CHAPTER 3

EXPERIMENTAL PROGRAM

3.1 INTRODUCTION

Chapter 3 presents the results of a programme of in-situ fields tests, standard laboratory soil tests, as well as electron microscope and x-ray diffraction work on typical South African gold tailings. All fieldwork was done at, and samples collected from, one of South Africa's foremost mining operations, Vaal River Operations in the Northwest Province. Two tailings dams were selected: Pay Dam, the oldest impoundment on the mine and Mizpah the most recent addition. The experimental programme focussed on examining the composition and state of the tailings. To this extent the following aspects have been addressed for the whole tailings mix, as well as assorted fine and coarse layer selections from both dams:

- *Fundamental particle properties:* Mineralogical make-up, features of the distribution of particle sizes as well as characteristics of particle shape and surface texture.
- *Compressibility:* Influence of composition on compressibility characteristics based on reconstituted remoulded laboratory samples.
- *Shear strength:* Influence of material composition and state on the shear strength properties and shear behaviour of tailings. Tests were performed on both reconstituted and undisturbed samples.
- *Undisturbed structure:* Although not a major focus of this study, evidence of structure including fabric and bonding has been explored.

Knowledge of the above not only leads to a better understanding of the in-situ state and expected engineering behaviour of tailings, but also to improved interpretation of site investigation data, especially from the piezocone.

Experimental work was basically limited to material collected from the pond areas of both dams. Special circumstances at these dams, reclamation at Pay Dam and delayed deposition at Mizpah, made it possible to perform field tests and collect samples from areas which are normally not accessible under operating conditions.

Test results are reported in this chapter with little or no additional analysis and interpretation. In the next chapter the data is further analysed, interpreted and discussed with the aim of defining the in-situ composition and state of a typical South African gold tailings.

3.2 SITE

Vaal River Operations, formally Vaal Reefs, is situated on the Vaal River bordering the Northwest Province and the Freestate Province between Potchefstroom and Klerksdorp. The nearest town, Orkney, is practically part of the mine. The mine operates mainly on the Vaal Reef of the Witwatersrand Complex. Vaal River Operations forms part of the Anglo Gold Corporation, which was formed in June 1998 through a merger of the gold operations, mineral rights division and exploration division of the greater Anglo American Corporation and its associated companies. Anglo Gold is the world's largest producer of gold, at 7.1 million ounces a year.

3.2.1 Mizpah

Mizpah, Figure 3-1a, is named after the farm Mizpah on which it is located, and is the latest addition to the mine's impoundment structures. The dam was commissioned in November 1993 and receives approximately 150,000 tons of tailings per month from the No. 8 Gold Plant, after the coarse fraction has been removed for backfill purposes, and from the No. 9 Gold Plant. The reduction plant is currently a conventional crusher and mill plant. After comminution, uranium is extracted by acid leach and gold by a carbon-in-pulp process. Leaching is followed by flotation for gold and pyrite extraction and removal of the coarse fraction from the tailings pulp. A metallurgical report for the month of March 1997 is reproduced in Table 3-1.

The dam is currently (March 2000) 15.3 m high with a planned final height of 60 m. The total surface area is approximately 165 Ha with ten deposition stations around the perimeter. The average rate of rise is 2.4 meters per year or approximately 200 mm per month, with one deposition cycle taking between 9 and 10 days.

At Mizpah a set of piezocone soundings was carried out through a cross-section of the dam on the south side. Five sounding locations were selected: on the daywall, on the upper beach, middle beach, lower beach and in the beach-pond interface (Figure 3-1b). Bulk samples for laboratory testing were also collected from the beach-pond interface. The operators of Mizpah interrupted deposition from the south side of the dam, station number five, and allowed the beach to dry to the extent that off-road vehicles could travel all the way to the beach-pond interface, see Figure 3-2. This allowed field tests to be performed and samples to be collected from the pond area.

Table 3-1: Mine Metallurgical Report for Mizpah Whole Tailings (March 1997)

Parent Rock	72% from Vaal Reef: "C"-reef, Mizpah Reef 28% from Vaal Reef: Zandpan Marker	
Metallurgical Process	*Washing & Screening* *Crushing:* Jaw & Cone Crushers *Milling:* Ball & Tube Mills *Uranium Extraction:* H_2SO_4 & MnO_2 leach; Counter Current Decantation *Gold Extraction:* Neutralising with CaO; CN-leach; Carbon-in-Pulp *Floatation* *Residue Disposal:* Pumped 2km to Mizpah slimes dam	
Relative Density of Pulp	1.250 - 1.350	
Grading	> 150µm < 150µm & > 75µm < 75µm	: 10% : 20% : 70%
Effluent Analysis	Total Dissolved Solids (TDS) Suspended Solids (SS) pH Total Alkalinity Conductivity Magnesium (Mg) Sodium (Na) Chlorine (Cl) Calcium (Ca) Iron (Fe) Manganese (Mn) Potassium (K) Nitrates (NO_3) Phosphates (PO_4)	: 3560 ppm : 30 ppm : 8.4 : 40 : 452 mS/m : 30 ppm : 468 ppm : 310 ppm : 640 ppm : <0.5 ppm : 0.8 ppm : 78 ppm : 42 ppm : <0.5 ppm

3.2.2 Pay Dam

The name of this dam, Figure 3-3a, was derived from the fact that it is located close to the original West Reduction Plant, and that the deposit is of a payable grade. The dam was originally started in the 1940's and has subsequently been expanded by the construction of the large West Complex comprising a number of separate compartments. Following the failure of the northern penstock in the 1970's a floating penstock was installed at this location. Since then an additional 10 m of fill has been deposited. Reclamation by hydro cannon or monitor, Figure 3-4, was started in 1994 and approximately 300,000 tons were reclaimed per month at a grade of 0.4 - 0.5 g/t, at the time of the investigation.

The reclamation of Pay Dam afforded the opportunity of gaining access to relatively undisturbed profiles of the deposit to a depth of at least 5 m. Two locations were selected: the site of the northern penstock, Figure 3-4, and a site in the upper beach, Figure 3-5, on the north side of the impoundment. See Figure 3-3b for the location of these sites.

3.3 IN-SITU PROFILES AND SAMPLING

3.3.1 Introduction

Reclamation with hydro cannon exposed near vertical faces of the pond and beach areas to a depth of approximately 5 m on Pay Dam, Figure 3-4. This rare opportunity was fully exploited for profiling and sampling purposes. Both bulk disturbed samples, and undisturbed block and tube samples were recovered from Pay Dam for the purposes of determining the composition and state by controlled laboratory testing. Great care was taken with sampling and transportation of the undisturbed samples to minimise disturbance.

3.3.2 In-situ Profiles at Pay Dam

Figure 3-6 shows the site of the penstock on Pay Dam as well as a 5 m exposed profile of the material deposited in the pond. Details of this profile, and a similar one in the upper beach area of Pay Dam, can be viewed in Figures 3.9 - 3.30 as summarised in Table 3-2. The profiles were described using the guidelines given by Jennings, Brink and Williams (1973), which are widely accepted in South Africa.

Table 3-2: Details of the in-situ profiles on Pay Dam - May 1999.

Site	Depth Interval	Photo	Profile
Penstock	Full	Figure 3-6	Figure 3-12
	0 - 1 m	Figure 3-7	Figure 3-13
	1 - 2 m	Figure 3-8	Figure 3-14
	2 - 3 m	Figure 3-9	Figure 3-15
	3 - 4 m	Figure 3-10	Figure 3-16
	4 - 5 m	Figure 3-11	Figure 3-17
Upper Beach	Full	Figure 3-18	Figure 3-24
	0 - 1 m	Figure 3-19	Figure 3-25
	1 - 2 m	Figure 3-20	Figure 3-26
	2 - 3 m	Figure 3-21	Figure 3-27
	3 - 4 m	Figure 3-22	Figure 3-28
	4 - 5 m	Figure 3-23	Figure 3-29
	5 - 6 m		Figure 3-30

3.3.3 Sampler Design

A stainless steel tube sampler was specifically designed and manufactured for the purpose of extracting undisturbed 75 mm tube samples for triaxial testing. The design and operation

of this sampler followed closely the guidelines of good quality undisturbed sampling proposed by Clayton et al. (1995) see Table 3-3.

Table 3-3: Good quality sampling practice after Clayton et al. (1995).

Clayton et al. (1995)	Tube Sampler Used
• Minimum sample size should be 5 to 10 times the maximum particle size.	• Inside diameter of the tube sampler is 75 mm, which is 375 times the maximum particle size of 200 μm sampled.
• The size of the sample should represent in-situ structure realistically.	• Samples were extracted from single deposited layers of thickness greater than the sample length and are, therefore, representative of the structure within a single layer.
• Disturbance prior to actual sampling should be minimised.	• Sampling pits were carefully excavated by hand prior to the sampling drive.
• To limit axial compressive and lateral shear distortion the sampler should have: Small area ratio Small cutting edge taper Minimal inside friction Length:Diameter ratio < 6	• For this tube sampler: Area ratio = 2.6% Cutting edge taper = 5° The inner sleeve is highly polished and the cutting edge slightly pinched Length:Diameter ratio = 3
• Disturbance during the driving of the sampler should be minimised.	• The sampler was steadily driven over a short length of approximately 200 mm. • The sampler is fitted with a vent (Klinger valve) to relieve pressure build-up on top of the sample during the driving action.
• Disturbance during extraction of a driven sampler should be minimised.	• The sampler with the sample was carefully dug out and severed from the base to eliminate disturbance caused by base suctions.
• Disturbance due to extrusion and specimen trimming should be minimised.	• Samples were extruded in the direction of the initial drive using a close fitting plunger immediately following extraction.
• Changes to the sample moisture should be limited, including: Moisture loss due to drying Migration of moisture Pore pressure migration Freezing or too high temperatures. Chemical reactions.	• Samples were immediately extruded after sampling and wrapped in three layers of cling film and tinfoil to preserve the moisture. • Samples were tested as soon as possible after sampling to minimise migration of pore water and pore pressures, as well as any chemical reactions. • Samples were only subjected to mild temperatures.
• Transportation disturbance should be minimised.	• Wrapped samples were carefully packed in buckets filled with loose tailings sand for support and transported with cushioning to damp shocks and vibrations.

The resulting sampler, Figure 3-31, consists of two parts, the top-cap and the sampling tube. The top-cap is fitted with a Klinger valve, which serves as a vent when driving the sampler slowly. The top-cap is also lined with a rubber mat to provide a good seal between the two parts when the sampler is extracted with the vent closed. However, for this investigation, the sampler was dug out rather than extracted to minimise disturbance. The sampling tube is 230 mm long with an inside diameter of 75 mm. Except for the top 30 mm the outside diameter is 76 mm resulting in a 1 mm wall thickness over the driving length. The top 30 mm section is 6.5 mm thick to provide support for the studs holding the top-cap. The cutting edge is tapered at 5°. Although no provision was made for inside clearance, the cutting edge is slightly pinched to a diameter of 74.75 mm as a result of the manufacturing process. The whole sampler was machined from a seamless stainless steel tube and was polished on the inside for smoothness.

3.3.4 Disturbed samples

Bulk samples were collected either directly from a discharge pipe, in order to be representative of the whole tailings slurry delivered, or by digging up material representative of a specific layer in the dam profile.

Mizpah:

- March 1997

  A bulk sample of the whole tailings slurry, delivered to the daywall through station number 1 on the north side of the dam, was collected directly from the discharge pipe. The total volume of solids was approximately 0.1 m^3.
- May 1999

  Samples were recovered from the surface of the beach-pond interface on Mizpah close to the piezocone sounding at this location. The top layer, approximately 150 mm deep, consisted of a very fine slurry of slimes, whereas the next layer, of more or less the same depth, consisted of a much coarser material. Bulk samples of both the fine and coarse layers were collected. The sampling location had been under water at the start of the week, on Monday, and by Friday when the samples were collected, the pond water had receded and exposed the site.

Pay Dam:

- May 1999

  Representative bulk samples of coarse and fine material were recovered at the location of the northern penstock in addition to the undisturbed samples noted in Section 3.3.5.

The coarser material was sampled at a depth of 2m, Figure 3-15, and the finer material at a depth of 4.3 m, Figure 3-17.

3.3.5 Undisturbed samples

Pay Dam:

A number of undisturbed block and tube samples were recovered from the site of the exposed penstock on Pay Dam in May 1999. These samples were selected to be representative of the finest and coarsest material deposited at this location.

(a) Block Samples - one per location:

- Coarse: 1.3 m below surface - Figure 3-14.
- Mixed: 1.8 m below surface - Figure 3-14.
- Coarse: 3 m below surface - Figure 3-15 and Figure 3-16.
- Fine: 4.7 m below surface - Figure 3-17.

(b) 75mm Tube Samples - four per location:

- Coarse: 2 m below surface - Figure 3-15.
- Coarse: 3 m below surface - Figure 3-15 and Figure 3-16.
- Fine: 4.3 m below Surface - Figure 3-17.
- Fine: 4.7 m below Surface - Figure 3-17.

Figure 3-32 and Figure 3-33 show the sampling of an undisturbed block at 4.7 m, followed by a tube sample at the same depth.

3.3.6 Summary of samples recovered at Vaal River Operations.

Table 3-4 summarises the particulars of the samples that were collected for the experimental work, together with the codes that will be used to refer to each in this document.

3.4 LABORATORY TESTS

3.4.1 Introduction

The results of a comprehensive range of basic indicator, compressibility and shear strength tests, as well as electron microscope work and x-ray diffraction tests, are presented in this section. In Chapter 4 these results are discussed and used to build a framework for the

Table 3-4: Summary of sample descriptions and codes.

Tailings Dam	Description	Location	Code
Mizpah	**Disturbed: Bulk Samples**		
	Whole Tailings	Daywall delivery station pipe	MPDWT
	Fine	Beach-pond interface, surface	MPDF
	Coarse	Beach-pond interface, just below fines	MPDC
Pay Dam	**Disturbed: Bulk Samples**		
	Coarse	2 m below surface next to penstock	PPNDC
	Fine	4.3 m below surface next to penstock	PPNDF
	Undisturbed: Block samples, 1 per location		
	Coarse	1.3 m below surface next to penstock	PPNBC1
		3 m below surface next to penstock	PPNBC2
	Mixed	1.8 m below surface next to penstock	PPNBM
	Fine	4.3 m below surface next to penstock	PPNBF
	Undisturbed: 75 mm Tube Samples, 4 per location		
	Coarse	2 m below surface next to penstock	PPNTC2
		3 m below surface next to penstock	PPNTC1
	Fine	4.3 m below surface next to penstock	PPNTF2
		4.3 m below surface next to penstock	PPNTF1

mechanical behaviour of gold tailings as a function of the in-situ composition and state. All tests were done according to the British Standard, BS 1377: 1990, *Methods of Testing Soils for Civil Engineering Purposes*, where applicable.

3.4.2 Basic Indicator Tests

Specific gravity, gradings and Atterberg limits were determined using representative specimens selected from the bulk samples recovered from Mizpah and Pay Dam. The words sample and specimen are used in the context of this thesis as:

- *Sample*: A selection of material extracted from an on-site location either in bulk or as an undisturbed portion.
- *Specimen*: A laboratory test specimen, which can be artificially prepared from a bulk sample or consists of a trimmed part of an undisturbed sample.

Specific Gravity

BS test procedure: *Density Bottle (Small Pyknometer - 500 ml) Method* (BS1377: Part 2:1990:8.3).

The density bottle test is not the preferred method in BS 1377. However, the test procedure was modified for the purposes of this study to ensure full saturation of the sample before the final measurements were taken. Regardless, it is still a major improvement over the South African Institute for Transport and Roads Research recommendations, as set out in TMH1 (1986) and widely used in South Africa. The value of the calculated specific gravity is extremely sensitive to small inaccuracies in the measurements, and every precaution was taken to enssure reliable results. If the specimen is not fully saturated a significant error may be incorporated into the final result. In order to aid saturation, de-aired water was added to the dry specimen and subjected to at least five cycles of stirring and vacuum. Following this, the whole pyknometer was placed in a vacuum desiccator and left overnight.

The first tests were performed with both distilled water and tailings water to verify that the use of distilled water does not affect results. All subsequent tests were, therefore, done using only distilled water (Table 3-5).

Table 3-5: Values of Specific Gravity for the tailings tested.

Tailings Dam	Description	Fluid used	G_s (Mg/m^3)			
			Individual Results			Avg.
Mizpah	Whole Tailings	Distilled water	2.736	2.737	2.738	2.74
		Tailings water[1]	2.737	2.738		2.74
	Pond Fines	Distilled water	2.750	2.758	2.752	2.75
	Pond Coarse	Distilled water	2.728	2.726	2.723	2.73
Pay Dam	Penstock Fines	Distilled water	2.742	2.746	2.736	2.74
	Penstock Coarse	Distilled water	2.728	2.739	2.735	2.73

From Table 3-5 it is evident that an average value of G_s = 2.74 should suffice in most cases.

Grading

BS test procedures: *Wet Sieving - Fine Non-Cohesive Soils* (BS1377: Part 2:1990:9.2) and *Hydrometer Analysis* (BS1377: Part 2:1990:9.5).

Pre-treatment procedures performed on the specimens before subjecting them to the sieve and hydrometer tests included:

[1] The density of the tailings bleed water was determined to be 1.0041 g/ml at 25°C

- *Removal of organic material* - Organic matter present, mainly wood fibres in the tailings, can be removed by chemical treatment. This is achieved by the addition of hydrogen peroxide which oxidises the organic matter.
- *Calcareous content test* - Acid treatment of calcareous compounds, although not called for in the BS code might sometimes be appropriate. Calcareous compounds can act as a cementing agent, preventing separation of individual grains. To check for calcareous compounds, a few drops of hydrochloric acid are added to a specimen of the material to be graded. Effervescence indicates the possible presence of these compounds. Hydrochloric acid showed no reaction with the tailings material and acid treatment was therefore not required.
- *Dispersion* - The soil must also be treated with a dispersant and thoroughly agitated to ensure the separation of discrete particles, especially in the silt and clay sized ranges. A stock solution of the standard dispersant, Calgon, was used. Calgon consists of 35 g sodium hexametaphosphate $(NaPO_3)_6$ and 7 g sodium carbonate (Na_2CO_3) to make a one litre solution with distilled water.

Parallel tests were carried out with and without pre-treatment on similar specimens to determine the effect of treatment on the test results. The details of these tests and the resulting gradings are available in Table 3-6 and Table 3-7 and will be discussed in Chapter 4.

Atterberg Limits

BS test procedures: *Liquid Limit - Cone Penetrometer Method* (BS1377: Part 2:1990:4.3), *Plastic Limit* (BS1377: Part 2:1990:5.3), *Shrinkage Limit - Alternative Method* (BS1377: Part 2:1990:6.4) and *Linear Shrinkage* (BS1377: Part 2:1990:6.5).

The cone penetrometer method is preferred over the Casagrande method for determining the liquid limit of tailings for the following reasons:

- It is less operator dependent.
- Results are more repetitive.
- Preparation and handling of the silty tailings is better suited to this method.

The standard plasticity chart or Casagrande A-line chart, Figure 3-45, classifies the tailings used in this study as follows:

- Mizpah whole tailings and pond coarse tailings as well as Pay Dam penstock coarse tailings, classify as low plasticity silt/clay right on the intersection of the A-line and the clay-silt boundary.
- Mizpah pond fines classify as intermediate plasticity silt.
- Pay Dam penstock fines classify as high plasticity silt.

Table 3-6: Grading curves.

Tailings Dam	Description	Figure	Pre-treatment
Mizpah	Whole Tailings	Figure 3-34	Dispersed Non-dispersed Tailings water as solution
	Pond Fines	Figure 3-35	Dispersed Non-dispersed Organic treated & dispersed Organic treated & non-dispersed
	Pond Coarse	Figure 3-36	Dispersed Non-dispersed Organic treated & dispersed Organic treated & non-dispersed
Pay Dam	Penstock Fines	Figure 3-37	Dispersed Non-dispersed Organic treated & dispersed Organic treated & non-dispersed
	Penstock Coarse	Figure 3-38	Dispersed Non-dispersed Organic treated & dispersed Organic treated & non-dispersed
Combined		Figure 3-39	Dispersed

Table 3-7: Summary of the grading properties of dispersed gold tailings from Vaal River Operations.

Tailings Dam	Description	D_{10} (μm)	D_{30} (μm)	D_{60} (μm)	D_{90} (μm)	[2]*CU*	[3]*CC*
Mizpah	Whole Tailings	2.0	10.0	55.0	125.0	27.5	0.91
	Pond Fines	1.5	4.5	16.0	55.0	10.7	0.84
	Pond Coarse	3.0	25.0	75.0	145.0	25.0	2.78
Pay Dam	Penstock Fines	1.7	3.2	8.3	41.0	4.9	0.75
	Penstock Coarse	2.0	9.0	43.0	115.0	21.5	0.94

[2] *CU* = Coefficient of Uniformity = D_{60}/D_{10}

[3] *CC* = Coefficient of Curvature = $D_{30}^2/D_{10}D_{60}$

The results of the Atterberg limit tests are summarised in Table 3-8.

Table 3-8: Atterberg Limits.

Tailings Dam	Description	LL		PL	PI
		(%)	Figure	(%)	(%)
Mizpah	Whole Tailings	29	Figure 3-40	22	7
	Pond Fines	43	Figure 3-41	32	11
	Pond Coarse	28	Figure 3-42	22	6
Pay Dam	Penstock Fines	56	Figure 3-43	39	17
	Penstock Coarse	29	Figure 3-44	22	7

Shrinkage tests on Mizpah whole tailings indicated a shrinkage limit of 22% resulting in a shrinkage ratio of 1.68. Linear shrinkage was measured at 2%.

3.4.3 Microscope and X-ray Analyses

It is often convenient to simplify soils to continuum media for analytical purposes. However, it is the properties at particle level that ultimately control its engineering behaviour. Fundamental particle properties which are of importance include: mineralogy, grain size distribution, shape and surface texture. The basic indicator tests give an indirect measure of the grain size distribution and the importance of the clay minerals in a soil, but give no direct information on any of the fundamental particle properties. For this reason it was decided to undertake a comprehensive study of the tailings under the Scanning Electron Microscope (SEM) and using x-ray analysis techniques. In addition to photo micrographs of the tailings particles and the undisturbed structure, x-ray emission and diffraction analysis provided a means of identifying the elemental and mineral compositions of the material through x-ray spectrography.

Scanning Electron Microscope Images

Vermeulen (2000) gives an overview of the SEM and its basic operation as well as specimen preparation techniques. A concentrated beam of electrons interacts with the specimen in a vacuum. By detecting back-scattered incident electrons or secondary electrons liberated from the specimen surface an image is formed representing the object. This image appears naturally illuminated by light and shadow to the human eye, and is readily interpreted. However, image quality on non-conductive specimens, such as tailings, suffers from charge

build-up on the surface of the specimen. To improve image quality the specimen may be coated with a thin coating of conductive material (gold, carbon, etc.), to eliminate charge build-up and interference with the electron imaging system. In this study the tailings specimens were sputter-coated with a very thin gold film for SEM imaging purposes.

Mizpah whole tailings were mainly used to study the fundamental properties of the particles throughout the size ranges. Specimens were selected from the fractions separated by wet sieving and from the hydrometer sedimentation cylinder. The level of the sediment in the cylinder was marked following each timed interval for reading the hydrometer. On completion of the test these layers were then carefully extracted and separated to provide specimens for the SEM work. The material subjected to the grading analysis had been pre-treated with standard dispersant and should represent the composition of the material in a segregated state. In addition to the whole tailings, undispersed specimens of Mizpah and Pay Dam fine and coarse samples were also imaged for comparison.

Undisturbed specimens, trimmed from the block samples collected from Pay Dam, were used to study the structure of the material in an undisturbed state. These specimens were dried in an oven at a maximum temperature of 35°C to simulate conditions which the material might have been subjected to during cycles of drying. For SEM work on fragile biological samples specialised techniques of flash freezing and freeze drying may be employed to preserve the undisturbed structure of the biological tissue. These techniques may be adapted for soil mechanics purposes, where weak bonding and fragile structure may be destroyed in drying the specimen. These methods are time consuming and highly specialised.

Specimens were mounted on the microscope stage using conductive double-sided carbon tape, which appears as a dark smooth background with regularly spaced pores. To further ensure conductivity of the otherwise non-conductive tailings particles, a thin coating of gold was applied by the sputter method. Five coatings, lasting 30 seconds each, were applied to minimise heating of the specimen. During the imaging process the beam of electrons was accelerated using a voltage of 15 kV in a relatively low vacuum of 10^{-4} torr. An image of the specimen surface was formed using a scintillator detector sensitive to low energy secondary electrons. The detector produces light when bombarded by accelerated electrons of a specific energy, and thus is able to differentiate between high energy back-scattered electrons and lower energy secondary electrons. Secondary electrons give a high definition of surface features as they can only escape from very near to the specimen surface.

SEM micrographs of the tailings considered in this study are catalogued in Table 3-9.

Table 3-9: Scanning Electron Micrographs.

Tailings Dam	Description		Figure
Mizpah	Whole Tailings	Dispersed and graded	Figure 3-46 to Figure 3-61
	Pond Fines	Undispersed, bulk	Figure 3-62
	Pond Coarse	Undispersed, bulk	Figure 3-63
Pay Dam	Penstock Fines	Undispersed, bulk	Figure 3-64
		Undisturbed	Figure 3-65
	Penstock Coarse	Undispersed, bulk	Figure 3-66
		Undisturbed	Figure 3-67

Energy Dispersive X-ray Spectrometry

As part of the SEM imaging process, energy dispersive x-ray spectrometry (EDS) may be performed for a qualitative and quantitative spectral analysis of elemental composition. One of the interactions of the incident electron beam with the specimen is the emission of characteristic x-rays as a result of transitions between energy levels in atoms ionised by the bombarding electrons. Elements are then identified by their characteristic spectrum lines, the amplitudes of which give an indication of the concentration. EDS is essentially a spot measurement, which can be applied to a single tailings particle. Spatial resolution, representing the smallest particle that can be analysed, is limited to about 1 μm due spreading of the electron beam within the specimen.

The specimens used for SEM imaging were also subjected to selective EDS analyses. The acceleration voltage was increased to 20 kV during spectrometry to comply with the calibration of the analytical system, which uses a silicon/lithium solid state detector. A detection time of 100 seconds was allowed for each reading resulting in approximately 20 seconds dead time in the detector, well within acceptable limits. It should be noted that all EDS spectra show a strong peak for the element gold due to the thin gold coating.

From a total of more than 100 EDS analyses that were performed on material from both Mizpah and Pay Dam, only four distinct spectra could be identified, see Table 3-10 and Figure 3-68. These are representative of:

- Smooth surfaced tailings sand: 93% silicon.
- Rough surfaced tailings sand: 64% silicon, 21% aluminium and 10% potassium.
- Flaky slimes: 75% silicon, 12% aluminium and 4% each of potassium and iron.
- Flocs of flaky slimes: 57% silicon, 17% aluminium, 13% iron and 6% potassium.

Table 3-10: Elemental composition of tailings particles by EDS.

Element	Percentages Detected														
	Smooth surfaced Sands			Rough surfaced Sands			Flaky Slimes			Slime flocs			Hydrometer Precipitate		
	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum	Maximum	Average	Minimum
Na	1	0	1	1	0	1	2	1	1	1	1	1		43	
Mg	0	0	0	0	0	0	1	0	1	7	2	1		0	
Al	4	2	1	29	21	11	25	12	1	24	17	7		0	
Si	96	93	89	82	64	49	97	75	48	75	57	36		1	
P	0	0	0	0	0	0	3	1	1	1	0	1		15	
S	1	0	1	1	0	1	3	1	1	0	0	0		31	
K	2	1	1	17	10	1	8	4	1	11	6	1		0	
Ca	1	0	1	0	0	0	4	1	1	2	1	1		4	
Fe	1	0	1	4	2	1	7	4	1	34	13	3		1	
Other	3	2	1	4	2	1	3	2	1	4	3	2		4	

Table 3-10 and Figure 3-68 also show the results of EDS analyses on the precipitate that remains after drying the clear solution floating on top of the sediment in a hydrometer sedimentation test. It should be noted that the chemistry of this solution must have been influenced by the addition of a dispersing agent. The results indicate 43% sodium, 31% sulphur, 15% phosphor and 4% calcium.

X-ray Diffraction Analyses

Powder X-ray Diffraction (XRD) is one of the primary techniques used by mineralogists and solid state chemists to examine the physico-chemical make-up of unknown solids. According to the XRD technique a powdered sample is placed in a holder, and illuminated with x-rays of a fixed wave-length. The intensity of the reflected radiation is then recorded using a goniometer. The results are represented in a collection of single-phase X-ray powder diffraction patterns or spectra. Each crystalline solid or mineral has its unique characteristic X-ray powder pattern, which may be used as a "fingerprint" for its identification.

XRD tests were not performed by the author, but were done by the University of Pretoria, Mineral Sciences Division. Two series of tests were performed, the first on untreated specimens of each of the five different tailings samples studied, and the second on five

selected size fractions of the Mizpah whole tailings: 150 μm, 75 μm, 10 μm, 2μm and 1μm. The Mizpah whole tailings fractions were pre-treated with dispersant, subjected to sieve and hydrometer tests and subsequently dried. The results are summarised in Table 3-11.

Table 3-11: XRD results on Mizpah Whole Tailings.

Mizpah and Pay Dam Tailings					
Tailings Dam	**Description**	**Figure**			
Mizpah	Whole tailings	Figure 3-69			
	Pond fine tailings	Figure 3-70			
	Pond coarse tailings	Figure 3-71			
Pay Dam	Penstock fine tailings	Figure 3-72			
	Penstock coarse tailings	Figure 3-73			
Mizpah Whole Tailings: Separate Fractions					
Mineral	**150 μm**	**75 μm**	**10 μm**	**2 μm**	**1 μm**
	Figure 3-74	Figure 3-75	Figure 3-76	Figure 3-77	Figure 3-78

3.4.4 Densities

In-situ Densities:

Table 3-12, summarises the in-situ densities measured on two undisturbed tube samples recovered from the Pay Dam penstock area for this purpose. Table 3-13 gives additional information from measurements on the undisturbed tube samples that were used for triaxial testing in Section 3.4.5 and 3.4.6.

Table 3-12: In-situ densities at Pay Dam penstock from undisturbed tube samples.

Description		**PPNTF2**	**PPNTC2**
		Fine	**Coarse**
Depth below surface	m	4.3	2.0
Moisture content	%	53.9	19.6
Degree of saturation	%	99	61
Bulk density, ρ_{nat}	kg/m^3	1694	1742
Dry density, ρ_{dry}	kg/m^3	1101	1457
Void ratio		1.49	0.87
In-situ vertical stress, σ_v	kPa	71	34
Pore pressure from CPTU dissipation tests	kPa	-4	1
Vertical effective stress, σ'_v	kPa	75	33

Table 3-13: In-situ stresses and densities at Pay Dam penstock from triaxial specimens.

Description		PPNTF1			PPNTC1		
		Fine			Coarse		
Depth below surface	m	4.3			3.0		
Moisture content	%	52.7	56.6	50.4	18.2	20.5	17.2
Degree of saturation	%	100	100	98	64	69	62
Bulk density, ρ_{nat}	kg/m^3	1750	1743	1700	1819	1812	1821
Dry density, ρ_{dry}	kg/m^3	1146	1100	1138	1539	1503	1553
Void ratio		1.39	1.46	1.41	0.77	0.81	0.76
In-situ vertical stress, σ_v	kPa	71			51		
Pore pressure from CPTU	kPa	-4			-4		
Vertical effective stress, σ'_v	kPa	75			55		
Pre-consolidation pressure σ'_{vmax}	kPa	150			100		
Overconsolidation ratio, (R_o)		2			2		

Compaction Densities of Mizpah Whole Tailings.

BS test procedures: *"Light" Compaction Test (2.5 kg hammer method)* (BS1377: Part 4:1990:3.3), *"Heavy" Compaction Test (4.5 kg hammer method)* (BS1377: Part 4:1990:3.5) and *Maximum Density - Sands* (BS1377: Part 4:1990:4.2).

All compaction tests were performed on Mizpah whole tailings in an ASTM 4" mould with internal volume of 944 cm^3 and applied energies as set out in Table 3-14. These tests were done to investigate the possibility of preparing reconstituted triaxial test specimens using standard compaction methods.

Table 3-14: Compaction energies applied to Mizpah Whole Tailings.

Compaction	Hammer (*kg*)	Fall Height (*mm*)	Layers	Blows / Layer	Energy (*kJ/m^3*)
BS Light	2.49	305	3	25	592
2 x BS Light	2.49	305	3	46	1089
BS Heavy	4.54	457	5	25	2695
2 x BS Heavy	4.54	457	5	46	4959
Maximum	4.54	457	5	75	8085

Dry density and optimum moisture content plots are shown at the various compaction energies in Figure 3-79 and summarised in Table 3-15.

Table 3-15: Density tests on Mizpah whole tailings.

Compaction densities: Mizpah whole tailings			
	Maximum Dry Density (kg/m^3)	**Bulk Density (kg/m^3)**	**Opt. Moisture Content (%)**
BS Light	1710	2010	17
2 x BS Light	1745	2030	16
BS Heavy	1850	2090	14
2 x BS Heavy	1905	2150	13
Limiting densities: Mizpah whole tailings			
	Dry Density (kg/m^3)	**Void Ratio**	**Moisture Content (%)**
Minimum	867	2.156	80
Maximum	1945	0.407	12

From the densities listed in Table 3-15 it was concluded that standard compaction techniques could not be used to prepare reconstituted laboratory specimens for triaxial testing. The compaction dry densities were far too high compared with typical values measured in-situ, which range from 1000 to a maximum of 1500 kg/m^3. It was, therefore, decided to use sedimentation techniques to prepare specimens artificially for compression and shear testing. The low density states attained following sedimentation (minimum density of approximately 900 kg/m^3 in Table 3-15) are more representative of in-situ densities and of the processes by which deposits are formed on a tailings impoundment.

3.4.5 Compression and Consolidation

Isotropic Compression and Consolidation

Isotropic compression and consolidation tests were performed in 75 mm triaxial cells according to the guidelines given in BS1377:1990 Parts 5 and 6. Special consideration was given to the techniques of specimen preparation to simulate the field or in-situ conditions as closely as possible. To this end the following methods were employed:

(a) 75 mm undisturbed specimens from tube samples:

Very little preparation was needed, resulting in the minimum time of exposure and moisture loss due to drying.

- Samples were extruded in the field and wrapped with successive layers of cling film and tin foil before being transported to the laboratory.
- After unwrapping the samples in the laboratory, triaxial specimens were carefully trimmed to the required length, measured and placed into the cell, ready for testing.

(b) Reconstituted remoulded slurry specimens:

Specimens were prepared in the form of a slurry by sedimentation and consolidation of tailings from a aqueous solution. These specimens should be representative of in-situ states.

- A specimen was selected from a bulk sample of tailings at the in-situ moisture content.
- This material was then mixed with tap water to form an aqueous solution at a moisture content of at least 3 times the liquid limit of the tailings.
- The solution was placed under vacuum to get rid of as much air as possible and then allowed to settle and consolidate for 48 hours.
- After sedimentation the bleed water was decanted and the sample thoroughly mixed (remoulded). Typical moisture content and densities at this stage are summarised in Table 3-16. These values correspond to the minimum densities attainable by sedimentation methods, see Table 3-15.

Table 3-16: Moisture content and void ratio after sedimentation.

Tailings Dam	Description	*w* (%)	*e*	ρ_d (kN/m^3)
Mizpah	Whole Tailings	65	1.8	979
	Pond Fines	90	2.5	786
	Pond Coarse	50	1.4	1138
Pay Dam	Penstock Fines	135	3.7	583
	Penstock Coarse	75	2.1	881

The void ratios are less than half those predicted by Carrier et al. (1983), Section 2.5.2, for the end of sedimentation start of consolidation phase. It is likely that the samples have undergone some self-weight consolidation in the 48 hour rest period in addition to sedimentation.

- The triaxial cell was prepared by cleaning, flushing, etc. and fitted with a 75 mm split mould, membrane, bottom porous stone and base filter paper. Side drains were not used.
- The mould was filled with de-aired water to just above the level of the bottom porous stone, followed by the remoulded tailings slurry to fill the mould.

- A slight suction (5 kPa) was then applied through the bottom porous stone to induce a small effective stress in the specimen. This provides enough strength in the specimen to allow the cell to be assembled without causing liquefaction.
- Under these conditions the specimen was allowed to consolidate. More slurry had to be added in increments until the mould was filled to the intended height at the applied suction.
- At no stage was the specimen allowed to dry or de-saturate by maintaining a free water level over the specimen.
- The top-cap, porous stone and top filter paper were then placed and secured and the split mould removed.
- Before the cell was assembled the specimen was measured through the membrane taking account of membrane thickness, etc.
- After the cell had been filled with water the suction was removed and the B-value checked under a "bedding" pressure of 5 kPa. At this stage the moisture content and density had reduced by approximately one half of the initial values as indicated in Table 3-17.

Table 3-17: Moisture content and void ratio before testing.

Tailings Dam	Description	w (%)	e	ρ_d (kN/m^3)
Mizpah	Whole Tailings	35	0.9	1442
	Pond Fines	45	1.2	1250
	Pond Coarse	25	0.7	1606
Pay Dam	Penstock Fines	60	1.7	1015
	Penstock Coarse	30	0.8	1517

The void ratios of the reconstituted remoulded Pay Dam fine and coarse specimens were in reasonable agreement with the void ratios of the undisturbed samples collected from the dam. For the fine tailings the void ratios were: 1.5 in-situ and 1.7 reconstituted in the laboratory; for the coarse tailings: 0.9 in-situ and 0.8 reconstituted. The lower in-situ values are probably the result of light overconsolidation following desiccation, as well as the slightly higher effective stress level of approximately 30 to 70 kPa in-situ. From these comparisons it was concluded that the method of preparing the reconstituted specimens from a slurry resulted in fine and coarse specimens representative of in-situ densities.

Procedures adopted for carrying out consolidation stages in the triaxial apparatus were:

(a) Once the triaxial cell had been assembled, the back pressure was gradually increased to 300 kPa, while the cell pressure was maintained at 5 kPa above the back pressure. During this procedure the specimen was therefore subject to a 5 kPa effective isotropic consolidation pressure. With reconstituted specimens a B-value of 0.98 to 1.00 could easily be attained, but with the undisturbed tube samples, especially the coarser drier material, a B-value of 0.95 or more was considered sufficient.

(b) Saturation was followed by isotropic consolidation stages at 12.5, 25, 50, 100, 200 and 400 kPa effective stress. Pore pressures were measured at the base of the specimen and drainage allowed through the top-cap without the use of side drains. The volume of pore water draining to or from a specimen, against the back pressure, was measured using a volumetric burette marked in increments of 0.1 ml. Both filter paper and a porous stones were used to cap the specimen and prevent material loss and clogging of the drainage system during consolidation.

The above procedures resulted in an isotropic stress condition during consolidation, but with one-dimensional upwards flow of pore water.

Figure 3-80 shows the combined results of the triaxial compression tests. The results of the individual compression and consolidation tests on reconstituted and undisturbed specimens are referenced in Table 3-18.

Table 3-18: Results of isotropic compression tests.

Tailings Dam	Description	Preparation	Figures
Mizpah	Whole Tailings	Slurry	Figure 3-81 to Figure 3-84
	Pond Fine & Coarse	Slurry	Figure 3-85 to Figure 3-91
Pay Dam	Penstock Fine & Coarse	Slurry	Figure 3-92 to Figure 3-98
	Penstock Fine & Coarse	Undisturbed	Figure 3-99 to Figure 3-105

These results are analysed and discussed in Section 4.3.1 in the next chapter. It will be demonstrated that the compression behaviour of tailings, as a log-linear relationship, can be normalised and correlated to composition related properties such as the Atterberg limits. An interesting observation is the large amount of secondary compression that took place during the consolidation stages. This is contrary to what is normally assumed for gold tailings. The fast draining properties of the tailings can cause problems during consolidation. It is uncertain whether the drainage facilities of the triaxial apparatus did not restrict free-flow of the drainage water to some extent.

3.4.6 Shear strength

Undrained Triaxial Shear

Consolidated undrained compressive triaxial shear tests were performed on the tailings material, according to the guidelines given in BS1377:1990 Part 8, as follows:

(a) Specimen preparation and consolidation followed the procedures described in Section 3.4.5. For purposes of determining the compression and consolidation response of a sample, the full set of consolidation increments (12.5, 25, 50, 100, 200 and 400 kPa effective) were applied. Once this behaviour had been established for a particular sample, subsequent specimens were consolidated in a single stage to either 50 or 200 kPa effective. This resulted in a set of three undrained shear stress paths for each sample at stress levels of 50, 200 and 400 kPa.

(b) Following consolidation, each specimen was subjected to undrained compressive shear by closing the internal drainage valve and applying axial compressive force using the loading ram. The axial force on the loading ram was measured using an external load-ring. The measured force, the calculated cross-sectional area of the specimen and the applied cell pressure could then be used to determine the axial total vertical stress in the specimen. An attempt was made at compensating for the mechanical friction between the loading ram and the cell body by zeroing the load dial-gauge as the ram was pushed towards the top-cap without making contact with the specimen. A flat top-cap was used to eliminate problems of disturbance if the sample is not perfectly aligned with the loading ram (Baldi et al., 1988). Axial deformation was measured using a dial-gauge fixed between the load ring and the cell body, and excess pore pressures using an electronic transducer measuring at the base of the specimen.

(c) The rate of shear was fixed at 0.38 mm/min, consistent with the drainage properties of the material determined from consolidation data and resulted in approximately 15% shear strain per hour.

Results of the triaxial tests are summarised in Table 3-19 and discussed in Section 4.3.3 in the next chapter. It will be shown that a single effective strength parameter of $\phi' \approx 34°$ is sufficient to describe the shear strength of all the samples considered in this study. However, the undrained shear behaviour of fine and coarse samples are separated by the fact that the fine samples reach a steady failure state, while the coarse samples tend to dilate and strengthen in post failure states.

Table 3-19: Results of undrained triaxial compressive shear on tailings material.

Tailings Dam	Description	Figure
Mizpah	**Reconstituted Specimens - (MPDWT, MPDF & MPDC)**	
	Whole Tailings - Triaxial results	Figure 3-106
	Whole Tailings - Stress paths	Figure 3-107
	Whole Tailings - Mohr's circles	Figure 3-108
	Pond Fine Tailings - Triaxial results	Figure 3-109
	Pond Coarse Tailings - Triaxial results	Figure 3-110
	Combined Fine & Coarse Stress paths	Figure 3-111
	Combined Fine & Coarse Mohr's circles	Figure 3-112
Pay Dam	**Reconstituted Specimens - (PPNDF & PPNDC)**	
	Penstock Fine Tailings - Triaxial results	Figure 3-113
	Penstock Coarse Tailings - Triaxial results	Figure 3-114
	Combined Fine & Coarse Stress paths	Figure 3-115
	Combined Fine & Coarse Mohr's circles	Figure 3-116
	Undisturbed Specimens - (PPNTF1 & PPNTC1)	
	Penstock Fine Tailings - Triaxial results	Figure 3-117
	Penstock Coarse Tailings - Triaxial results	Figure 3-118
	Combined Fine & Coarse Stress paths	Figure 3-119
	Combined Fine & Coarse Mohr's circles	Figure 3-120

3.5 IN-SITU TESTS

3.5.1 Piezocone

Piezocone tests were conducted at both sites to obtain a measure of the in-situ state within each dam. The instrument used measures cone resistance, pore pressure and inclination with depth, and records the test data automatically in electronic format. The equipment and test procedure conform to the international reference test procedure, ISSMFE (1989), with the filter element placed immediately above the cone tip, commonly referred to as position-u_2.

Five soundings were made through a cross section of Mizpah Dam starting on the southern daywall and progressing down the beach to the beach-pond interface area, Figure 3-1b. Two soundings were made on Pay Dam, one on the beach and one next to the northern penstock where the bulk of the laboratory test samples were taken (Figure 3-3b).

Results of the piezocone soundings are summarised in Table 3-20 and discussed in Section 4.4.

Table 3-20: Summary of piezocone test results.

Description	Field Log	Pore pressure Dissipations	Ambient Pore pressure	Normalised Log	Identification Chart
Mizpah					
Daywall	Figure 3-121	Figure 3-122	Figure 3-123	Figure 3-124	Figure 3-125
Upper Beach	Figure 3-126	Figure 3-127	Figure 3-128	Figure 3-129	Figure 3-130
Middle Beach	Figure 3-131	Figure 3-132	Figure 3-133	Figure 3-134	Figure 3-135
Lower Beach	Figure 3-136	Figure 3-137	Figure 3-138	Figure 3-139	Figure 3-140
Pond	Figure 3-141	Figure 3-142	Figure 3-143	Figure 3-144	Figure 3-145
Pay Dam					
Beach	Figure 3-146	Figure 3-147	Figure 3-148	Figure 3-149	Figure 3-150
Penstock	Figure 3-151	Figure 3-152	Figure 3-153	Figure 3-154	Figure 3-155

The terms used in Table 3-20 are explained as follows:

- **Field log**: Raw field penetration data, including cone resistance and pore pressure. These values were taken directly from the electronic data acquisition system without any corrections or adjustments.
- **Pore pressure dissipations**: Results of pore pressure dissipation tests taken at stationary intervals during a sounding.
- **Ambient pore pressure**: The ambient or equilibrium in-situ pore pressure distribution based on the piezocone pore pressure dissipation data. This information is also used to determine the depth of the phreatic surface at the location of the sounding.
- **Normalised log**: A representation of the piezocone sounding normalised with respect to the effects of overburden pressure and the ambient pore pressure. For this purpose the field data have been corrected for: electronic drift in the sensors if applicable, extended length of the first rod carrying the instrumented cone as well as the offset in measurement depths between the cone tip and pore pressure element due to their physical separation.

Excess cone resistance: $q_e = q_c + \lambda \cdot u_t - \sigma_{vo}$ **Eq. 3-1**

Excess pore pressure: $u_e = u_t - u_o$ **Eq. 3-2**

where q_c = corrected cone resistance
λ = correction factor for unequal areas effect
u_t = measured pore pressure
u_o = ambient pore pressure

σ_{vo} = total vertical overburden pressure assuming γ_{sat} = 17.8 kN/m^3 below the water table and a bulk weight of γ_{nat} = 16.9 kN/m^3 above the water table

- **Identification chart**: Normalised penetration data represented on the Jones and Rust soils identification chart for classification purposes.