Laboratory Properties of Mine Tailings

By

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ABSTRACT

A vast amount and variety of mine tailings are produced around the world each day. These mining wastes must be properly managed. To evaluate mine tailings disposal technology, the appropriate engineering properties of the tailings must be ascertained. The results of a laboratory investigation on the engineering properties of four different tailings are presented. First, some of the basic properties of the tailings are described. Large strain consolidation tests and hydraulic conductivity tests are then described. The techniques for saturating and placing the tailings sample prior to carrying out the consolidation tests are given. Column drying test and shrinkage test for investigating the desiccation behavior of mine tailings are outlined. Furthermore, water retention characteristic tests using both the pressure-plate extractor and the saturated salt solution desiccator are outlined. Finally, shear strength parameter tests are described. The engineering properties derived from these tests are then presented and compared to the published results on similar types of tailings.

***Keyword**: mine tailings, laboratory, engineering properties, consolidation, hydraulic conductivity, water retention curve, evaporation rate, shear strength.*

INTRODUCTION

In the mining industry, a vast amount of fine-grained milling wastes (tailings) are produced in mineral processing plants each day. The wastes are generally in the form of a slurry that is deposited hydraulically in the disposal area. How to effectively and economically dispose of the waste has become a major issue facing all mining operations. Knowledge regarding the basic physical properties of the tailings, and their consolidation and desiccation behaviors are necessary to understand the tailings material behavior and to further improve the efficiency of disposal (Qiu and Sego 1998a).

The objective of this laboratory study was to ascertain basic properties of tailings and to examine their consolidation and desiccation behavior. Most laboratory tests were carried out using the standard ASTM test procedures. However, due the complexity of the tailings and the technical requirement for deposition, some special test techniques were needed. Therefore, special experimental methods were used to carry out the consolidation and desiccation behavior tests.

In this study, four different mine tailings, (copper mine tailings from Kennecott Mining, gold mine tailings from Echo Bay's Lupin Mines, coal wash plant tailings from the Coal Valley Mine of Luscar Sterco (1977) Ltd. and oil sand composite/consolidated tailings (CT) from Syncrude Canada Ltd.) were selected to represent a wide range of tailings from different types of mines. Laboratory tests on these tailings were carried out (Qiu and Sego 1998b), and the measured engineering properties of the tailings will be presented and compared to results taken from the literature on similar types of materials.

BASIC PHYSICAL PROPERTIES

A series of laboratory tests were carried out to study the tailings' basic physical properties, including tests for specific gravity, Atterberg limits, particle size, pH values, and soil classification. The basic physical properties of the tailings are summarized in Table 1. Figure 1 shows the grain-size distribution of each tailings.

Based on their grain-size distributions and their basic physical properties, the tailings were non-plastic except for the coal wash tailings. The copper tailings' specific gravity and liquid and plastic limits were within the range presented by Mittal and Morgenstern (1975) and Volpe (1979). The plastic limits for the copper, gold, and CT tailings were same as the value presented by Aubertin et al (1996). The copper tailings and oilsand CT are sandy soils and are classified as SM according to the Unified Soil Classification System (USCS). The gold tailings are silty and are classified as ML, while the coal wash tailings are clayey silts and are classified as CL according to the USCS.

CONSOLIDATION AND HYDRAULIC CONDUCTIVITY TESTS

The purpose of the consolidation and hydraulic conductivity tests was to determine the consolidation behavior of tailings over the effective stress range of 0.5 to 100 kPa. This low range in stresses is appropriate as it is operative in the majority of tailings management facilities. The saturated hydraulic conductivity at the end of each applied stress increment was also determined through direct measurement by applying a constant head difference across the sample to measure the upward flow through the sample.

Most mine tailings are processed as a slurry to allow them to be deposited hydraulically because of the economics of slurry transport. Due to the large initial void ratio associated with the low solids content in the original tailings, a large strain consolidation apparatus was used to carry out the test. Figure 2 shows a sketch of the apparatus.

The tailings samples taken from mine sites were unsaturated. To saturate the tailings, a special laboratory technique was adopted. First, the required amount for a specimen was carefully placed into a de-airing cylinder (Figure 3). Then the de-airing cylinder was placed on a vibrating table while a vacuum of 60 kPa was applied to it for at least 2 hours to draw off any gas entrapped in the specimen. It is easy to trap air in the specimen when it is being placed into the consolidation apparatus. To eliminate the entrapping of air, a special placement technique was used as illustrated in Figure 4. The specimen was placed into the consolidation cell while a suction was applied to both the de-airing cylinder and the consolidation cell.

For CT, due to the presence of bitumen, saturation is difficult to maintain throughout the test as gases are released from the tailings due to biological processes. To eliminate this problem, the tests on CT were carried out in a cold room maintained at an average temperature of +3 °C to suppress the biological action. All test results were converted to20 °C.

Consolidation tests were conducted by applying incremental loads to the specimen. Load increments that applied stresses of 0.5, 2, 4, 10, 20, 50 and 100 kPa were used. At least 4 specimens were tested for each type of tailings.

Hydraulic conductivity has an important influence on both the consolidation and desiccation behavior of the tailings as it controls the water flow characteristics. It is difficult to measure the unsaturated hydraulic conductivity of tailings. In this study, only the saturated hydraulic conductivity was measured directly.

Constant head hydraulic conductivity tests were carried out at the end of each consolidation stress increment to measure the hydraulic conductivity. During the tests, water from the constant head reservoir flowed upward through the samples under a low constant gradient.

The consolidation parameters, e.g. the coefficient of consolidation, coefficient of volume compressibility and hydraulic conductivity, were then calculated from the test results from each load increment using techniques outlined by Head (1992). The main results of the consolidation and hydraulic conductivity tests are presented in Table 2. The void ratio (e) versus log effective stress plots for the saturated tailings are shown in Figure 5. Figure 6 shows the relationship between hydraulic conductivity and void ratio.

The compression index for copper tailings was the same as has been summarized in collected data (Vick 1983; Volpe 1979). The C_c values of the gold tailings were lower than those presented by Vick (1983) (C_c = 0.35) and Stone et al. (1994) (C_c = 0.75), while the data for coal wash tailings were larger than those provided by Vick (1983) (0.06-0.27) and Williams et al's (1990) (0.2). These differences may be due to differences in the samples used for the tests. For the coal wash tailings, the variations might have been due to the samples, in that Vick's collections had smaller initial void ratios (0.6-1.0) and less clay content (15%). The values of the compression index for the coal tailings and CT (0.27 to 0.40) were within the range for uranium tailings obtained by Santos et al. (1992). The values of the consolidation parameters of the copper and gold tailings also compared fairly well with those obtained from other tailings tested by Aubertin et al. (1996), while the parameters of the coal tailings and CT were different. For instance, the values of the compression index for coal tailings and CT (0.27 to 0.40) were much greater than those presented by Aubertin et al. (1996) (0.046 to 0.13).

The values of the coefficient of consolidations (C_v) for the copper were much lower than those presented by Volpe (1979) (473 m^2/y for the pond area and 1167 m^2/y for near the dam area). The C_v values of the gold tailings were also much smaller than the mean value (200 m^2/y) for gold slime outlined by Blight and Steffen (1979). These differences might have been caused by the different tailings in the test samples. The C_v values for coal and CT tailings were similar to the data (15-60 m^2/y) for coal wash tailings presented by Williams et al (1990) and (0.25-11.3 m^2/y) for CT provided by Liu et al. (1994).

The measured values of the saturated hydraulic conductivity for the copper and gold tailings fell into the usual range for homogenized tailings (10^{-4} to 10^{-5} cm/s) (Aubertin et al. 1996). The data for the copper tailings were within the range (9×10^{-6} to 1×10^{-4} cm/s) for undisturbed samples presented by Volpe (1979). The values for the gold tailings were larger than those for the undisturbed sample (3.6×10^{-6} cm/s) presented by Blight and Steffen (1979). The hydraulic conductivity of the coal wash tailings was similar to the average result (3×10^{-7} cm/s) presented by Williams et al. (1990). The results for CT coincided with the results (2.5 to 8.5×10^{-7} cm/s) presented by Liu et al. (1994).

COLUMN DRYING TEST

A drying column or a lysimeter is commonly used to measure the evaporation behavior of a soil under laboratory conditions. To measure the desiccation behavior of the various mine tailings, laboratory column drying tests were conducted in a controlled environment. Most columns or lysimeters used in the laboratory are PVC or Perspex cylinders 100 to 300 mm in diameter (Wilson 1990; Swarbrick 1992). In this study, a 153 mm outside diameter PVC tube with a wall thickness of 10 mm was selected for the test column. Two drying columns, A and B, with a height of 500 mm, were used for the tailings drying tests, and a water evaporation pan (column C) with a height of 200 mm was selected. Column A was used to allow sampling and temperature profile measurement, while Column B was used to monitor the actual evaporation rate from the surface. Figure 7 shows a diagram of the sampling column. The layout of the column drying test is shown in Figure 8. To avoid elevation differences, the surface elevations of the top of each column were the same. The scales had a precision of 0.01g to provide accurate measurement of the evaporation losses. However, it was difficult to find a reasonably priced scale with a capacity of 20 kg and a precision of 0.01 g. Therefore, a beam system with a counter weight and a lower capacity high precision scale were used (Wilson 1997). A sketch of the beam measuring system is provided in Figure 9. The potential evaporation rate, the actual evaporation rate, the water content and temperature profile, along with the settlement of each tailings, were measured.

Figure 10 presents the normalized evaporation rate change of the tailings. The normalized evaporation rate is the ratio of the actual evaporation rate to the potential evaporation rate. Figure 10 shows that the drying processes of the tailings can be seen as involving two stages. In the first stage, the normalized evaporation rate drops quickly to around 0.6 (0.64 for coal wash tailings and CT). Since the tailings' surface desaturates as drying continues, the hydraulic conductivity of the surface decreases significantly, and, consequently, the actual evaporation rate of the tailings drops dramatically. In the second stage, the hydraulic conductivity of the surface layer decreases slowly, and, therefore, the evaporation rate eventually drops from around 0.6 to 0.2 for copper tailings, from 0.6 to 0.15 for gold tailings, from 0.64 to 0.52 for coal tailings, and from 0.64 to 0.6 for CT.

SHRINKAGE LIMITS AND SHRINKAGE CURVE TESTS

When moisture content changes, volume expansion and/or contraction occur over a period of time. These changes depend both on soil type and changes in water content. To obtain a quantitative indication of how much volume changes in sub-aerial tailings disposal, a shrinkage limit test and a shrinkage curve test are required. The shrinkage limit was defined as the water content at which the volume of the soil reaches its lowest value as it dries out (Craig 1992). A shrinkage curve indicates the void ratio changes with moisture content. In this study, an ASTM standard test method for shrinkage factors of soils using the mercury method, i.e. ASTM D 427-93 (ASTM 1999), was used.

Shrinkage limits of the mine tailings are presented in Table 1. The shrinkage curves of the mine tailings are shown in Figure 11. The shrinkage curves are similar to a typical shrinkage curve for a soil sample as presented by Fredlund and Rahardjo (1993).

WATER RETENTION CHARACTERISTICS TEST

The soil-water retention characteristics indicate the relationship between soil suction and its contained water. This is an important property of unsaturated soils. In the sub-aerial tailings disposal method, the tailings are deposited in a thin layer and allowed to desiccate under climatic influences. Thus, the tailings desaturate. As mentioned previously, the unsaturated hydraulic conductivity can be derived using the data from saturated samples and the tailings-water retention curve. Therefore, it is necessary to understand the water retention characteristics of the materials being deposited.

To obtain the tailings-water retention curve over the entire moisture suction range, pressure plate extractors were used to measure the tailings-water retention curve from 0 to 1500 kPa suction, while glass desiccators with saturated salt solutions were used to measure the retention characteristics from 1500 to 296 000 kPa of suction.

The water retention characteristics tests using the pressure-plate extractor were performed in the laboratory according to D2325 standard (ASTM 1997a). The saturated tailings specimens were held in individual sample rings which were placed directly on the porous plates in the pressure chamber. To prevent loss of the fines portion of the tailings, the bottom of each ring was covered with a filter paper. Several pressure intervals, (2, 4, 5, 7, 10, 30, 50, 75, 100, 300, 500 and 1500 kPa) were used in order to obtain a smooth water retention curve. At least 8 specimens of the each type of tailings were tested. A reference ring filled with saturated standard loam was placed in the center of each plate for comparison to the data obtained for the tailings. Furthermore, two filter papers of the same type as those used in each ring were placed on each plate for back calculations.

The water retention curve for higher values of suction can be determined using osmotic pressures generated by salt solutions (Wilson et al 1997). The basic principle of the method is described as follows. At a constant temperature, any salt solution at a certain chemical concentration is in equilibrium with a fixed partial vapor pressure of water and, consequently, defines a fixed relative humidity (Young 1967). Robinson and Stokes (1955) proposed the following formula to calculate the osmotic pressure (or suction):

$$[3] \quad \Pi = \frac{RT}{V_A} \ln a_w$$

where Π is osmotic pressure or suction (kPa), R is the universal gas constant (R=8.31439 J/mol·K), T is the absolute temperature in Kelvin (T=273 + t, t is the temperature in °C), V_A is the partial molar volume of the solvent (V_A=18.0545x10^{-3} m^3/mol for water at 22°C), and a_w is the activity of the solvent, here equal to the relative humidity, R_h.

As a result, we can select different salt solution to establish different suctions. In this research program, four separate saturated salt solutions were used for the best control of humidity (Young 1967), i.e., potassium sulfate [K_2SO_4], sodium chloride [NaCl], magnesium nitrate [$Mg(NO_3)_2.6H_2O$], and lithium chloride [$LiCl.H_2O$]). A laboratory room temperature of 22°C was established as the control temperature. Thus, the osmotic pressures of 3928, 38793, 84543, and 295848 kPa were obtained from the solutions of potassium sulfate, sodium chloride, magnesium nitrate, and lithium chloride respectively.

To carry out the saturated salt solution tests, an airtight container was needed to act as a humidity chamber. In this research, a vacuum glass desiccator was used as a humidity chamber. Furthermore, a rigid plastic ring was also used to hold the tailings specimens.

The water retention curves of the tailings are shown in Figure 12. Through the use of a graphical analysis method, the soil-water retention characteristic parameters, such as the air-entry value and residual moisture content, were obtained from the semi-log plot of the soil-water retention curve (Fredlund and Xing 1994), the results of which are summarized in Table 3. The desaturation process of the tailings can be divided into three stages: the boundary effect, the transition, and the residual stages of desaturation (Vanapalli et al. 1996). The suction ranges for each stage are also included in Table 3. The measured values for water retention characteristics of the loam are presented and compared with the standard results (Ostermann 1997) in Figure 13. Figure 13 shows that the measured values are very close to the standard values. This indicates that the effect of the filter paper at the ring bottom can be neglected and the results for the tailings are reliable.

STRENGTH TESTS

Consolidated undrained compression triaxial tests (CU) are usually carried out to determine the effective shear strength parameters of the tailings. In this study, the tests were performed in the laboratory according to the standard test procedure D 4767 (ASTM 1997b; Bishop et al 1957; Head

1992). Before the specimens were sheared, the saturated specimens were consolidated under the effective stresses of 25, 50, and 100 kPa. A total of 20 tailings specimens were tested in this study.

Figure 14 shows a typical deviator stress versus strain relationships, while the correspondent relationship between the pore water pressure and strain is presented in Figure 15. The effective stress strength parameters were determined based on the Mohr circles. The interpreted results are presented in Table 4.

The values of shear strength parameters $c'$and ϕ' and Atterberg limits indicate that the copper, gold, and oil sand CT tailings behaved as cohesionless soils, while the coal tailings are characterized as cohesive soils. Furthermore, Figure 14 shows that the copper and gold tailings both have slight strain weakening characteristics and behave like dense sandy soils, while the coal tailings and CT have strain hardening characteristics. From the pore pressure change (Figure 15), the deviator stress changes can be explained. For the copper and gold tailings, their pore pressures increase continuously, thus resulting in the effective stresses decreasing and, consequently, causing the deviator stresses to decrease after peak. For CT, however, the pore pressure change has a peak value, and the decrease in the pore pressure in the sample causes an increase in the effective stress and thus an increase in the deviator stress. The CT is different from the other cohesionless tailings such as the copper and gold tailings. This is due to the presence of the clay mineral and bitumen. For coal wash tailings, the pore pressure drops slowly from the peak, and, therefore, the deviator stress increases slowly.

Based on the above discussion, it can be clearly seen that sandy tailings can totally lose their effective stresses due to their pore pressure increases. In other words, the sandy tailings have the potential for both static and cyclic liquefaction failures. Most mineral mine tailings are sandy tailings. Therefore, pore pressure reduction should be addressed in the design of tailings facilities, or a good drainage system should be provided in the design to enhance the stability of the facility.

SUMMARY AND CONCLUSIONS

A series of laboratory tests were carried out to study the properties of mine tailings. The basic physical and engineering properties were obtained. The results presented in this paper provide valuable information related to the tailings disposal. The main conclusions from the study are as follows:

- A linear relationship exists between the void ratio and the log-effective stress for the tailings under study. The measured values of the consolidation parameters are within the published typical ranges for similar types of tailings.
- The relationships between the void ratio and log-saturated hydraulic conductivity of the tailings are almost linear. The measured values of the saturated hydraulic conductivity are in the same range as those reported for similar tailings in the literature.

- The copper, gold and oil sand CT tailings are non-plastic cohesionless soils. They behave like sandy soils, except for the CT, which has an unusual behavior due to the presence of the bitumen. However, the coal wash tailings behave as plastic cohesive soils.
- The copper and gold tailings behave as strain softening soils, while the coal tailings and CT exhibit strain hardening behavior.
- It is important to address pore pressure reduction in the design of a tailings facility.

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Tailings	Copper	Gold	Coal	CT
Specific Gravity, Gs	2.75	3.17	1.94	2.60
pH value in process water	7.8	9.7	7.2	7.7
Liquid limit (%)	----	----	40	----
Plasticity Index (%)	----	----	16	----
Shrinkage Limits (%)	24.4	21.6	21.1	25.2
Clay size particles(< 2μm) (%)	1.3	5.3	22.5	8.9
Sand content (>0.06mm) (%)	74.5	33.3	40	77
Fines content (<74 μm) (%)*	31.3	81.3	66.4	21.2
D_{10} (μm)	16.28	5.0	1.31	2.7
D_{30} (μm)	72.25	19.0	4.13	11.2
D_{50} (μm)	120.6	44.8	29.2	182
D_{60} (μm)	153.5	54.0	60.0	204
Unified Soil Classification	SM	ML	CL	SM

Note: fines are referred to the particle size less than 45 μm for CT.

Table 1. The basic properties of mine tailings

Tailings	C_c	c_v (m^2/yr)	m_v (m^2/MN)	k_s (cm/s)
Copper	0.056 to 0.094	22.32 to 104.23	0.63 to 19.76	4.5E-5 to 9.8E-5
Gold	0.083 to 0.156	13.58 to 80.07	0.29 to 162.5	2.7E-5 to 6.7E-5
Coal	0.37 to 0.396	1.48 to 17.26	1.08 to 188.2	4.0E-7 to 1.1E-5
CT	0.271 to 0.319	0.31 to 8.46	0.61 to 379.9	2.2E-7 to 6.3E-7

Note: C_c, compression index; c_v, coefficient of consolidation; m_v, coefficient of volume compressibility; k_s, saturated hydraulic conductivity; effective stress range is 0.5 to 100 kPa; void ratio range is 0.5 to 1.6.

Table 2. Consolidation parameters and measured saturated hydraulic conductivity of mine tailings

Tailings type	Air-entry Value (kPa)	θ_r (%)	Boundary effect stage (kPa)	Transition stage (kPa)	Residual stage (kPa)
Copper	5	3.4	< 5	>5 and <1500	> 1500
Gold	6	2.2	<6	>6 and <1500	> 1500
Coal	18	18	<18	>18 and <3900	> 3900
CT	6	6.2	< 6	>6 and <3900	> 3900

Note: θ_r is the residual volumetric water content, and the suction is a negative pressure.

Table 3. Tailings-water retention characteristic data

Tailings Type	Copper Tailings	Gold Tailings	Coal Tailings	CT
c'	0	0	10	3
ϕ'	34°	33°	32°	30°

Table 4. Strength parameters of mine tailings

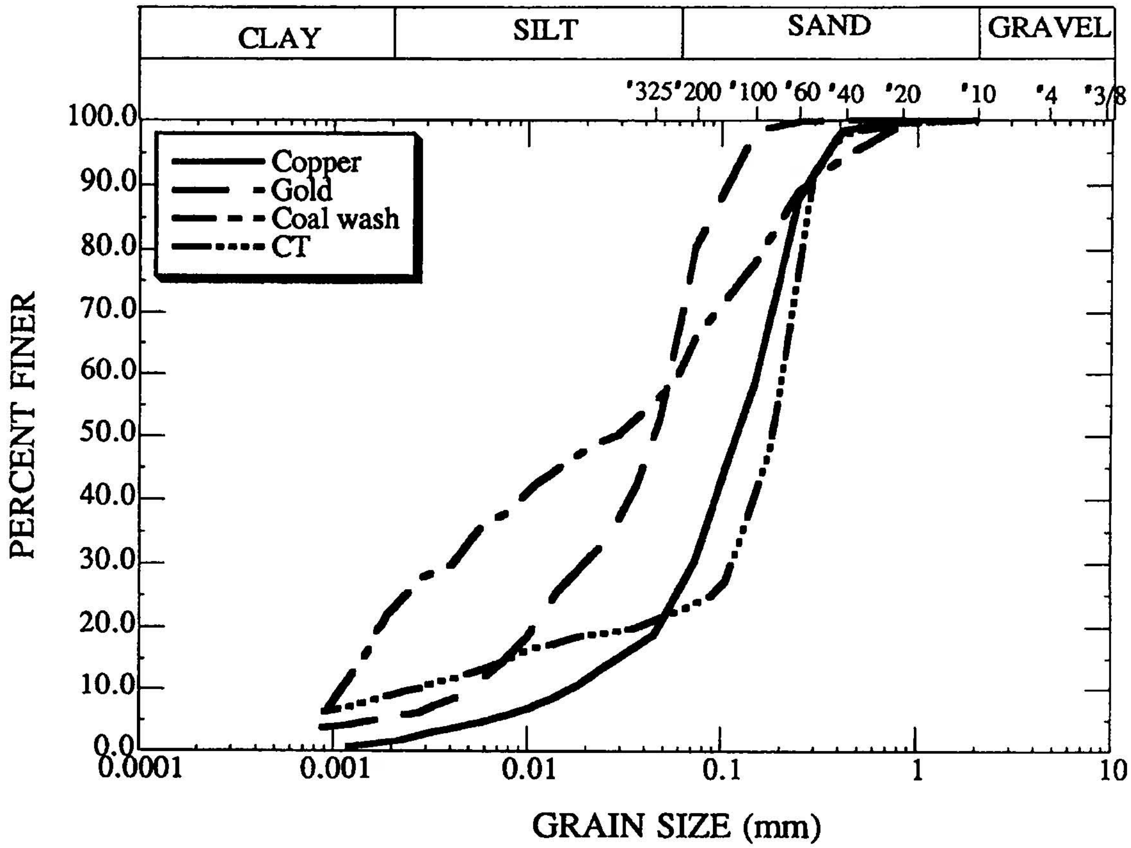

Figure 1. Grain size distribution of tailings

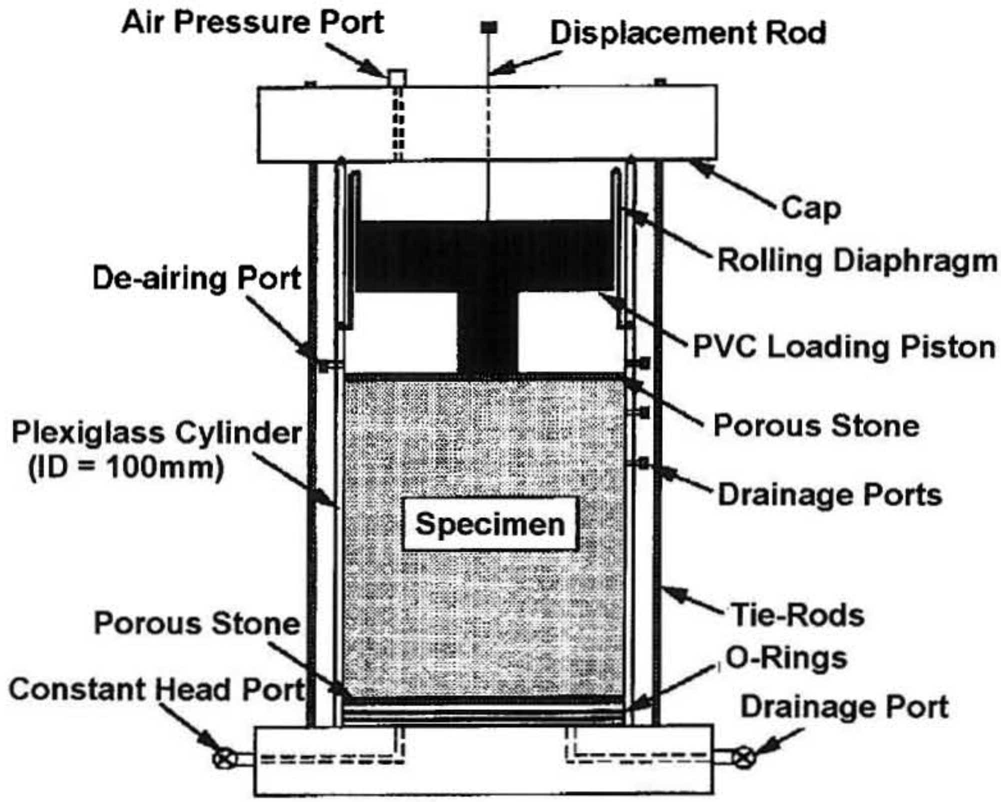

Figure 2. Large strain consolidation apparatus

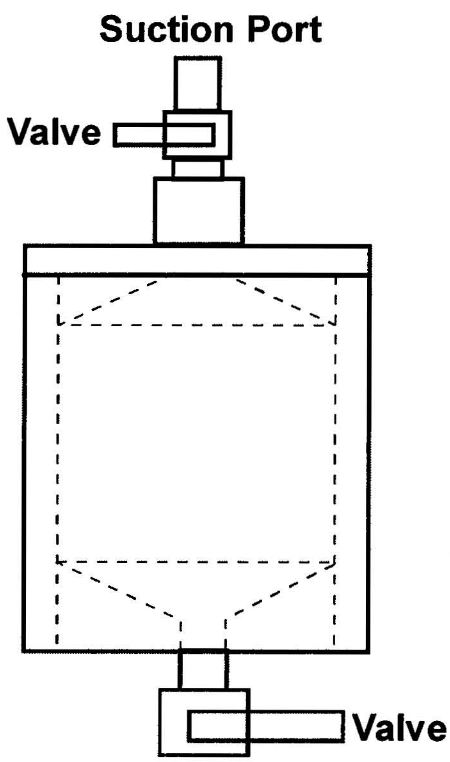

Figure 3. The de-airing cylinder

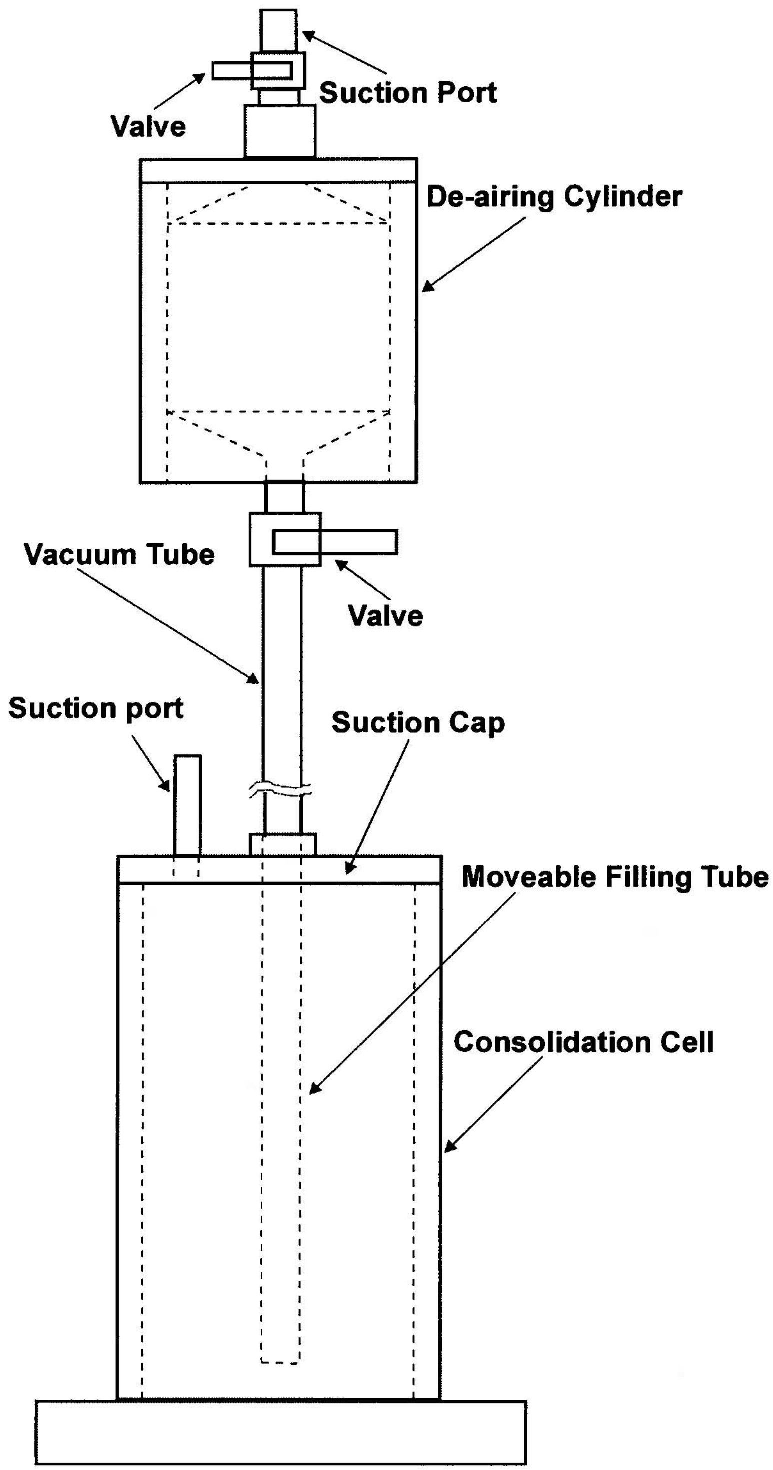

Figure 4. The tailings placement technique

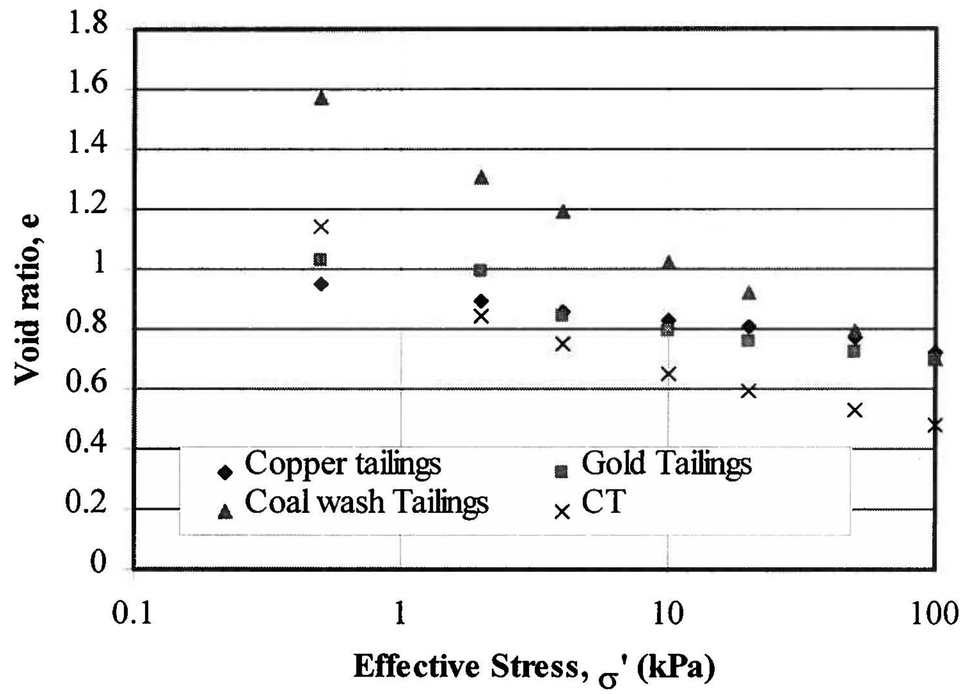

Figure 5. The compressibility of tailings

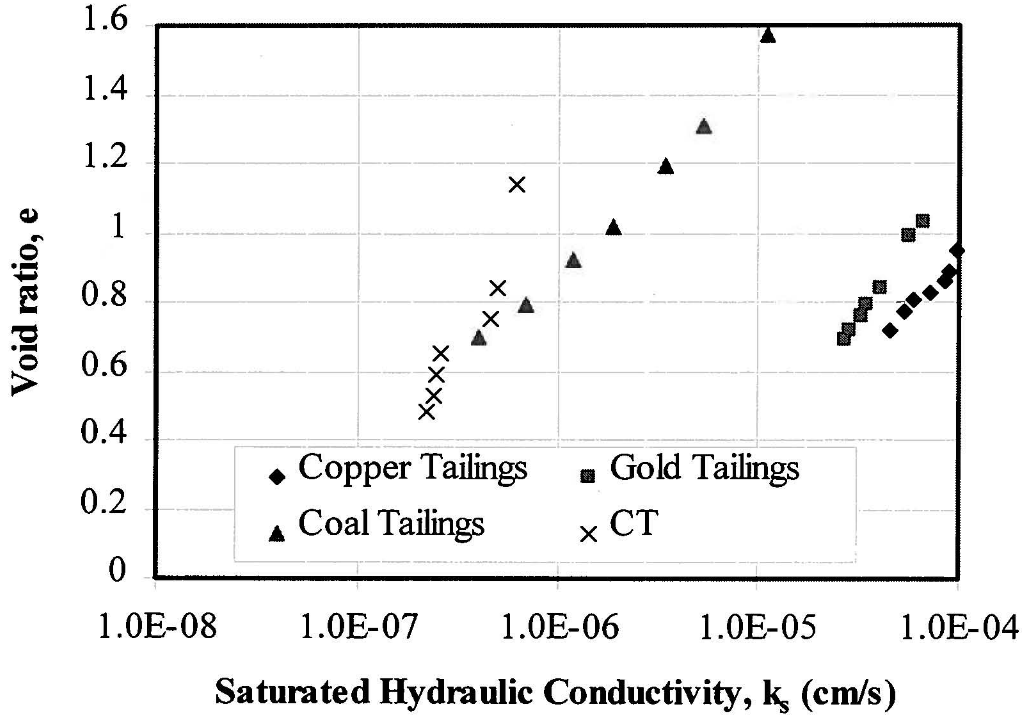

Figure 6. Void ratio versus log hydraulic conductivity

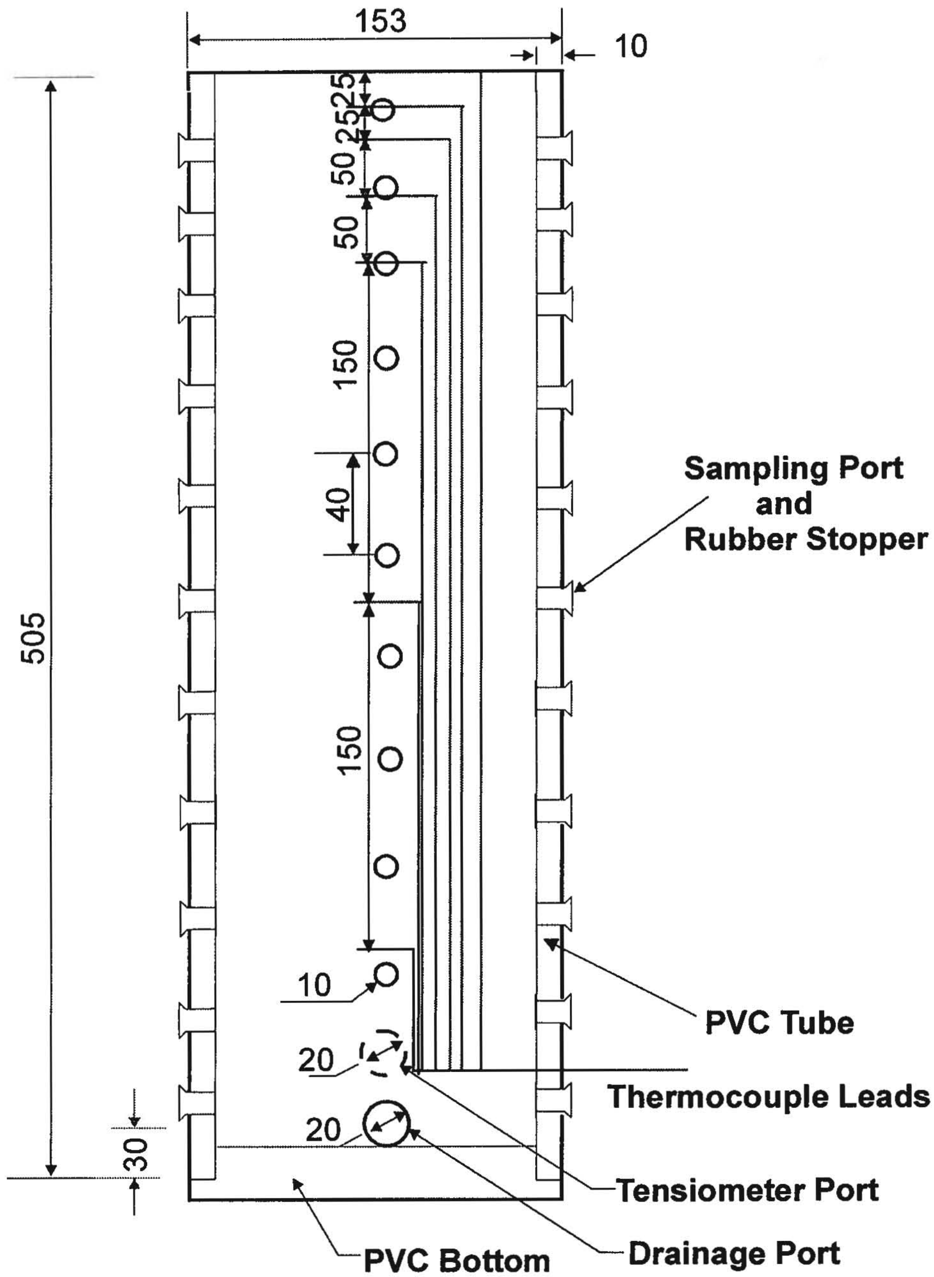

Figure 7. Sketch of the sampling drying column

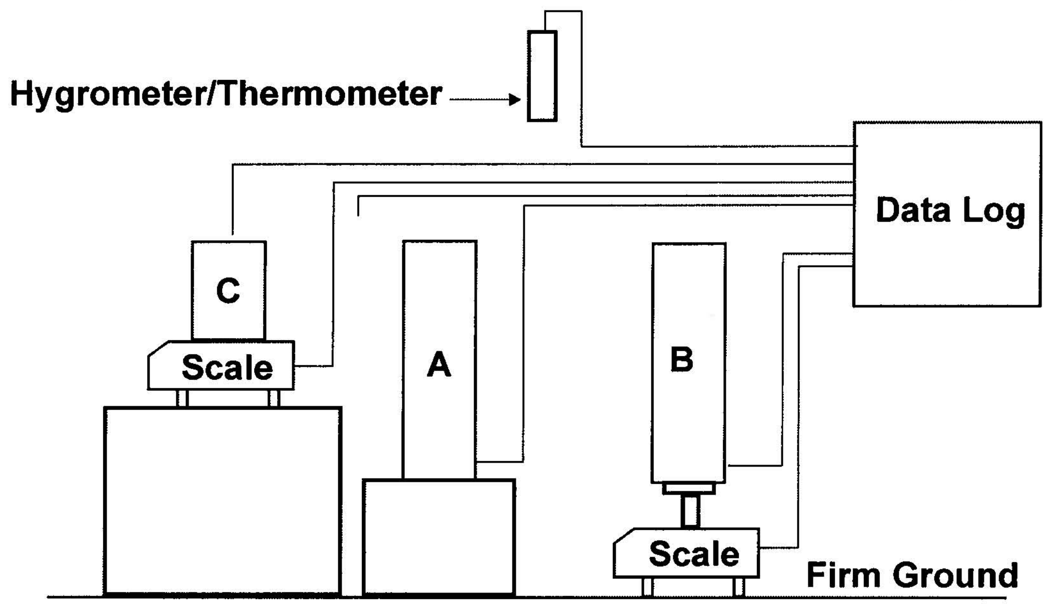

Figure 8. The layout of the drying test apparatus

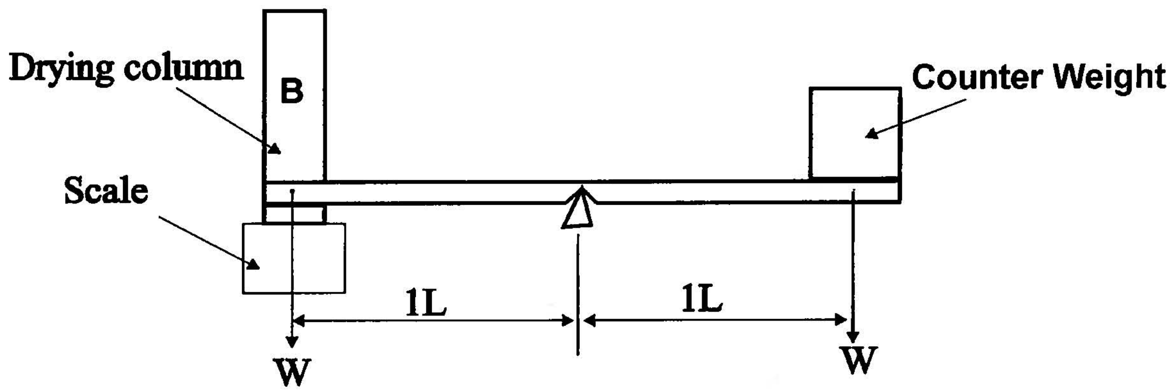

Figure 9. The beam system used to accurately weigh 20 kg samples

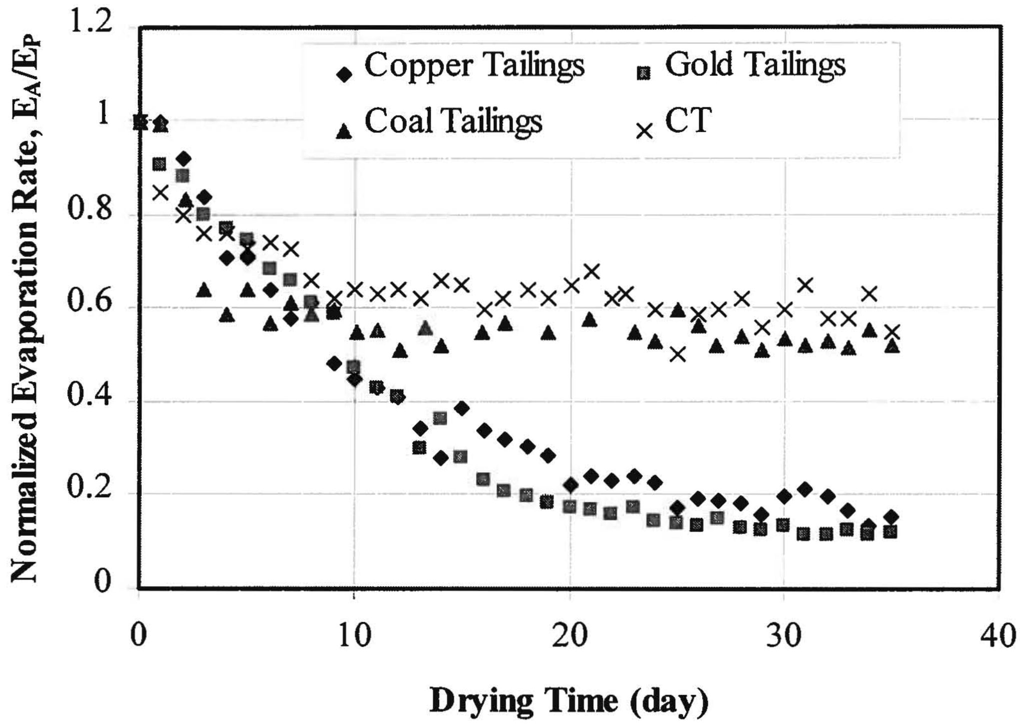

Figure 10. Normalized evaporation rate changes in the tailings

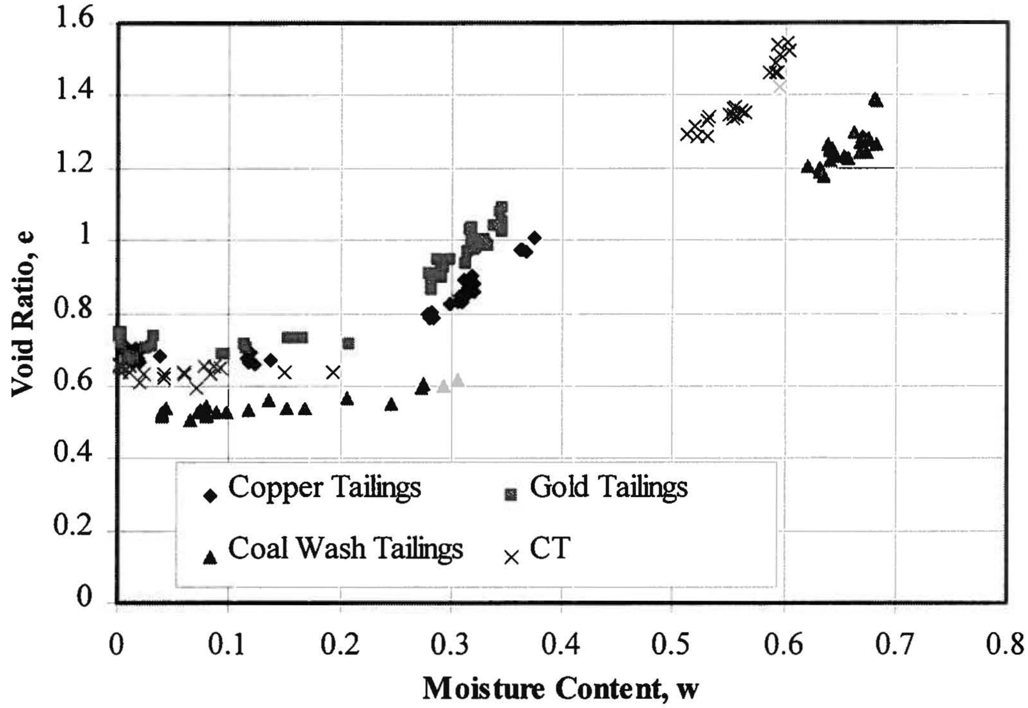

Figure 11. Measured shrinkage curves for tailings.

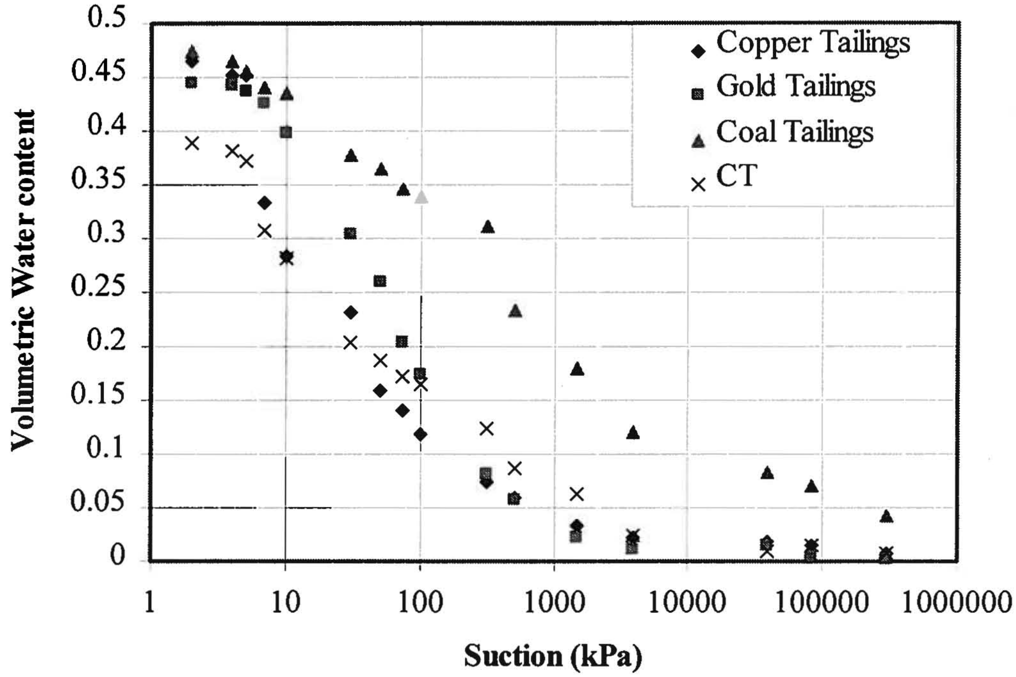

Figure 12. Water retention curves of the tailings

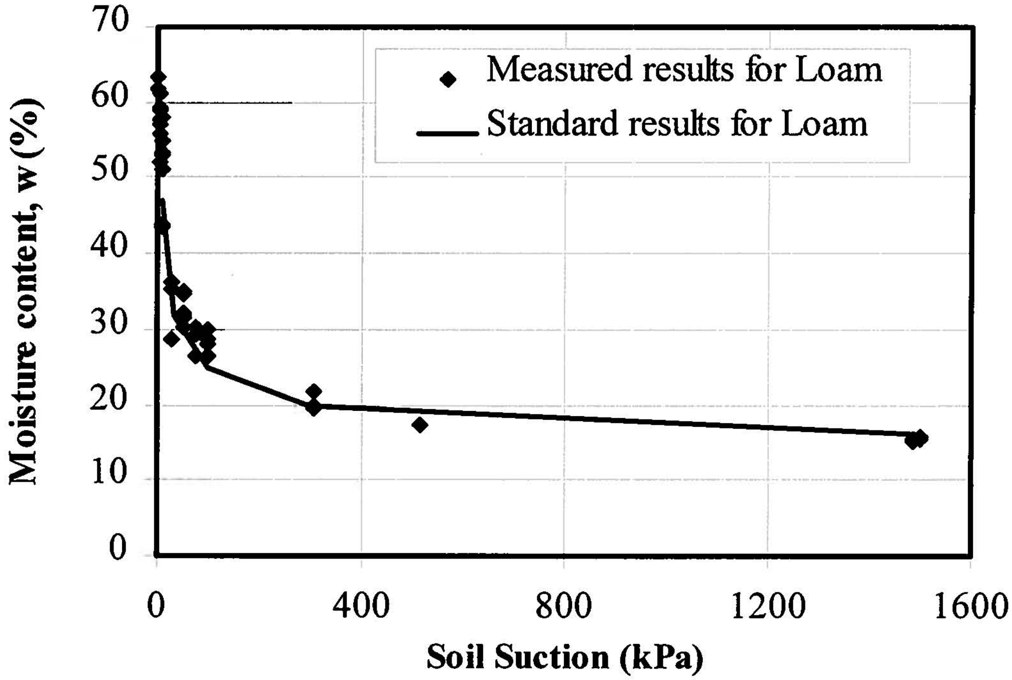

Figure 13. A comparison between measured and standard water retention data for Loam

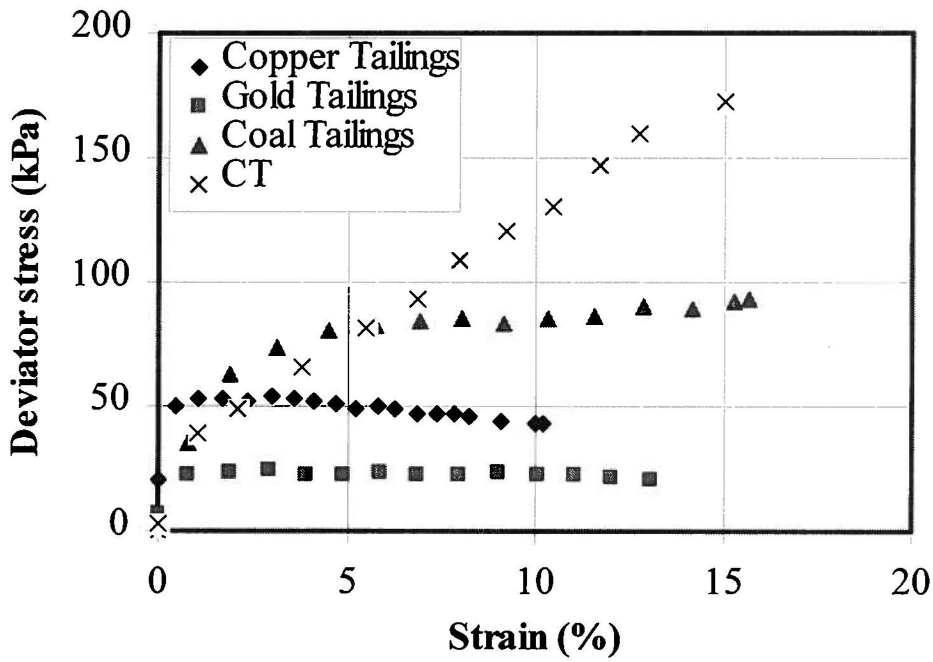

Figure 14. Deviator stress versus strain plot after 50 kPa consolidation

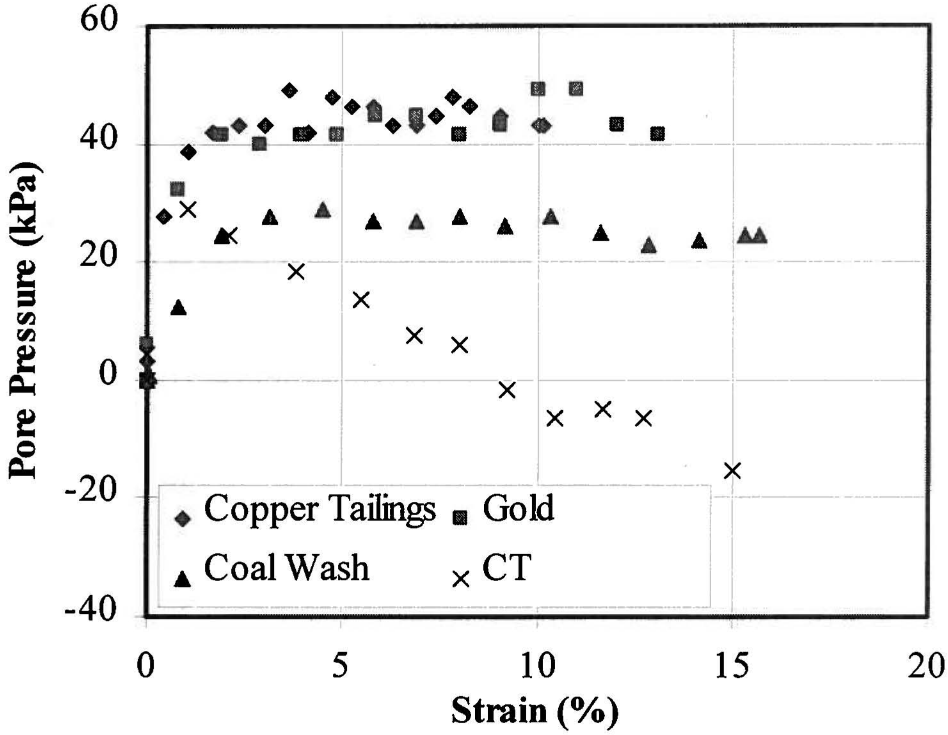

Figure 15. Pore pressure change versus strain plot after 50 kPa consolidation