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.

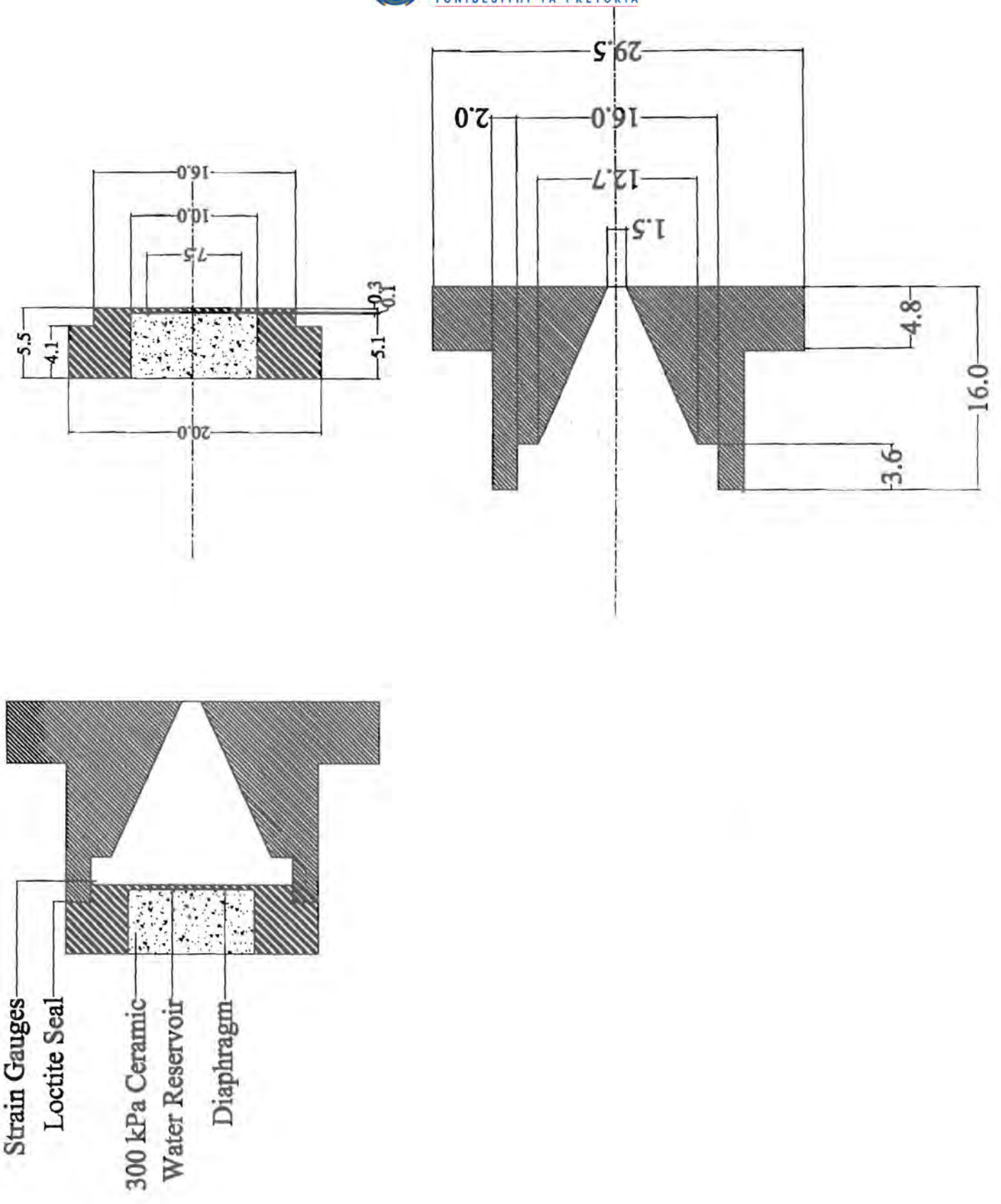


Figure 3.1: Machine drawing of suction probe

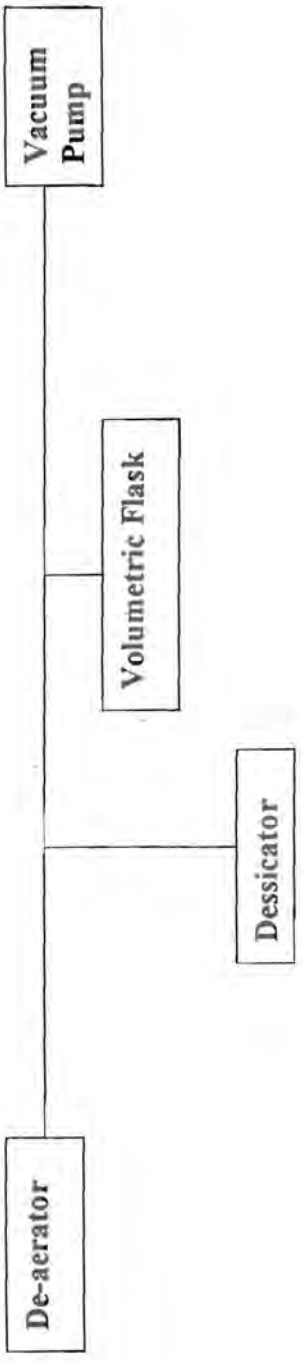


Figure 3.2: Schematic illustration of de-airing equipment

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

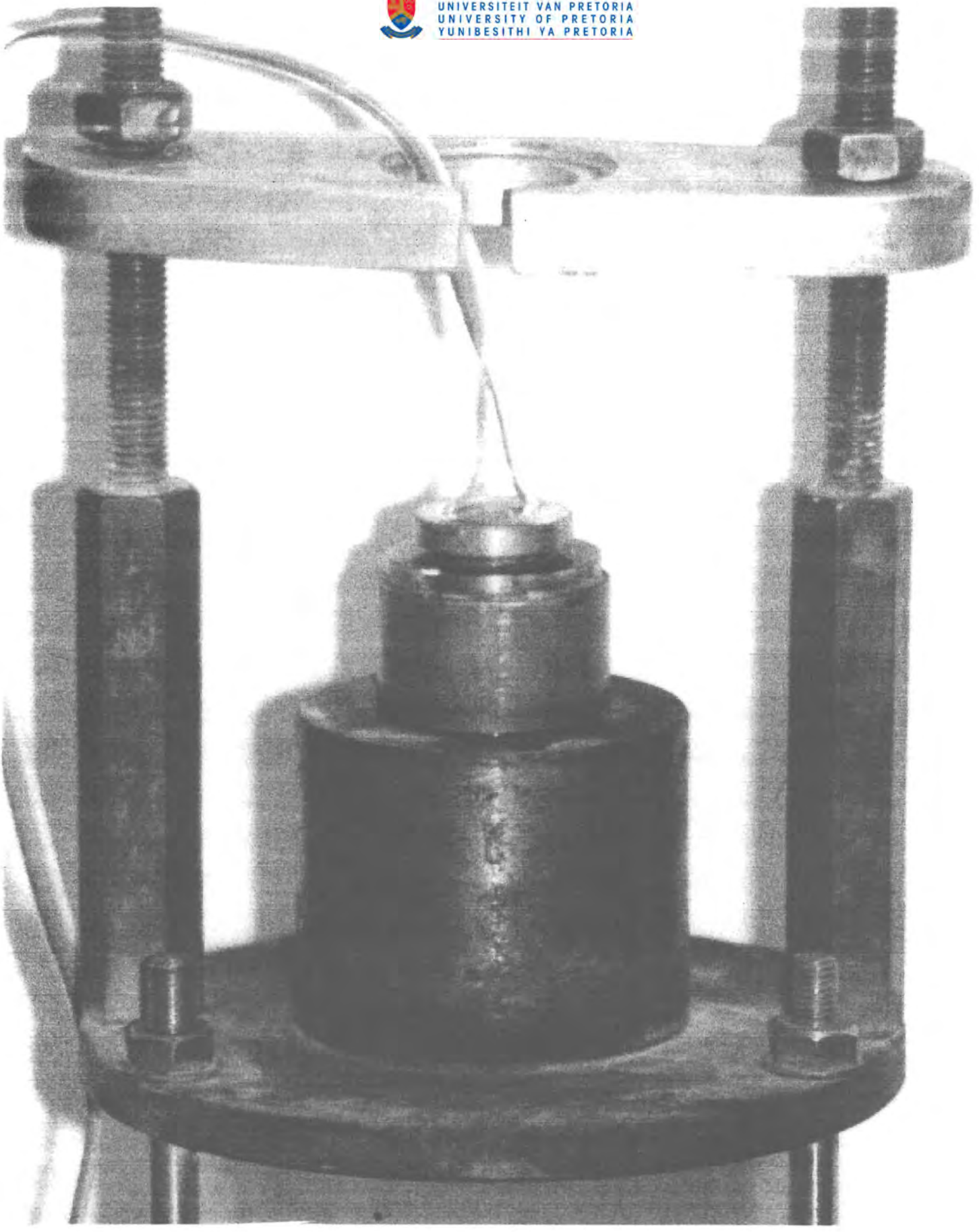


Figure 4.1: Suction probe in modified triaxial cell

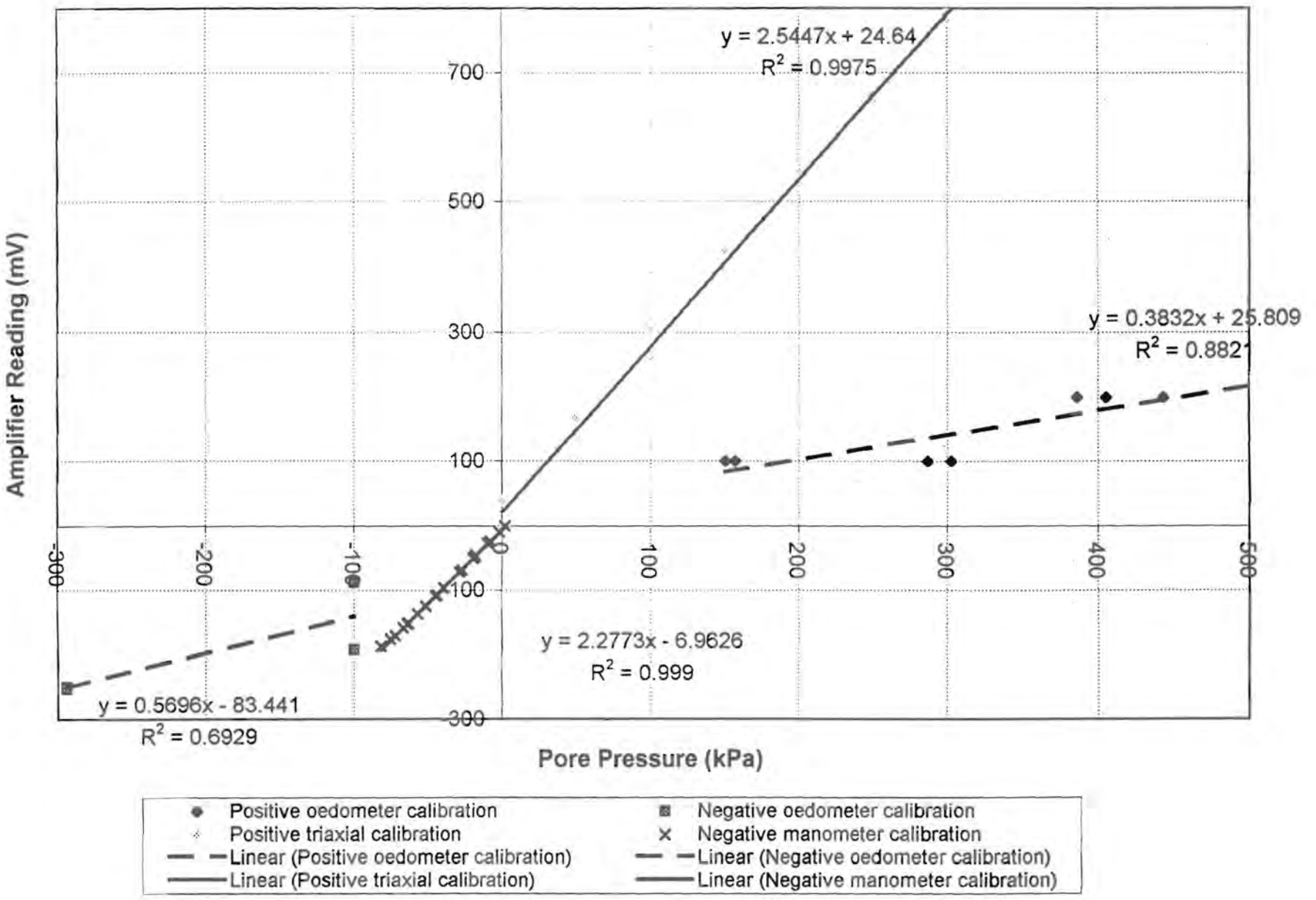


Figure 4.2: Combination calibration curve of adopted methods

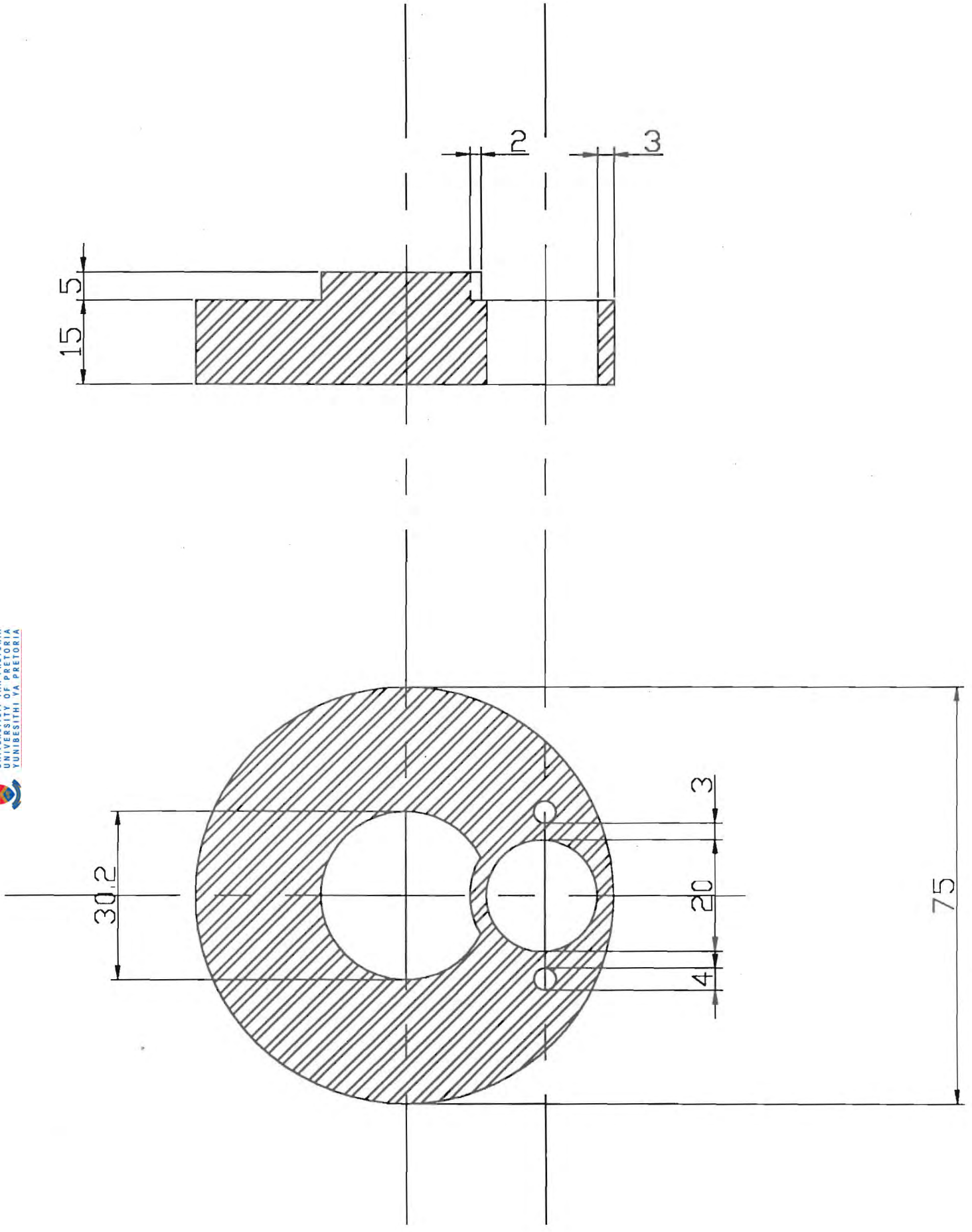


Figure 4.3: Machine drawing of modified oedometer top-cap

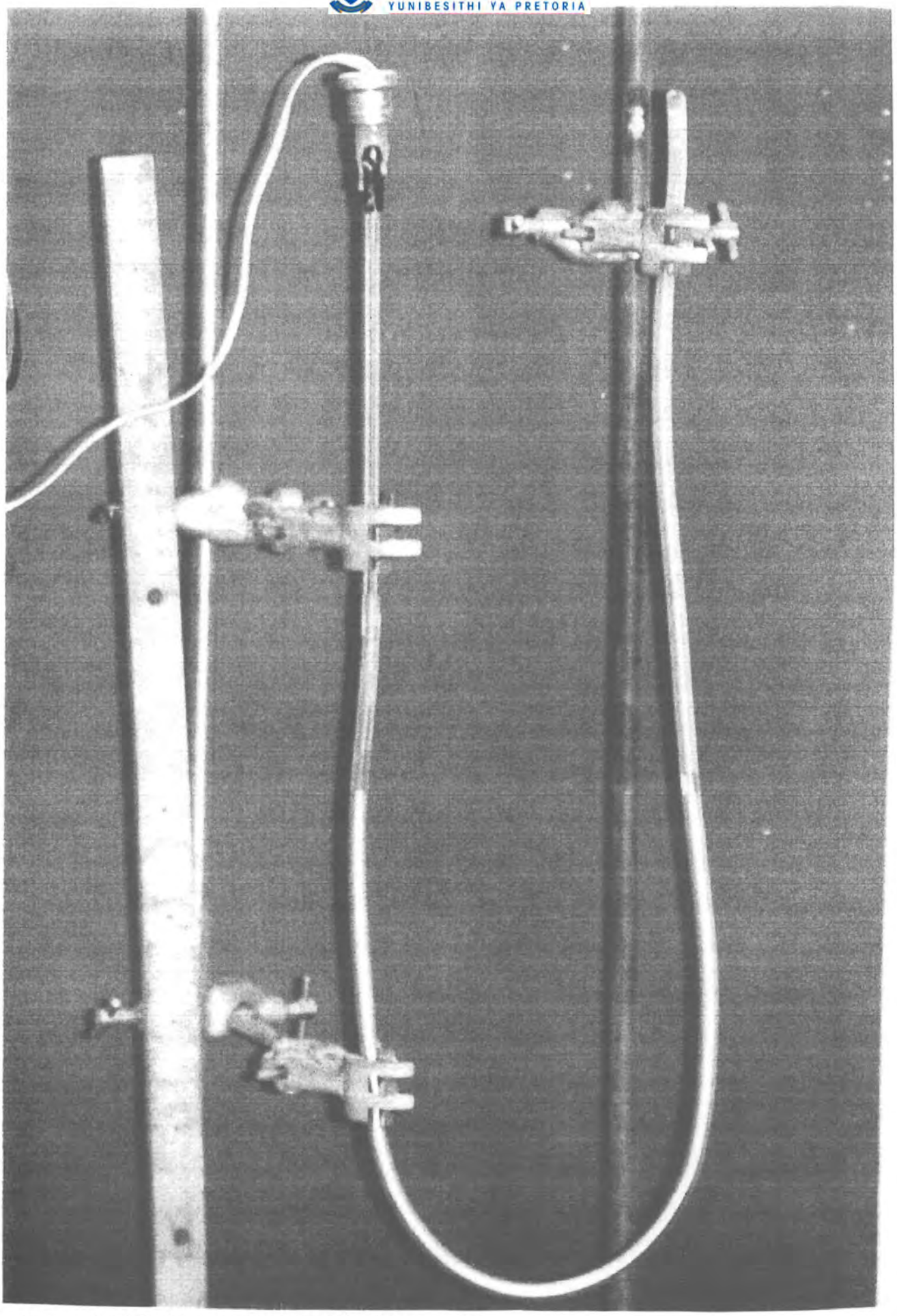


Figure 4.4: Modified manometer calibration apparatus

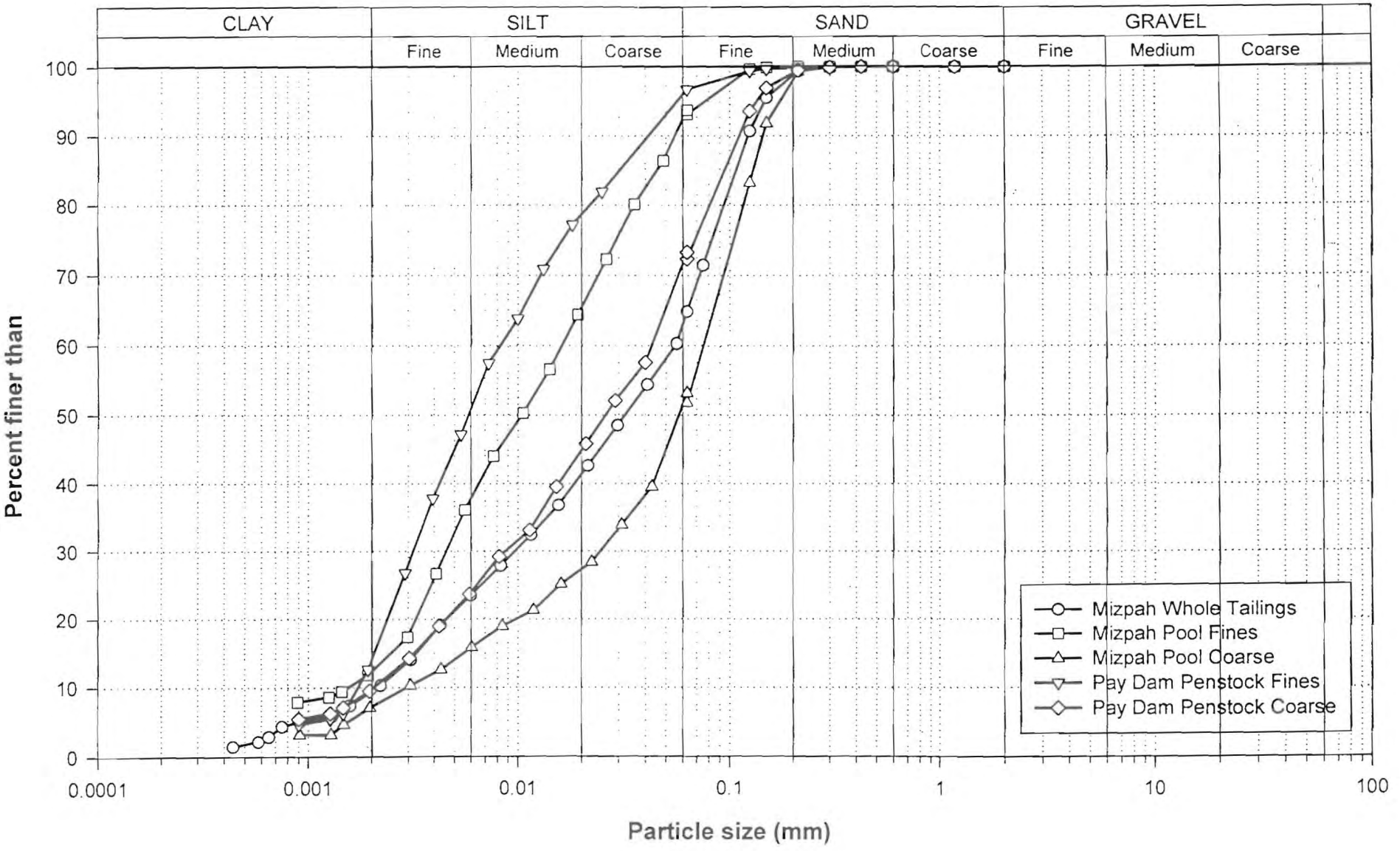


Figure 4.5: Grading analysis of mine tailings samples (after Vermeulen)

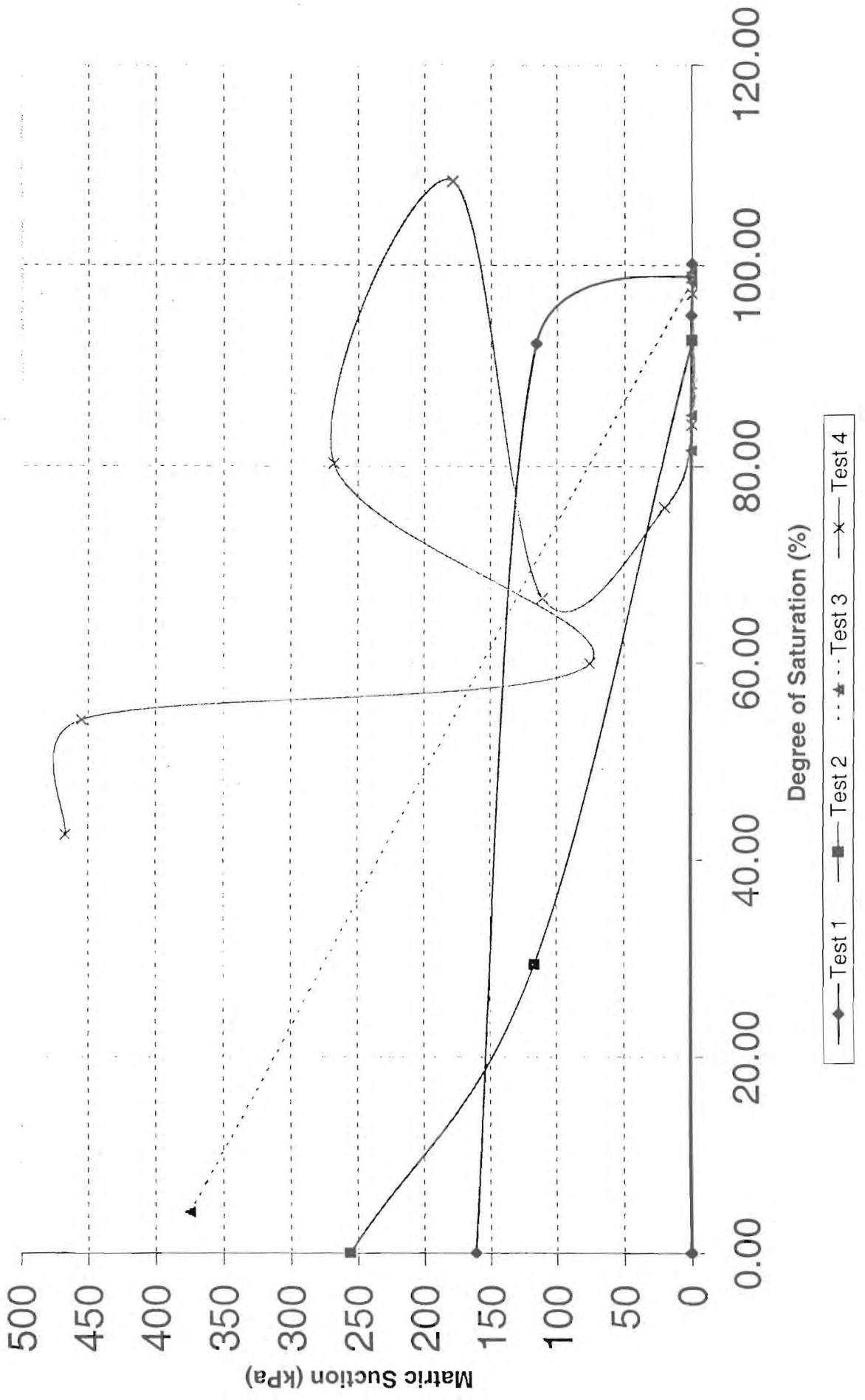


Figure 4.6: Relationship between matric suction and degree of saturation of fine tailings for the various desorption tests

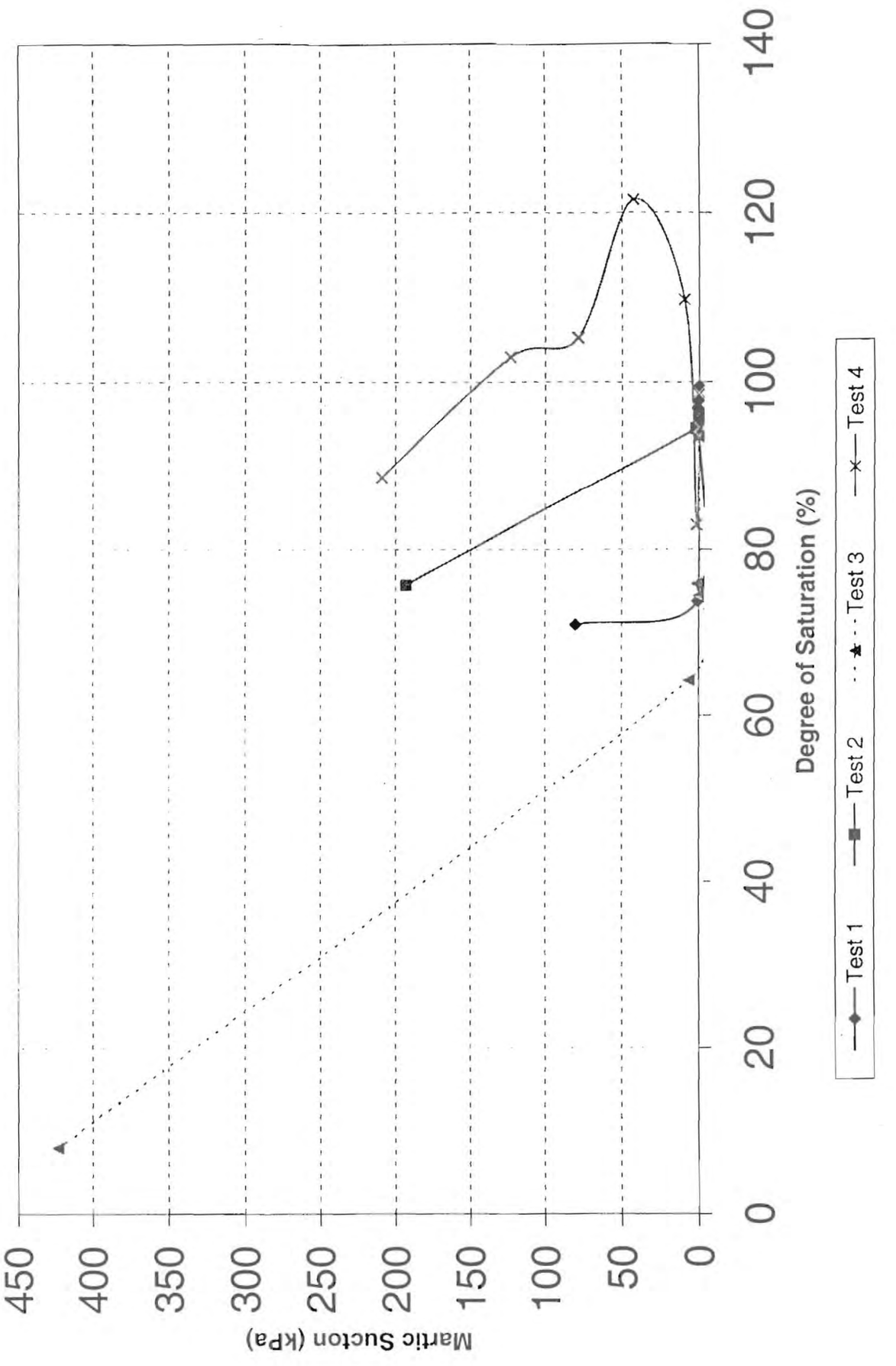


Figure 4.7: Relationship between matric suction and degree of saturation of coarse tailings for the various desorption tests

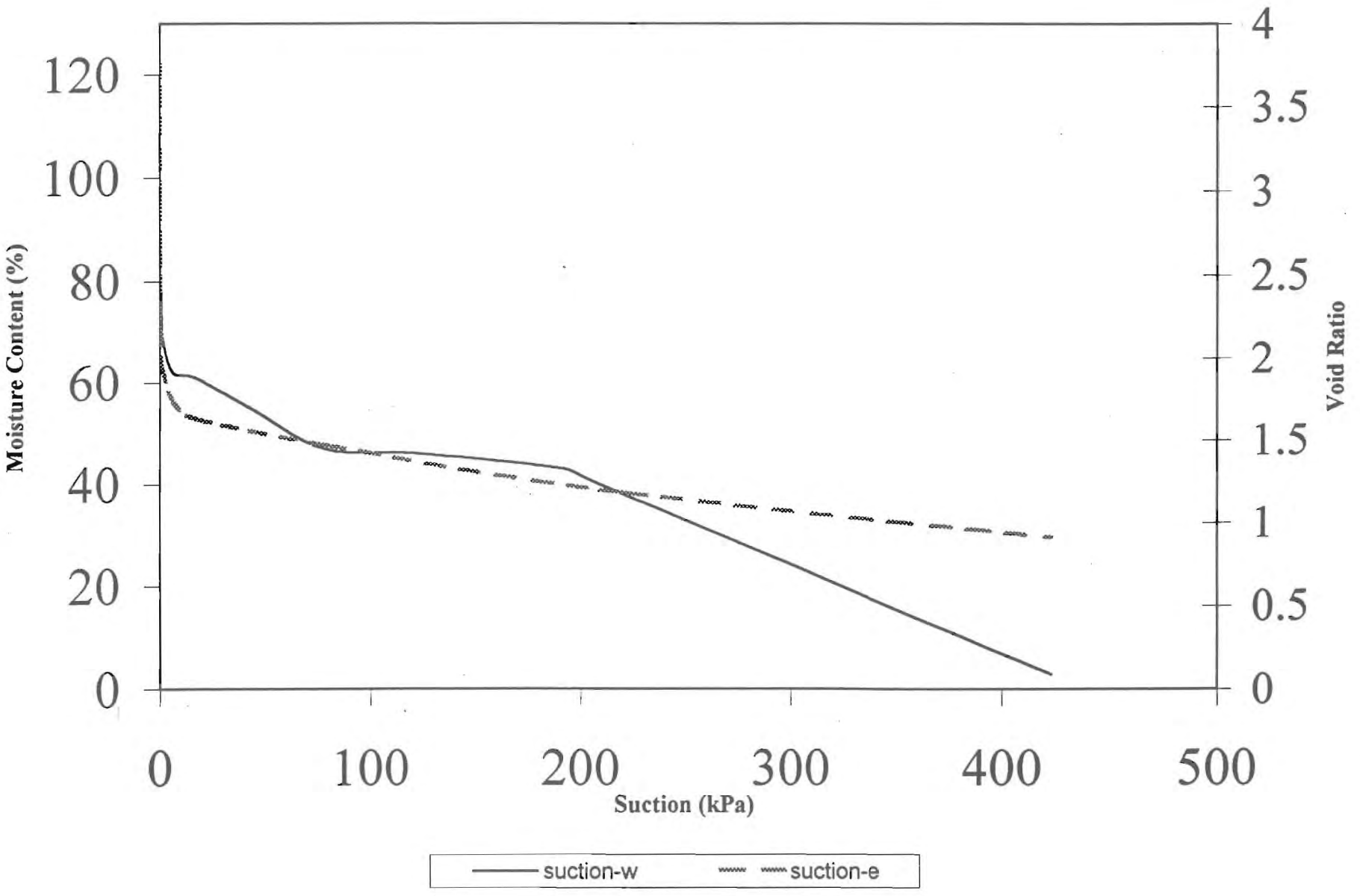


Figure 4.8: Combination soil water characteristic curve and shrinkage curve of fine tailings

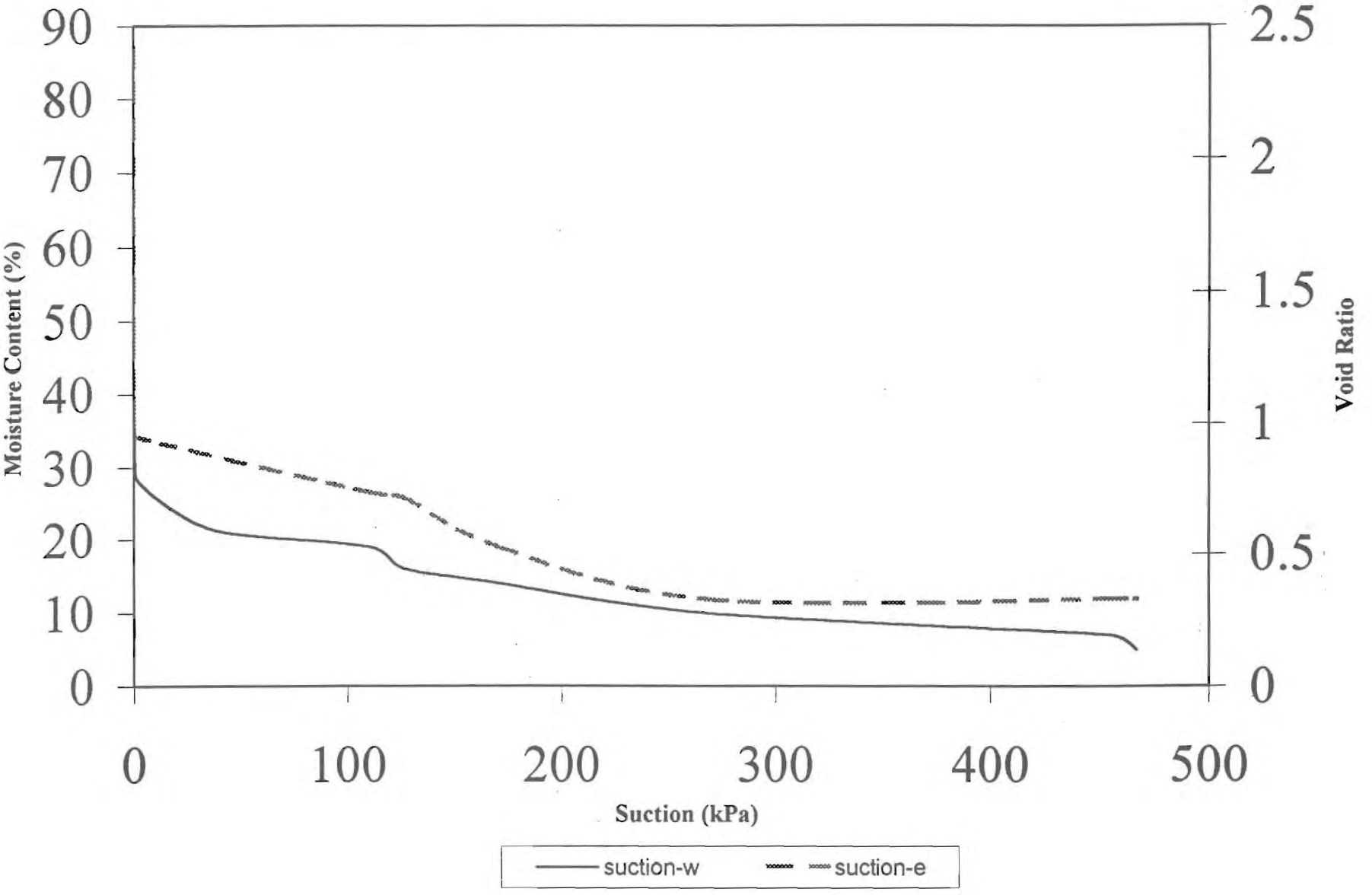


Figure 4.9: Combination soil water characteristic curve and shrinkage curve of coarse tailings

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				

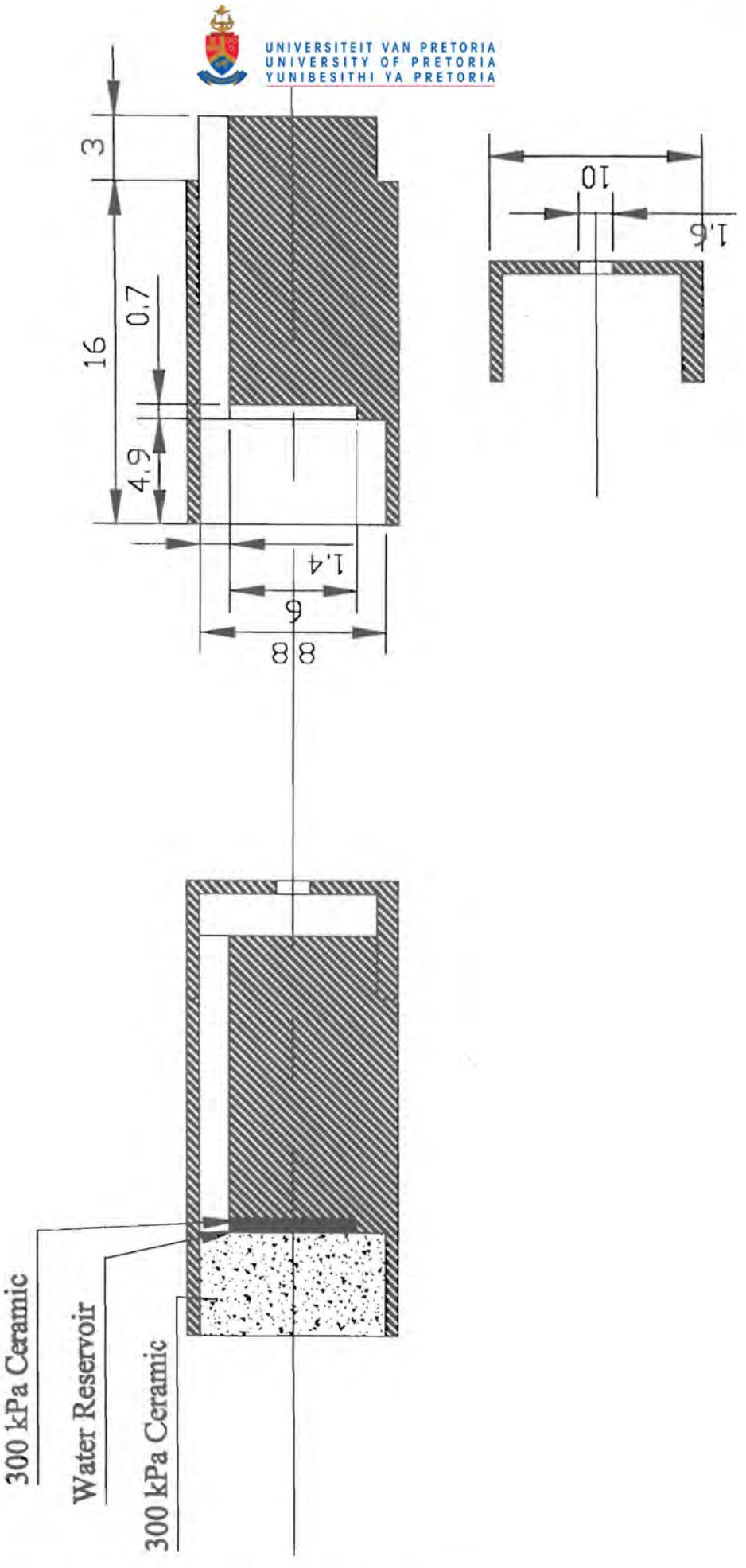
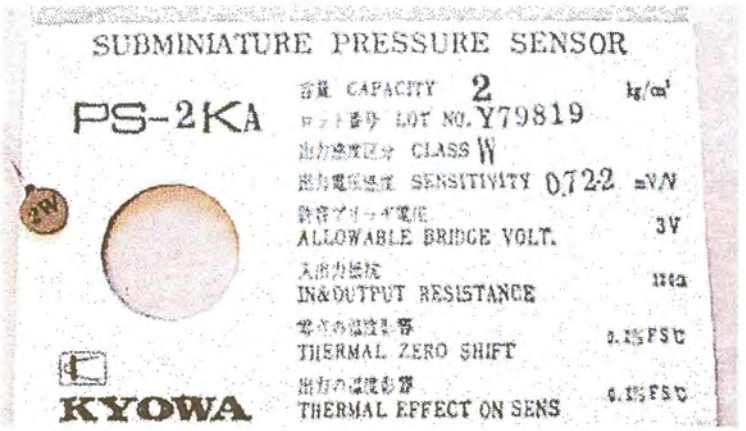
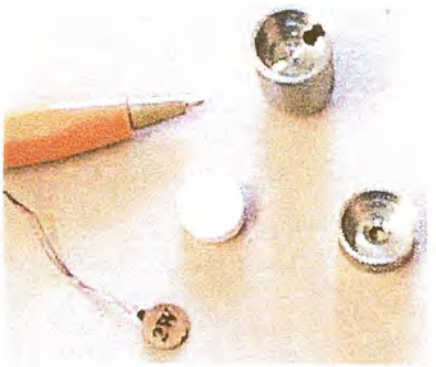


Figure 5.1: Machine drawing of mid-plane suction probe

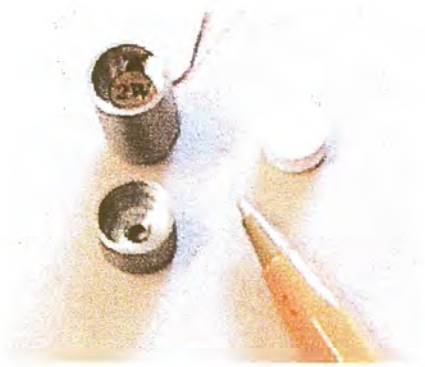


KYOWA Pressure Transducer

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

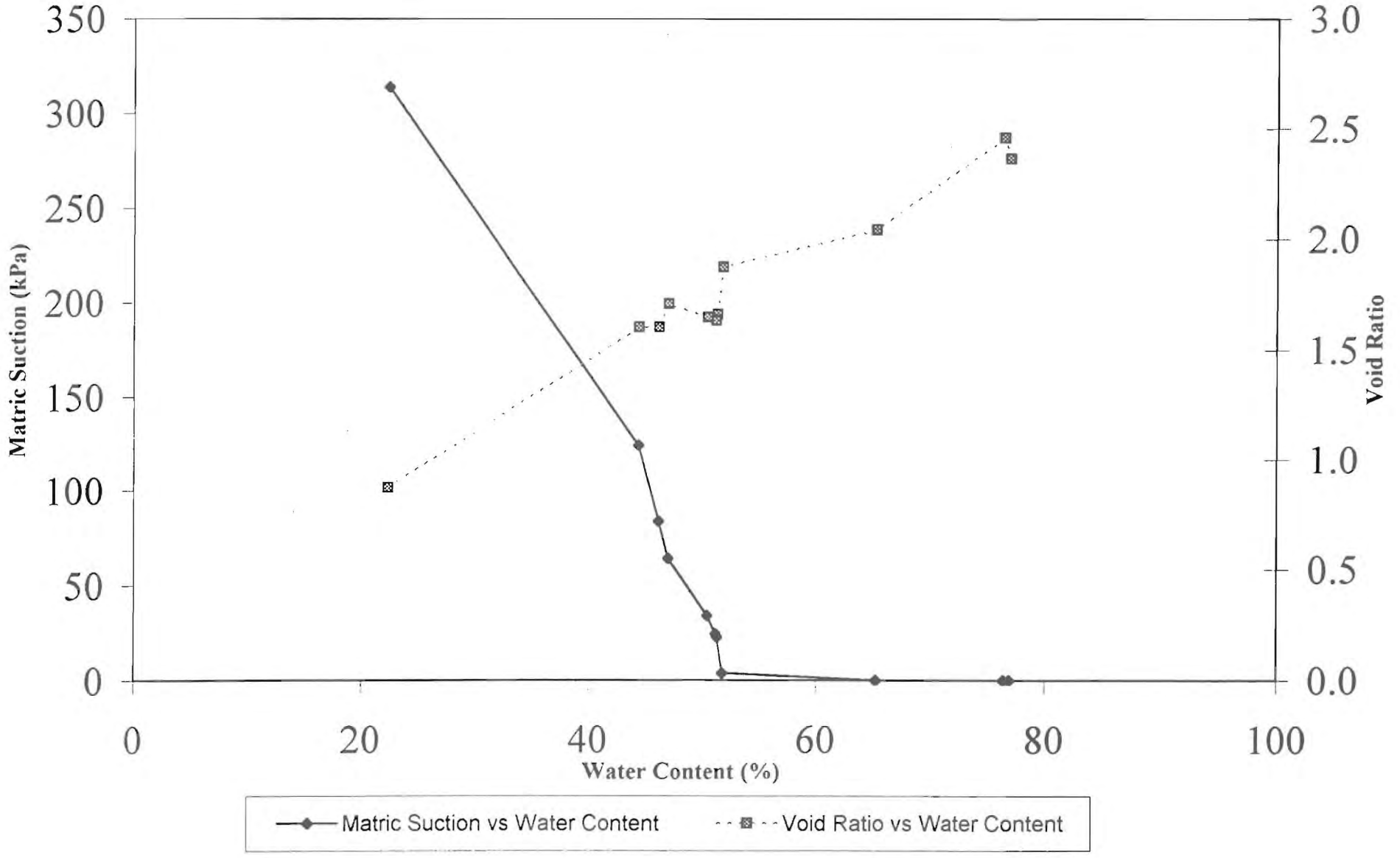


Figure 5.3: Combination soil water characteristic curve and shrinkage curve of fine tailings

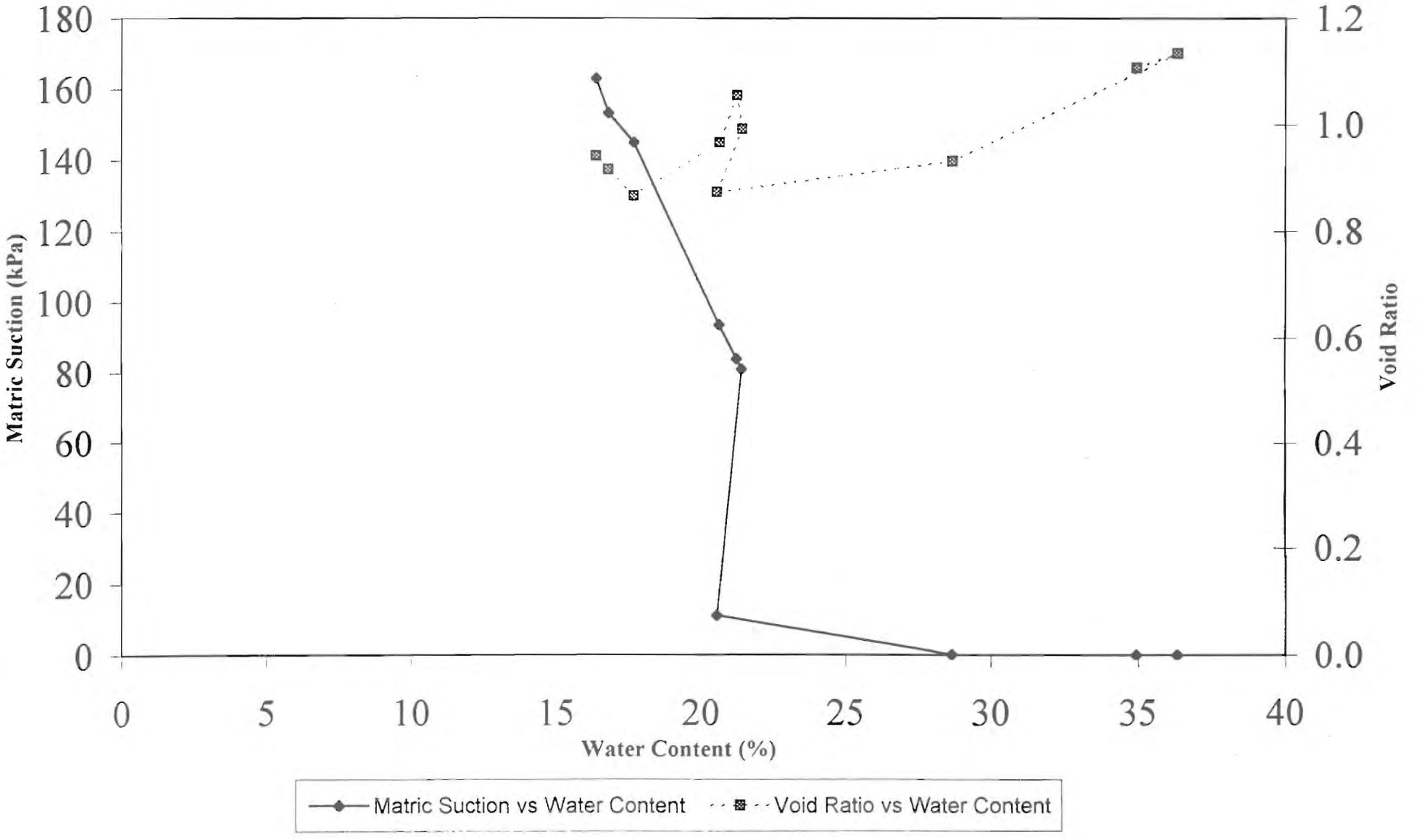


Figure 5.4: Combination soil water characteristic curve and shrinkage curve of coarse tailings

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.

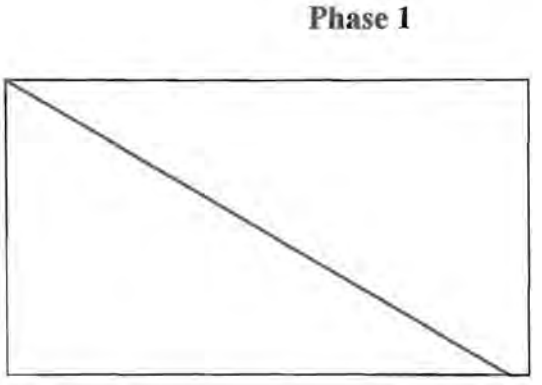


Figure 6.1: Pressure gradient in a tailings sample

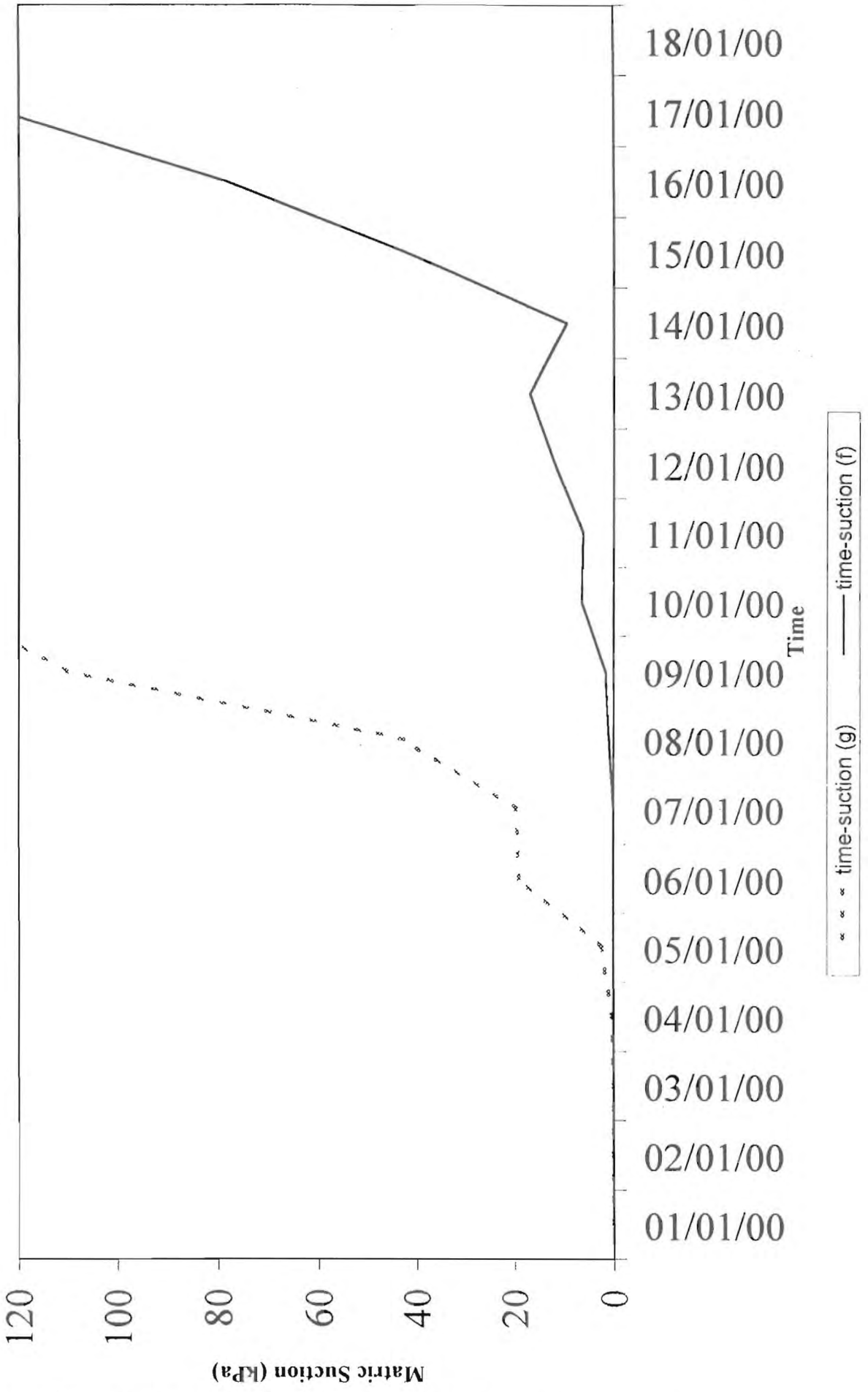


Figure 6.2: Relationship between matric suction and time for both fine and coarse tailings

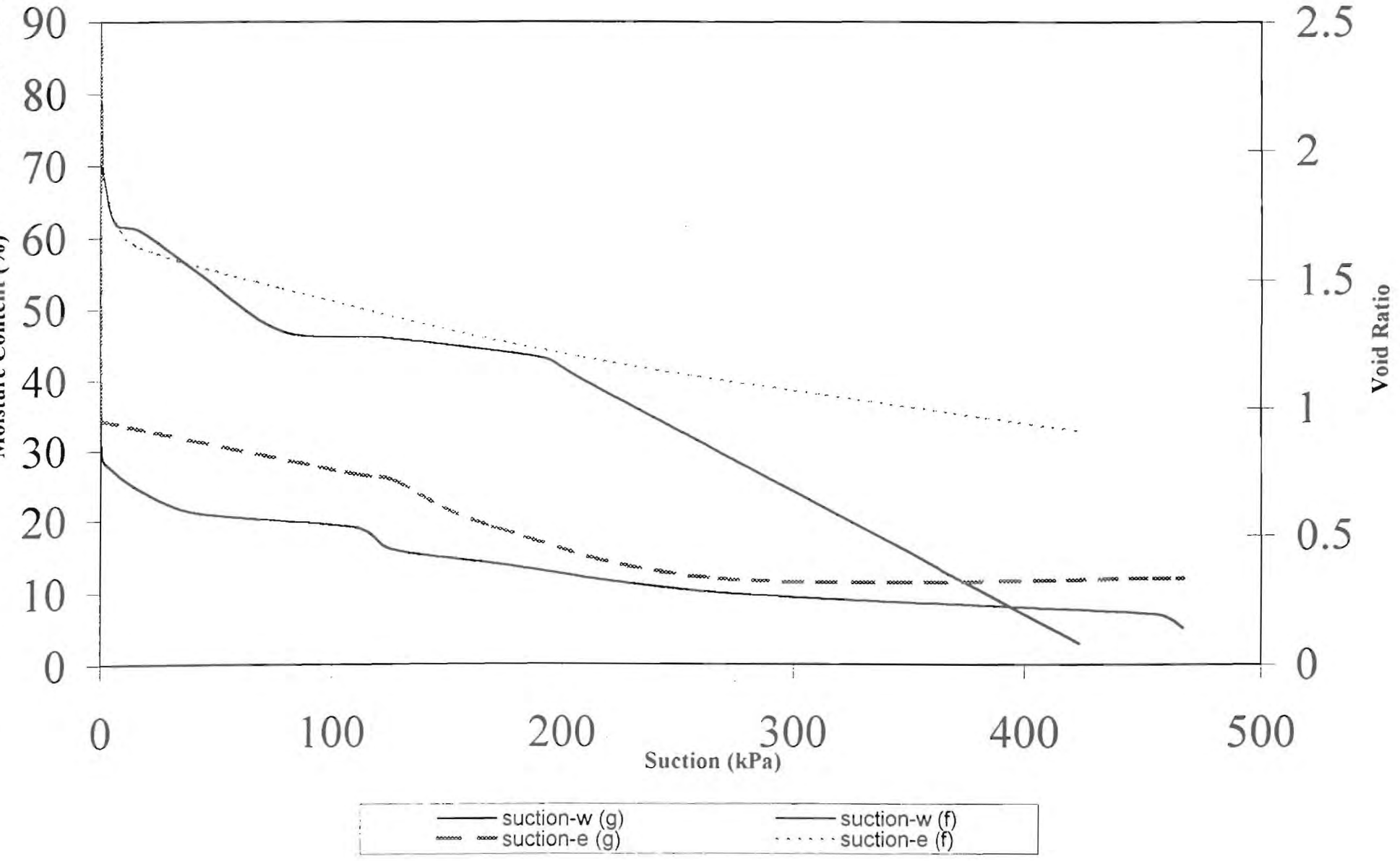


Figure 6.3: Combination soil water characteristic and shrinkage curve of fine and coarse tailings

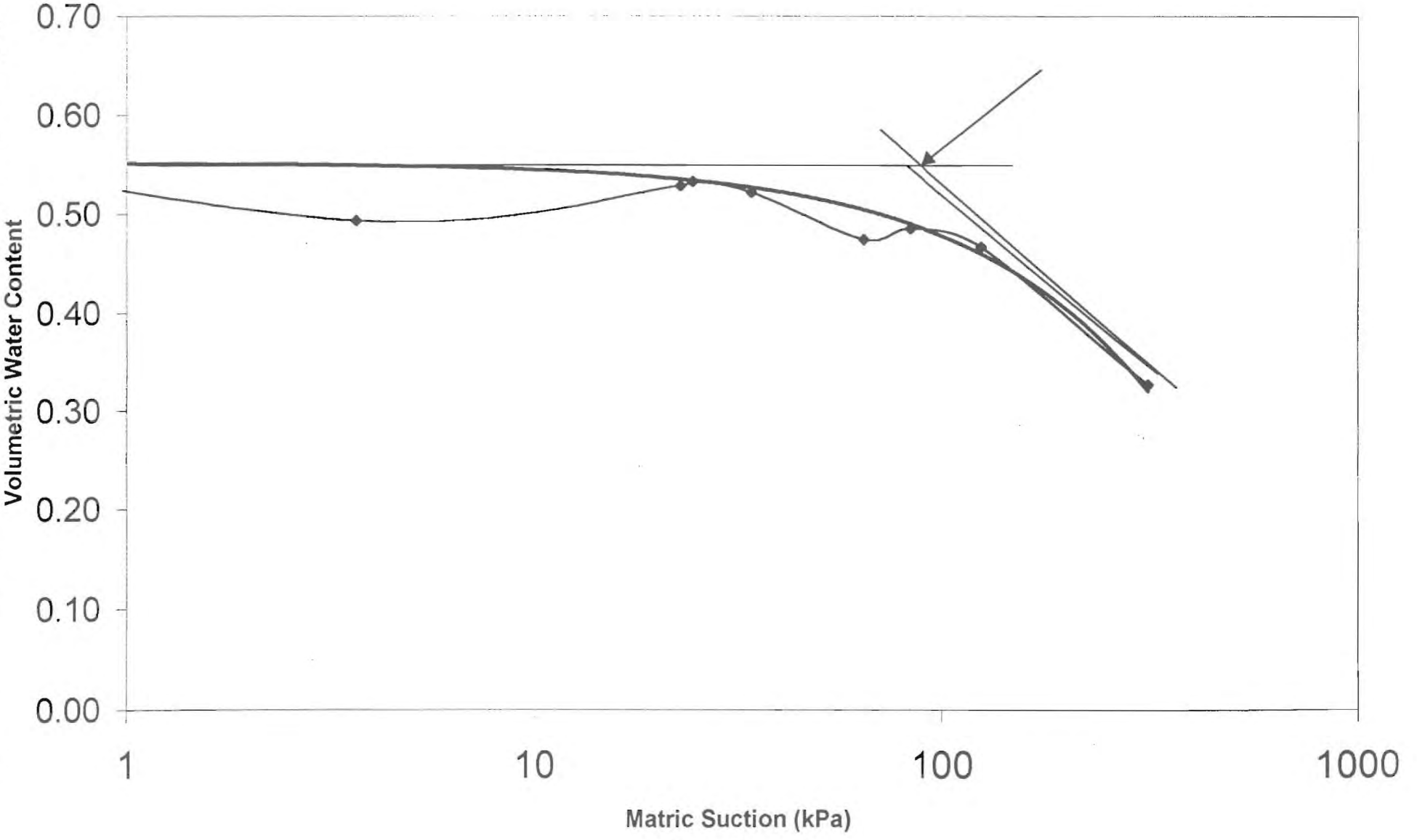


Figure 6.4: Soil water characteristic curve of fine tailings using the mid-plane suction probe

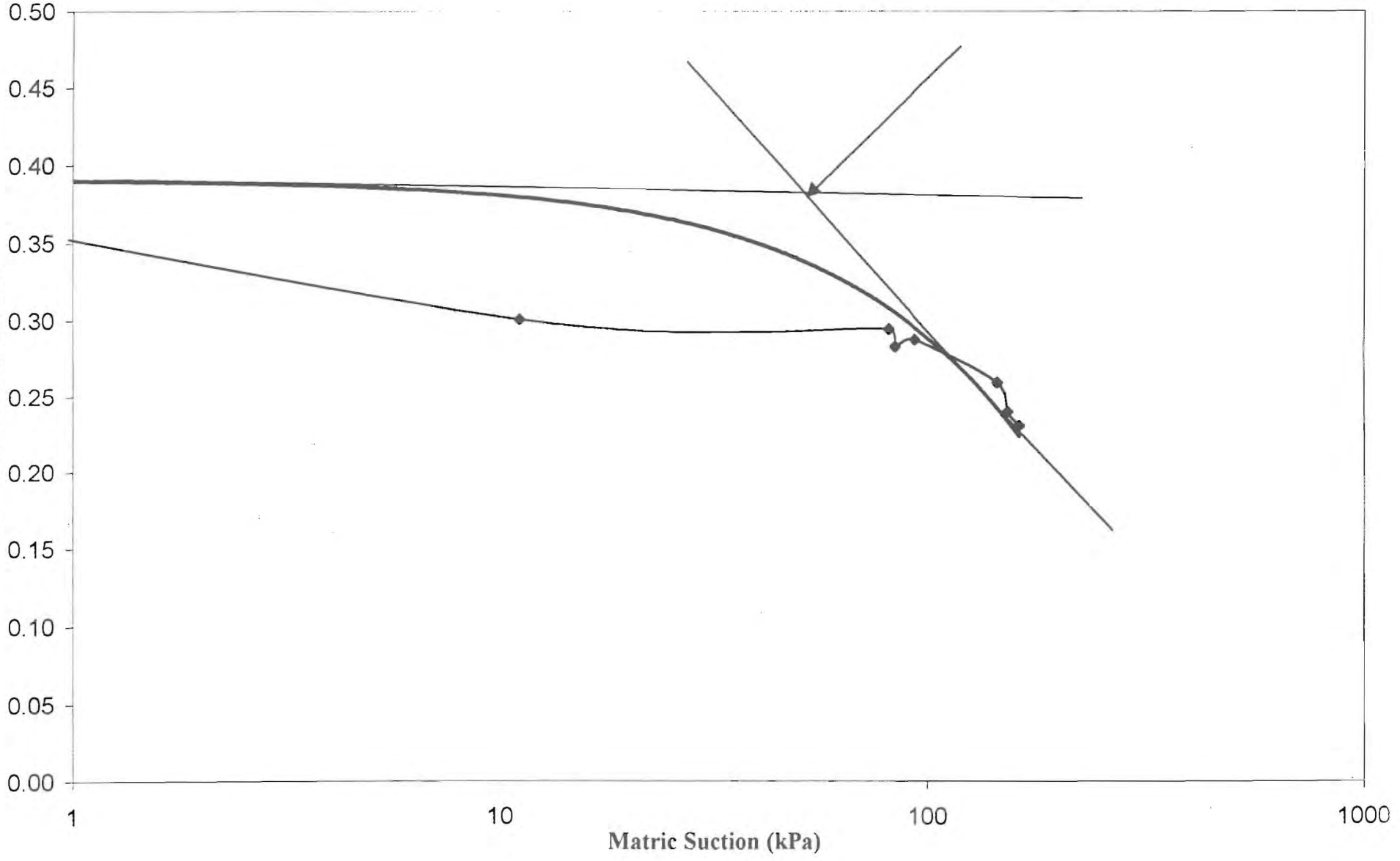


Figure 6.5: Soil water characteristic curve of coarse tailings using the mid-plane suction probe

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.