DETERMINATION OF UNSATURATED FLOW CHARACTERISTICS IN MINE TAILINGS

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ABSTRACT
The design details of a modified permeameter for determining the unsaturated flow characteristics of tailings are presented in this paper. The key modifications in comparison to a conventional permeameter include the provision of adjustable sensors that move along with the slurry tailings as it settles due to desaturation during the testing period. The Instantaneous Profile Method (IPM) is proposed to estimate the representative field unsaturated coefficient of permeability of tailings in the laboratory using a large size specimen in the newly designed modified permeameter. The unsaturated flow behaviour determination is based on the measurements of volumetric water content and matric suction readings. Details with respect to the instrumentation used for the measurement of volumetric water content and matric suction readings are also presented.

RÉSUMÉ:
Dans cet article les détails d'un perméamètre modifié pour déterminer les caractéristiques de stériles miniers non saturés sont présentés. Un perméamètre conventionnel a été modifié de façon à permettre aux sondes de ce déplacer avec l'affaissement des stériles durant les essais en laboratoires. La Méthode du Profile Instantané est proposée pour déterminer le coefficient de perméabilité non saturé pour un échantillon de grande taille. Afin de déterminer les propriétés de stériles non saturés, la teneur d'eau volumétrique, ainsi que la succion matricielle sont mesurées. L'instrumentation utilisée pour mesurer les divers paramètres est aussi décrite.

1. INTRODUCTION

Several experimental methods are available to determine the flow behaviour in unsaturated soils and tailings. However, the unsaturated flow behaviour is commonly predicted and not measured. This has become a conventional engineering practice since the direct measurements of unsaturated flow properties require elaborate equipment and qualified personnel, which prove time consuming and expensive. Due to these reasons, several investigators focused their research on developing procedures to predict the unsaturated coefficient of permeability, k_{unsat}, using the saturated coefficient of permeability, k_{sat}, and the soil-water characteristic curve (SWCC) (Brooks and Corey 1964; Mualem 1976; Gardner 1958; van Genuchten 1980; Fredlund et al. 1994, Leong and Rahardjo, 1997). The SWCC is defined as the relationship between the water content (gravimetric w, or volumetric, θ) or degree of saturation, S, and the soil suction, ψ. Several researchers have also proposed further simplifications in the prediction of unsaturated flow behaviour of soils and tailings based on conventional soil properties such as grain size analysis, degree of saturation, and Atterberg limits (Gupta and Larson 1979; Aubertin et al. 1998; Fredlund et al. 1997; Vanapalli and Lobbezoo 2002).

Many of the prediction procedures available in the literature that use the saturated coefficient of permeability, k_{sat}, and the SWCC provide reasonably good comparisons between the measured and predicted values of the unsaturated coefficient of permeability, k_{unsat}. Comparisons are usually provided between the predicted results and the laboratory test data determined on small size specimens. Conventionally, small size specimens are used in laboratory testing for determining engineering properties of unsaturated soils mainly to reduce the testing time. Several factors such as the density, soil structure, compaction water content, stress state, mineralogy, and hysteresis influence the SWCC behaviour (Vanapalli et al. 1999, Zapata et al. 2000). The parameters that influence the SWCC behaviour also influence the flow behaviour in unsaturated conditions.

A number of studies have shown significant differences between the predicted unsaturated flow behaviour using the SWCC and the field measured unsaturated flow behaviour (Meerdink et al. 1996; Amraoui et al. 1998; Holland et al. 2000). The differences between the predicted and measured flow behaviour can be attributed to the influence of various parameters that govern the unsaturated flow behaviour. One of the key parameters may be associated with the non-representative size of the specimen used in the laboratory to measure the SWCC to predict the field behaviour.

Research suggests that the macro and micro features of an *in situ* soil must be adequately represented in laboratory specimens for proper assessment of the flow behaviour in soils. Various investigators have demonstrated that the field flow properties in saturated conditions can vary by several orders of magnitude in comparison to laboratory test specimens, which are typically smaller (Daniel 1984; Elsbury et al. 1990). Other investigators recommend using large size specimens in the laboratory for determining the flow properties to represent the field flow behaviour (Elsbury et al. 1990; Benson et al. 1994). While these investigations are related

to the flow behaviour in saturated soils, they should also be valid for the interpretation or prediction of unsaturated flow behaviour, both in soils and tailings. Many researchers recommend relying on field measurements rather than laboratory measurements due mostly to the inaccurate representation of the flow behaviour using laboratory specimens (Benson and Gribb 1997; Houston and Houston 1995; Fredlund and Rahardjo 1993).

The research summarized in this paper was initiated when a preliminary search for permeability functions (i.e., relationship between the unsaturated coefficient of permeability, k_{unsat} versus suction) of nickel mine tailings yielded limited data (Vick, 1983; Gonzalez and Adams 1980). It was then decided to explore the methods to obtain permeability functions for nickel tailings. Different approaches, both empirical and experimental were evaluated. Preliminary investigations have shown that there are significant differences between the measured and predicted flow behaviour of nickel tailings using the presently available empirical methods. For this reason, research was concentrated on the development of an experimental technique using large tailings specimens to determine the flow behaviour in nickel tailings.

In this research program, a modified permeameter was specially designed and an experimental program was undertaken to determine the unsaturated flow behaviour of nickel mine tailings. The modifications in comparison to a conventional permeameter include the use of a large specimen and monitoring specimen settlement while collecting the flow characteristics data using non-destructive techniques. Design details of the equipment are described in this paper.

2. BACKGROUND

Several experimental methods are available to determine the coefficient of permeability of unsaturated soils (Klute, 1972; Mansell 1975; Raimbault 1986; Abu-Hejleh et al. 1993; Amraoui. et al. 1998; Elzeftawy et al. 1996; Meerdink; Benson and Gribb 1997). Benson and Gribb (1997) have summarized fourteen different techniques that include both laboratory and field methods for determining the coefficient of permeability of unsaturated soils. The laboratory methods are based either on steady state or transient state flow conditions. The steady state methods require a series of tests to obtain water content, w, and soil suction, ψ, data to interpret the unsaturated flow behaviour (Klute 1971; Benson and Gribb 1997). The main drawbacks associated with these methods are the long time periods required to attain equilibrium conditions to properly assess the flow behaviour characteristics.

The Centrifuge method (Nimmo et al. 1987) is not feasible for routine geotechnical testing as it requires a commercial centrifuge and elaborate testing facilities. This method also applies large stresses to the specimen through centrifugal forces during testing and is suitable only for soils whose flow behaviour is not sensitive to applied stress state.

Some of the transient state methods, namely the Bruce-Klute Method, the Sorptivity Method, and the different Outflow Methods, are based on diffusivity relationships that require the estimation or determination of a large number of parameters (Benson and Gribb 1997). In addition, these methods also require SWCC determination on separate specimens. The flow behaviour characteristics can be significantly influenced even if there are small differences in the specimens used for testing. In other words, great care should be taken to prepare "identical" specimens for testing. Furthermore, the outflow methods require larger time periods to obtain test results.

Benson and Gribb (1997) report lack of accuracy in the test results obtained using the Thermal Method. The major disadvantage with respect to this method is related to the difficulties associated with the identification of specimen equilibrium conditions. There can be significant scatter in the measured results if the equilibrium conditions are not properly assessed in this method.

Instantaneous Profile Method (IPM) appears to be one of the most promising and practical methods for determining the unsaturated flow behaviour. Richards and Weeks (1953) originally described this method. Several other investigators have also used this technique (Klute 1971, Hamilton et al. 1979, and Meerdink et al. 1996).

The flow behaviour in unsaturated conditions using IPM can interpreted using conventional Darcy's law shown below:

$$k_{unsat} = -\frac{\Delta V}{A \Delta t}\left(\frac{1}{dh/dz}\right) \qquad [1]$$

where:

ΔV is the volume of water flowing past a specific depth, z, in a specimen of cross-sectional area, A, over a given time increment, Δt, with a hydraulic gradient, dh/dz.

The volume of water flowing through a given location is obtained from Equation 2.

$$\Delta V = A\int_{z_o}^{z_i}(\Delta\theta)dz \qquad [2]$$

where:

z_o and z_i are two consecutive depths. The volume of water flowing between the two consecutive depths is obtained by measuring the volumetric water content, θ, at these two known depths at a given time.

Equation [3] relates the hydraulic gradient, dh/dz to the measured matric suction, $\delta\psi$ and two successive depths at which volumetric water contents, θ, are also measured.

$$-\left(\frac{dh}{dz}\right) = 1 + \left(\frac{\delta\psi}{\delta z}\right) \qquad [3]$$

The soil-water characteristics can be measured in IPM both in the desoprtion (i.e., drying) and absorption (i.e., wetting) stages using a single specimen. Large and more representative size specimens are used in this method contrary to other transient methods. Due to this reason uncertainties associated with using small specimens can be eliminated when applying IPM results to actual field conditions. Furthermore, the IPM requires significantly less time to obtain the unsaturated flow characteristics in comparison to other methods.

3. TAILINGS PROPERTIES

The laboratory experiments in this research were conducted on nickel tailings from the Sudbury operations of Falconbridge Ltd. The tailings were collected from different locations along the discharge line, in order to obtain the three typical gradations common to spigotted tailings. The terms feed, overflow and underflow, frequently used, refer to a particular size fraction found in the slurry at different location of the deposition line. The whole tailings slurry that is hydraulically transported to the impoundment reservoir is known as the *feed*. As the feed reaches the impoundment, it passes through a mechanical device known as a cyclone, which separates the feed into fine and coarse particles. The finer particles (*overflow*) are evacuated in the impoundment, whereas the coarser particles *(underflow)* are used to elevate the embankment, as more storage space is required (Vick, 1983).

Figure 1 shows the grain size distribution of all three gradations *(i.e., feed, overflow and underflow)*.

Table 1. Physical properties of undisturbed tailings

Properties	Underflow	Overflow	Feed
k_{sat} (m/s)	4.2×10^{-6}	3.0×10^{-8}	4.0×10^{-7}
e_{sat}	0.61	0.89	0.59

Physical properties were measured on "undisturbed" specimens, and on "re-slurried" specimens. The term "undisturbed" is used to describe the specimens that were carefully removed from the original pails of nickel tailings that were stored in the laboratory for several years. The tailings settled and slightly consolidated under its own weight during this period of time. "Undisturbed" specimens were extracted from the consolidated portion of the tailing using a piston sampler. These specimens were directly placed in a permeameter and the saturated hydraulic conductivity, k_{sat} was measured under a constant head. The void ratios, e_{sat} of these specimens were also measured. The results are summarized in Table 1.

The other measured parameters determined using "re-slurried" tailings are summarized in Table 2. The term "re-

slurried" refers to the tailings specimens that were stirred to attain their original slurry form. Unless otherwise specified, the term tailings is used in the remainder of the paper to refer to "re-slurried" tailings.
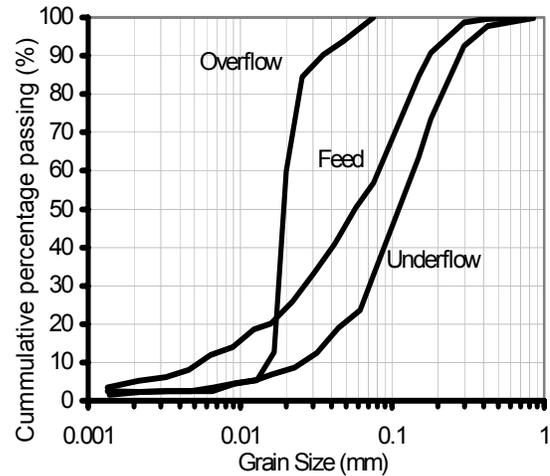
Figure 1. Grain size distribution curves of nickel tailings

Table 2. Physical characteristics (re-slurried tailings)

Properties	Underflow	Overflow	Feed
Clay (%)	3.55	0	9.46
Silt (%)	27.60	99.99	42.96
Sand (%)	68.83	0.01	47.58
D_{10} (mm)	0.0261	0.0161	0.0056
D_{30} (mm)	0.0727	0.0180	0.0258
D_{60} (mm)	0.1356	0.0206	0.0984
C_c	1.495	0.978	1.22
C_u	5.196	1.28	17.705
G	2.99	2.91	2.92

4. THE IPM TESTING PROCEDURE

The Instantaneous Profile Method (IPM) was selected as it facilitates the determination of the flow behaviour under unsaturated conditions with large size specimens using non-destructive testing techniques. Typically, large size specimens provide more representative flow behaviour of the actual field conditions.

Several investigators used the IPM to determine the flow behaviour in compacted soils (Hamilton et al. 1981; Malicki et al. 1992; Meerdink et al. 1996). The volumetric water content, θ in the compacted soils was determined using fixed TDR probes. The use of TDR does not pose problems in the measurements of volumetric water contents of compacted specimens since there is no concern related to the possibility of formation of water pockets near the TDR probe's parallel rods. The

measured volumetric water content values may not be reliable if water pockets are formed within in the vicinity of the probes, which are zones of high sensitivity. Baker and Lascano (1989) found that the sensitivity of parallel rod probes was largely confined to an area of 20mm by 65mm surrounding the 2-rod probe. A greater area of a lesser sensitivity was found to extend outwards approximately 70mm from the centre of the rods (Topp and Davis 1985).

Figure 2 shows typical contours of dimensionless electrical field distribution normal to a two-rod probe in a material of uniform dielectric constant (Zegelin et al. 1989). The measurements cannot be representative of the actual conditions if voids are formed within the vicinity of the TDR probe's rods during the settlement of the specimen.
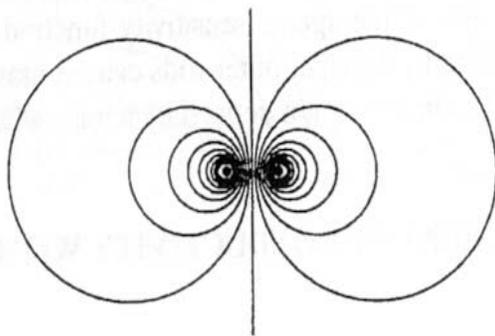
Figure 2. Contours of electric field distribution normal to direction of two-rod parallel probe in material of a uniform dielectric constant (after Zegelin et al. 1989)

If fixed probes are used in a slurry specimen during the measurement of flow behaviour, it is likely that water pockets will develop around the TDR probes. The water pocket formation can take place at the time of the specimen's settlement during testing. To alleviate this problem, it is necessary to provide vertically mobile supports to the TDR probes, and allow the probes to move upon settlement of the slurry tailings specimen. By introducing mobile supports, continuous, non-destructive testing can be performed as the saturated slurry specimen desaturates to a dry or close to dry condition during desorption (i.e., drying phase). More design details with respect to these mobile sensors are detailed in later sections of the paper.

The IPM requires simultaneous measurements of volumetric water content and matric suction to determine the flow behaviour under unsaturated conditions. Thermal conductivity sensors were chosen to measure the matric suction (i.e., negative pore water pressure) in the specimen. These sensors are useful to determine matric suction values in the range of 0 to 500 kPa for long periods of time (Shuai et al. 2000, Shuai and Fredlund, 2000). It was also decided to add tensiometers to determine matric suction values in the range of 0 to 90 kPa. Tensiometers will be useful to validate lower suction

values measured with the thermal conductivity sensors. The tensiometers were also added to provide instantaneous readings of matric suction values. The thermal conductivity sensors require a longer period of time to reach equilibrium conditions to provide readings of matric suction values.

5. INSTRUMENT CALIBRATION

Trial tests were undertaken using Time Domain Reflectometry (i.e., the Moisture Point™ Model MP-917) to check the validity and reproducibility of the measurements of volumetric water contents in nickel tailings. Specimens of known water content (gravimetric) were prepared in a standardized volume, acrylic tube. Using Equation 4, the theoretical volumetric water content was computed.

$$\theta = \frac{w\,S\,G}{S + wG} \qquad [4]$$

where:

w is the gravimetric water content, S, is the degree of saturation, and G is the specific gravity of the material.

The results of the trial tests undertaken on fine tailings specimens are presented in Figure 3.
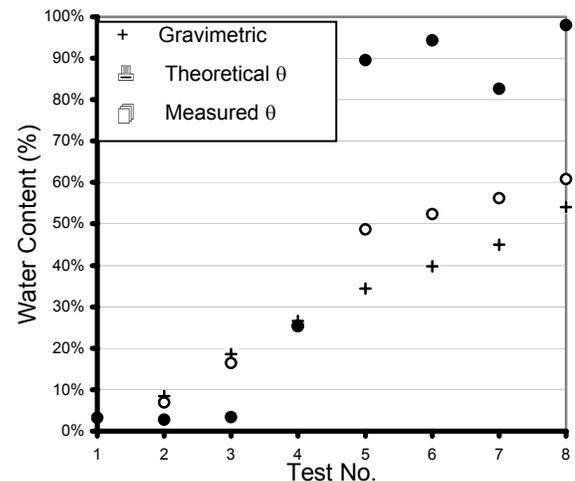
Figure 3. Comparison of Theoretical and Experimental Volumetric Water Contents

The results show significant differences between the volumetric water content, θ determined using Equation 4 and experimental measurements using TDR. It should be noted that some scatter was expected because of the intrinsic software of the MP-917 (programmed for 30cm long probes) was used while the length of the probes was 20cm. This difference should have given a constant error in the readings since the travel time of the electromagnetic wave along the probes is directly proportional to the length

of the probe, as seen in Equation 5 (Davis and Chudobiac 1975).

$$t = \frac{2l_p}{V_p} \quad [5]$$

where:

l_p is the length of the probe, and V_p is the velocity of the wave. The propagation velocity, V_p is defined below:

$$V_p = \frac{c}{\sqrt{\in}} \quad [6]$$

where:

c is the speed of an electromagnetic wave in free space, and $\in$ is the permitivity of the medium (Topp et al. 1980).

From Equation 7 it can be seen that if a shorter probe is used, the apparent dielectric constant, K_a, measured with TDR increases, if both c and $\in$ are assumed constant.

$$K_a = \left[\frac{ct}{2l_p}\right]^2 \quad [7]$$

However, as shown in Figure 3, the test results did not show a constant error. Due to the discrepancies observed in the experimental results, it was decided to add a destructive testing component to the modified permeameter (i.e., using Equation 4) to verify the TDR readings and to further investigate the reasons for the differences in the results. It was planned to remove small specimens at regular intervals during testing from the permeameter to compute volumetric water content from direct measurements at specific locations along the length of the soil specimen.

6.   THE MODIFIED PERMEAMETER

Meerdink et al. (1996) originally designed a permeameter to determine the unsaturated flow behaviour in compacted soils. The major difference in the modified permeameter in comparison to Meerdink et al. (1996) permeameter lies in the placement of sensors in the permeameter and their mobility characteristics.
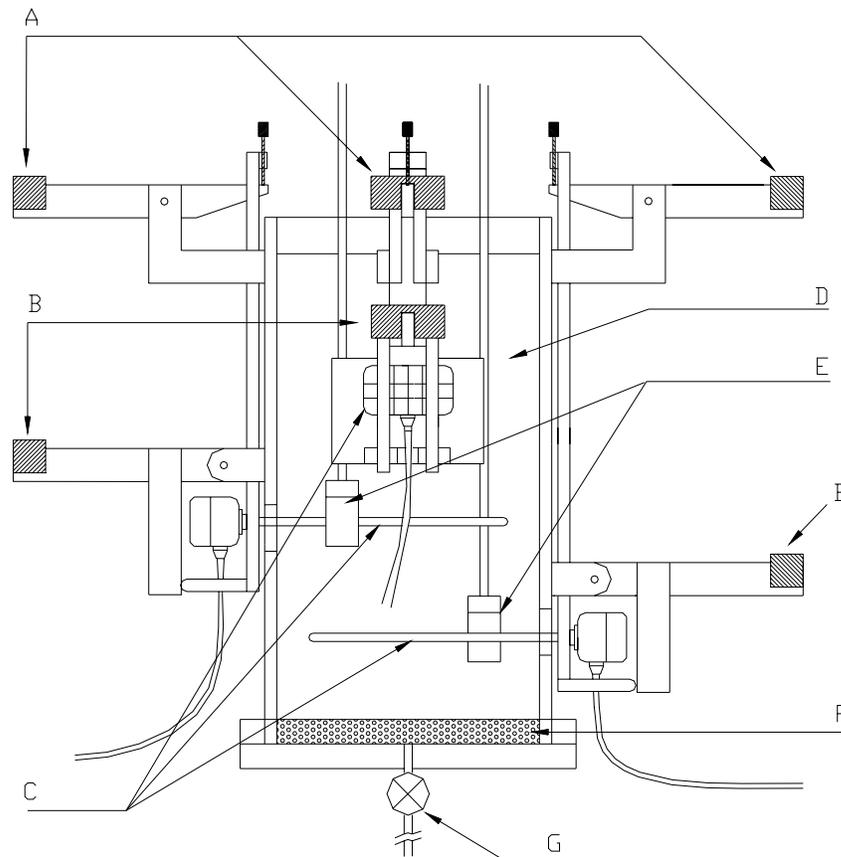
Figure 4. Schematic of rigid wall permeameter with adjustable sensors

Design modifications mainly facilitate the sensors to move along with the tailings specimen. The modified permeameter accommodates larger size specimens in comparison to other conventional laboratory tests. The dimensions of the base of the permeameter are 200mm x 200mm, and can hold a 400mm high soil specimen. There are other reasons for using a large size permeameter. First, the permeameter has to be large enough to contain all the instrumentation to collect the required information. Second, there has to be sufficient distance between the sensors to prevent disturbance or even overlaying regions of influence. For example, the TDR probes, as discussed previously, have a region of higher sensitivity extending approximately 20 mm from each of the two rods. It is therefore important to allow sufficient space between probes to prevent the presence of a probe in the region of higher sensitivity of an adjacent probe.

To allow the sensors to move with little or negligible resistance, the sensors had to be essentially buoyant in the slurry specimen. To accommodate the above design criteria, a system of counterweights was devised to allow vertical movement of the TDR probes, while retaining the water-tightness of the permeameter.

Figure 4 provides design details of the modified permeameter showing both sets of counterweights (A, B), the TDR probes (C), the location of the specimen (D), the thermal conductivity matric suction sensors (E), the low air-entry value porous stone (F), and the control valve at the bottom (G). For clarity, the tensiometers were omitted, but it should be noted that they are positioned at the same depth and parallel to the thermal conductivity sensors.

For the TDR probes, two sets of counterweights were required to maintain mobility and the water-tightness of apparatus. Figure 5 shows design details of the counterweights. The top counterweights can be moved horizontally on their acrylic support (see arrow 1) to balance the weight of the TDR probes and their support. This balancing action basically eliminates the weight of the probes and allows them to move along with the soil as it settles when the soil is subjected to desaturation (i.e., drying). A fine adjustment screw is provided to allow counterweight's supporting arm to level-off in order to counteract the deflection of the probes once the specimen is in place (see arrow 2 in Figure 6). Arrow 3 shows the horizontal shift that the bottom counterweights can be subjected to in order to apply the necessary pressure on the TDR support to neutralize the hydrostatic pressure acting on the specimen. In this case, it was more appropriate to have a single weight that could be moved for adjustment, rather than making a number of weights, which would have to be changed with every new specimen tested. A graphite-based grease was placed on the back of the TDR probe supports to ensure a proper seal and prevent inhibiting the probe's movement ability. As well, a rubber seal was placed around the stainless steel TDR probes to provide water-tightness at their entry point in the specimen.

Ideally, the function of the sampling tool is to cause minimal disturbance to the slurry tailings specimen and also be positioned such that loss of water is prevented during extraction of tailing specimen. A thin walled hollow tube was used as a sampling tool to minimize disturbance. It was also essential that once a sample was confined in the sampling tool, a seal formed to prevent a change in water content or suction of the tailings specimen in the modified permeameter.

To satisfy the above design criteria, a fixed sampling tool was used inside the permeameter through the wall on the free wall of the permeameter (i.e., where no TDR probes and counterweights are located). Several of these sampling tools are required in order to take samples along the length of the tailings specimen.
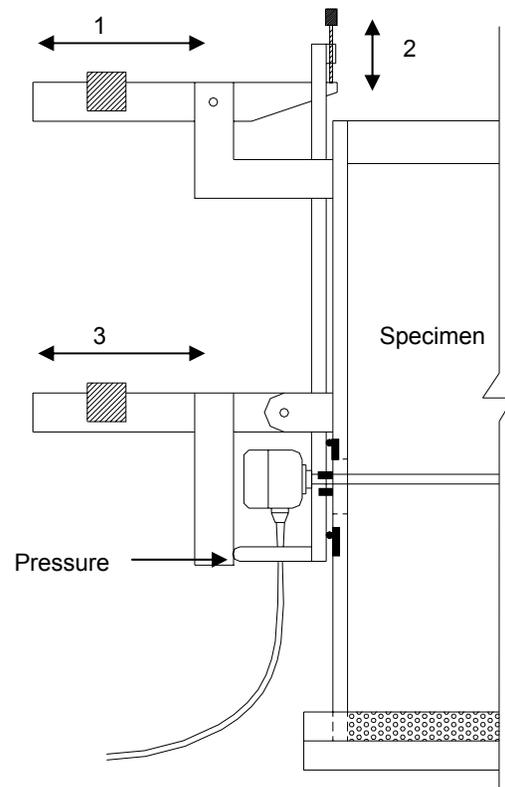
Figure 5. TDR probes counterweight system

Figure 6 provides the schematic of the sampling tool. The exterior wall of the permeameter (1) is located on the right side of the tailings specimen. Arrow 2 points at the hollow tube acting as a sleeve for the inner solid cylinder. Both tubes (hollow and solid) have a circular hole in the vertical direction at the same location, through which the tailings specimen, as well as the water can flow. Hence, at a desired time, the knob (3), which is fixed to the inner solid cylinder, can be turned to trap a small sample inside the outer hollow tube and within the confines of the hole in the

inner cylinder (4). The tubes are held securely in place by an acrylic extension (5) and sealed with rubber O-rings (6) to prevent any water from leaking out. Other O-rings are placed around the inner cylinder just beside the hole to prevent water from migrating between the sleeve and solid cylinder. The sampling tool can therefore remain in the tailings specimen during testing since it is watertight. Upon completion of the test, the tubes are removed with a sample taken at a specific point during drainage of the specimen. Essentially, a small sample is trapped at a given time in a zone of known volume, from which volume-mass properties can be measured. The volumetric water content, θ for a given time at a known location in the tailings specimen can then be computed using Equation 4, and compared with the TDR reading taken during the drying process.
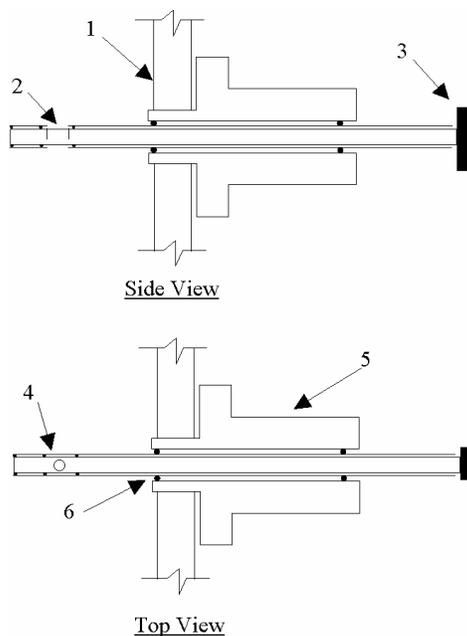
Figure 6. Schematic of destructive water content sampling tool

With all the sensors in place, the tailings specimen is poured into the modified permeameter in a slurry state. At different stages, pouring of the slurry has to be briefly halted to properly position the suction sensors that are hanging from the rigid frame above the permeameter. During this brief halt, additional segregation occurs in the tailings specimen since the coarser particles settle faster than the finer ones. This segregation creates layering that bears resemblance to the natural deposition of tailings at impoundment sites (Vick, 1983). Finally, when the entire slurry has been placed in the permeameter, testing can commence by allowing a flow of water out of the specimen by means of the bottom valve.

7. SUMMARY

The described modified permeameter can be used in conjunction with the Instantaneous Profile Method to determine the unsaturated flow behaviour of mine tailings. At the time of submitting the paper, experimental studies were in progress. The permeameter is showing promising signs of simultaneously obtaining the permeability function and the SWCC of nickel mine tailings. Experimental results will be presented at the time of presenting the paper at the conference.

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