on the glass plate the following morning. The evaporated water was taken into account by measuring the difference in weight and suction pressure between successive uncovered stage i. e. prior to covering and after removing of the glass plate.

Suction properties of the samples such as saturation, void ratio, moisture and volumetric water content as well as both the dry and natural density were calculated by applying the measured values to basic geotechnical principles. Reduction in the sample height was noted on the glass container and measured once the test was completed. The reduction in volume was calculated by multiplying the reduction in height (h) with the area of the container. The new sample volume (V) is obtained by subtracting the reduction in volume (v) from the original total volume (V_o). This was done as the bottom of the containers is curved and the accurate estimation of height is impossible.

Figure 4.6 and Figure 4.7 indicate the relationship between matric suction and degree of saturation which is clearly non-linear and inversely proportional. The degree of saturation for Test 4 of both tailing samples indicated an unexpected increase which will be discussed in Section 6. The best spread of suction measurement was obtained with Test 4 so that only these results will be considered for further analysis.

Table 4.2 summarises the results of Test 4 for both of the tailing samples. Figure 4.8 and Figure 4.9 is a combination of the soil-water characteristic curve on a normal scale and the shrinkage curve. Both the void ratio and water content decreases with increasing matric suction. Initially the gradient of the matric suction vs. water content curve is close to zero but increases to a positive value once the excess water has evaporated. On the other hand, the gradient of the void ratio vs. water content decreases as zero is approached. The shrinkage

limit of the tailings is reached at this point. According to the figures this is at void ratio of 1.2 and 0.33 and moisture content of 55% and 10% for fine and coarse tailings respectively.

The adopted test procedure for the first three tests were unsuccessful due to inadequate readings. An attempt was made in Test 4 to improve on this by removing the samples from the oven at night and covering them with a glass plate. The test results of this procedure indicated some anomaly (see Section 6). Following this observation it was decided to repeat the test to validate the reliability of the results. However, the probe failed to measure suction of the samples during the repeated test. Several attempts were made to establish the nature of the problem, but with no avail. These attempts include replacing the current stain gauge with a new one and saturating the probe by using the complete method as set out in Section 3.3. This suction probe was then abandoned and a new suction probe designed to avoid the shortcomings of the first suction probe.

Table 4.1 Fundamental Properties of Pay Dam Tailings

Description	Unit	Fine Tailings	Coarse Tailings
Depth below surface	m	4.154	1.975
Moisture content	%	53.9	19.6
Degree of saturation	%	99.2	61.1
Natural density (ρ_{wet})	kg/m^3	1694	1742
Dry density (ρ_{dry})	kg/m^3	1101	1457
Void ratio		1.488	0.873
In-situ vertical stress	kPa	68	34
Pore pressure from CPTU test	kPa	-4	1
Vertical effective stress	kPa	73	33
Specific density		2.74	2.74
Liquid limit (LL)	%	56	29
Plastic limit (PL)	%	39	22
Plastic index (PI)	%	17	7

Table 4.2: Laboratory Desorption Test Results using the Original Suction Probe

Date	Time	Fine Tailings				Coarse Tailings			
		Suction (kPa)	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Suction (kPa)	Void Ratio	Degree of Saturation (%)	Moisture Content (%)
28/2	09:26	0	1.10	1.00	40.22	0	2.94	1.01	108.13
29/2	08:46	0	0.97	0.87	30.71	0	2.63	0.97	92.76
01/2	11:43	0.3			29.35	0			87.10
01/3	13:05	2.4			28.94	0			83.67
01/3	16:08	19			27.82	0			77.05
02/3	09:20	19.7	0.84	0.78	24.29	0	2.18	0.96	76.37
02/3	12:35	42.7			24.11	1			71.09
02/3	14:51	110.4	0.74	0.69	21.04	1.6	2.18	0.85	67.45
02/3	16:56	137			18.71	6.4			64.05
03/3	08:10	136			16.55	6.1			63.69
03/3	10:01	175			16.41	11.8			61.77
03/3	11:05	177.3			14.90	17			60.75
06/3	08:20	178.7	0.33	1.16	14.17	9.4	1.46	1.13	59.95
06/3	11:34	268	0.33	0.86	13.86	42.6	1.20	1.25	54.69
07/3	08:21	75.4	0.33	0.64	10.27	78.4	1.20	1.08	47.33
08/3	10:17	455	0.33	0.58	7.66	123.2	1.20	1.06	46.30
	16:45	467	0.33	0.45	6.93	209.3	1.20	0.91	39.93

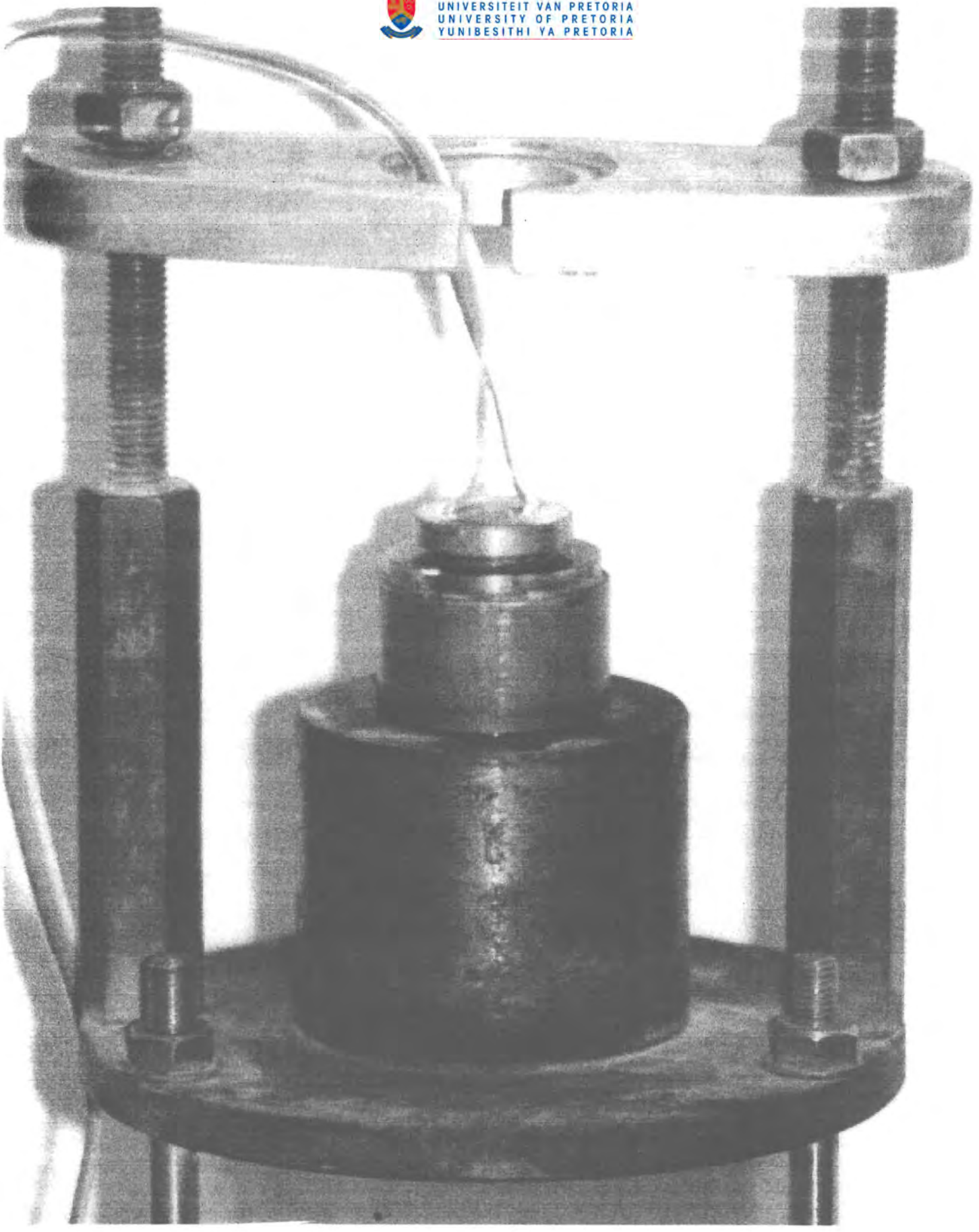


Figure 4.1: Suction probe in modified triaxial cell

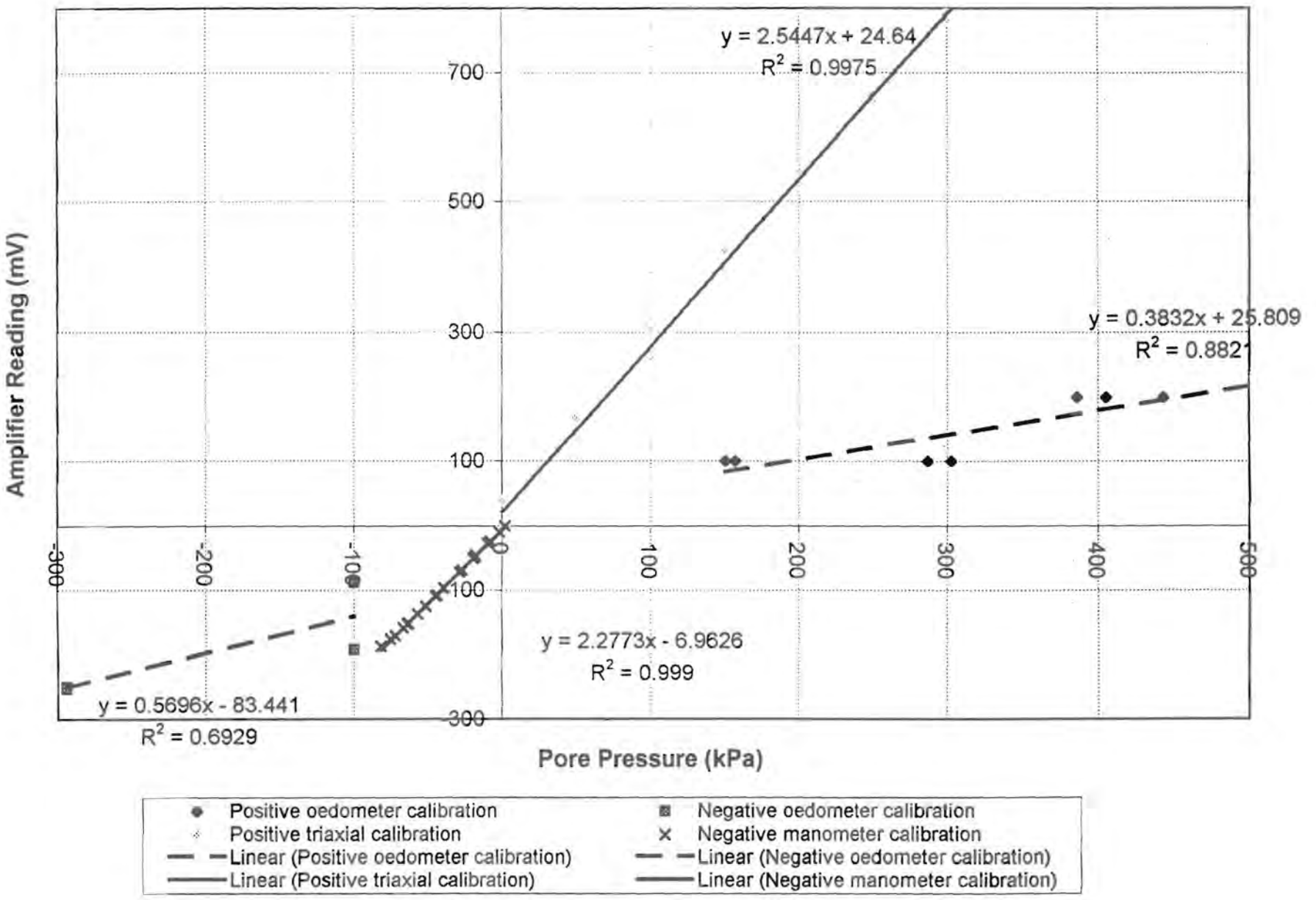


Figure 4.2: Combination calibration curve of adopted methods

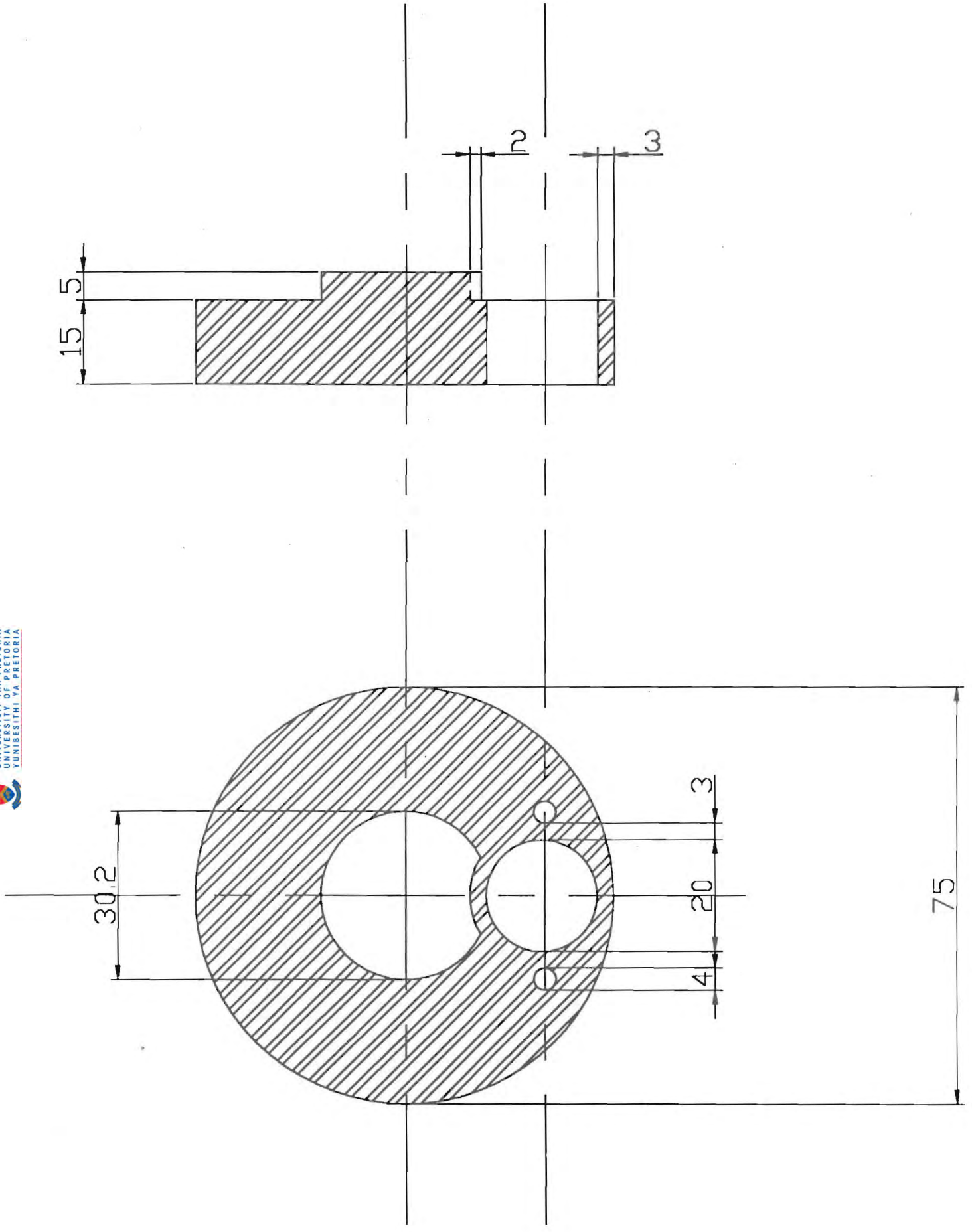


Figure 4.3: Machine drawing of modified oedometer top-cap

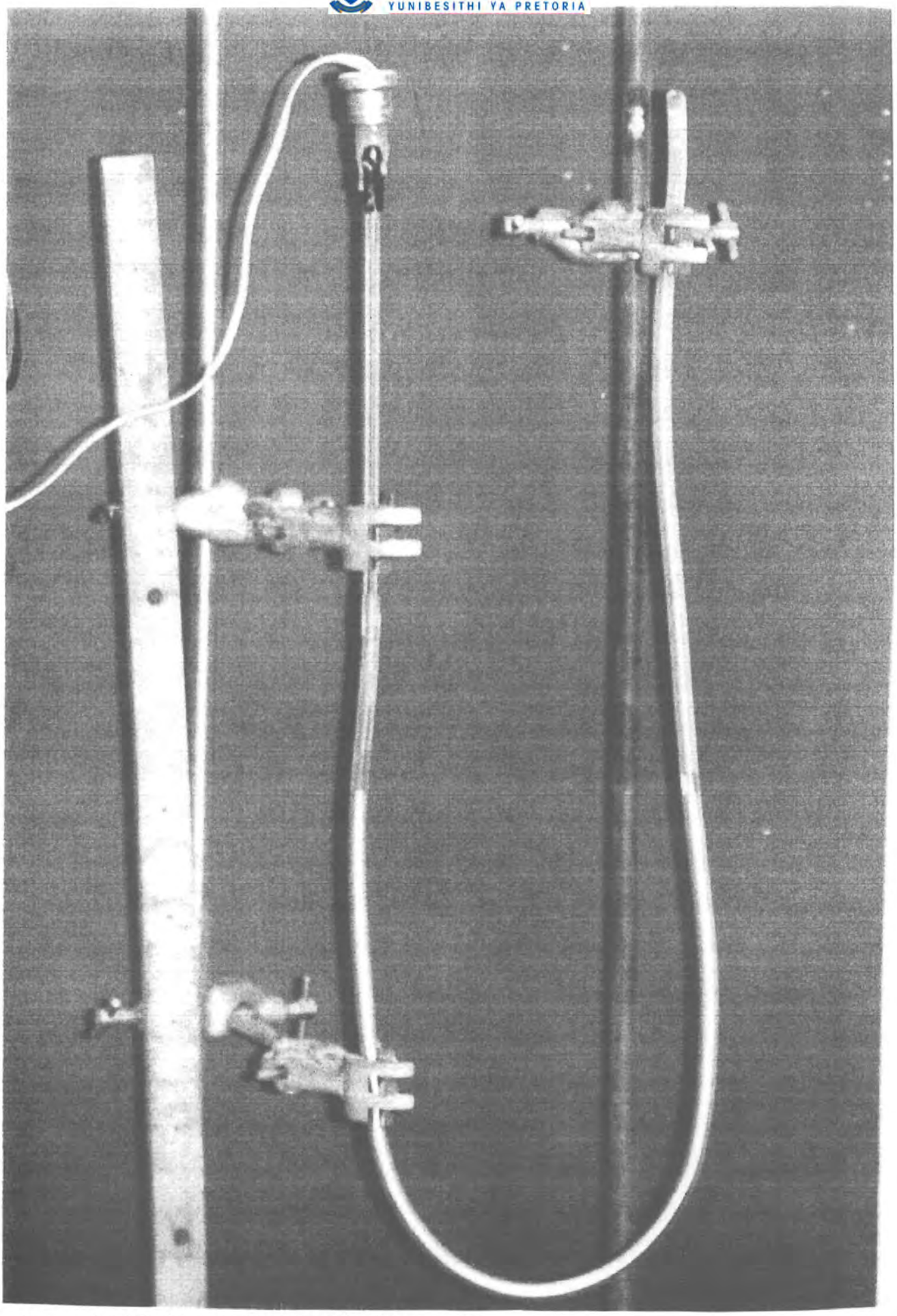


Figure 4.4: Modified manometer calibration apparatus

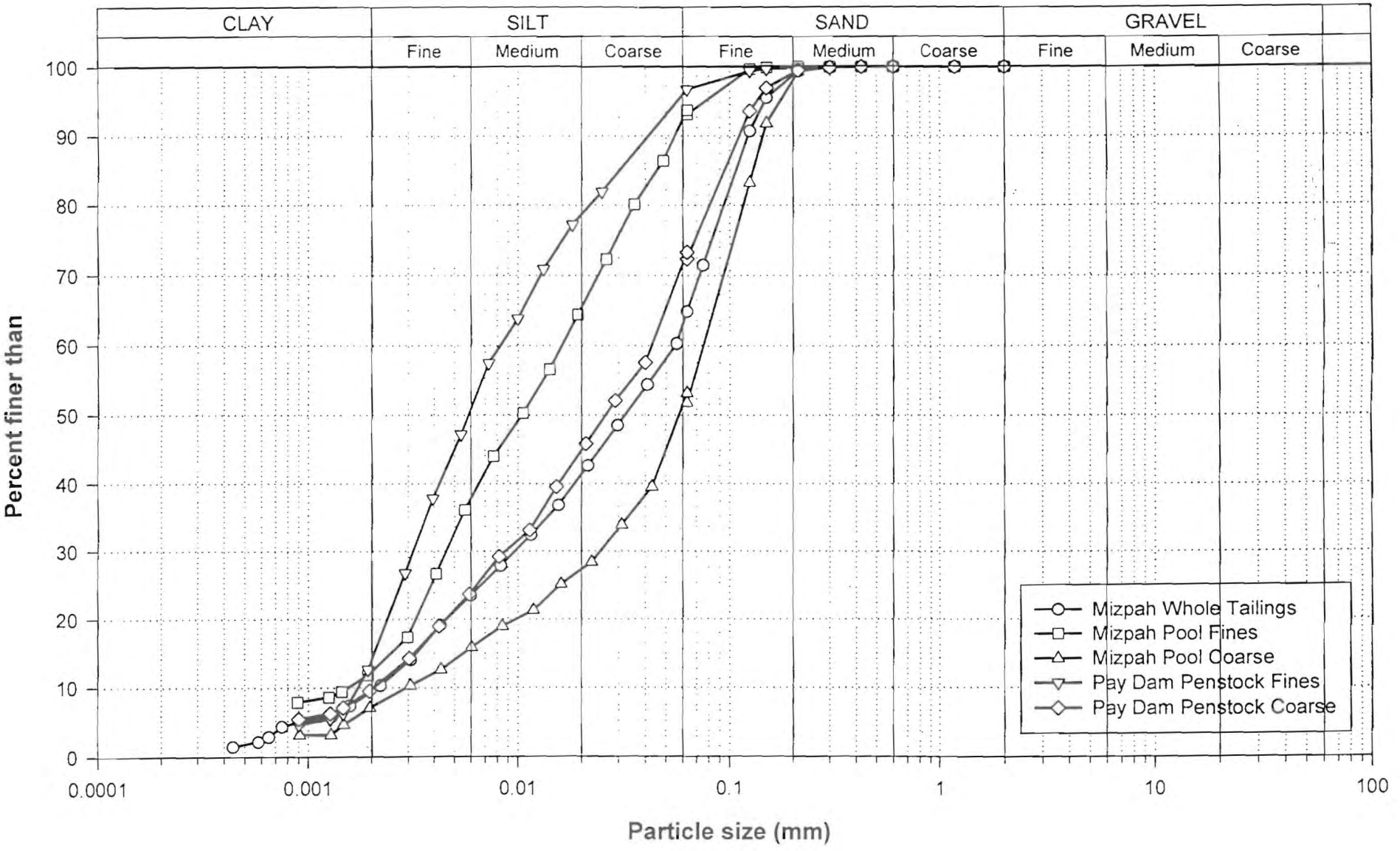


Figure 4.5: Grading analysis of mine tailings samples (after Vermeulen)

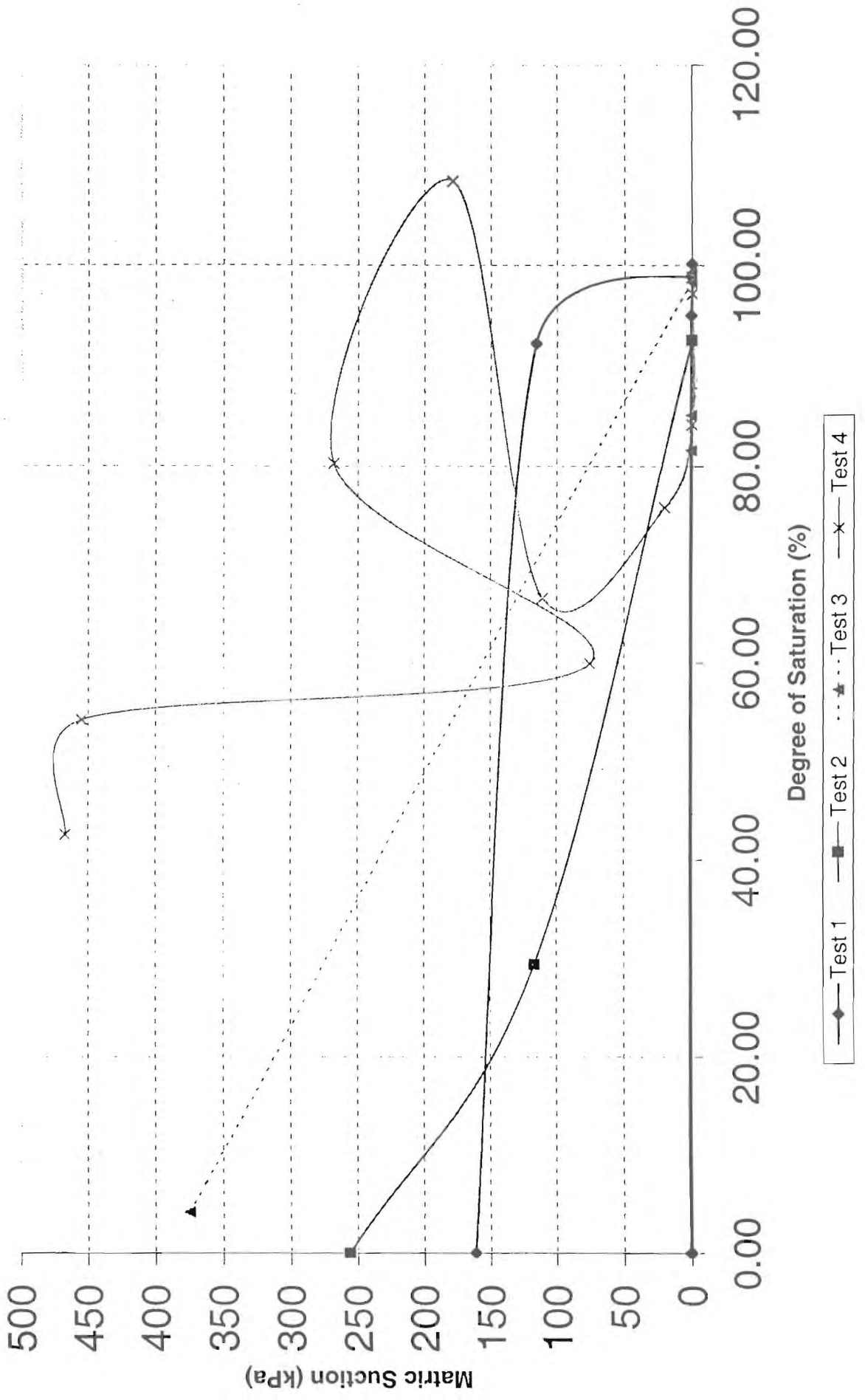


Figure 4.6: Relationship between matric suction and degree of saturation of fine tailings for the various desorption tests

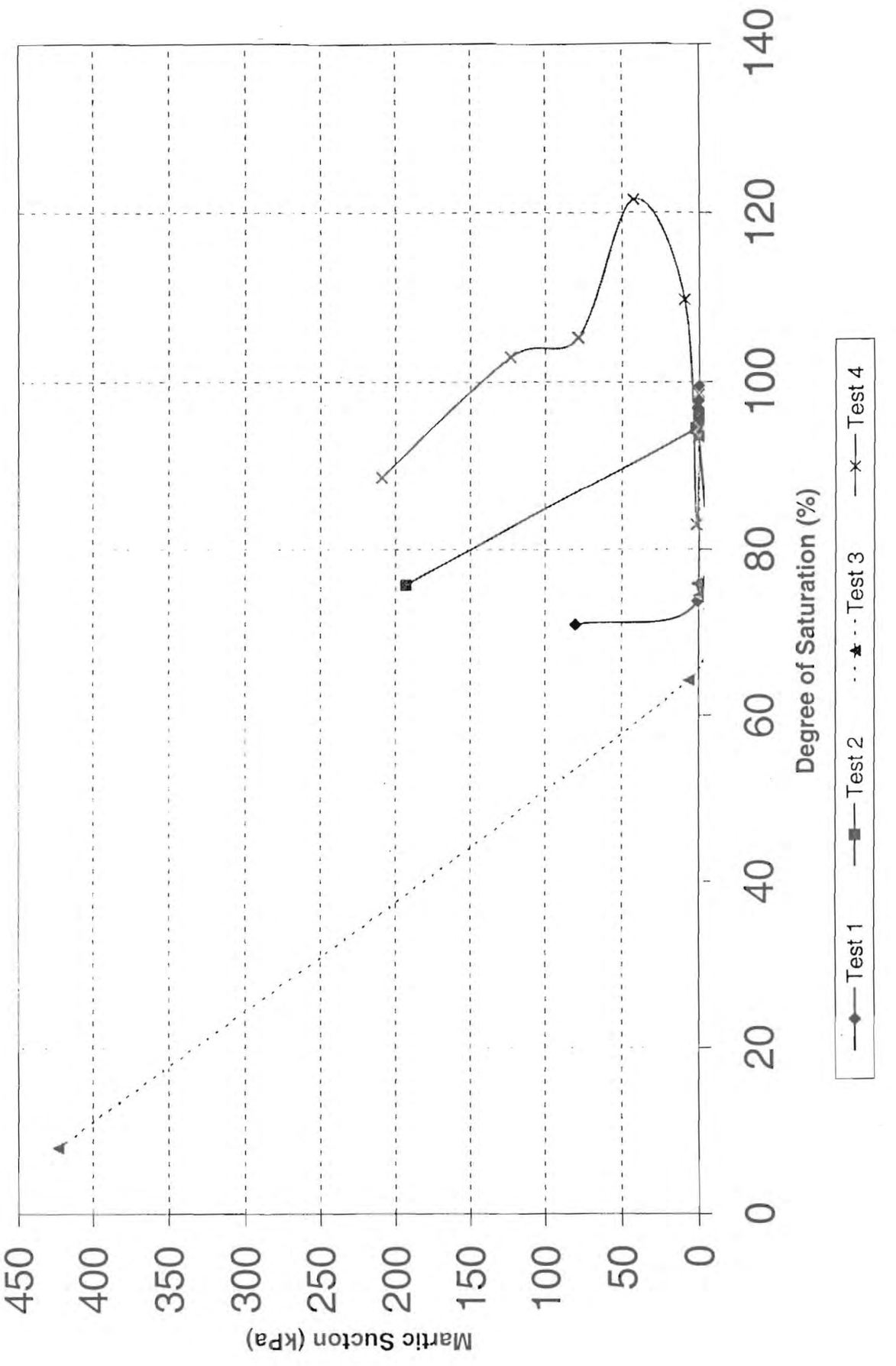


Figure 4.7: Relationship between matric suction and degree of saturation of coarse tailings for the various desorption tests

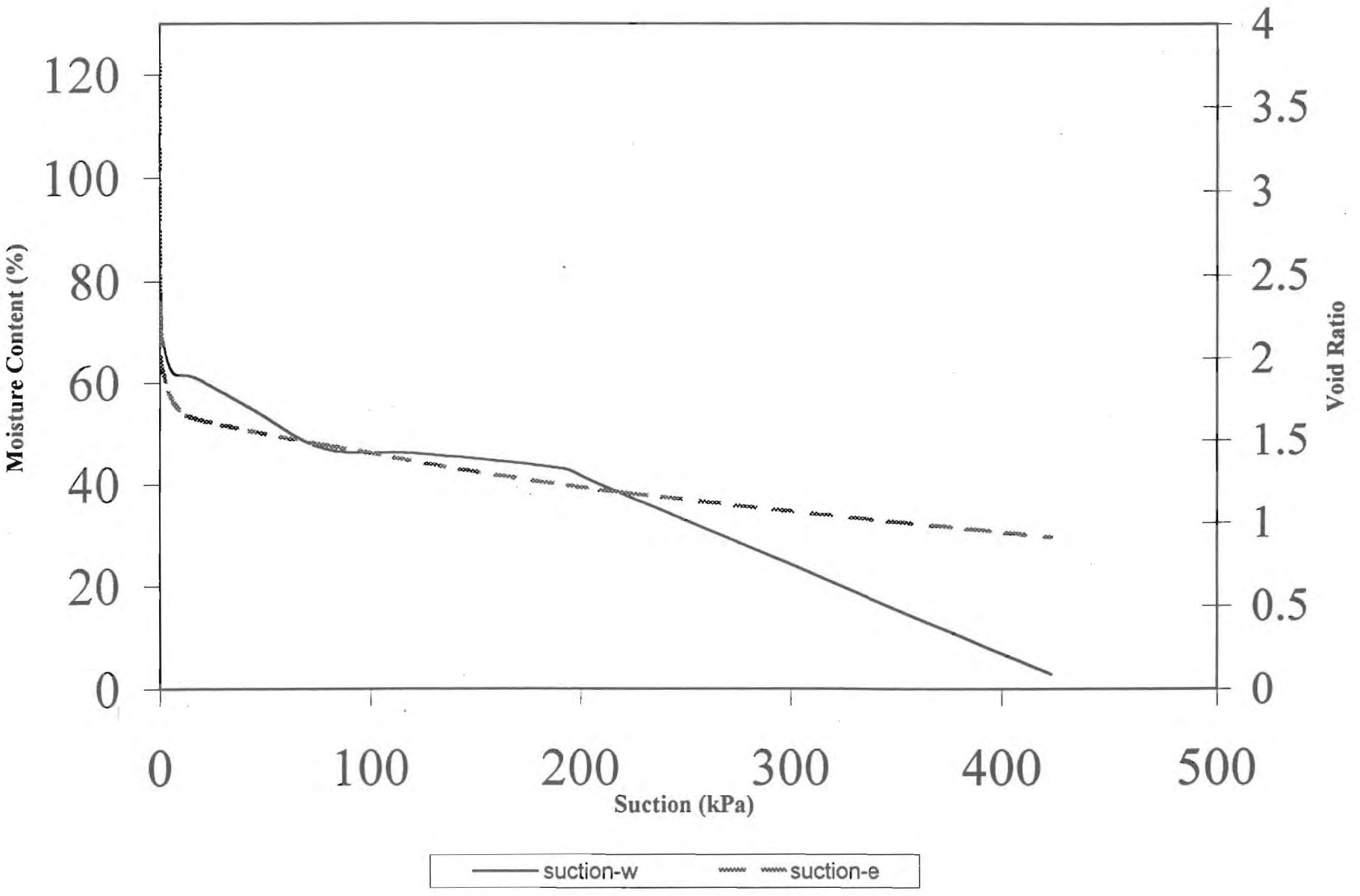


Figure 4.8: Combination soil water characteristic curve and shrinkage curve of fine tailings

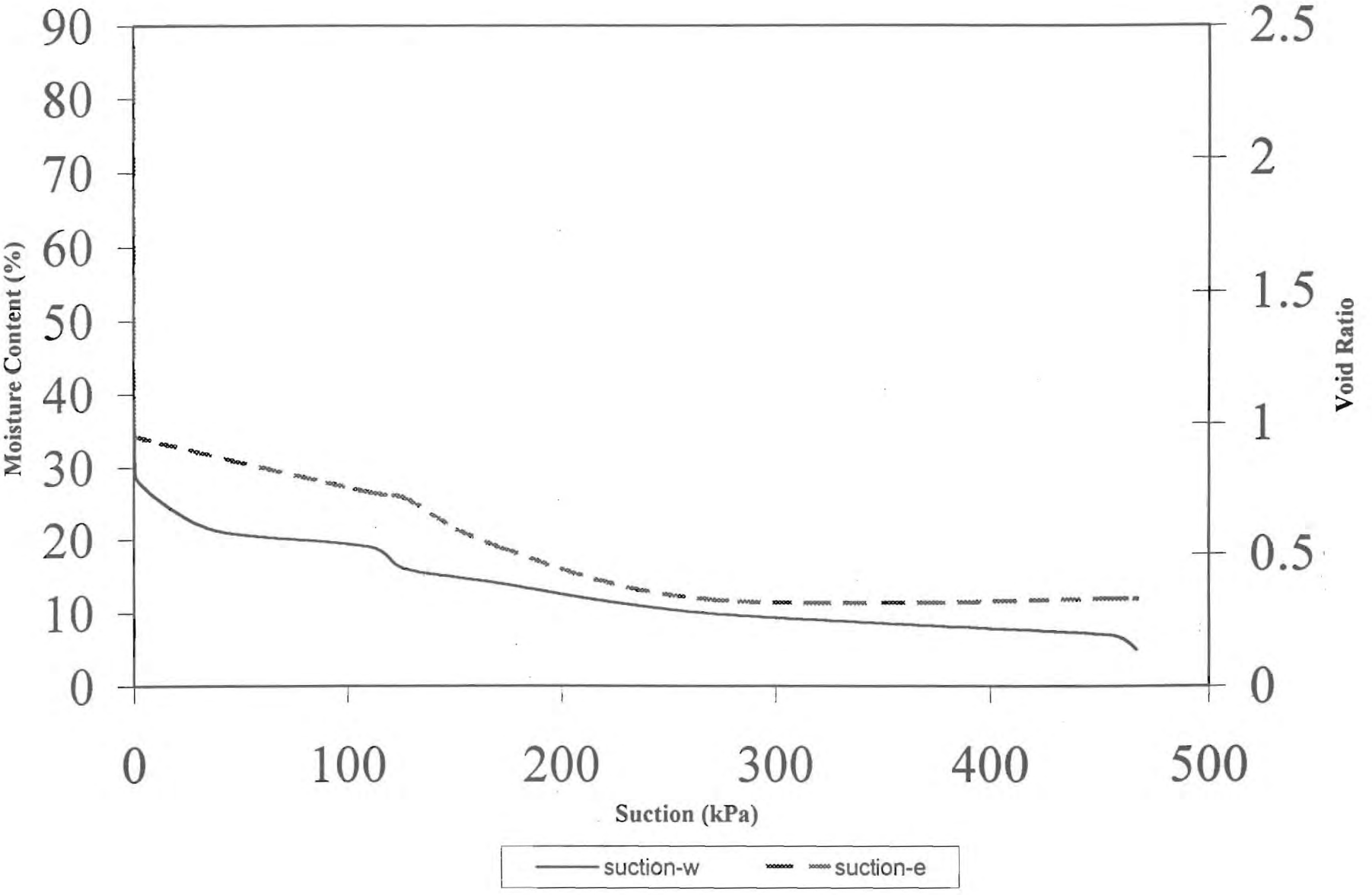


Figure 4.9: Combination soil water characteristic curve and shrinkage curve of coarse tailings

5 DEVELOPMENT OF A MID-PLANE SUCTION PROBE

The literature review with special regards to the Imperial College suction probe indicated that most of the problems experienced with matric suction measurement devices are related to cavitation. Due to this fact the design of the suction probe for tailings aimed at preventing cavitation. Calibration and laboratory testing highlighted serious shortcomings and design flaws in this original probe. It was decided to redesign to probe an attempt to eliminate these shortcomings.

5.1 Design of the Mid-plane Suction probe

The design of the suction probe was altered to isolate the diaphragm from the body of the probe without sacrificing the characteristics that prevents cavitation (Figure 5.1 and Figure 5.2). The strain-gauged diaphragm was replaced with a sub miniature Kyowa PS 2KA pressure transducer. The pressure sensor was embedded in a cavity leaving a gap of 0.1 mm for the water reservoir between the surface of the transducer and the ceramic.

Several other changes were also made such as the body material now being stainless steel, the reduced water reservoir and smaller overall size. The water reservoir was reduced to a diameter of 6 mm so to a volume of 2.827 mm^3. These changes improved the cavitation characteristics of the instrument in terms of reduced metal surface area as well as reduced cavity volume. This drastically reduced the crevices in the metal exposed to the cavity pore water. The overall size of the instrument is also reduced, making other applications such as a mid-plane pore pressure measurement in triaxial cells possible. Based on this feature the name of the probe was changed to the mid-plane suction probe. The working principle of conventional mid-plane probes is similar to that of a tensiometer and therefore shares the main limitation of the instrument namely the limited suction range. Suction pressures in samples however, are often in excess of 100 kPa with the result that cavitation of the reservoir water occurs. This can be eliminated by the use of high back pressure. The mid-plane suction probe being able to measure suction in excess of a 100 kPa could become a useful application in laboratory testing.

5.2 Maching and Assembly

The probe consists of two stainless steel sections with the front section containing the water reservoir, embedded pressure sensor cavity and the wire exit hole. Finer tolerances and finishes were used on the water reservoir for reasons as already discussed in Section 2.6.1. The back section contained the electrical connections.

The mid-plane suction probe was assembled dry. Firstly the pressure sensor wire exits were electrically isolated with M-coat, an air drying polyurethane coating. They were then routed through the hole provided for them. The sensor was glued into the cavity with Kyowa CC-33A strain gauge cement. Finally the area is waterproofed by sealing all exists from the section with strain gauge cement.

The machine shop trimmed the ceramic to the correct dimensions so that a tight fit between the ceramic and probe body is ensured. Epoxy glue was placed on the circumference of the ceramic only prior to pushing it into position. Care was taken not to smear the glue onto the rest of the ceramic as it would influence its permeability and hence the performance of suction pressure.

5.3 De-airing an Saturation

As mentioned previously, one of the alterations to the original design was the reduced overall size of the instrument. This made it possible to de-air the mid-plane probe in a volumetric flask. The flask was partly filled with de-aired water and the probe was dropped into it. A vacuum was then applied to it for a period of two hours. At the end of this period the mid-plane suction probe was removed form the flask and placed in a triaxial cell for saturation. The procedure adopted for saturation was similar to that discussed in Section 3.3.

5.4 Calibration

Calibration of the original suction probe was conducted using the previously discussed instruments and procedures. As can be seen from Figure 4.2 only the triaxial cell and

manometer calibration was reliable. It was assumed that the mid-plane suction probe would behave in a similar manner so that only calibration in the positive range was required. Calibration was thus done by connection the mid-plane suction probe to the cell pressure tube and applying pressure to it in increments of 50 kPa. Once again the reduced overall size of the probe made it possible to do so. The response of the probe was noted and seemed to behave in a linear fashion. A gauge factor of 1.6 was used during this procedure.

5.5 Laboratory Tests

One of the main problems experienced during the laboratory testing of the original suction probe was that inadequate volume readings were taken. Present desorption tests (utilising the mid-plane probe) aimed at improving on this aspect by measuring the decreasing height of the sample at three different positions and adopting the average value. Measurements were made relative to the top of the container. Independent volume calculations were made to provide a crosscheck. The calculation assumes that the decrease in sample weight is purely the due to the loss in weight caused by the evaporated water and that the sample remains saturated. The volume of evaporated water was calculated. Each new sample volume was thus the difference between the original volume and the volume of evaporated water. The calculated volume of the two methods compared well.

Differing from the previous testing procedure samples were left to dry at a control room temperature of 21°C as to opposed to oven drying at 28°C. This reduced the rate of evaporation extensively. Suction measurements could thus be made selectively, resulting in a better spread of measurements with time. Other than these changes, the adopted testing procedure is similar to that carried out using the original suction probe. The results are summarised by Table 5.1 and Figures 5.3 to 5.4.

Table 5.1: Laboratory test results using the mid-plane suction probe

Date	Time	Fine Tailings				Coarse Tailings			
		Suction (kPa)	Void Ratio	Degree of Saturation (%)	Moisture Content (%)	Suction (kPa)	Void Ratio	Degree of Saturation (%)	Moisture Content (%)
16/9	10:45	0	2.12	1.0	77	0	0.90	1.1	35
17/9	15:00	0	2.21	1.0	77	0	0.83	1.1	36
18/9	16:50	0	1.82	1.0	65	0	0.74	1.1	29
20/9	15:22	4	1.67	1.0	52	11	0.69	0.8	21
21/9	13:13	23	1.32	1.1	51	81	0.8	0.7	21
21/9	14:26	24	1.44	1.0	51	84	0.85	0.7	21
21/9	16:55	34	1.46	1.0	50	94	0.77	0.7	21
22/9	9:09	64	1.51	0.9	47	145	0.68	0.7	18
22/9	11:35	84	1.41	0.9	46	153	0.73	0.6	17
22/9	14:10	125	1.41	0.9	44	163	0.75	0.6	16
26/9	13:00	314	1.55	0.4	22				

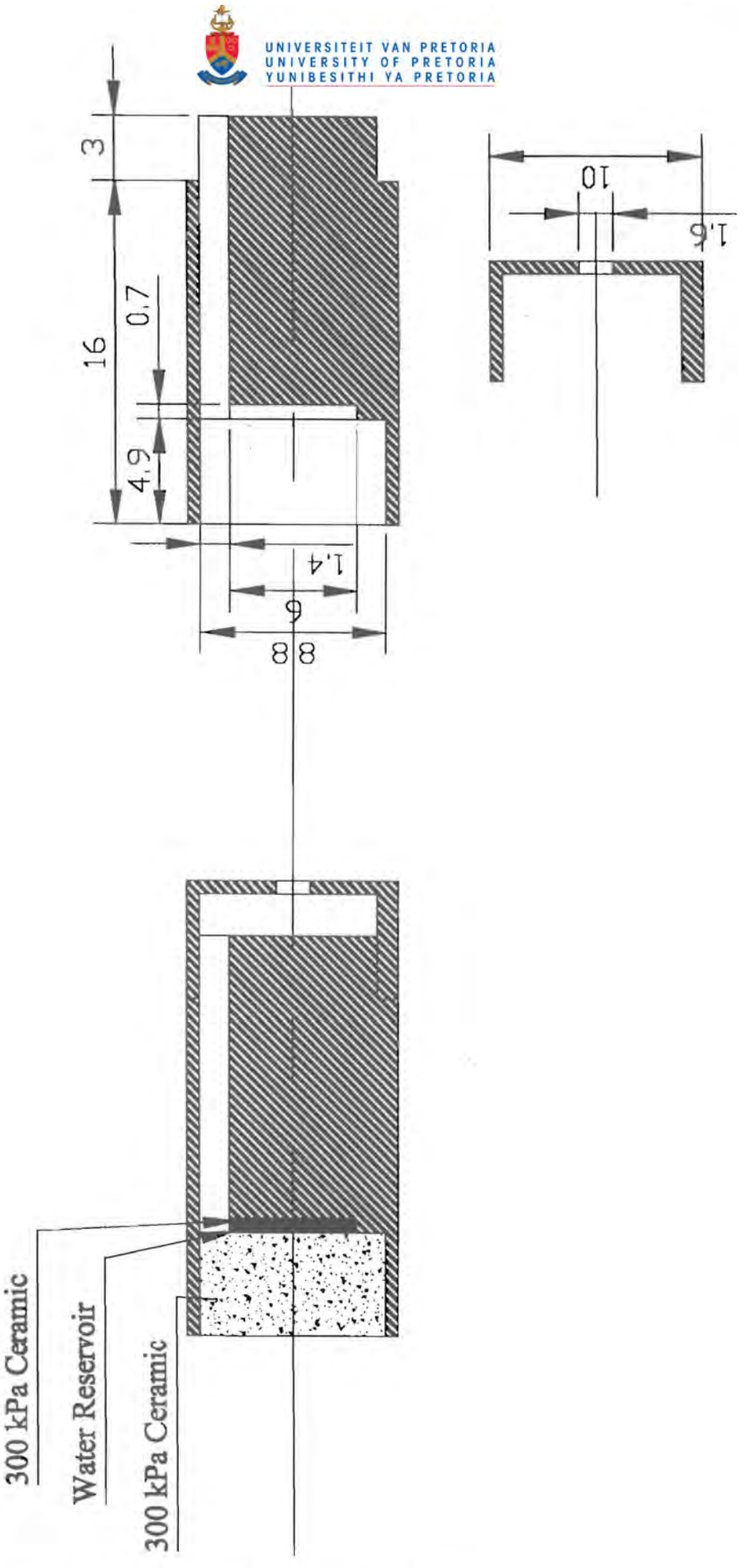
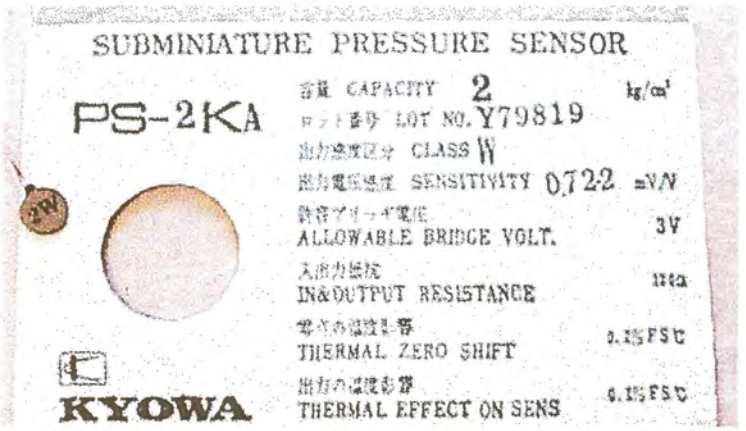
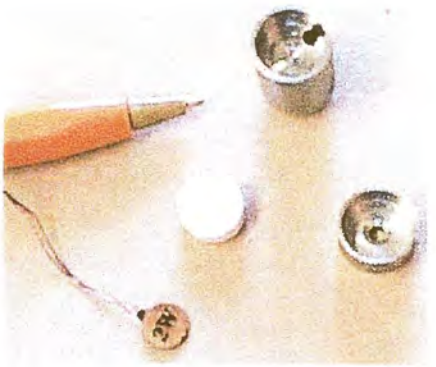


Figure 5.1: Machine drawing of mid-plane suction probe

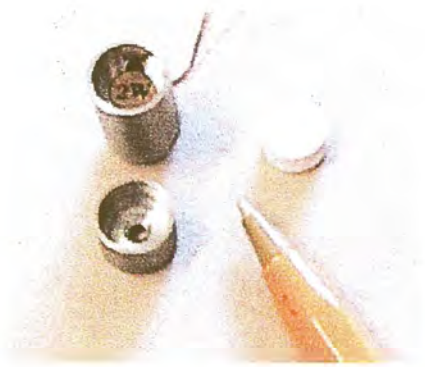


KYOWA Pressure Transducer

Side on view



Components for mid-plane suction probe



Pressure transducer installed

Completed Mid- plane suction probe

Figure 5.2 : Construction of mid-plane suction probe

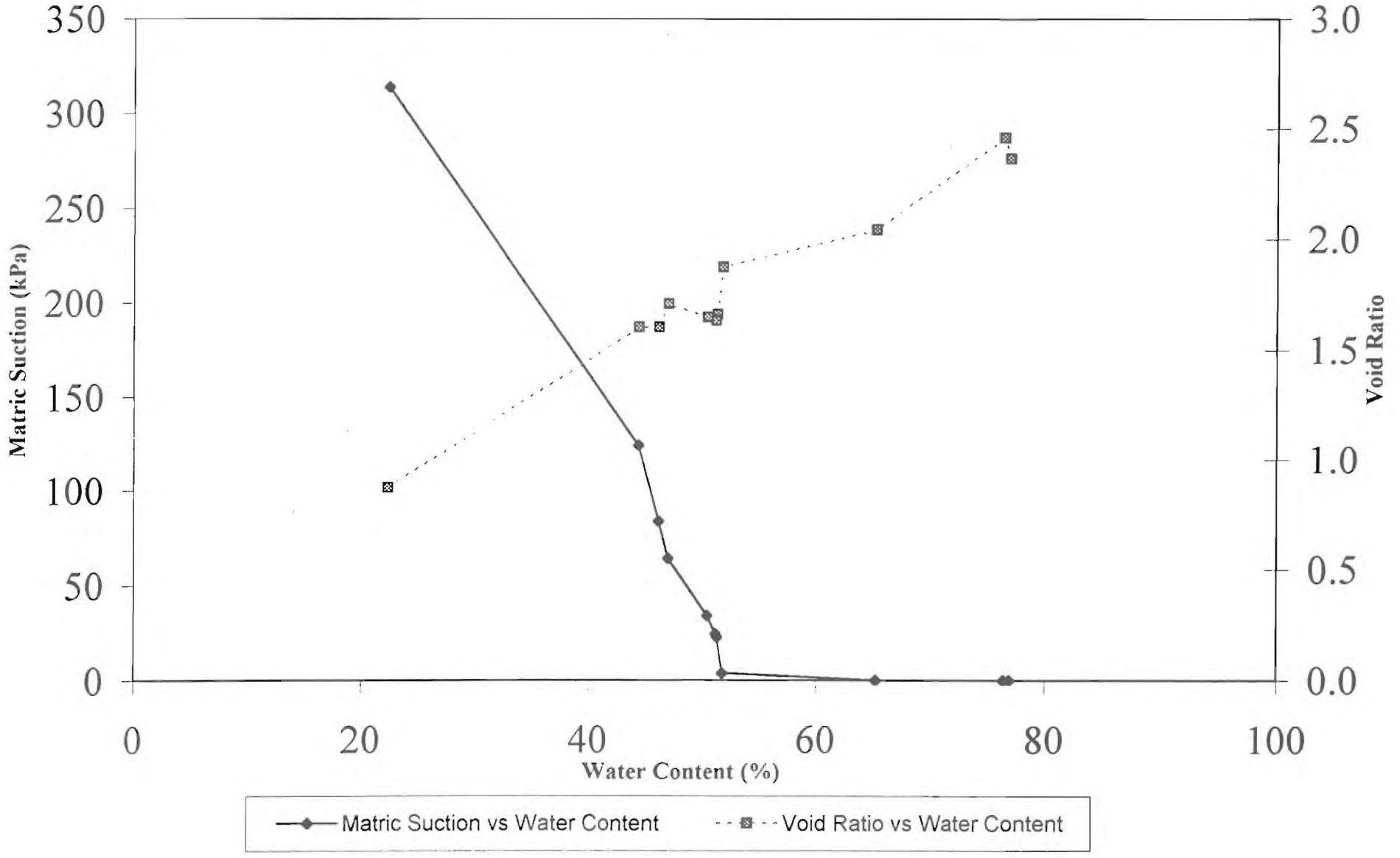


Figure 5.3: Combination soil water characteristic curve and shrinkage curve of fine tailings

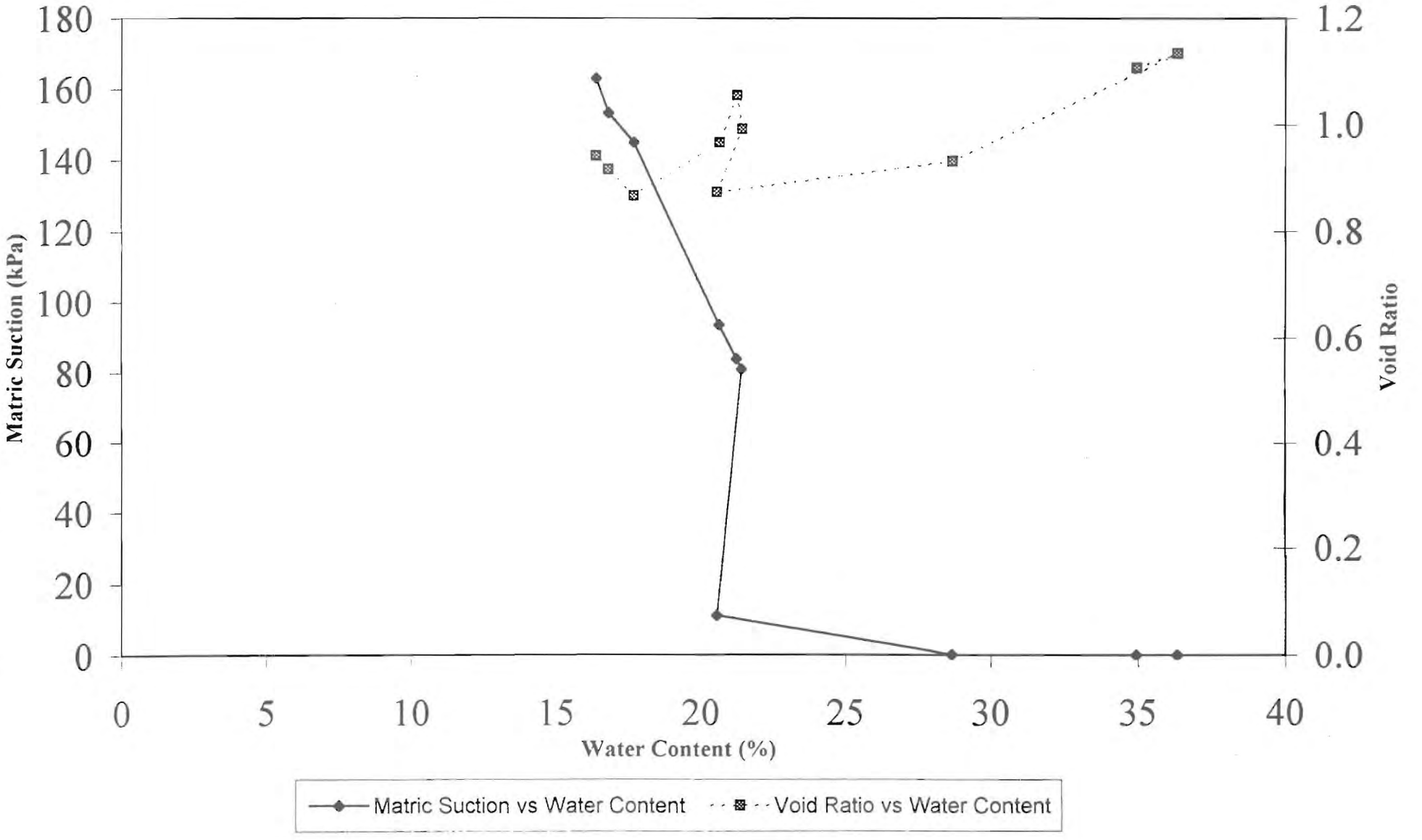


Figure 5.4: Combination soil water characteristic curve and shrinkage curve of coarse tailings

6 DISCUSSION

Calibration

A suction probe was built which was fundamentally a copy of the original probe developed by Ridley (1993) at Imperial College. The literature review stressed that the main problem with development of a suction probe was cavitation within the water chamber. This was found to be the case however, the calibration and testing of the instrument showed that there was a fundamental problem with the functioning of the probe. There was a serious problem with cross-talk between the load imposed on the body of the probe and the pressure sensor. The only means of eliminating this problem was to apply pressure purely via the water reservoir or to alter the design.

The suction probe was successfully calibrated in the negative pressure range with a modified manometer (Section 4.1.2) eliminating all cross-talk. This set-up only achieved a suction pressure of 84 kPa (Figure 4.2) before cavitation of the water between the suction probe and mercury in the manometer occurred. This cavitation pressure is in line with what can be expected for the set-up as well as the height above sea level. It was assumed that the calibration could be extrapolated beyond 84 kPa. As mentioned previously the diaphragm of the probe would deflect in such a way that it obeys Hooke's law, therefore deflections corresponding to positive and negative applied pressure should be equal but opposite in sign.

First measurements of suction pressures in gold tailings

The adopted methodology for measuring the suction properties of gold mine tailings during desorption mainly focussed on obtaining a representative spread of suction measurements against moisture content and volume with time using the above-mentioned copy of the Imperial College suction probe. After the processing of these results it became evident that the technique used to measure the volume was insufficiently accurate. Non the less, the test results followed the trend of published data and some information was gained with regards to the characteristics of the tailings. More importantly, it demonstrated that the suction probe functioned well in mine tailings. The cross-talk discussed earlier did not affect the functioning

of the probe during these readings. No load was placed on the probe and the suctions were transmitted via the ceramic only.

Rate of evaporation and subsequent suction gradient.

Suction measurement of Test 4 (Table 4.2), especially that of the fine tailings, indicated some anomaly around the reading taken at 8:20 on 6 March. These readings indicate a decrease of suction pressures against the trend while the sample was supposed to loose water with the void ratio and moisture content decreasing. The time lapse between the previous reading and these specific readings was in the order of 72 hours and moisture loss during this period was at a reduced rate. As mentioned in Section 4.2 the samples were removed overnight from the oven and covered with a glass plate to reduce evaporation. The period (72 hours) between the successive measurements thus correspond to covering the samples over a weekend. The decrease in suction measurement could best be explained by investigating the distribution of pore pressures within the sample during desorption. One of the assumptions of the testing procedure was that the pore pressure distribution in the sample was uniform and consequently the suction pressure on the upper surface should be representative of the rest of the sample. It was also assumed that the depth of the glass container was sufficiently shallow that this assumption would hold. In reality this was not the case. The pore water was free to evaporate from the upper surface which resulted in a moisture gradient developing within the sample. Covering the sample with a glass plate prevented the evaporation and therefore the gradient was reduced resulting in a decrease in suction pressures at the surface. This process could be considered in terms of phases. Phase 1 could be defined as the stage where evaporation takes place from the surface of the sample before it is covered by the glass plate. At this point the pressure gradient will be a maximum (Figure 6.1). The sample is then covered with the glass plate reducing evaporation leading to Phase 2, a transitional phase. Evaporation and the migration of water will slowly decrease until equilibrium is established between the dew pressure of the environment (the enclosed volume between the sample and glass plate) and the suction pressure of the sample. The enclosed evaporated water has now increased the relative humidity which in turn decreases the matric suction at the surface of the sample. The gradient should now be hydrostatic (assuming that the material is saturated) and a steady state is reached which could be defined as Phase 3.

The coarse tailing did not exhibit the above-mentioned behaviour. In fact, the suction pressure hardy changed during the period during which it was covered by the glass plate. The coarse tailings has a higher permeability and therefore the pore water will migrate at a higher rate resulting in a lower pressure gradient. The gradient was probably already close to its minimum (i.e. hydrostatic) before it was covered by the glass plate.

Volume-suction measurements

Owing to the theory, it was expected that the samples would remain fully saturated until the air entry suction pressure was reached. One of the assumptions of the experimental procedure was that any cracks that developed in the samples would be small and could therefore be neglected in the calculation of the volume of the sample(see Section 4). However, these cracks were fairly large resulting in unrealistic saturation calculations (Table 4.2). The original aim of these tests was to evaluate the performance of the suction probe and not to determine the soil-water characteristic curves of the tailings. It was seen an opportunity to attempt such readings but the shortcomings were abundantly clear and a carefully designed test procedure will need to be embarked upon to assess these properties. It is not seen as part of this thesis.

Comparison of suction pressures in fine and coarse tailings.

A comparison between the behaviour of the coarse and fine tailings with regards to matric suction and time highlights the influence of grading on suction pressure (Figure 6.2). It can be seen that matric suction develops at a greater rate in the coarse tailings than in the fine tailings. The coarser grading has a higher permeability and a larger pore size from which evaporation can take place and consequently suction pressures develop at a greater rate. The smaller pore radii of the fine tailings on the other hand generates a greater tensile pull. This results in a higher matric suction at any given moisture content.

Figure 6.3 compares the soil-water characteristics and shrinkage curves of the two samples. These results should be viewed in the light of the shortcomings in the volume measurements as discussed above. The figure indicates the large difference in both the initial and final void ratio of the samples, i. e. fine tailings having the greater void ratio. As generally accepted, a material that is uniformly graded will have a higher void ratio than a material that is well

graded. If the grading analysis of the two material is considered (Figure 4.5), it can be seen that their grading reflects their mechanical behaviour namely the coarse tailings having the lower shrinkage limit. Other effects such as surface forces also play a role.

Failure of suction probe

As mentioned (Section 4.2) the original suction probe based on the Imperial College probe seized to function. The reason was not clear. Tests and inspection indicated that the strain gauge was in perfect condition indicating that the problem was located in the diaphragm itself. The last sensible reading taken with this probe was at 314 kPa in the fine tailings. At this stage the suctions increased at a rapid rate and it is possible that these high suction pressures caused the diaphragm to plastically deform.

Mid-plane suction probe

Failure of the first suction probe necessitated a total redesign and construction of a new probe. The strain-gauged diaphragm was replaced with a sub miniature Kyowa PS-2KA pressure transducer. Referring to Section 5.1 the overall size of the instrument was greatly reduced. This feature had a number of advantages such as improved cavitation characteristics and versatility. This probe could also in future be used as a mid-plane probe in a triaxial cell.

The testing program that was carried out with the first suction probe was repeated with the re-designed "mid-plane suction probe". Improvements were mainly focused in the measurement of the sample volume during desorption. This was done by careful measurements of the shrinkage as well as calculating the volume change from the water loss. This obviously assumed full saturation. Close agreement between the two was obtained.

Air entry values with mid-plane probe.

The improved volume measurement made it possible to obtain the first part of the soil water characteristic curve and hence the air entry value of the samples. The procedure adopted for estimating the air entry value was in accordance with the method proposed by Brooks and

Corey (1964). The air entry value of the samples were estimated as 45 and 70 kPa for the coarse and fine tailings respectively (Figures 6.4 and 6.5).

Assessment

These last tests demonstrate the effectiveness of the re-designed mid-plane suction probe in gold mine tailings. The development of this probe and the demonstration of its abilities to measure these suctions (in terms of range and response time) concludes this research. The objectives set out in the introduction to this thesis were therefore successfully reached.

Future research

The next field of research will be the measurement of in-situ suction pressures in a mine tailings deposit. These could be done from surface or in shallow excavations. Down hole testing will be challenging but would ultimately produce a complete pressure regime and therefore a effective stress regime. This would enhance the understanding of the behaviour of a tailings dam and could lead to more realistic stability analyses and risk assessments.

Future development in laboratory applications includes the use of the mid-plane suction probe in a triaxial cell. Tests could also be designed to better measure the volume –moisture content- suction characteristics of the tailings. This will make it possible to obtain the full soil water characteristic water curve and assess both the air entry value as well as the residual water content. This could lead to a better understanding of aspects of tailings such as rate of rise and desiccation of the beach.

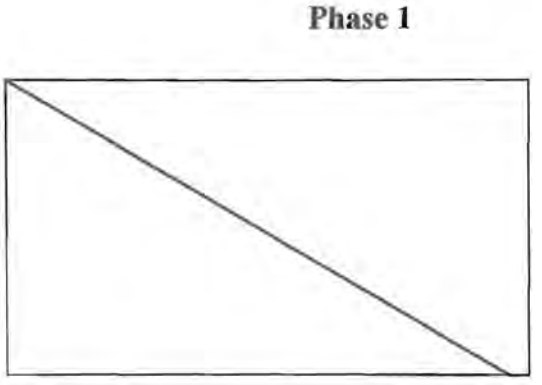


Figure 6.1: Pressure gradient in a tailings sample

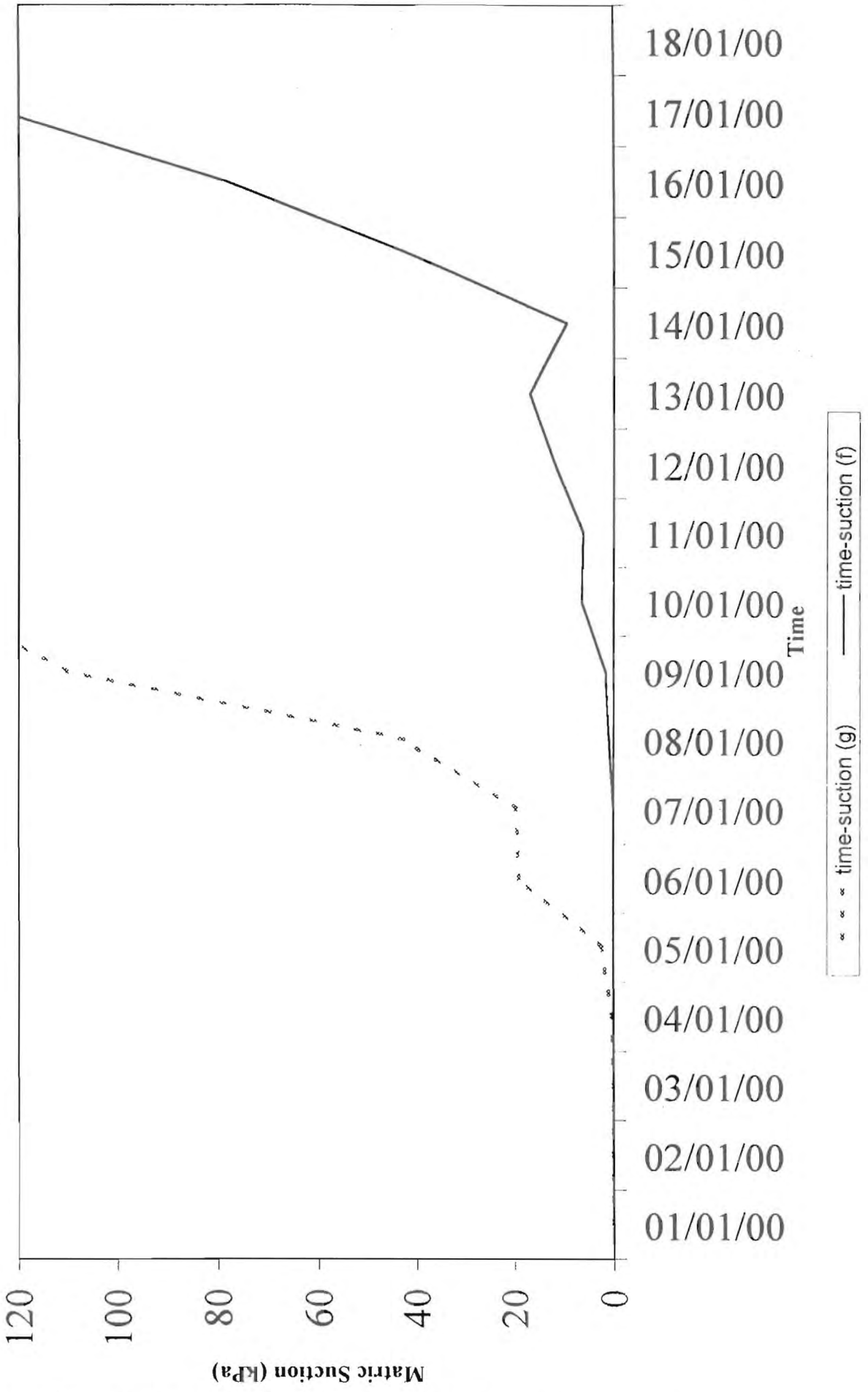


Figure 6.2: Relationship between matric suction and time for both fine and coarse tailings

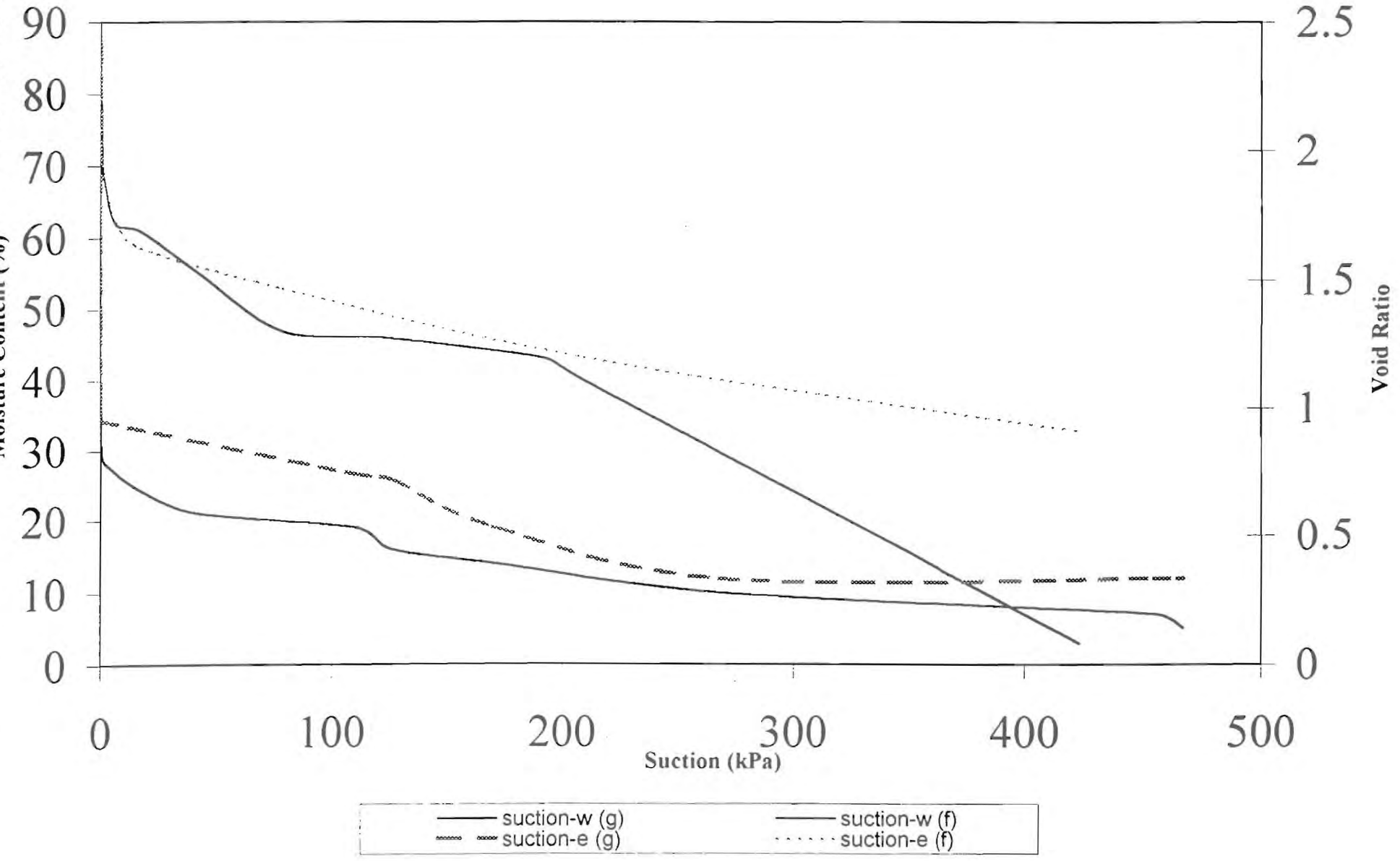


Figure 6.3: Combination soil water characteristic and shrinkage curve of fine and coarse tailings

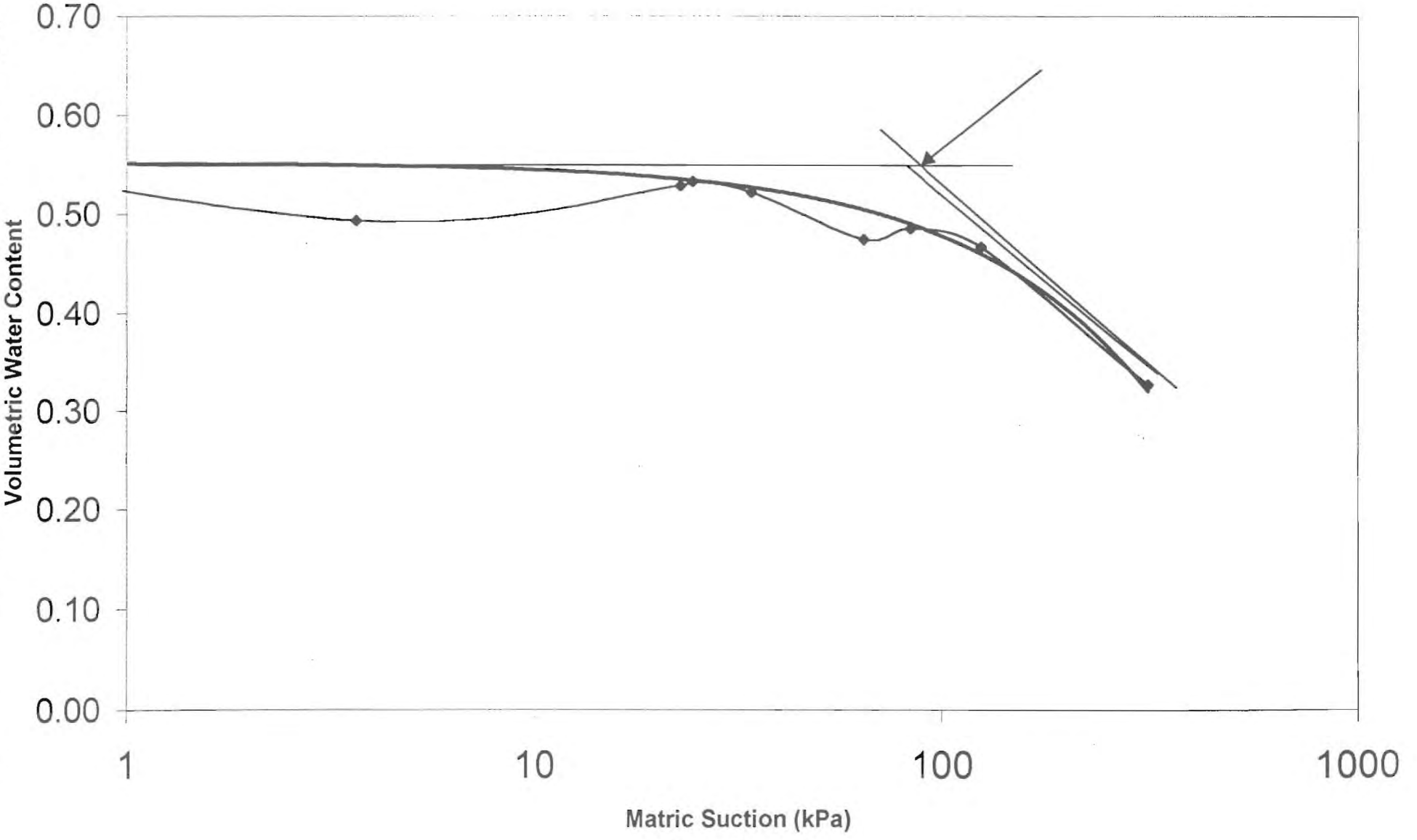


Figure 6.4: Soil water characteristic curve of fine tailings using the mid-plane suction probe

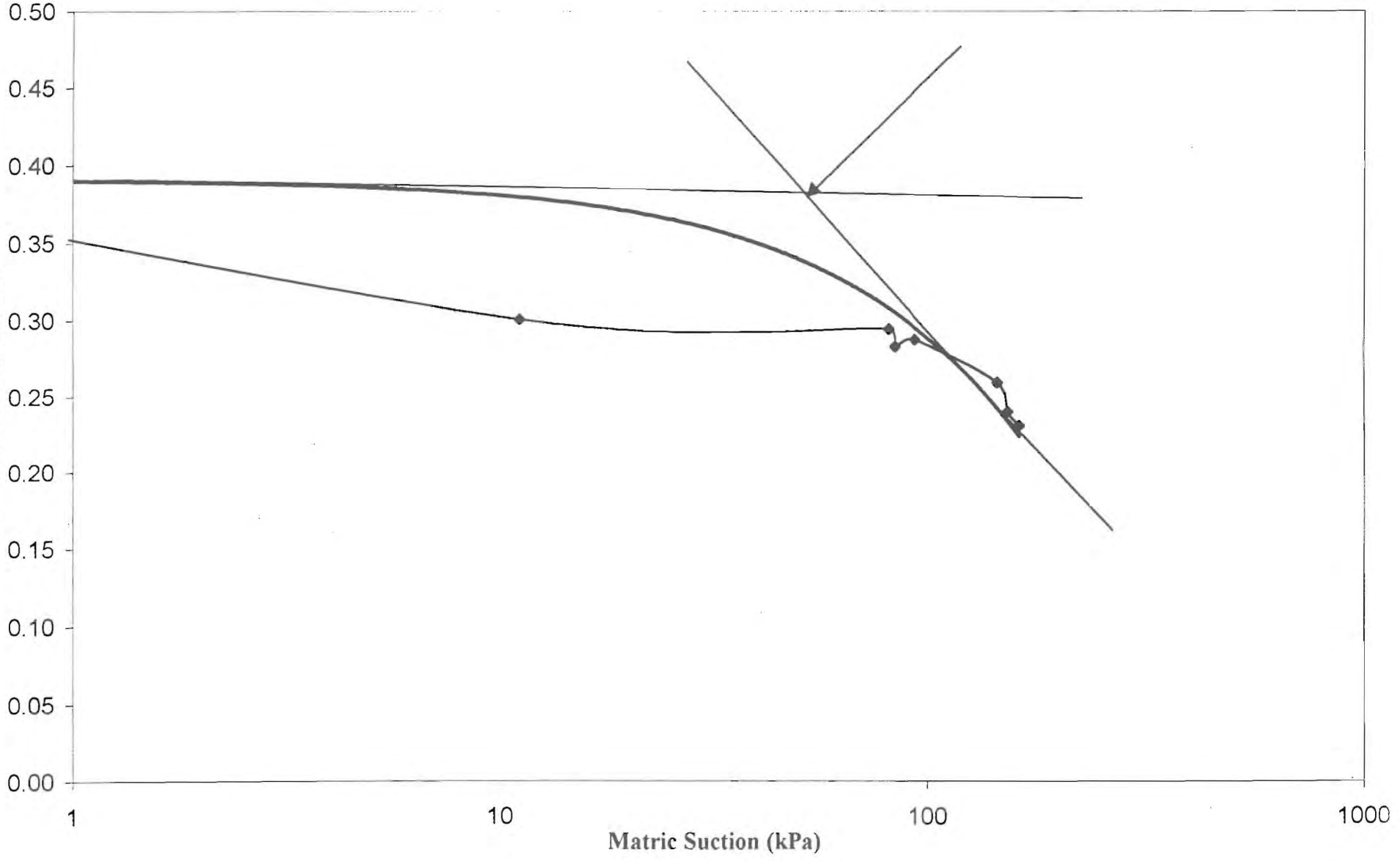


Figure 6.5: Soil water characteristic curve of coarse tailings using the mid-plane suction probe

7 CONCLUSIONS

The following conclusions are drawn form the thesis:

- The literature review indicated that the major problem associated with the suction probe was cavitation. Although this might be the case, the calibration and testing of a suction probe based on the Imperial College probe had a fatal design flaw. Cross-talk between external load on the body of the probe and the pressure sensor made this probe unusable in all but the simplest of applications.

- Calibration of this instrument in the negative pressure range was only achieved to 84 kPa using a modified manometer. It was assumed that the calibration curve could be extrapolated beyond this value. Other techniques such as unloading in an oedometer was not successful due to the above-mentioned cross-talk.

- The adopted method for measuring the decreasing volume of the samples during desorption proved to be inadequate and insufficient. A detailed soil water characteristic curve could thus not be obtained.

- The observed irregularity in the results of the suction measurements in the fine tailings (Table 4.2) was caused by the suction pressure gradient in the sample. The presence of this pressure gradient was demonstrated by the covering the samples with a glass plate. This eliminated the evaporation thereby reducing the gradient. It was also demonstrated that this phenomenon was related to the grading and permeability of the tailings.

- The degree of saturation changes with time as the volume of voids and water change during the evaporation of the pore water. Fundamental properties of the tailings such as the air entry and the shrinkage limit govern this process.

- Referring to the grading analysis of the two samples, the fine tailings correspond to a uniform grading while that of the coarse tailings is well graded. This explains the higher shrinkage limit and moisture content of the fine tailings.

- Failure of the original suction probe was probably due to plastic deformation of the sensing diaphragm.

- A new instrument (mid-plane suction probe) was designed incorporating an off-the-shelve sub miniature pressure transducer. This eliminated all cross-talk and also improved the performance of the probe. Specifically the cavitation properties, response time, simplified testing and instrument saturation as well as the possibility of using this suction probe as a mid plane pressure sensor in a triaxial cell.

- An improved method to measure the volume of the samples during the desorption test was devised. These volume measurements correlated well with the volumes calculated from the loss of water up to the air entry point.

- Future application of this instrument should include in situ suction measurements in tailings dams.

- Future laboratory based research should include developing the instrument as a mid-plane probe for triaxial testing. The ability of this probe to measure large suctions in triaxial samples makes it possible to carry out tests that were previously not possible.

- A test procedure should be designed to obtain the full moisture content-volume-suction characteristics of tailings using this suction probe. This, combined with the previous two conclusions will lead to a better understanding of the properties of mine tailings and ultimately to improved designs for tailings dams.

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