Factors affecting the drained strength of deposited mine tailings beds in the very low stress range

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ABSTRACT
Ultra low consolidation stresses are commonly observed in mine waste management facilities and should be considered when assessing the stability and erosion resistance of mine tailings beds. The present study utilized a specially built tilting tank to measure the drained shear strength of deposited mine tailings beds in the stress range below 1 kPa. The effect of tilting rate and time for consolidation on the shear strength of the beds was investigated. Linear drained and partially drained shear strength envelopes were defined and the corresponding effective and total friction angles were determined.

RÉSUMÉ
Des contraintes de la consolidation ultra faible sont habituellement observées dans les installations de gestion des déchets miniers et devraient être considérés dans les évaluations de la stabilité et la résistance à l'érosion pour des lits des résidus miniers. L'étude à présent a utilisé un réservoir de l'inclination construite spécialement pour mesurer la résistance au cisaillement non drainés des dépôts de résidus miniers pour des contraintes en dessous de 1 kPa. L\`effet de l\`inclination et le temps pour la consolidation sur la résistance au cisaillement des lits a été étudiée. Les limites linéaires de la résistance au cisaillement non drainés et drainés partial ont été définies et les angles de frottement total et effectif ont été calculés.

1 INTRODUCTION

Tailings are a waste product of mining and milling operations. In the conventional milling process, the crude ore is crushed and then ground in mills to a particle size small enough to allow the extraction of the valuable metals from the waste. To minimize their disposal costs, mine operators often use the coarser fraction of the tailings in the construction of embankments, while the finer tailings are deposited in the lagoons or ponds behind retaining tailings dams. Bussière (2007) noted that mine tailings possess some unique geotechnical properties, which must be considered in order to evaluate their potential application as a construction material; as well as to estimate the settlement and erosion resistance of the tailings beds. Usually the mine tailings are composed of sand- or silt-sized particles ranging between 2 and 80 µm. Being man-made materials, most mine tailings are more uniform than natural soils and exhibit lower density, higher angle of internal friction and smaller cohesion. Mittal and Morgenstern (1975) outlined the principal differences between earth and tailings dams engineering and conducted a laboratory investigation of the basic geotechnical properties of mine tailings, which demonstrated that the highly angular tailings give 5° to 6° higher friction angles than the rounded natural sands at all density and stress levels. Pettibone and Kealy (1971) investigated the engineering properties of nine tailings materials obtained from mines in the United States and Canada. They found that the studied tailings exhibited close to zero cohesion and a high effective friction angle between 34° and 42.5°, which they attributed to the particle angularity. Matyas et al. (1984) performed standard triaxial compression (drained and undrained) and direct shear (drained) tests on undisturbed and remoulded tailings samples. They found that the angle of internal friction varied between 30° and 42° depending on the void ratios of the tested samples prior to shearing. It was concluded that the presence of silt in tailings increased their internal friction angle due to higher percentage of needle-shaped particles in the silt.

The selection of correct strength parameters has been long recognized as a major factor critical to reliable slope stability or erosion resistance analysis. Undrained shear strength, S_u is used in the analysis when the engineering loading is assumed to take place so rapidly that there is no time for the induced excess pore water pressure to dissipate or for consolidation to occur during the loading period (Holtz and Kovacs 1981). Drained shear strength, τ_f is preferred when analysing tailings embankment dams with long term steady seepage or the long tem stability of excavations or slopes. The rate of loading here is either sufficiently slow to ensure that no excess pore pressures are induced in the soil or full dissipation of excess pore pressures with time has already occurred.

In geotechnical practice different tests can be used to evaluate the shear strength of soils, among which are triaxial (consolidated-drained, CD, and consolidated-undrained, CU) and direct shear tests. The Mohr-

Coulomb failure criterion is usually applied to obtain the failure envelope of the soil, from which values of cohesion and angle of internal friction are estimated. Common practice is then to extend the obtained failure envelope linearly to the low stress range (<1 kPa) and to assume zero cohesion intercept for sandy tailings (Zreik et al. 1998a; Mittal and Morgenstern 1975; Pettibone and Kealy 1971). However, the stress range in the majority of tailings management facilities is extremely low and varies between 0.5 and 100 kPa (Qui and Sego 2001). Within this range, the sediment and mine tailings deposits exhibit very low shear strength that often cannot be measured using conventional geotechnical techniques (Qui and Sego 2001; Zreik et al. 1995; Zreik et al. 1998b). In addition, tailings placed in ponds under water behave differently from the ones in the tailings embankment. For instance, they tend to assume flatter slopes, are more sensitive to the presence of fines and exist in a looser state (Sarsby 2000). The literature offers a few examples of studies on strength properties of cohesive bottom sediments. For instance, Zreik et al. (1998a) performed tests on deposited normally consolidated Boston Blue Clay sediment beds and obtained drained strength parameters (true cohesion and angle of internal friction) at very low stresses (16.5 to 155 Pa). They reported effective friction angles between 16º and 28º and true cohesion values between 10 and 15 Pa.

To the present authors' knowledge, a thorough investigation of the strength behaviour of deposited mine tailings beds in the ultra low stress range has not been performed yet. Therefore, the objective of this research work was to: i) provide information on the drained shear strength of mine tailings under extremely low consolidation stresses (0.1 to 1 kPa); ii) evaluate the effect of rate of loading on the shear strength; and iii) provide a description of the failure mechanism of the tailings beds.

2 TESTING MATERIALS AND PROCEDURES

2.1 Deposited Tailings Beds Preparation

The mine tailings, used in the present study, were obtained from the Clarabelle Copper Mine, Sudbury Ontario. The material was composed predominantly of silty sand and its physical characteristics are summarized in Table 1.

Table 1. Physical characteristics of mine tailings

Characteristics	Value
Fine fraction (< 0.075 mm)	32 %
Clay-sized fraction (< 2 μm)	4 %
Diameter of 60% finer, D_{60}	0.15 mm
Diameter of 10% finer, D_{10}	0.019 mm
Uniformity Coefficient, C_u	7.89
Coefficient of Gradation, C_c	1.97
Specific Gravity, G_s	2.99

Tailings beds with a final thickness from 1 to 6 cm were deposited from tailings/water slurries with 180% water content and an initial height between 3 and 16 cm. The beds were left to consolidate under self weight for a period of 6 or 18 days and were then tested using a specially constructed Tilting Tank. All tests were performed at an ambient temperature of 22°±1°C.

2.2 Shear Strength

Drained and partially drained shear strength experiments were performed using the Tilting Tank shown on Figure 1a. The conceptual design of a similar apparatus was previously described by Zreik et al. (1998a) and Kamhavi and Arthur (1992), however, the equipment used in the present study was modified from their original design. Tailings beds were directly deposited from slurries with varying heights in an acrylic tank, 45 cm long, 22.5 cm wide and 12.5 cm high. Slurries with an initial height of more than 12.5 cm (the height of the tank) were required to obtain beds with final thickness of 4.5 cm and above and in these cases a removable open-ended extension was placed on the top of the tank to bring its total height to 42 cm. The tailings beds were tested after a period of self consolidation of 6 or 18 days. When the extension was used to prepare a tailings bed from slurry with an initial height greater than the height of the tank, the water above the upper rim of the tank was pumped out first and then the extension was removed. In the cases when the initial slurry height was smaller that the height of the tank, it was filled up with water prior to the test using a mini pump. A very slow pumping rate (0.384 L/min) was selected to ensure minimum disturbance of the bed during the filling/emptying process. The cover was then sealed in place using clamps positioned on all four walls of the tank (Figure 1a). The cover was equipped with two openings: a water spout, connecting the tank to a constant head flask; and an air vent allowing the air trapped within the tank to escape (not shown on Figure 1). The tank was then placed on a tilting platform and tilted at one side by the means of a pulley and DC motor system until failure of deposited bed occurred. The failure was defined as the sliding of a portion of the bed under the influence of gravity forces to the bottom of the tank and it was detected by a cadmium sulphide photosensor that at failure automatically broke the electric circuit, preventing further tilting. The portable photosensor was placed in a protective rubber sleeve and mounted on a small acrylic block. Prior to tilting it was positioned at approximately 1 cm above the bed surface and held in place on the outside of the tank using adhesive tape as shown in Figure 1b. A light source (desk lamp) on the side of the tank opposite the photosensor ensured that the sensor remained illuminated (and the electric circuit open) throughout the tilting. Prior to bed failure the light from the source was able to penetrate the relatively clear water above the bed and reach the photosensor (Figure 1b). Upon bed failure, the soil above the failure plane slid to the bottom of the tank and accumulated there thus impeding the light from reaching the photosensor and triggering a circuit breaker, terminating the tilting (Figure 1c). The tilting angle, at which failure occurred, was measured with an electronic digital protractor (AN451-101 Electronic Digital Protractor) and recorded.

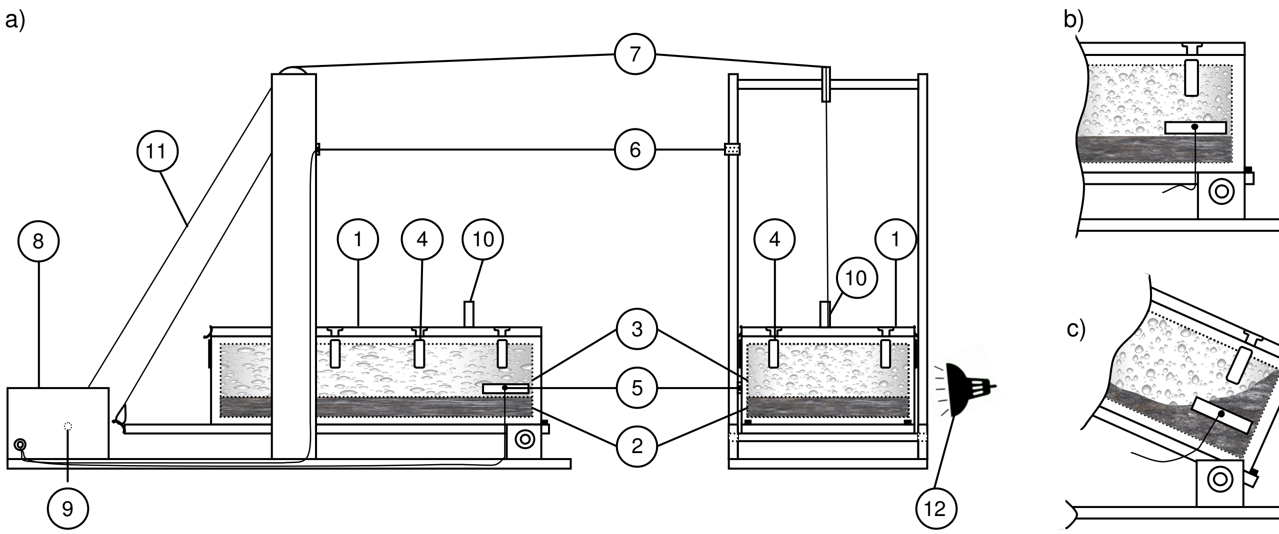

Figure 1. a) The Tilting Tank: 1 Acrylic tank, 2 Deposited tailings bed, 3 Water, 4 Clamps, 5 Photosensor, 6 Back up photosensor, 7 Pulley, 8 DC Motor, 9 Motor shaft, 10 Water spout, 11 Cable, 12 Light source; b) Tailings bed and photosensor at the onset of tilting; c) Tailings bed and photosensor at failure.

The configuration of the Tilting Tank allowed a maximum tilting angle of 50° and if it was reached a back up cadmium sulphide photosensor was triggered, activating a relay switch that automatically broke the electric circuit. Two tilting modes were employed during the experimental program: i) slow tilting at a speed of 0.25°/min, and ii) rapid tilting at a speed of 1.7°/min. The tilting speed was controlled by a timer (DELTA D6DI) switching the motor for 10 s every 4 min during the slow tilting. The rapid tilting was achieved by allowing the motor to run continuously at full speed. A thin sand layer was glued to the acrylic base of the tank to prevent slippage along the bottom of tailings/tank interface. Once bed failure had occurred as a result of tilting, the thickness of the soil layer still remaining on the bottom of the tank was measured with a ruler placed along the outer wall of the box. This value was subtracted from the total bed thickness prior to tilting and the location of the failure plane relative to the bed surface was determined.

The infinite slope theory was adopted to analyse the stability of the tested mine tailings deposited beds. In this type of analysis, the thickness of the unstable material is small compared to the overall thickness of the bed and the failure surface is parallel to the slope (Lambe and Whitman 1969). This behaviour corresponds to the observed failure mode of the tested beds. In all calculations the bed was assumed to be homogeneous. For drained conditions and zero excess pore pressures, the normal effective and shear stress at the base of a soil layer are given by:

$$\sigma'_n = \gamma' h \cos^2\beta \qquad [1]$$

$$\sigma_t = \tau = \gamma' h \sin\beta \cos\beta \qquad [2]$$

where σ'_n is the effective normal stress at the base of the soil layer in kPa, γ' is the average buoyant unit weight of the tailings bed in kN/m^3, h is the thickness of the layer in m, β is the measured angle of tilting in degrees, and σ_t is the shear stress at the base of the layer in kPa.

Zreik et al. (1998a) showed that, at failure, the effective normal and shear stress at the failure plane can be calculated using the effective vertical stress before tilting, at a depth corresponding to the depth of the failure plane, and from the failure angle as follows:

$$\sigma'_{nf} = \sigma'_{v0} \cos\beta \qquad [3]$$

$$\tau_f = \sigma'_{nf} \tan\phi' = \sigma'_{v0} \sin\beta \qquad [4]$$

where σ'_{nf} is the effective normal stress at the failure plane at failure in kPa, τ_f is the shear strength of the tailings bed in kPa, ϕ' is the drained (effective) friction angle in degrees, and σ'_{v0} is the vertical effective stress at a depth corresponding to the depth of the failure plane at the start of tilting in kPa.

At the onset of tilting, the vertical effective stress at a depth corresponding to the depth of the failure plane can be computed using the average buoyant unit weight of the tailings bed and the thickness of the soil layer above the failure plane:

$$\sigma'_{v0} = \gamma' h_f \quad [5]$$

where h_f is the thickness of the soil layer above the failure plane in m.

At failure the total normal stress and shear strength at the failure plane can be determined from:

$$\sigma_{nf} = \sigma_{v0} \cos\beta \quad [6]$$

$$\tau_f = \sigma_{nf} \tan\phi_T = \sigma_{v0} \sin\beta \quad [7]$$

where σ_{nf} is the total normal stress at the failure plane at failure in kPa, τ_f is the shear strength of the tailings bed in kPa, ϕ_T is the total friction angle in degrees, and σ_{v0} is the vertical total stress at a depth corresponding to the depth of the failure plane at the start of tilting in kPa.

The vertical total stress at a depth corresponding to the depth of the failure plane at the start of tilting is given by:

$$\sigma_{v0} = \gamma_{sat} h_f + \gamma_w h_w \quad [8]$$

where γ_{sat} is the average saturated unit weight of the tailings bed in kN/m^3, γ_w is the unit weight of water in kN/m^3, and h_w is the depth of the water above the tailings bed.

5 RESULTS AND DISCUSSION

5.1 Sedimentation and Consolidation Behaviour

Sedimentation experiments were performed in a water column with a diameter of 6.5 cm and a height of 47.0 cm. A pore water pressure (PWP) transducer (VIATRAN 245) was mounted at the base of the column to provide a measurement of PWP changes with time. Mine tailings beds with final thickness between 8.6 and 10.3 cm were deposited in the column from 180% water content slurries and the (PWP) changes at the bottom of the beds were monitored during bed formation and consolidation i.e. from the moment the tailings/water slurry was poured into the column until the excess PWP was fully dissipated. The following scenario describing bed formation from slurry was proposed. During its formation from slurry the deposited sediment bed undergoes three simultaneously occurring stages of behaviour: suspension, sedimentation and consolidation (Imai 1981; Been and Sills 1981; Pane and Schiffman 1985). When in suspension stage, the speed of fall of particles is determined solely by the particles density. If the solids concentration is as high as in the present study, the settling is characterized by mutual collision between particles and is termed “hindered” settling (Kynch 1952). In the transitional zone between suspension and consolidation, i.e. the sedimentation stage, the settlement rate is decreasing and large concentration gradients with depth exist. The sediment in the consolidation stage behaves like a soil and the traditional consolidation theories, e.g. Terzaghi’s theory (Terzaghi 1942), are applicable here. The consolidation of the beds occurs through compaction of the soil mass under its self weight accompanied by drainage of the pore water held in the pore spaces. The drainage is in upward direction through the bed surface and into the ambient water. The beginning of primary consolidation is marked by the development of effective stress, which is transmitted by virtue of particle-to-particle contact. Primary consolidation continues until the excess PWP is completely dissipated and at this stage a consolidated bed is formed (Imai 1981; Mehta et al. 1982). All tailings beds prepared in this way are normally consolidated.

The rate of consolidation is controlled by the length and cross sectional area of the drainage path. In the studied mine tailings, being a highly permeable coarse grained waste soil, the length of the drainage path was short resulting in rapid drainage and a short time for consolidation. It was found that the PWP at the bottom of the beds returned to its hydrostatic value within 60 to 90 min from the beginning of each experiment, i.e. the excess PWP generated during the settling and primary consolidation phases were fully dissipated by the end of that period (Figure 2). In our previous study (Dimitrova and Yanful 2010) we also indirectly determined that the primary consolidation of all tested beds was complete in approximately 60 to 90 min. Performed PWP measurements provided additional confidence in this conclusion.

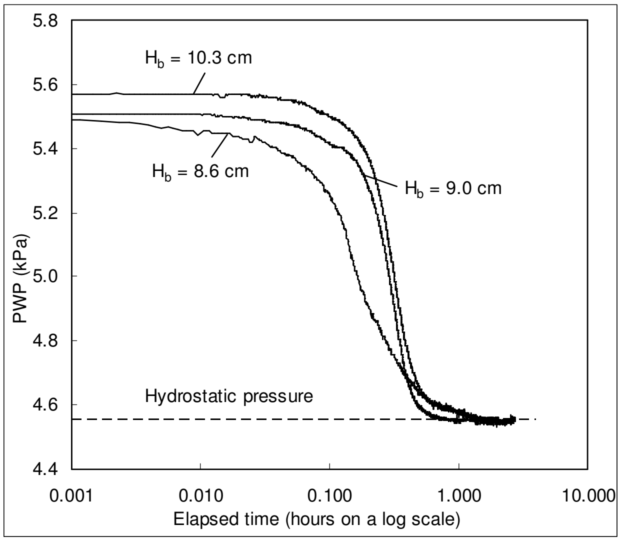

Figure 2. Pore water pressure variation with time at the bottom of tailings beds during bed formation and consolidation

Sedimentation experiments helped determining the time required to complete the primary consolidation of tailings beds with final thickness between 8.6 and 10.3 cm. Since the tested 10.3 cm-thick beds had the longest drainage path measured from the bottom of the beds to their surface, it was deemed safe to assume that the primary consolidation of the thinner beds would also be complete within this time frame.

To investigate the conditions that govern the failure of the deposited tailings beds as a result of titling, PWP measurements were performed during both slow and rapid titling. Tailings beds were deposited from 180% tailings/water slurries in the same water column used in the sedimentation experiments and left to consolidate for 6 or 18 days. Prior to tilting, the column containing the deposited bed and water was sealed using a rubber stopper and then tilted to 50° at the desired speed using the same tilting platform shown in Figure 1. The PWP at the bottom of the beds was continuously measured during the slow and rapid tilting and recorded at 2 and 1 sec intervals, respectively, by means of a data logger (SCIEMETRIC INSTRUMENTS LLSYS). Reference hydrostatic pressure variation at that elevation throughout tilting experiments was obtained by filling the column with distilled water and then tilting it at the desired speed. In each tilting mode, the generated excess PWP as a result of tilting was calculated by subtracting the hydrostatic pressure at the base of the column from the total pressure measured in the tailings beds at the same elevation. Figures 3a and b show the variation of the excess PWP with time at the bottom of deposited tailings beds aged 6 and 18 days during rapid and slow tilting experiments, respectively.

a)

b)

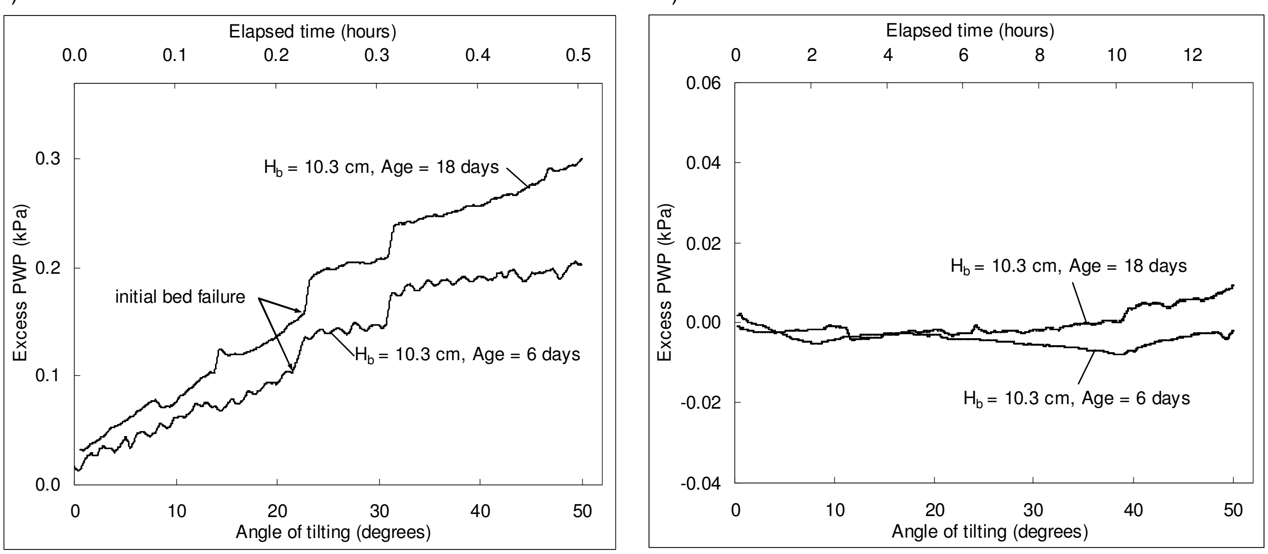

Figure 3. Pore water pressure variation with time at the bottom of tailings beds aged 6 and 18 days during a) rapid and b) slow tilting experiments

Referring to Figure 3a, it can be seen that during the rapid tilting experiments excess PWP begins to build up from the onset of tilting and it increases with increasing the tilting angle. In both tested beds the maximum excess PWP value was reached at the end of tilting i.e. at 50º tilting angle and it was 0.19 and 0.29 kPa for the 6 and 18 days old beds, respectively. The longer time for consolidation of the 18 days bed compared to the 6 days bed resulted in a denser structure (lower void ratio) of the older bed. This in turn, caused slower dissipation of the excess PWP generated during tilting in the 18 days bed and, ultimately led to higher excess PWP values. The authors hypothesize that the rapid excess PWP build up, that is observed at approximately 21º for the 6 days old bed and 22º for the 18 days and is denoted by a jump in the plots, precedes the initial bed failure. During the experiments, the actual sliding of the soil mass above the failure plane occurred at about 2º higher in both beds; that is at 23.4º and 24.3º in the 6 and 18 days old beds, respectively. The portion of the bed that after failure remained still attached to the bottom of the tank had an overall thickness of 0.4 to 1.5 cm smaller than the initial bed thickness, which led to a lesser excess PWP build up in this portion of the beds after failure. Indeed, as evident from Figure 3a after the point of failure the slope of the plots flattens. Unfortunately, the depth of the failure plane could not be predicted prior to each experiment and thereby, the PWP transducer could not be positioned at its exact location to provide a measurement of PWP changes with time and at failure. In the presence of excess PWP with an unknown magnitude at the failure plane, the obtained failure envelope was a total strength envelope. It was hypothesized that because of the open upper boundary (bed's surface) some volume changes and dissipation of excess PWP during the rapid tilting might had occurred and therefore, the soil shearing occurred under partially drained conditions. In contrast to rapid tilting experiments, during slow tilting the excess PWP build up was negligible for the tested beds aged 6 and 18 days (Figure 3b). The PWP variation throughout the slow tilting experiments generally followed the hydrostatic pressure. Although it appeared that at times the measured PWP at the bottom of the tested beds was lower than the hydrostatic pressure at that elevation (negative values), the deviation was most probably caused by variation in the experimental conditions (i.e. water temperature, PWP transducer calibration, etc.). In all tested beds it was observed that the failure plane was always located at much shallower depths than their overall thickness. This, coupled with the slow tilting rate ensuring full excess PWP dissipation, can explain why the PWP measured at the bottom of the beds appeared unaffected by the failure event. The absence of excess PWP during the slow tilting experiments suggested that the soil shearing occurred under drained conditions and the measured bed's shear strength was also "drained".

5.2 Failure Modes

During all performed tests failure of the slope occurred at a sheet-like plane parallel to the bottom of the tank and located at a distance of 0.4 to 1.5 cm from the surface of the bed. The failing soil layer showed complete loss of integrity and the liquefied tailings mass advanced like a wave to the bottom of the tank, leaving behind a rippled surface. It was shown that this behaviour was caused by a rapid excess PWP build up at the time of failure resulting in a loss of effective stress. The observed angle at which failure occurred during slow tilting (drained conditions) was approximately two times higher than during the rapid tilting (partially drained conditions) angle.

5.3 Drained Shear Strength

Drained shear strength tests were performed on beds aged at 6 and 18 days by selecting the slow tilting mode of the Tilting Tank. Obtained results were plotted as a function of the normal effective stress at the failure plane as shown in Figures 4a and b for 6 and 18 days old beds, respectively. The stress paths followed by the effective normal and shear stresses at the location of the failure plane from the onset of tilting until failure of the slope are also presented.

a) b)

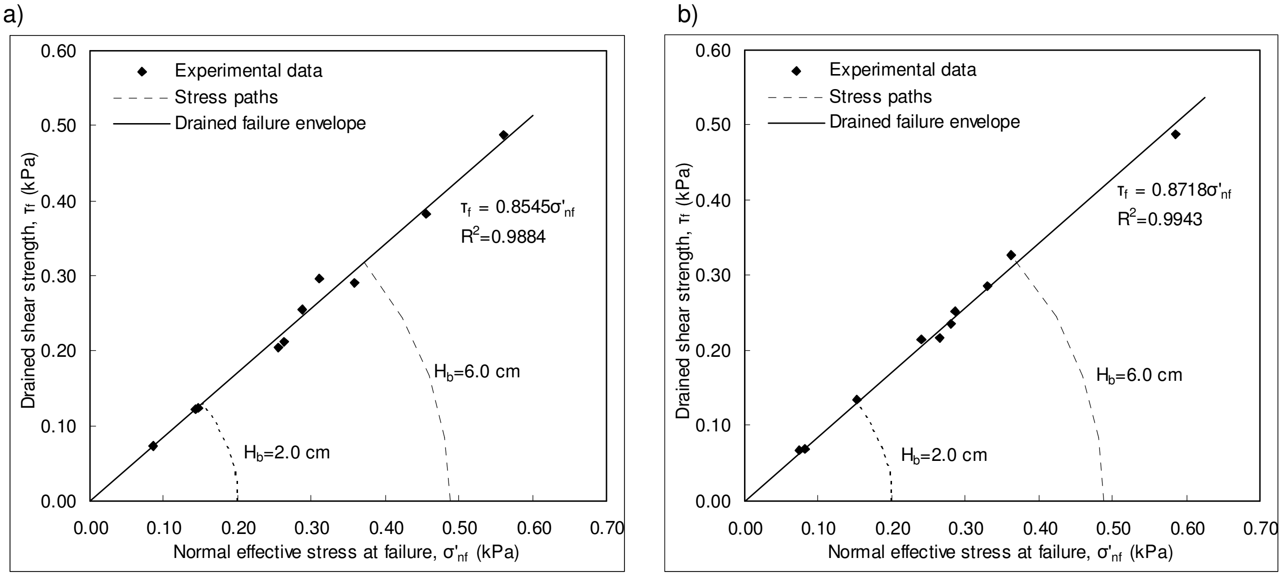

Figure 4. Drained strength envelope and effective stress paths for deposited tailings beds of various thicknesses aged at a) 6 and b) 18 days

Each set of experimental data was successfully fitted with a straight line passing through the origin and yielding a high correlation factor of 0.99. Given that the tested Clarabelle mine tailings were coarse grained, the assumption of a zero cohesion intercept was deemed reasonable. The effective friction angle, ϕ' computed from the slope of the fit lines was 40.5° and 41.1° for the 6 and 18 days old beds, respectively. Effective (drained) friction angle between 30° and 42° and close to zero cohesion were previously reported in the literature for initially saturated hard rock mine tailings (Rassam 2002; Masengo and Julien 2003; Pettibone and Kealy 1971; Abadjiev 1985). When compared to natural sand or silts, it appears that ϕ' of the tested mine tailings is slightly higher. For example, naturally occurring silty sands at the same dry density as the tested tailings show an effective friction angle, ϕ' of about 34°-35° (Holtz and Kovacs 1981). Therefore, ϕ' of the tailings is approximately 5° to 6° higher than of natural soils, which researchers have attributed to the more pronounced particle angularity of tailings (Pettibone and Kealy 1971; Mittal and Morgenstern 1975; Sarsby 2000). From Figures 4a and b it can be concluded that ϕ' is relatively independent of the bed age. This finding is consistent with results reported in the literature, which show that, in sandy soils, the time for consolidation has little effect on the friction angle of the soil (Holtz and Kovacs 1981).

Referring to Figures 4a and b, the stress states lying on the stress paths are derived from Equations 3 and 4 and by varying the angle of titling, β from zero to the angle of failure. Thus, at an angle of tilting β equal to zero, the normal effective stress at the depth of the failure plane σ'_n equals the vertical effective stress, σ'_{v0} at the same depth. Respectively, when β is set to be equal to the angle of tilting at failure, σ'_n is equal to the normal effective stress at failure, σ'_{nf}, and the corresponding shear stress, τ is equal to the drained shear strength, τ_f of the tailings bed.

5.4 Effect of Tilting Rate on the Shear Strength

The authors believe that the following scenario best describes the drainage and excess PWP evolution during rapid tilting. When rapid tilting rate is employed, some of the excess PWP generated as a result of tilting is being dissipated at the same time through drainage across the unconfined upper boundary, i.e. bed's surface. Thus, undrained conditions cannot be assumed, rather the soil shearing occurs under partially drained conditions. The rate of PWP generation is much higher than the dissipation rate due to partial drainage and the net result is a constant increase in excess PWP in the tailings bed throughout the entire tilting experiment (Figure 3a). In response to the excess PWP increase, the effective stress decreases to the point when failure of the bed occurs. In the absence of data about the PWP at the location of the failure plane, obtained strength parameters are total stress parameters. Figures 5a and b show a comparison between slow (drained conditions) and rapid tilting (partially drained conditions) shear strength results for 6 and 18 days old tailings beds, respectively. As evident from Figures 5a and b, the drained shear strength is higher than the partially drained over the entire stress range for all tested tailings beds.

a) b)

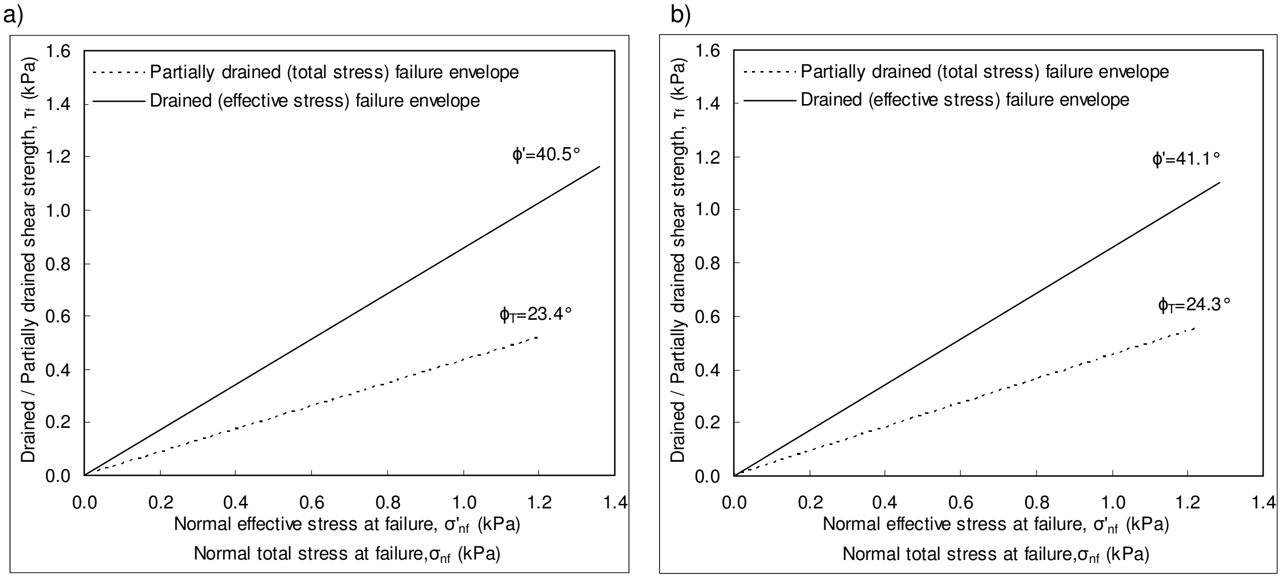

Figure 5. Comparison between drained and partially drained shear strength obtained using the Tilting Tank for deposited tailings beds at a) 6 and b) 18 days

Additionally, the total friction angle, ϕ_T, determined from the partially drained experiments (rapid tilting) is almost two times lower than the effective friction angle, ϕ', obtained from the drained experiments (slow tilting).

6 SUMMARY AND CONCLUSIONS

Normally consolidated mine tailings beds with various thicknesses were deposited from concentrated slurries with 180% water content. The primary consolidation of all tested beds was complete within 60 to 90 min from poring the slurry into the sedimentation column and all excess PWP was fully dissipated by the end of that period. The beds were then tested using a Tilting Tank at an age of 6 and 18 days. Two modes of tilting were employed during the Tilting Tank experiments. A slow titling speed of 0.25°/min was applied to obtain a measure of the drained shear strength of the tested beds, whereas rapid tilting at 1.7°/min was adopted in the partially drained shear strength experiments. During partially drained and drained shearing of the tailings beds in the Tilting Tank it was observed that slope failure always occurred along a failure plane parallel to the bottom of the tank and located at 0.4 to 1.5 cm from the bed surface. At the time of failure the structure of the failing layer was completely destroyed and the liquefied soil moved slowly like a wave to the bottom of the tank.

Effective (drained) and total (partially drained) shear strength envelopes were successfully defined at a vertical stress range from 0.10 to approximately 1.0 kPa, which was much lower than the stresses utilized in conventional geotechnical testing equipment. It was found that both the drained and partially drained failure envelopes were linear within the tested stress range with zero cohesion intercept, which was expected for a normally consolidated sandy soil. The effective friction angle, ϕ' fell between 40.5° and 41.1°, whereas the total friction angle, ϕ_T was determined to be almost two times lower than ϕ' and in the ranged from 23.4° to 24.3°. Experimental results demonstrated little variation of both ϕ' and ϕ_T with bed age which was consistent with reported in the literature for cohesionless soils.

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