Factors affecting the shear strength of mine tailings/clay mixtures with varying clay content and clay mineralogy

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A B S T R A C T

Artificial mine tailings/clay mixtures were used to prepare concentrated slurries, from which beds with different composition, thickness and age were obtained through sedimentation. Those beds were sheared in a specially built Tilting Tank capable of simulating drained and partially drained conditions by varying the tilting rate. The stress range of interest was below 1.2 kPa, which was much lower that the stresses utilized by conventional geotechnical equipment, but of the same order of magnitude as those measured in the tailings management facilities. Negligible excess pore water pressure developed in the deposited beds when the rate of shearing was sufficiently slow, whereas a rapid shearing rate caused a significant excess pore pressure buildup that reduced the shear strength of the beds. Linear drained (effective stress) and partially drained (total stress) failure envelopes were defined for beds, prepared from various mixtures. The effective friction angle was found to vary between 35.2° and 40.4° depending on the percentage of clay in the mixtures and the type of the clay additive. Shearing under partially drained conditions yielded a total friction angle of the mixtures that was always lower than the effective friction angle and varied between 15.1° and 23.3°. It was found that adding clay to mine tailings generally caused a decrease in the frictional strength of the latter; however, the magnitude of this decrease was greater when the clay was bentonite and lower when it was kaolinite. The time for consolidation had little effect on the shear strength of the tailings/kaolinite mixtures, but led to an approximate increase of 2° in the frictional resistance of the tailings/bentonite mixtures.

1. Introduction

Tailings are the waste product generated during the recovery of mineral commodities from ore. In the conventional hard-rock milling process, the crude ore is crushed and then ground in mills to a particle size of less than 0.1 mm in order to allow the extraction of the valuable metals (Jewell, 1998). The milling of ore-bearing, hard silicate rocks produces very sharp angular particles typically in the sand and silt size range whereas the colloidal particles are generally lost when the excess water and fines are removed from the mill tailings. As a result, the percentage of clay-size particles (less than 2 μm) in base metal tailings usually does not exceed 10–15% by weight, which is confirmed by the literature examples given in Table 1.

The tailings, along with the spent process water, form a slurry, which is then pumped to a tailings storage facility. Although the solid fraction of this slurry behaves like a soil, the tailings are different from most naturally occurring soils in several respects (Jewell, 1998). The ores, typically containing some base, rare or precious metals, are often sulphide-rich and extraction of these metals results in the generation of large quantities of sulphide-rich tailings. In the presence of oxygen and water, these tailings have the potential to oxidise and generate acid. Elevated acidity leads to solubilisation and subsequent release of toxic heavy metals such as Pb, Cu, Zn, As, Ni, Co and Cd. Acidic waters can cause discoloration and turbidity in the mining effluent, but it is the dissolved metals that can cause a decrease in aquatic life, bioaccumulation of metals, and reduction in the groundwater quality. Some chemical reagents such as cyanide used to recover precious metals are also toxic in sufficient concentrations. The density and strength of a body of tailings are initially low and increase relatively slowly with time (Jewell, 1998; Wilson et al., 2006). If a breach develops in the confining embankment, low strength tailings can flow for considerable distances and the impact from such failure or from seepage of contaminants on public safety and the environment can be disastrous. Another notable difference between mine tailings and natural soils is the wide range of specific gravity values observed in the former due to the presence of heavy metals in the tailings (Pettibone and Kealy, 1971; Rankine et al., 2006). Whereas for most natural soils the specific gravity typically varies between 2.65 and 3.0, for mine tailings it can fall anywhere between 2.6 and 4.4 (Table 1). Larger range of void ratios in mine tailings in comparison to natural sandy soils has also been observed (Mittal and Morgenstern, 1975). Mine tailings also exhibit close to zero cohesion and 5 to 6° higher friction angles than most natural soils of similar gradation, which researches have attributed to the angularity of tailings

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Table 1
Characteristics of mine tailings samples used in published research work. C — Chlorite; B — Biotite; K — Kaolinite, S — Serpentine, Ms — Muscovite, Mc — Mica, and T — Talc.

No. samples analyzed	Description of material used	G_s	D_{50} (mm)	% clay-size particles by weight	Source	Clay mineralogy	Reference
4	Hard-rock mine sulphide tailings	2.9–3.8	0.016–0.040	5–9	Canada	Unknown	Benzaazoua et al. (2002)
3	Hard-rock mine tailings (low plasticity silts, ML)	–	0.028–0.038	4–6	Unknown	Unknown	Aubertin et al. (1998)
1	Gold mine tailings	2.6	0.01	2–4	Kirkland Lake, ON	Unknown	Amaratunga and Yaschyshyn (1997)
6	Hard-rock mine sulphide tailings (sand with minor layers of silt)	–	–	0	Sudbury, ON	C, B	Shaw et al. (1998)
4	Hard-rock mine tailings (fine to medium grained, well graded sand)	–	0.08–0.18	0	Sudbury, ON	C, B	McGregor et al. (1998)
9	Hard-rock mine tailings	–	0.016	7–10	Eastern Canada	–	Fall et al. (2009)
10	Hard-rock mine tailings, (low plasticity silts, ML)	–	0.012	3–5	North-eastern Cuba	S	Rodríguez (2006)
3	Mine tailings, silt and fine sand	–	0.017	10	Val-d'Or, Quebec	Ms, C	Ouangrawa et al. (2009)
4	Hard-rock tailings from base and precious metal mines	–	0.023–0.037	4–8	Abitibi, Quebec	C, Mc,T	Benzaazoua et al. (2000)
9	Hard rock tailings	2.80–3.35	0.05–0.26	2–3	USA, Canada	C	Pettibone and Kealy (1971)
27	Copper-gold and copper-gold-zinc tailings	2.78–4.42	–	6–14	BC, Canada	–	Wijewickreme et al. (2005)

particles (Pettibone and Kealy, 1971; Rankine et al., 2006; Rodríguez, 2006). For instance, Rankine et al. (2006) compared the estimated friction angle of mine tailings using existing empirical relations for granular soils with the actual effective peak friction angles measured in the laboratory. The authors observed that the measured drained friction angles were substantially higher than the estimated and concluded that empirical relations developed for granular soils cannot be applied successfully to mine tailings.

The literature offers many examples of utilizing mine tailings as engineering material. Because the tailings provide a convenient and economic source of borrow material, mining companies often use the coarse fraction for construction of engineered tailings dams (e.g., Penman, 1998) or for backfilling purposes (e.g., Amaratunga and Yaschyshyn, 1997; Benzaazoua et al., 2002; Rankine et al., 2006) whereas the fine fraction is disposed of in tailings ponds. If the physical and chemical properties of the whole tailings fraction are modified in a way so that they can be utilized in an environmentally safe manner for surface or underground applications, this would reduce their accumulation in the tailings pond and even possibly eliminate the need for tailings impoundments altogether. Additional benefits would include the reduction of costs associated with constructing, managing and reclaiming tailings ponds and the removal of constraints placed upon fine grinding as an effective means of valuable minerals liberation (Amaratunga and Yaschyshyn, 1997). Researchers have proposed the incorporation of acid-generating tailings into paste backfill as a viable means of preventing sulphide mineral oxidation and subsequent release of toxic metals in the environment (Benzaazoua et al., 2004). The use of desulphurised tailings as construction material for an engineered cover to prevent acid mine drainage (AMD) has been considered as well (Benzaazoua et al., 2000; Bois et al., 2004; Demers et al., 2009). The feasibility of using bentonite/mine tailings paste mixtures as a barrier (liner or cover) material for mine waste containment facilities has also been investigated (Wilson et al., 2006; Fall et al., 2009). Such mixtures would offer the benefit of reducing the amount of waste to be managed by mining operators as well as the cost of surface tailings management and can potentially also be used in municipal landfills (Fall et al., 2009).

Whether disposed in tailings ponds or used in constructing containment walls, there are many geotechnical issues involved in tailings management, including the rate of sedimentation of the tailings, their consolidation behaviour, erodibility and compaction characteristics (Fahey and Newson, 1997). From the geotechnical point of view, the basic tailings characteristics are specific gravity, particle size distribution, mineralogy of the clay-size fraction, strength, density and hydraulic conductivity. These properties are often used as input parameters in various models of tailings behaviour (e.g., Holtz and Kovacs, 1981; Aubertin et al., 1998) and when evaluating the stability and long term performance of tailings embankments and cover systems (Wilson et al., 2006). For example, the stability and resistance of tailings dams against erosion strongly depend upon the strength of the tailings used in their construction and upon the type of loading (static or dynamic), whereas the rate at which seepage from a tailings embankment occurs is governed by the permeability of the tailings (Bell, 1999). Those properties that are related to the constitution and general nature of tailings are referred to as intrinsic variables. An example of intrinsic variable is the critical state friction angle, which is commonly taken as a unique value for a given granular soil, regardless of the initial relative density of the sample and initial confining stress (Salgado et al., 2000). In tailings sands and other soils with rotund particles, for which particle orientation during shearing does not occur, the critical shear strength is equal to the residual strength. Other intrinsic variables are the particle shape and size distribution, particle surface characteristics, and mineralogy. Many researchers have shown that the engineering behaviour of tailings, and soils in general, is strongly influenced by both the percent clay-size particles (less than 2 μm) present and the clay mineralogy (e.g., Kenney, 1967; Mittal and Morgenstern, 1975; Stark and Eid, 1994; Raudkivi, 1998; Al-Shayea, 2001; Di Maio et al., 2004; Tiwari and Marui, 2005). With increasing clay-size fraction, the soil becomes more plastic, its swelling and shrinkage potential increases and so does its compressibility. In contrast, the permeability and angle of internal friction of the soil mass decrease (e.g., Stark and Eid, 1994; Al-Shayea, 2001; Mitchell and Soga, 2005; Tiwari and Marui, 2005). Only 10% of clay is sufficient to assume control of the properties of a soil (Raudkivi, 1998). Clay mineralogy controls the size, shape and surface characteristics of the clay particles and thus determines the engineering properties of the soil (Mitchell and Soga, 2005). For instance, volume change behaviour of artificial mixtures and natural soils reconstituted using distilled water is strongly influenced by the clay mineral composition and, in particular, by the percentage of smectite (Di Maio et al., 2004). The effect of smectite content is stress-dependent, i.e., it is most pronounced at low axial stresses and decreases with the stress level increase. Furthermore, the influence of the salt concentration of the pore water solution is close to negligible for mixtures containing kaolinite as primary clay mineral, and increases with increasing

percentage of montmorillonite in the samples. Thus, compressibility of bentonite reconstituted with concentrated salt solutions becomes close to that of commercial kaolin, irrespective of the pore water solution. Fahey and Newson (1997) noted that even a relatively small percentage of montmorillonite can severely affect the sedimentation rate, consolidation behaviour, permeability and strength of mine tailings. Stark and Eid (1994) found that the drained residual strength of soils was related to both the type of clay mineral and percentage of clay-size particles. They proposed to use the liquid limits as an identificator of clay mineralogy and defined a relationship between the liquid limit, clay-size fraction and the residual shear strength of the soil. Tiwari and Marui (2005) proposed a correlation method based on mineralogical composition for the estimation of the residual friction angle of soils with various proportions of clay and non-clay minerals. Lupini et al. (1981) noted that the clay fraction may not be sufficient to determine the residual strength of a soil and the proportion of platy to rotund particles present should also be considered. Thus, depending on clay fraction and the proportion of platy to rotund particles, three residual shearing modes are likely to take place. A turbulent shearing mode is observed in soils with clay fraction below 25% and a high proportion of rotund particles or with platy particles of high interparticle friction, in which preferred orientation of platy particles does not occur. A sliding mode is characteristic of soils with clay fraction above 50% in which a low strength shear surface of strongly oriented low friction platy particles forms. In soils with clay fraction in the intermediate range, i.e., between 25% and 50% both turbulent and sliding shear modes take place.

The present paper studies the various factors that control the shear strength of artificially prepared mine tailings/clay mixtures with various clay content and clay mineralogy. Considered are the effect of mixture composition, rate of load application, drainage conditions and time for consolidation under constant effective stress. As discussed above, the importance of clay content and clay mineralogy as parameters influencing the behaviour of soils has been well established and widely publicised. The originality of the present work lies in the experimental methods used to measure the extremely low mechanical strength of freshly deposited mixed tailings/clay beds in their undisturbed, structured state closely simulating conditions in a tailings pond. Performance of the shear strength measurements under different rates of loading and degrees of drainage also contributes to the novelty of the research. Although test results were obtained using specific mine tailings and clay additives, and therefore may not be generalized for all mine tailings and clay minerals, they can facilitate the interpretation of the behaviour of other saturated tailings with varying clay mineral composition or other tailings/clay mixtures.

2. Testing materials and procedures

2.1. Deposited tailings beds preparation

The original mine tailings used in the present study were received in the form of tailings/water slurry from the Clarabelle Copper Mine located in Sudbury, Ontario, and were obtained from the processing of the Sudbury Basin ore. The mineralogical composition of the Sudbury Basin ore, as given in Agar (1991), is: pentlandite (3%), chalcopyrite (3.7%), pyrrhotite (20%), quartz (16%), feldspar (14%), chlorite (21%), biotite (11%), amphibole (10%) and carbonates (2%). The primary minerals found in the tailings are: pentlandite, chalcopyrite, pyrrhotite, quartz, feldspar, chlorite, biotite, amphibole, carbonates plus minor pyroxene, apatite, magnetite, ilmenite, marcasite, galena and pyrite (McGregor et al., 1998; Shaw et al., 1998). Reported studies (Agar, 1991; McGregor et al., 1998; Shaw et al., 1998) have also indicated that the predominant clay minerals in the Sudbury tailings are chlorite and biotite. These clay minerals are traditionally not reactive and possess low cohesive strength. Artificial mine tailings/clay mixtures were prepared in the laboratory by mixing the original non-cohesive and

non-plastic silty sand tailings with various amounts of dry kaolin (Fisher Scientific Chemical) or bentonite powder (Baroid Quick-Gel Fast Mixing High Viscosity Bentonite). The primary clay mineral in the selected commercial kaolin was kaolinite, whereas the bentonite was composed of Na-montmorillonite. The total clay content in the obtained mixed soil samples was 8, 12 or 16% (by weight), with the upper boundary selected to correspond to the maximum clay percentage found in most tailings in Canada. Kaolinite (the main constituent in kaolin) was chosen as an additive because it is a common clay mineral and, in terms of physico-chemical properties, it exhibits characteristics close to those of chlorite (Mitchell and Soga, 2005), the dominant clay mineral present in the original tailings. Kaolinite possesses low plasticity and cohesion, low compressibility and limited surface activity and thus, it is not likely to react with the pore-water solution in the course of testing. This makes it a suitable candidate for additive, since the present study was also concerned with the effect of clay content on the geotechnical properties of tailings/clay mixtures. Another part of the study aimed at investigating the effect of clay mineralogy on the engineering behaviour of mine tailings. Researchers have shown that for reconstituted samples prepared using distilled water, the percentage of smectite has the highest influence on the geotechnical properties of soils, such as shear strength, compressibility, void ratio and hydraulic conductivity (Di Maio et al., 2004). Na-montmorillonite with its thin particles exhibits very high specific surface (50–800 m^2/g), combined with high plasticity and cohesion. The high shrink/swell potential of Na-montmorillonite makes soils containing this mineral extremely compressible (Holeman, 1965). Since even a small quantity of Na-montmorillonite can have a major effect on engineering properties of mine tailings, it was used as a second additive in the present study.

The characteristics of the original tailings (denoted T) and soil mixtures prepared in the laboratory with increased amounts of clay-size material (denoted M) are summarized in Table 2. Grain size distribution curves of the dry tailings mass and the artificial tailings/clay mixtures are presented in Fig. 1. As shown in Fig. 1, the original tailings material (T1) was composed of 68% coarse (more than 0.075 mm) and 32% fine fraction (less than 0.075 mm), of which only 4% was clay-size material (less than 2 μm). The grain size distribution curve of the T1 tailings gave the lower boundary of the range of curves describing the particle size distribution of the mixtures used in the present study. As clay (kaolin or bentonite) was added to the tailings, the total clay content of the mixtures was brought up to 16% while keeping a constant sand/silt ratio. The mixture with the highest total clay content was M4 and it gave the upper boundary of the range of curves for all tested soil specimens. The grain size distribution curves of the mixtures with clay content intermediate between T1 and M4 fell in the shaded area in Fig. 1 between the M4 and T1 curves.

Distilled water was added to the tailings/clay mixtures to obtain slurries with high concentration of solids (50% by volume). The slurries were thoroughly mixed with an electrical mixer (ARROW 1750) for about ten minutes after which they were poured directly into an acrylic tank (L = 45 cm, W = 22.5 cm, H = 12.5 cm) and left to consolidate under self-weight for a minimum period of 3 days. This minimum consolidation time was proven sufficient to ensure that primary consolidation of the beds was complete as explained in greater detail

Table 2
Composition and physical properties of mine tailings and artificial mixtures. C – Chlorite; B — Biotite; K — Kaolinite; M — Montmorillonite; w_L — liquid limit; w_P — plastic limit; I_P — plasticity index.

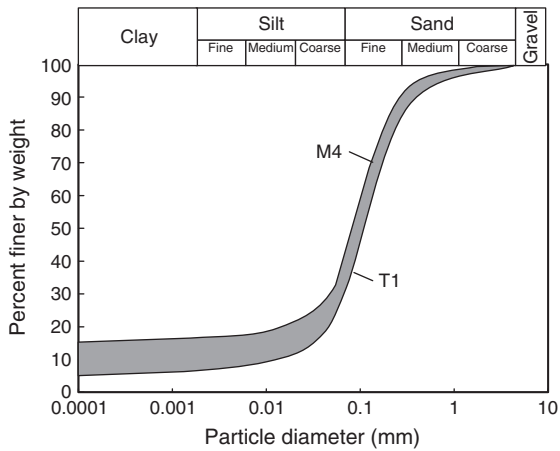| Sample ID	Clay (%)	Silt (%)	Sand (%)	Clay mineralogy	G_s	w_L (%)	w_P (%)	I_P (%)	Casagrande classification
T1	4	28	68	C, B	2.986	12–15	NP	–	SM
M2	8	27	65	C, B, K	2.968	15–16	NP	–	SM
M3	12	26	62	C, B, K	2.955	16–17	NP	–	SM
M4	16	25	59	C, B, K	2.949	18–20	NP	–	SM
M5	8	27	65	C, B, Na-M	2.913	26	21	5	SM-SC

Fig. 1. Grain size distribution curves of the original mine tailings and artificial tailings/clay mixtures.

later in this paper. Distilled water was used in the slurry preparation to minimize chemical interactions in the tailings–clay–water system, whereas the specific slurry concentration was chosen to obtain deposits with relatively homogeneous properties over depth. Deposited mixed tailings/clay beds with final thickness between 1 and 11 cm were prepared using slurries of the same concentration (50% by volume) but with various initial heights. All sedimented tailings beds were normally consolidated and were tested at consolidation times of 3 and 12 days. During the experiments, the ambient temperature in the laboratory was kept constant at 22° ± 1 °C.

2.2. Shear strength testing

The shear strength of the sedimented mixed beds under drained and partially drained conditions was obtained using the Tilting tank, previously described in Dimitrova and Yanful (in press) and shown in Fig. 2. The acrylic tank with the deposited tailings bed was first filled with water, sealed and then tilted on one side by the means of a pulley and a motor system. The angle of tilting at which failure of

the tested bed occurred was measured and recorded. Bed failure was defined as sliding of a portion of the bed to the bottom of the Tank as a result of tilting and it was detected by a photosensor mounted on the sidewall of the Tank. The evolution of excess pore water pressure (PWP) with time within the beds was monitored and recorded using pressure transducers (VIATRAN 245) at three ports numbered P1, P2 and P3 and positioned in a vertical array at elevations 0.5, 3.5 and 7.0 cm from the bottom of the Tank, respectively, and at 17 cm horizontal distance from the left side wall (Figure 2a). The diameter of the pressure tubes at the pressure connection was 8 mm. The selected Viatran 245 pressure transducers are high accuracy transducers and measure from 3 psi to 5000 psi (0.2 to 345 bar) with standard accuracy of ≤±0.06% FSO (full scale output).

Two tilting modes were employed during the experimental program: i) slow tilting at an average speed of 0.07°/min, and ii) rapid tilting at a speed of 1.61°/min. Further details on sample preparation procedure and used equipment can be found in Dimitrova and Yanful (in press).

Observed failure patterns during shearing suggested that infinite slope theory may be adopted to analyse the stability of the tested 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). For drained conditions and under the assumption of zero excess pore pressures, at failure, the normal effective and shear stress at the failure plane are given by:

$$\sigma'_{nf} = \sigma'_{v0} \cos \beta \tag{1}$$

$$\tau_f = \sigma'_{nf} \tan \Phi' = \sigma'_{v0} \sin \beta \tag{2}$$

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, 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, and β is the measured angle of tilting in degrees.

At the onset of tilting, the vertical effective stress at a depth corresponding to the depth of the failure plane can be computed
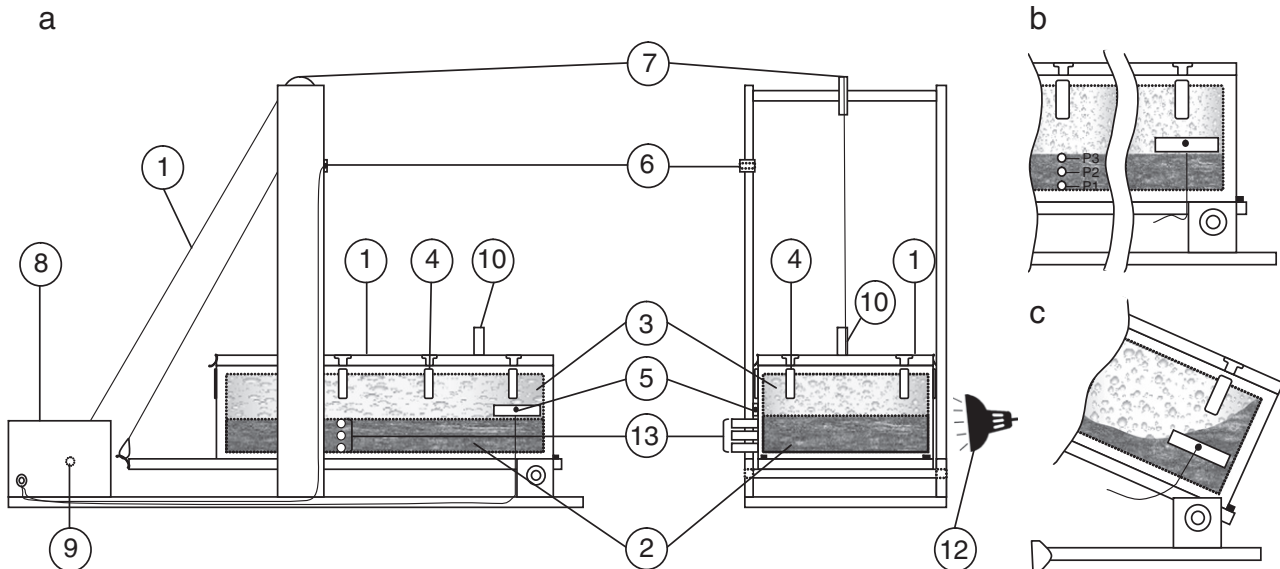

Fig. 2. (a) The Tilting Tank: 1 acrylic tank; 2 deposited tailings bed; 3 water; 4 clamps; 5 photosensor; 6 back-up photosensor; 7 pulley; 8 DC motor; 9 motor shaft; 10 water spout; 11 cable; 12 light source; 13 pore water pressure measuring ports; (b) Tailings bed and photosensor at the onset of tilting; (c) Tailings bed and photosensor at failure. After Dimitrova and Yanful, in press.

from the average buoyant unit weight of the tailings/clay bed and the thickness of the soil layer above the failure plane:

$$\sigma'_{v0} = \gamma' z_f \tag{3}$$

where γ' is the average buoyant unit weight of the tailings bed in kN/m^3, and z_f is the depth from bed surface to the failure plane measured along the normal to the slope in m.

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

$$\sigma_{nf} = \sigma_{v0} \cos\beta \tag{4}$$

$$\tau_f = \sigma_{nf} \tan\Phi_T = \sigma_{v0} \sin\beta \tag{5}$$

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 the depth of the failure plane at the start of tilting is given by:

$$\sigma_{v0} = \gamma_{sat} z_f + \gamma_w z_w \tag{6}$$

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 z_w is the depth of the water above the tailings bed in m.

3. Results and discussion

3.1. Physico-chemical properties of the tailings/clay mixtures

As the data presented in Table 2 suggest, increasing the amount of clay in the tailings/clay mixtures produces a corresponding increase in their liquid limit (w_L) while reducing their specific gravity (G_s). This can be expected since the water in the soils is almost entirely associated with the clay-size fraction and thus, increasing the clay content of the mixtures would also increase their water content at the liquid limit (Mitchell and Soga, 2005). When the added clay is highly expansive, as is the case with bentonite, a large amount of water is absorbed as interlayer water, which is effectively immobilized within the soil matrix thereby leading to high water content of tailings/clay mixture at both the liquid and plastic limits. Furthermore, pure kaolinite and Na-montmorillonite both have specific gravities (2.61 and 2.51, respectively) that are lower than that of the pure tailings (2.99) and, therefore, adding clay would result in lowering the G_s of the entire mixture (Fang and Daniels, 2006). Mixing the tailings with up to 12% kaolinite did not result in development of plasticity, whereas addition of only 4% bentonite (Na-montmorillonite) gave the samples some low but measurable plasticity.

3.2. Excess pore water pressure (PWP) measurements

3.2.1. Sedimentation and consolidation

The high concentration of solids in the slurries used in the preparation of the mixed tailings/clay beds ensured relatively constant particle gradation in the bed profile. This was also confirmed by visual observations which showed uniform texture and colour of the beds. The void ratio, e, of the sedimented beds generally increased with increasing percentage clay in the mixture in the following order T1<M2<M3<M4<M5. Thus, the average bed e was approximately 0.67 for T1, 0.69 for M2, 0.71 for M3, 0.74 for M4, and 1.34 for M5. These results indicate that kaolinite had a much smaller effect on bed e than bentonite, which may be explained by the highly expansive character of bentonite as indicated in literature. For instance, Di Maio et al. (2004) demonstrated that with

respect to compression and swelling, at the low stress range (between 10 and 100 kPa) the void ratio and compression behaviour of kaolinite was similar to that of pure sand, while bentonite exhibited 5 to 8 times higher void ratio and much higher compressibility than sand.

Fig. 3 shows the PWP variation with time at the bottom of three mixed tailings/clay beds prepared from mixtures T1, M4 and M5 (Table 2), during bed formation and primary consolidation, i.e., from the moment the tailings/clay/water slurry was poured into the Tank until the excess PWP was fully dissipated. It was found that in the T1 bed with 4% clay content and clay fraction comprising only inactive clay minerals (chlorite and biotite), the PWP at the bottom of the bed returned to its hydrostatic value within 1–1 1/2 hour from the beginning of the sedimentation/consolidation experiment. In the M4 bed with the highest clay content (16%) of all investigated mixtures and clay fraction comprising inactive minerals (chlorite, biotite and kaolinite) it took approximately 24 h for the excess PWP generated during the settling and primary consolidation phases of bed formation to fully dissipate (Figure 3). In the M5 bed with intermediate clay content (8%) composed of equal percentage of active (Na-montmorillonite) and inactive (chlorite, biotite) clay minerals, it took nearly 42 h for the excess PWP to dissipate.

It can be seen from Fig. 3 that the shape of the plots for beds deposited from T1 and M4 mixtures is generally similar suggesting similar sedimentation/consolidation behaviour of these two artificial soils, whereas the plot for the bed prepared from M5 mixture is entirely different. In both T1 and M4 beds the excess pore pressure dissipation began immediately after the slurry was poured into the container. Recalling that the T1 mixture (the original tailings) represented coarse grained silty sand and, as such, was a fast draining material, a relatively short time for full dissipation of excess PWP was expected. Increasing the total clay content from 4 to 16% by adding kaolinite resulted in significantly longer sedimentation phase in the bed with the highest clay content (M4), the end of which phase was delineated by the first change in the slope of the plots (compare T1 and M4 plots in Figure 3). While in the T1 bed (4% clay content) the settling phase continued for approximately 0.12 h from the beginning of the test, in the M4 bed (16% clay content) it extended to 1.7 h. Although not immediately obvious because of the logarithmic time scale in Fig. 3, an examination of the slope of the second portion of the T1 and M4 plots suggests that in the T1 bed the primary consolidation occurred faster (approximately 0.4 to 0.6 h) compared to the M4 bed (7.3 h). This can be attributed to increased drainage path length in the latter bed due to the higher percentage of platy clay particles in the M4 mixture coupled with slightly greater bed thickness. In Fig. 3, the plot for the M5 bed shows that after the slurry is poured into the container, initially there is no change in the excess pore water pressure. The authors believe that this portion of the plot corresponds to a
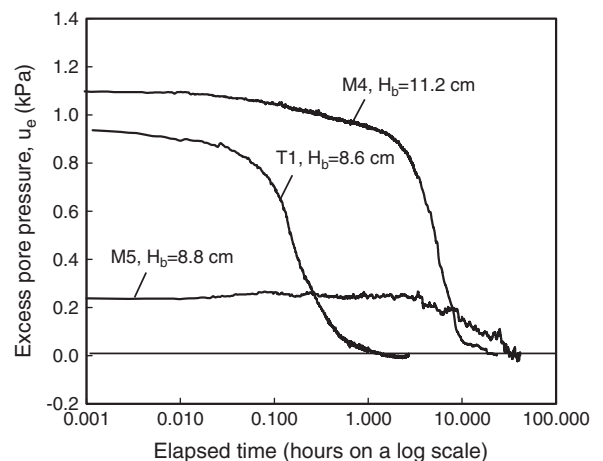

Fig. 3. Excess pore water pressure variation with time at the bottom of three tailings/clay beds during sedimentation and consolidation.

period of gellation (or floc formation) when no settling takes place, which continues for about 0.02 h. Although distilled water rather than electrolyte was used in the preparation of the tailings/bentonite slurries, according to the manufacturer's data sheet (Baroid, 2011), the utilized Baroid Quick-Gel Fast Mixing High Viscosity Bentonite is capable of imparting gellation even in fresh water suspensions. Since Baroid Quick-Gel Fast Mixing High Viscosity Bentonite is manufactured to be used primarily as a drilling fluid, the observed flocculation was most probably triggered by the soluble salts, which are always present in the drilling fluids in sufficient concentration to cause at least a mild degree of flocculation (Darley and Gray, 1988). At the end of flocculation (i.e., at about 0.02 h), the flocs gradually begin to settle and form a layer of sediment on the bottom of the container. The onset of the settling stage is marked by initial rise in the excess pore water pressure, after which the PWP slowly begins to decrease (Figure 3). Throughout the settling stage, the bottom sediment grows while the settling zone becomes thinner and finally vanishes at about 3.7 h from the beginning of the test. A distinct change in the slope of the plot for the M5 bed at about 3.7 h delineates the beginning of the primary consolidation phase during which the sediment deposit undergoes self-weight consolidation and reduction in water content. Equilibrium condition is reached at the end of primary consolidation, i.e., at about 42 h from the beginning of the test when all excess PWP becomes fully dissipated.

Overall, the sedimentation/consolidation behaviour of the beds prepared from T1 and M4 mixtures was similar, a finding that is consistent with the results of other researchers. For instance, Jacobs et al. (2007) reported that adding kaolinite to sand increased the void ratio but did not significantly change the permeability and compressibility of the sand/clay mixtures, whereas adding bentonite also resulted in more loose packing of the bed (higher void ratio) but led to a significant decrease in the permeability of the mixtures. Al-Shayea (2001) also observed significant reduction in the hydraulic conductivity of sand/clay mixtures with the addition of expansive smectite clay which effect was more pronounced at low clay contents (up to about 10%). He attributed the effect to the fact that at low clay content, pore spaces are larger, thus allowing more freedom for clay particles to freely expand and effectively block the relatively larger drainage paths. Al-Shayea (2001) found that the coefficient of permeability (hydraulic conductivity), k, for sand/clay mixtures with 10% clay content was five to six orders of magnitude lower than that of pure sand. The substantial difference in the behaviour of tailings/bentonite beds could be explained by the following hypothesis. As the highly expanding bentonite (Na-montmorillonite) absorbs water and swells, it reduces the pore spaces and blocks the drainage paths leading to the reduction in the overall hydraulic conductivity of the mixture and longer time for drainage and excess pore water pressure dissipation. Adding kaolinite to the tailings has a similar effect of reducing the pore spaces and decreasing the hydraulic conductivity of the beds but is much less effective than bentonite. Furthermore, in their study of the mechanisms controlling the permeability of clays, Mesri and Olson (1971) suggested that the reduction in the coefficient of permeability at constant void ratio, from kaolinite to montmorillonite is largely the result of a reduction in the size of individual flow channels and an increase in the tortuosity of the flow paths. The smaller the particle size the smaller the size of the individual flow channels, all other variables being constant. Thus at the same void ratio, kaolinite, which has the largest particles of all clay minerals is 200,000 time more pervious than montmorillonite, which has the smallest particles (Mesri and Olson, 1971).

The results of the sedimentation/consolidation experiments demonstrated that the primary consolidation of all beds was complete in less than two days and, thus, all beds used in the experimental program were considered fully consolidated prior to the shear strength testing.

3.2.2. Slow tilting experiments

The tilting of the Tank results in generation of excess pore water pressure (PWP) within the tested mixed tailings/clay beds, the magnitude of which at a given horizon depends on the tilting speed, angle of tilting, β, and depth, z, of that horizon below the bed surface. When the tilting speed is sufficiently slow, the generated excess PWP is so small that, for practical purposes, the response of the bed can be considered drained. A drained response to an applied loading is characterised by parallel total and effective stress paths, i.e., $d\sigma = d\sigma'$, and zero (or close to zero) excess PWP, $du_e = 0$ at all times.

Fig. 4a to c shows the evolution of the excess pore water pressure with time and angle of tilting at the three measuring ports (P1, P2 and P3) within beds prepared of mixtures T1, M2, and M5. The beds were 7.2 to 7.8 cm thick and consolidated for 3 days prior to testing. Referring to Fig. 4a, at port P1 located at the bottom of the beds, the excess PWP, u_e, within each bed increased continuously throughout the tilting test and reached its maximum value at time corresponding to the failure of the slope within the tank. It is interesting to note, that for the bed prepared from the M5 mixture, the excess PWP buildup did not start immediately from the beginning of the test but with some 30 min offset (approximately 5°). Bed failure through sliding of a portion of the bed to the bottom of the Tank under the influence of gravitational forces was recorded at different angles of tilting for the beds prepared from various mixtures. These angles were 40.4°, 39.6° and 35.2° for the beds deposited from the T1, M2 and M5 mixtures, respectively. As soon as the sliding soil reached the bottom of the Tank, the photosensor on the side wall was activated thus preventing further tilting. Upon cessation of tilting, the generated u_e immediately began to dissipate, which process continued for about 0.3, 7.1 and 17.6 h for the beds prepared from T1, M2 and M5 mixtures, respectively.

For the M5 bed, the recorded u_e variation with time at port P2 (Figure 4b), located approximately in the middle of the bed, closely resembled that at port P1. However, the pattern of u_e evolution at port P2 observed in T1 and M2 beds was different from that at port P1 within the same beds. For instance, in the M2 bed, u_e steadily increased until about 20° angle of tilting after which point the slope of the curve flattened suggesting that the rate of pore water pressure generation became almost equal to the rate of pressure dissipation. This trend persisted to approximately 35° angle of tilting, beyond which u_e began to rapidly increase again until bed failure at 39.6°. In the T1 bed, the rate of u_e generation dominated over the rate of dissipation up until about 10° angle of tilt. Tilting from 10° to 16° resulted in the opposite trend and the net excess pore water pressure decreased over this period. Past 16° angle, u_e began to gradually increase again until slope failure at 40.4°. In all beds, dissipation of the excess pore water pressure started right after the cessation of tilting and continued for about 0.2, 6.3 and 15.4 h for the beds prepared from T1, M2 and M5 mixtures, respectively.

Referring to Fig. 4c, in the mixed tailings bed prepared from M5 mixture, the u_e evolution at port P3 located immediately below bed surface followed that in ports P1 and P2. The excess PWP within this bed steadily increased throughout the slow tilting and reached its maximum value at failure of the bed slope at 35.2°. It is worth noting here that at all three ports (P1, P2 and P3), the maximum u_e values reached during the slow tilting experiments, were very close to each other, suggesting that excess PWP dissipation through drainage did not occur at any horizon within this bed. In contrast, the u_e variation with time at port P3 within the beds prepared from M2 and T1 mixtures significantly differed from that recorded at ports P1 and P2 for the same beds. For instance, the maximum u_e value reached at P3 within the T1 bed was 32% of that at P1 for the same bed. Within the M2 bed, the maximum u_e reached at P3 was about 43% of that at port P1. The slope of the u_e-plot versus time and angle of tilting for the T1 bed clearly shows that the rate of excess PWP dissipation was greater than the rate of pressure dissipation from 16° to about 40° angle of tilting (Figure 4c). In the M2 bed, the shape of the plot at P3 suggests that the rate of pressure dissipation was close to or greater than the rate of pressure generation between approximately 12° and 32° angle of tilting. A peak in u_e versus time
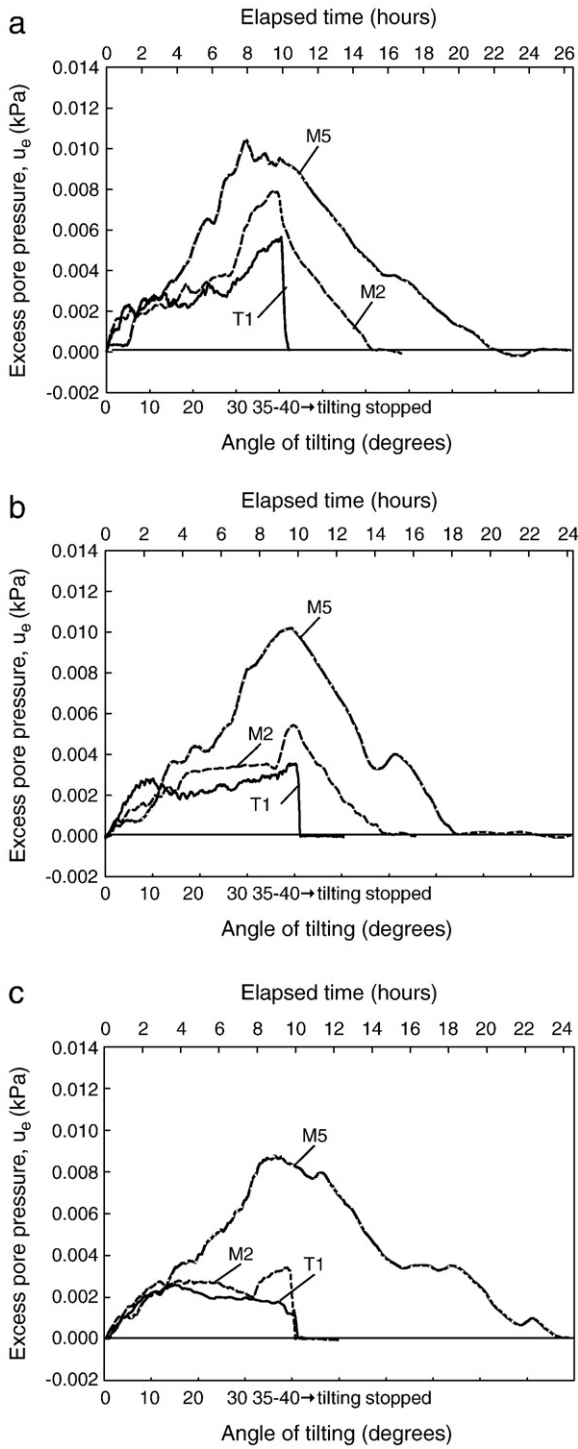
Fig. 4. Excess pore water pressure variation with time during slow tilting of beds prepared from various tailings/clay mixtures and consolidated for 3 days at: (a) Port P1 (bottom of the bed); (b) Port P2 (middle of the bed); and (c) Port P3 (immediately below bed surface).

and angle of tilting plots was registered in both M2 and T1 beds at failure, with the peak in the M2 bed being much more pronounced than that in the T1 bed.

In Fig. 5a and b, profiles of u_e with depth below surface of beds were plotted on a semi-logarithmic scale at various angle of tilting. A line representing the variation of the normal effective stress at the onset of tilting, σ'_n, with depth below the bed surface was also drawn for comparison. In our previous paper (Dimitrova and Yanful, in press) we demonstrated that the spatial distribution of u_e within

the T1 tailings bed during slow tilting was nonuniform, showing lower u_e values at port P3 compared to those at P1 and P2. We attributed the observed nonuniform u_e distribution to drainage through bed surface, which accelerated with the angle of tilting and became greatest at failure of the slope. Thus, at 10° angle of tilting, drainage was present only in the shallow horizons and resulted in lowering the u_e values at port P3 in comparison with those at P1 and P2. With increasing angle of tilting, the excess PWP dissipation progressed in downward direction to the lower horizons and reduced the u_e values at port P2 as well. At failure, the drainage affected the entire bed. A similar pattern of u_e evolution during slow tilting was evident in the bed prepared from M2 mixture (Figure 5a) suggesting that adding 4% kaolinite to the mine tailings did not alter significantly the permeability of the latter. This was not the case with the M5 beds, though. Referring to Fig. 5b, it can be seen that the plots at 10°, 20°, and 35.2° are nearly straight vertical lines implying a relatively uniform u_e distribution within the M5 bed at all angles of tilting. These results suggest that almost no drainage occurred in this bed during slow tilting and confirm that adding bentonite to the tailings introduced a major modification in the permeability of the tailings. The most important finding from the slow tilting experiments, however, is that in all beds, the u_e values at each horizon remained at least an order of magnitude lower than the σ'_n values at the same horizon. This observation led to the conclusion that the excess pore water pressure generated during slow tilting did not significantly affect the strength of the beds, and consequently bed failure occurred under drained conditions when the shear stress at the failure plane exceeded the shear strength of the bed at this depth.
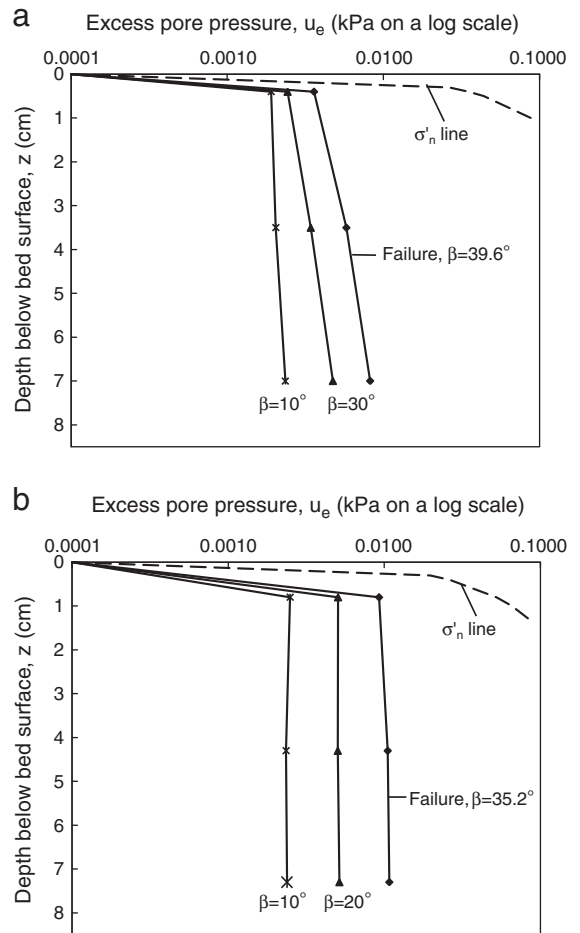

Fig. 5. Profiles of the excess pore pressure versus depth below bed surface recorded at various angles during slow tilting in 3 days-old tailings beds prepared from: (a) M2; and (b) M5 mixtures.

3.2.3. Rapid tilting

During rapid tilting, the excess pore water pressure generated in the mixed tailings/clay beds was much more substantial than during slow tilting and thus, affected the shear strength of the tested beds. The response of the beds to loading could no longer be considered fully drained and since volume change during tilting was not prevented and drainage through the bed surface was allowed, shearing occurred under partially drained conditions. Fig. 6a to c shows the evolution of excess PWP within beds prepared of T1, M2 and M5 mixtures at the three measuring ports during rapid tilting. The final thickness of the beds varied between 7.2 and 7.8 cm and they were consolidated for 3 days prior to testing.

Fig. 6a shows that, at port P1, u_e increased continuously during rapid tilting until failure of the slope, which occurred at 23.3°, 21.2° and 15.2° in the beds prepared of T1, M2 and M5 mixtures, respectively. The failure event activated the photosensor on the side wall of the Tank, which broke the electrical circuit and prevented further tilting. Upon cessation of tilting, u_e immediately began to dissipate and returned to zero within 0.16, 0.89 and 1.20 h in the T1, M2 and M5 beds, respectively. The maximum u_e value reached during the experiment on the M5 bed was about 60–65% of that reached within the T1 and M2 beds.

A similar pattern of u_e evolution with time and angle of tilting was recorded at P2 in all tested beds (Figure 6b). Similar to P1, the maximum u_e for the bed prepared from M5 mixture was about 66–71% of that reached within the T1 and M2 beds.

At port P3 (immediately below the bed surface), the plots for the M2 and T1 beds suggest that partial drainage occurred in both beds at this horizon, which caused some excess PWP pressure dissipation (Figure 6c). The rate of u_e dissipation dominated over the rate of pressure generation from about 2° angle of tilting to slope failure in the T1 bed, and from 8° to 20° angle in the M2 bed. It is believed that drainage in these beds proceeded in an upward direction through the bed surface into the ambient water and was driven by the pressure gradient brought about by the nonuniform excess PWP distribution. A distinct peak in u_e was recorded in the T1 and M2 beds at failure. Beyond this point, the tilting ceased and the excess PWP returned to zero. In the bed prepared from the M5 mixture u_e steadily increased during rapid tilting towards a maximum value, which was reached at failure. It is interesting to note, that the maximum u_e values recorded within the M2 and T1 beds constituted about 75% and 21%, respectively, of the maximum value reached in the M5 bed probably because of the lack of drainage in the latter bed.

The excess PWP buildup within the mixed tailings/clay beds in response to the rapid tilting ultimately led to liquefaction of the mixture and bed failure. The phases in the development of excess PWP can be seen more clearly in Fig. 7a and b, where u_e-profiles with depth below the surface of M2 and M5 beds are plotted for various angles of tilting. The figures also show the variation of σ'_n within the same beds. Referring to Fig. 7a, in the M2 bed the distribution of u_e at 5° angle of tilting is nearly uniform, which is evident from the close u_e values measured at ports P1, P2 and P3. The plot at 15° angle of tilting shows u_e value at port P3 significantly lower than those at P1 and P2, indicating that excess PWP dissipation through drainage has occurred at this shallow horizon. The nonuniform distribution of u_e within the bed brought about hydraulic gradient that became the driving force for subsequent drainage in the upward direction. The plot at failure ($\beta = 21.2°$) also indicates the presence of drainage. As shown in Fig. 7a, the generated excess PWP at the bottom (P1) and in the middle (P2) of the beds remained lower than the σ'_n value at these horizons during the experiment and reached a maximum of 10 to 20% of the σ'_n at failure. In contrast, at port P3 u_e moved close to the σ'_n line throughout rapid tilting and, at failure, was about 65% of σ'_n at the same depth. This could explain why the failure plane within the beds was always located close to the P3 elevation, i.e., at 0.4 to 2.0 cm below bed surface. In the M5 bed, the
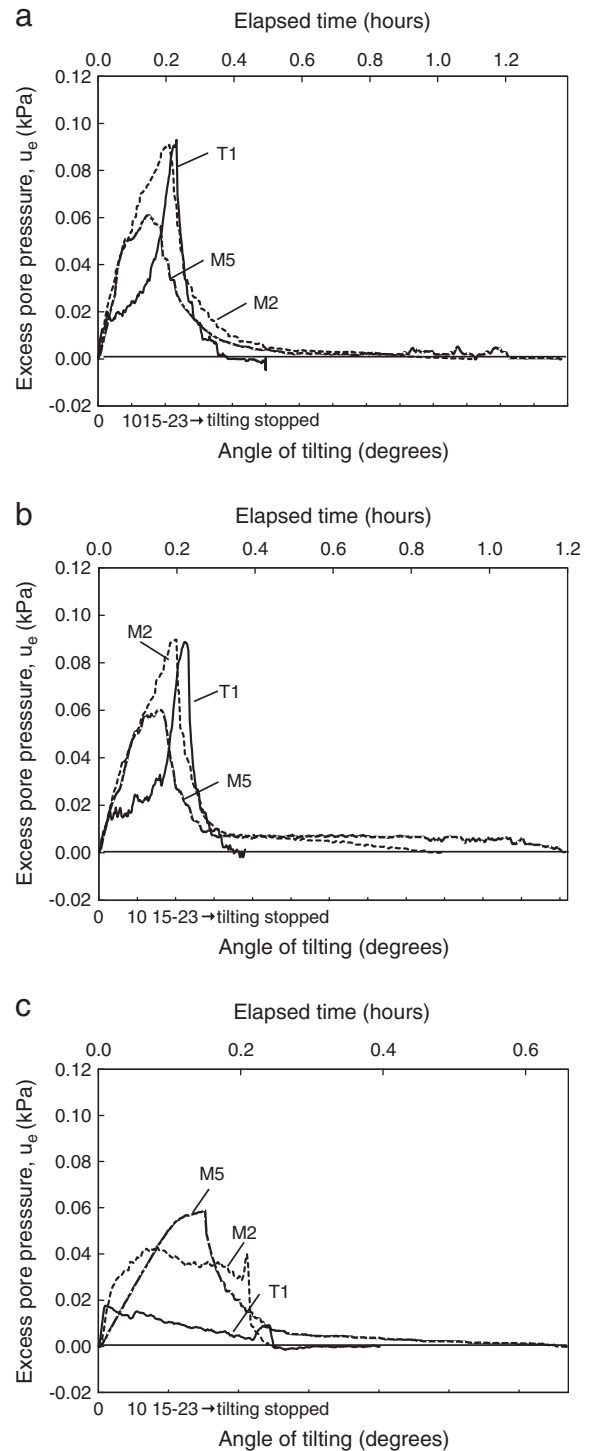

Fig. 6. Excess pore water pressure variation with time during rapid tilting of beds prepared from various tailings/clay mixtures and consolidated for 3 days at: (a) Port P1 (bottom of the bed); (b) Port P2 (middle of the bed); and (c) Port P3 (immediately below bed surface).

distribution of excess PWP remained relatively uniform during rapid tilting until failure as seen from the nearly vertical u_e profiles obtained at 5°, 10° and 15.2° angles of tilting (Figure 7b). These results suggest that drainage from the bed was minimal and that the rate of excess pore pressure generation far exceeded the rate of dissipation at all times during the experiment. Failure in all investigated beds occurred when the excess PWP generated in response to tilting
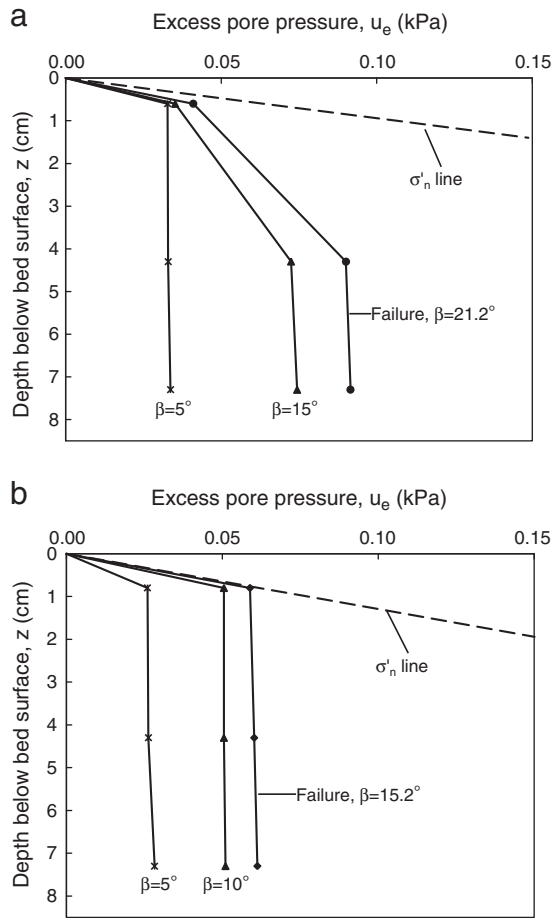
a

Excess pore pressure, u_e (kPa)

b

Excess pore pressure, u_e (kPa)

Fig. 7. Profiles of the excess pore pressure versus depth below bed surface recorded at various angles during rapid tilting in 3 days-old tailings beds prepared from: (a) M2; and (b) M5 mixtures.

reached the σ'_n value at a given horizon at which point the soil mixture liquefied leading ultimately to slope failure along this plane.

3.3. Failure modes

During tilting the gravity components of the bed self weight produce shear stress throughout the soil mass and, if it exceeds the shearing resistance of the mixtures on any possible failure surface, sliding will occur. In both slow and rapid tilting experiments, failure of the slope was observed as a sheet along a failure plane parallel to the bottom of the Tank. In the beds prepared from tailings and kaolinite mixtures (M2, M3, and M4) the failure plane was located approximately 0.5 to 2.0 cm from the surface of the beds, whereas in those prepared from the tailings and bentonite mixture (M5) the depth of the failure plane was slightly greater, i.e., 0.9 to 2.5 cm below bed surface. Failure happened quickly over a period of 5–6 s in the beds prepared from T1 and M2 mixtures and even faster (1–2 s) in the beds prepared from M3, M4 and M5 mixtures. During failure, the soil mass above the failure plane liquefied and travelled down the slope like a wave to the bottom of the Tank. The authors propose the following hypothesis to explain the failure mechanism of the studied mixtures. At failure, a rapid excess PWP buildup occurs at the failure plane, which excess pressure propagates in upward direction and causes a complete loss of shear strength in the soil mass above that plane. For beds of the same thickness and age, failure under drained conditions (slow tilting) occurred at an angle of tilting approximately two times higher than under partially drained conditions (rapid tilting).

3.4. Shear strength

As demonstrated in Section 3.2.1 the longest time for completion of primary consolidation was observed in the M5 beds and it was approximately 42 h. The beds used in the shear strength experiments were consolidated at least 3 days (72 h) prior to testing and were, therefore, believed to be fully consolidated. The consolidation time was defined as the time that elapsed from pouring the slurry into the tank and the beginning of the tilting. Measurements of excess PWP during tilting experiments showed that negligible excess PWP was generated if a slow tilting mode was selected, whereas a more substantial excess PWP buildup occurred during the rapid tilting. It was believed that during slow tilting soil shearing occurred under drained conditions and the measured bed shear strength was also "drained". In contrast, rapid tilting resulted in partially drained shearing and this mode was chosen to evaluate the effect of rate of loading on the shear strength of the deposited mixed tailings/clay beds. Accordingly, the recorded angle of failure during slow tilting was considered effective friction angle, whereby the friction angle measured during rapid tilting was related to the total stress parameters at failure (Eqs. (4), (5)).

3.4.1. Drained shear strength

In granular soils of low plasticity, where particle orientation is not a factor, residual shear strength, equal to the critical state strength, is mobilized during drained slope failure. Critical state is defined as constant shear stress and volume with increasing shear strain. The large shear displacements at failure reduce the shearing resistance to the residual condition along the entire slip surface (Mesri and Shahien, 2003). The residual shear strength depends on many factors, among which the most important are: clay content and mineralogy, particle shape and size distribution, pore-water chemistry, and rate of shear displacement (Kenney, 1967; Lupini et al., 1981; Skempton, 1985; Stark and Eid, 1994; Stark et al., 2005). The studied mine tailings/clay mixtures with clay content of 16% or below were most likely to exhibit a turbulent shearing mode as defined by Lupini et al. (1981). In this mode, soil shearing occurs through rolling and translation of the coarse particles. The residual shear strength is high, no preferred particle orientation occurs and the residual friction angle depends primarily on the shape and packing of the rotund particles and is relatively independent of the applied stress (Lupini et al., 1981; Stark et al., 2005). The Mohr–Coulomb shear strength criterion, representing stress state at failure, was applied to determine the drained (effective) residual shear strength envelope of the studied tailings/clay beds under drained conditions. For a normally consolidated soil this criterion can be expressed with the following relationship:

$$\tau_f = \sigma'_{nf} \tan\phi' \tag{7}$$

The Morh–Coulomb failure criterion (Eq. (7)) yields a linear failure envelope passing through the origin and assuming a zero cohesion intercept. Tiwari and Marui (2005) studied more than 35 mixtures of smectite, kaolinite and quartz in different proportions and with liquid limit between 26 and 120%. They found that, for the majority of mixtures, the drained residual failure envelope was linear and the cohesion intercept ranged between 0 and10 kPa. Stark and Eid (1994) also concluded that the drained failure envelope of soils with clay-size fraction less than 45% and liquid limit below 120% was essentially linear. Since all tailings/clay mixtures used in the present study satisfied both conditions for clay-size fraction lower than 45% and liquid limit below 120%, it was believed that a straight line would accurately describe the drained residual failure envelope of the tested soils. The assumption of zero cohesion was based on the following facts: i) the tested tailings/clay mixtures were coarse grained for all investigated clay contents; ii)

all tailings/clay deposited beds were prepared in the laboratory, i.e., were reconstituted, and iii) all beds were normally consolidated under self-weight.

The drained shear strength results for beds prepared from T1, M2, M3 and M4 mixtures and consolidated for 3 days were plotted as a function of the normal effective stress at the failure plane as shown in Fig. 8a and b. These figures present data obtained for tailings/clay mixtures in which the percentage of added clay is varied but the clay mineralogy is kept constant, and as such illustrate the effect of clay content on the shear strength of the tested artificial soils. At the onset of tilting, the vertical effective stress at a depth corresponding to the depth of the failure plane (Eq. (3)) varied between 0.03 and 0.23 kPa. Assuming a zero cohesion intercept, a straight line passing through the origin was used to fit the experimental data points with a high degree of confidence based on the high R-squared (correlation) factors between 0.96 and 0.99. Referring to Fig. 8a and b, the slopes of the fitted lines fall between 0.76 and 0.85 and decrease with increasing clay (kaolinite) content in the order T1 > M2 > M3 > M4. These results imply that in the effective stress range of interest, i.e., between 0 and 0.18 kPa, the drained shear strength of the investigated tailings/clay mixed beds also decreases with clay content increase.

The effect of clay mineralogy on the drained residual shear strength of mine tailings/clay mixtures can be seen in Fig. 9, where results from drained shear strength testing of mixed beds with the same percentage (4%) of added clay but different clay mineralogy (i.e., kaolinite versus bentonite) are compared. As seen in Fig. 9, adding either kaolinite or bentonite to the original mine tailings resulted in a decrease in the effective friction angle and respectively, the drained shear strength of the tailings. Adding bentonite, however, had much greater effect and thus, only 4% added bentonite brought about a reduction in the effective friction angle of the tailings from 40.4° to 35.2°, i.e., in about 5°. For comparison, adding the same percentage (4%) of kaolinite reduced the effective friction angle of the tailings to 39.6°, i.e., in less than 1°.

Similar observations of decreasing effective friction angle (and shear strength) of sandy soils with increasing clay content were reported by Kenney (1967), Stark and Eid (1994), Al-Shayea (2001) and Tiwari and Marui (2005). The results presented by Al-Shayea (2001) show that when the clay (smectite) content in a sand/clay mixture is increased from 0 to about 4%, the peak effective friction angle is reduced by about 5°, which finding is consistent with the results of the present study. An effective friction angle of 35.6° and a cohesion of zero were reported by Rodríguez (2006) who performed undrained triaxial tests on tailings samples containing 3–5% clay by weight, which is close to the clay content of the beds used in the present study. Tiwari and Marui (2005) demonstrated that although adding kaolinite or bentonite to sand both resulted in a decrease in the residual friction angle, the magnitude of the decrease was much higher for sand/bentonite samples than for sand and kaolinite. For instance, mixtures with approximately 20% kaolinite showed the same residual friction angle as mixtures with only 4% bentonite.

Ishihara et al. (1980) suggested that relative density is not a suitable index for the characterization of the mechanical behaviour of silty sands and that void ratio should be used instead. Kuerbis et al. (1988) noted that the void ratio of a silty sand bed deposited from slurry depends upon the fines (silt and/or clay) content and introduced the concept of sand skeleton void ratio to explain the undrained behaviour of silty sand tailings with varying fines content under cyclic loading. The skeleton void ratio, e_{sk}, is the void ratio corresponding to a fines content for which the fines completely separate adjacent sand particles and it can be determined from the following relationship:

$$e_{sk} = \frac{1+e}{1-f} - 1 \qquad (8)$$

where e is the overall void ratio of soil, and $f = \frac{Weight\ of\ fines}{Weight\ of\ solids}$ is the fines fraction of the soil. Thus, when e_{sk} calculated for a given sand/fines mixture (Eq. (8)) is greater than the maximum void ratio for clean sand, e_{max}, it appears that the soil matrix can reach a void ratio higher than it could achieve in the absence of fines. In this case, the sand particles are no longer in contact, i.e., they are floating in the fines matrix, and the mechanical behaviour of the soil is controlled by the fines matrix. In
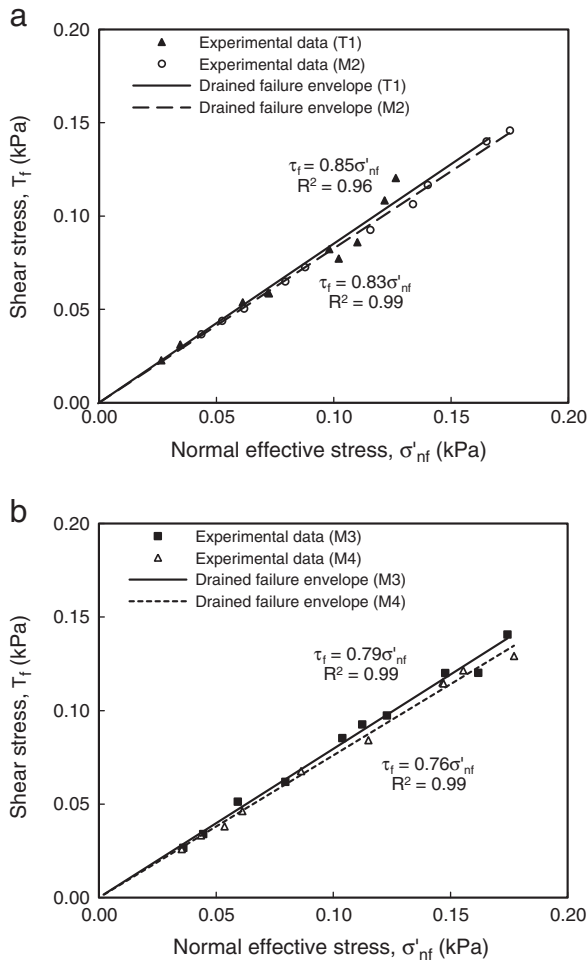

Fig. 8. Drained failure envelopes for beds prepared from: (a) T1 and M2; and (b) M3 and M4 mixtures and consolidated for 3 days.
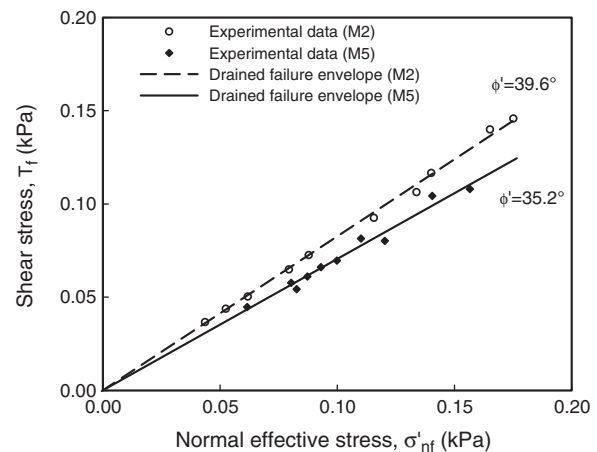

Fig. 9. Drained failure envelopes for beds prepared from M2 and M5 mixtures and consolidated for 3 days.

contrast, when $e_{sk} < e_{max}$, the fines simply occupy the void spaces in the sand skeleton and the mechanical behaviour is controlled essentially by the sand matrix. Kuerbis et al. (1988) determined that the threshold for transition between sand dominated and fines dominated matrix occurred at about 20% fines fraction, depending on the gradation and mean particle size of the sand. The artificial tailings/clay mixtures, used in the present study, had relatively high percentage of fines, i.e., from 32% in the original tailings to 41% in the M4 samples with 12% added kaolinite. Additionally, for the investigated mixed tailings/clay beds the skeleton void ratio, e_{sk}, calculated using Eq. (8) was found to vary between 1.46 and 2.60, i.e., was always greater than the maximum void ratio of the pure tailings sand, $e_{max} = 1.01$. For this comparison, e_{max} was determined following ASTM standard D4253-00 (ASTM, 2006) on the sand fraction of the original tailings (i.e., the fraction greater than 0.075 mm). Therefore, it was concluded that the quantity of fine material (silt and clay) in the original mine tailings was sufficient to fully occupy the voids between larger sand particles and they were floating within the fines matrix. Adding clay to the mine tailings led to a further increase in the distance between the sand grains, which was reflected in a corresponding increase in the void ratio of the deposited beds. It should be noted here that there is also a tendency for clay particles to coat granular particles thus preventing direct interparticle contact of the granular particles. The decrease in the particle-to-particle contact between sand grains caused a decrease in the frictional resistance of the beds and hence in the measured drained residual friction angle.

3.4.2. Partially drained shear strength

The rapid tilting of the Tank resulted in excess PWP buildup, which at the horizons where the measuring ports were located within the beds, was found to be of the same order of magnitude as the normal effective stress (Figure 6a to c). As discussed in Section 3.2.3, during rapid tilting shearing occurred under partially drained conditions with the two phenomena of excess pore water pressure generation and dissipation taking place simultaneously. The authors suggest the following hypothesis to explain failure of the beds within the Tank. During rapid tilting experiments the magnitude of the residual (net) excess pore water pressure, u_e, at shallow depths was generally close to that of the normal effective stress at the onset of tilting, σ'_n, at these depths. At a certain angle of tilting and depth, u_e became equal to σ'_n causing complete loss of shear strength within the soil mass at that horizon and failure of the slope along that plane. Thus, for the partially drained condition, the ratio $u_e/\sigma'_n = 1.0$ was adopted as a failure criterion and the angle of tilting, β, at which the failure criterion was satisfied was considered the failure angle. However, because the exact location of the failure plane could not be predicted in advance, it was not possible to position any of the PWP transducers at this exact depth and to measure the u_e-value at failure. Therefore, the recorded angle of tilting at failure was reported as a total friction angle, Φ_T and the obtained partially drained failure envelope as total stress envelope.

In Fig. 10a and b, the partially drained shear strength results from testing of beds prepared from mixtures T1, M2, M3 and M4 and consolidated for 3 days are plotted as a function of the normal total stress at the failure plane. These figures serve as an illustration of the effect of clay content on the total strength envelope (and total friction angle) of the mine tailings/clay mixtures. At the onset of tilting, the vertical total stress at the depth of the failure plane was calculated from Eq. (6) and found to vary between 0.72 and 1.25 kPa. Straight lines, passing through the origin and with R-squared values between 0.92 and 0.97, were used to successfully fit the four sets of experimental data. As shown in Fig. 10a and b, the slopes of the failure envelopes decrease with increasing clay content in the mixed tailings/clay beds, from 0.43 for the T1 bed to 0.31 for the M4 bed. These results suggest that, similar to the drained strength, the effect of increasing clay content the content of clay-
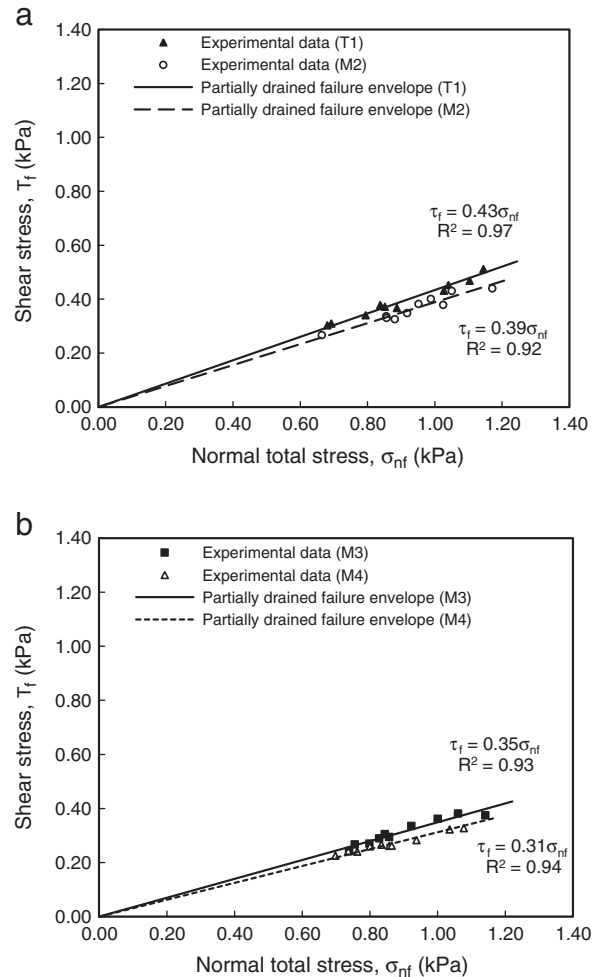

Fig. 10. Partially drained failure envelopes for beds prepared from: (a) T1 and M2; and (b) M3 and M4 mixtures and consolidated for 3 days.

size particles in the mixed mine tailings/clay beds was to decrease the partially drained strength of the beds.

At the same total clay content, the effect of clay mineralogy on the partially drained strength of mine tailings/clay mixtures can be seen in Fig. 11, where the measured partially drained shear strengths of the M2 and M5 beds are plotted as a function of the normal total stress at failure. Adding clay (kaolinite or bentonite) to the mine tailings generally decreased the total friction angle of the mixture but the magnitude of that decrease was greater for the tailings/bentonite samples than for the tailings/kaolinite ones. For instance, adding 4% kaolinite to the tailings reduced the total friction angle by 2.1°, i.e., from 23.3° in the original tailings to 21.2° for the M2 mixture, while adding the same percentage of bentonite caused a decrease of 8.1° in the total friction angle. It is hypothesised that two factors contributed to the observed decrease in the total friction angle with clay content increase. The first factor is related to the reduced interparticle contact between coarse sand particles caused by the presence of fine material and was discussed in Section 3.4.1. The second factor concerns the drainage conditions during rapid tilting. Because the investigated mixed beds exhibited different permeability and void ratios, the degree of drainage during the tilting experiments was also different. Observed excess PWP profiles (Figure 7a and b) and consolidation times (Figure 3) confirm this hypothesis and imply that the permeability of the mixed beds decreased in the order T1 > M2 > M3 > M4 > M5, as would be expected. It was assumed, therefore, that drainage during rapid tilting decreased in the same order, i.e., highest degree of drainage was present in the T1 bed and
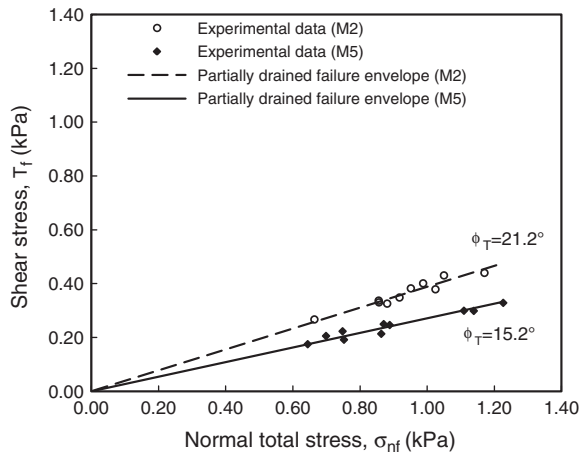
Fig. 11. Partially drained failure envelopes for beds prepared from M2 and M5 mixtures and consolidated for 3 days.

lowest in the M5 bed. Reduced drainage in the latter bed caused a more rapid buildup of excess PWP, which, along with the reduced bentonite interparticle contact between tailings sand particles, led to earlier failure of this bed.

3.4.3. Effect of aging

To investigate whether bed age under constant effective stress had any effect on the mechanical strength of the mixed mine tailings/clay beds, drained and partially drained strength experiments were performed at 3 days and 12 days consolidation times and the respective effective and total friction angles were determined. Fig. 12a and b shows a comparison between the observed drained residual failure envelopes of the beds prepared from mine tailings/kaolinite mixtures and consolidated for 3 and 12 days. Referring to Fig. 12a, at a consolidation time of 3 days, the slopes of the drained failure envelopes correspond to effective friction angles, Φ' of 37.3, 38.5, 39.6 and 40.4°, for the M4, M3, M2 and T1 beds, respectively. In comparison, when the time for consolidation was increased to 12 days, the effective friction angles in the respective beds demonstrated only a small (0.4° to 1.5°) increase (Figure 12b). Such a minor increase could be either caused by a variation in the experimental conditions or by a minor strength gain with time. Since the exact cause of the strength increase remained unclear, it was concluded that Φ' of the deposited tailings/kaolinite beds was relatively independent of the bed age.

Similar plots to those in Fig. 12a and b, but showing partially drained failure envelopes of mixed tailings/kaolinite beds consolidated for 3 and 12 days are shown in Fig. 13a and 13b. As evident from Fig. 13a, the slopes of the obtained partially drained (total stress) failure envelopes correspond to total friction angles, Φ_T of 17.4°, 19.3°, 21.2° and 23.3° for the 3 days old beds prepared from M4, M3, M2 and T1 mixtures, respectively. At consolidation time of 12 days (Figure 13b), computed Φ_T was less than 1° higher, suggesting a negligible increase in the partially drained shear strength with time for consolidation. On the basis of the experimental results presented in Figs. 12a and b and 13a and b, it can be concluded that increasing the clay content of the original mine tailings by adding up to 12% kaolinite did not modify the time-dependent strength behaviour of the tailings.

To investigate the effect of adding bentonite to the mine tailings, drained and partially drained shear strength experiments were conducted with beds prepared from the M5 mixture and consolidated for 3 or 12 days and the obtained results are shown in Fig. 14a and b. As can be seen from Fig. 14a and b, the tailings/bentonite beds with 4% added bentonite (M5) exhibited a more pronounced strength gain with time in comparison to the tailings/kaolinite beds with the same percentage of added clay (M2), that is, an increase of 2.1° for both drained and partially drained strength. A possible explanation
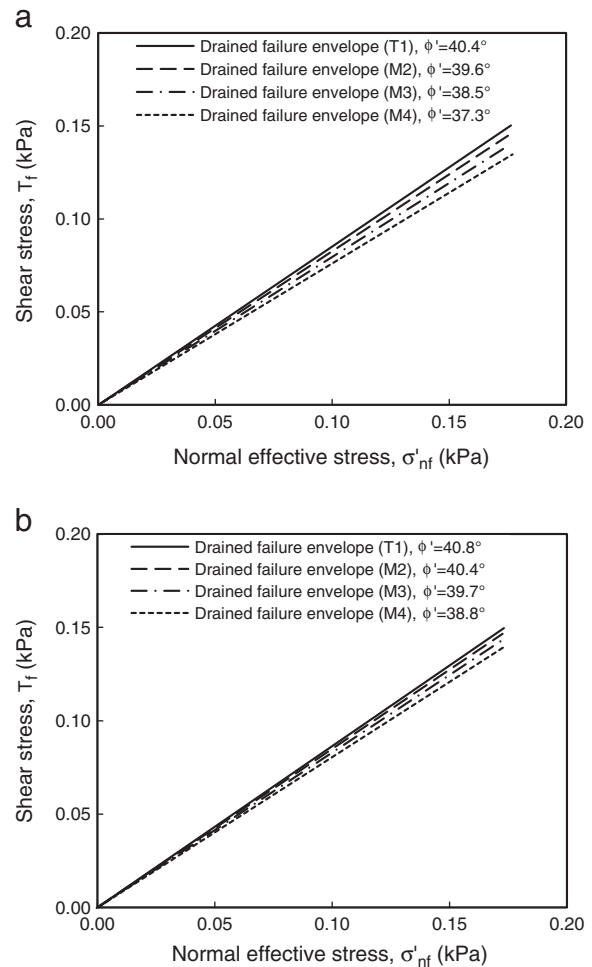

Fig. 12. Drained failure envelopes for beds prepared from T1, M2, M3 and M4 mixtures and consolidated for: (a) 3 days; and (b) 12 days.

for the observed strength gain with time in the M5 beds is given below. As discussed in Section 3.2.1., the utilized bentonite showed a tendency to flocculate even in slurries prepared with distilled water. Thus, during sedimentation of the tailings/bentonite beds, flocs develop in the suspension and settle under the influence of their self-weight. A load-bearing skeleton consisting of sand and silt grains, clay aggregates (flocs) and pores begins to develop marking the onset of primary consolidation. The fabric of the resulting sediment deposit depends on the applied effective stress (Imai, 1981), and under very low stresses such as those induced by self weight consolidation, the tailings/bentonite beds exhibit more open and flocculated fabric with higher void ratio than the tailings/kaolinite beds. In tailings/bentonite beds, as additional material settles on the top, the weaker flocs in the forming deposit break up, pore spaces are further reduced and pore water is expulsed from within the flocs and interparticle spaces (Toorman, 1999). The resulting smaller and stronger aggregates together with the coarse sand and silt particles form a more compact bed with lower permeability. Primary consolidation is considered complete when excess water pressure has fully dissipated. During secondary compression the particles and flocs tend to rotate and assume more stable configuration at an almost constant volume and water content (Mitchell and Soga, 2005). The mechanism of secondary compression involves sliding at interparticle contacts, expulsion of water from microfabric elements, and rearrangement of adsorbed water molecules and cations into different positions. This phenomenon of structural change at constant effective stress is referred to as thixotropy and in the investigated
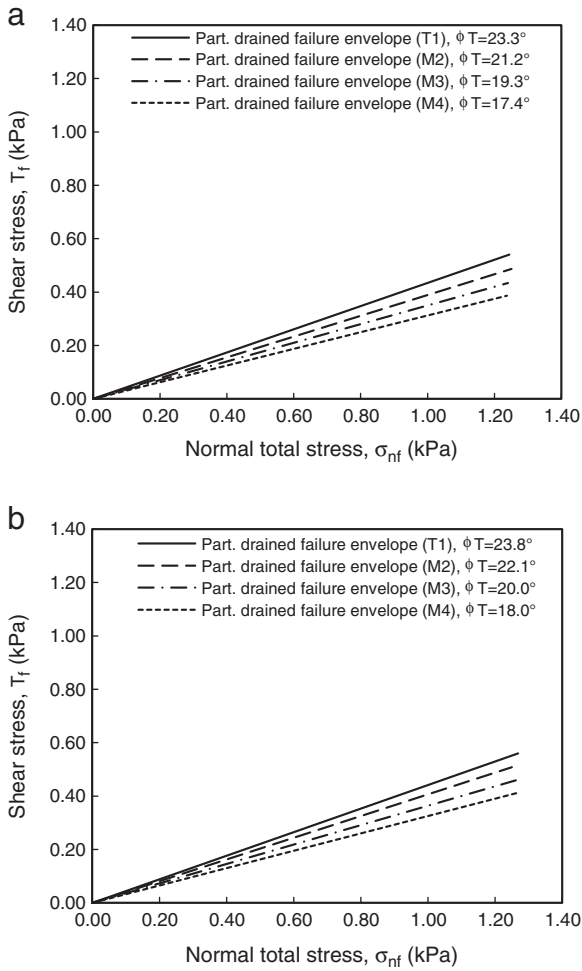
a

b

Fig. 13. Partially drained failure envelopes for beds prepared from T1, M2, M3 and M4 mixtures and consolidated for: (a) 3 days; and (b) 12 days.

a

b

Fig. 14. Drained and partially drained failure envelopes for beds prepared from M5 mixture and consolidated for: (a) 3 days; and (b) 12 days.

tailings/bentonite beds, it has probably caused the observed small shear strength increase with time of consolidation.

The stable configuration sought by the particles during secondary compression is a function of the magnitude of the effective stress and the water content, that is, the higher the effective stress and water content, the greater the particle rearrangement during secondary compression (Zreik et al., 1997). Unlike bentonite, kaolinite particles are inert and behave as a sandy material forming a deposit with lower void ratio and water content. Furthermore, due to the high permeability of these beds, the rate of water content decrease during primary consolidation is much more remarkable than in the tailings/bentonite beds. Thus, at a low effective stress of approximately the same magnitude, the void ratio and, correspondingly, the water content of the tailings/kaolinite beds are lower than that of the tailings/bentonite beds and hence, little or no particle rearrangement occurs in the former during secondary compression.

3.4.4. Comparative evaluation of drained and partially drained shear strength results

The results from the drained and partially drained shear strength testing of mixed mine tailings/clay beds, consolidated for 3 and 12 days, are summarized in Table 3. The drained and partially drained shear strengths are expressed in terms of Φ' and Φ_T, respectively.

During rapid tilting, the beds probably experienced different degree of drainage due to their varying permeability, and, as such, the partially drained strength results were not strictly obtained under the same drainage conditions. However, they can still serve to illustrate the effect
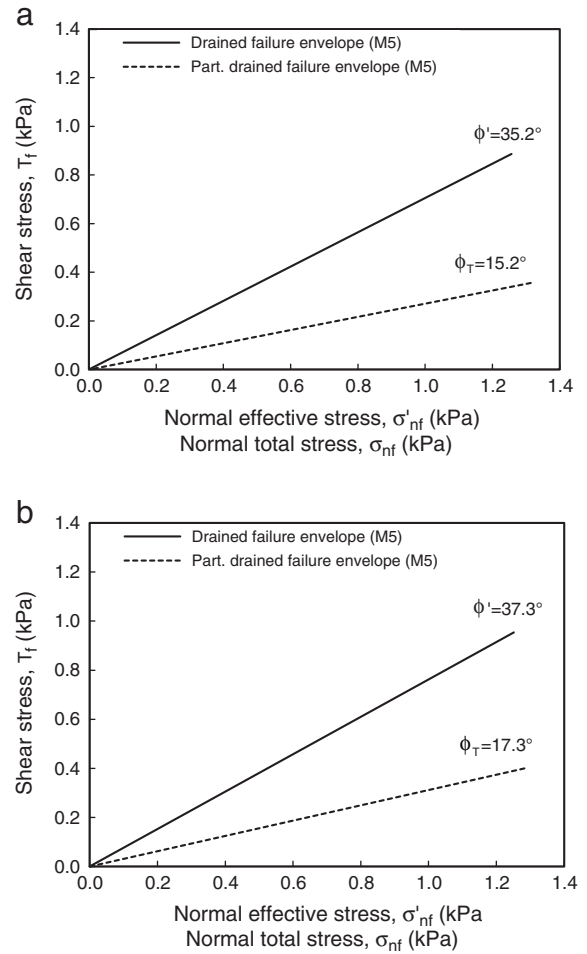
of tilting rate and partial drainage on the shear strength of the beds. As expected for a normally consolidated soil, the drained shear strength was higher than the partially drained over the entire stress range for all tested tailings/clay beds. This was due to the positive excess pore pressures generated during rapid shearing in the Tilting Tank and causing a reduction in the normal effective stress. The total friction angle, Φ_T, was lower than the effective friction angle, Φ', with the difference between Φ_T and Φ' decreasing in the order M5 > M4 > M3 > M2 > T1. It is believed that, in the M5 beds, drainage was minimal and therefore, shearing occurred under nearly undrained conditions. No dissipation of excess pore pressure was evident in this bed, unlike in the mixed tailings/kaolinite beds which all experienced some degree of drainage. Thus, the excess pore water pressure in the M5 bed built up rapidly with the onset of tilting and reached a higher value than in the M2 and T1 beds,

Table 3
Effective and total friction angles for beds prepared from mine tailings/clay mixtures with various compositions, consolidated for 3 or 12 days.

Sample ID	3 days		12 days	
	$\Phi'(°)$	$\Phi_T(°)$	$\Phi'(°)$	$\Phi_T(°)$
T1	40.4	23.3	40.8	23.8
M2	39.6	21.2	40.4	22.1
M3	38.5	19.3	39.7	20.0
M4	37.3	17.4	38.8	18.0
M5	35.2	15.2	37.3	17.3

for example. As a consequence of the rapid excess PWP generation and lack of pressure dissipation through drainage, the M5 bed failed at a lower angle of tilting than the T1, M2, M3 and M4 beds. In contrast, drainage at the bed surface reduced the net excess PWP in the tailings/kaolinite beds and, as a result, they failed at higher angles of tilting. The increase in the angle of tilting at failure in the order M4<M3<M2<T1 in the tailings/kaolinite beds followed the increase in the degree of drainage within these beds, i.e. from lowest in the M4 beds to highest in the T1 beds.

A detailed investigation of the water content and density distribution in the deposited mixed tailings/clay beds is currently underway. Further research efforts will also focus on measuring the undrained shear strength of the beds. It is expected that the results would provide additional insight into the effect of drainage on the shear strength of the mixed mine tailings/clay beds in the entire range of drainage conditions, i.e., from fully drained to completely undrained.

4. Summary and conclusions

Artificial mine tailings/clay mixtures were prepared in the laboratory by adding kaolinite or bentonite clay to hard rock mine tailings. The total clay content of the obtained samples varied from 4% in the original mine tailings to 16%, with the upper boundary corresponding to the maximum clay percentage found in most tailings in Canada. The mixtures were used in the preparation of slurries with high concentration of solids (50% by volume), from which mine tailings/clay beds with final thickness between 1 and 11 cm were sedimented. The beds were allowed to consolidate under self weight for a minimum of 3 days, which period was sufficient to complete their primary consolidation. Thus, the obtained normally consolidated beds were tested in a specially built Tilting Tank where the excess pore water pressure, generated as a result of tilting, was monitored using pressure transducers. The transducers were positioned in a vertical array at three elevations: near the surface, in the middle and close to the bottom of the beds. An average slow tilting speed of 0.07°/min was applied to obtain a measure of the drained shear strength of the beds, while rapid tilting at 1.61°/min was adopted to simulate partially drained shearing conditions. The main findings of the research are summarized below:

- During shearing, all tailings/kaolinite beds experienced some degree of pore water pressure dissipation through drainage from the bed surface, the magnitude of which depended on the clay content of the bed, i.e., the higher the clay content the lower the degree of drainage. In contrast, the excess pore water pressure distribution within tailings/bentonite beds was relatively uniform, indicating that minimum or no pressure dissipation occurred in these beds.
- In all beds during slow tilting, the excess pore water pressure at each monitored horizon remained at least an order of magnitude lower than the respective normal effective stress. Failure of the beds occurred when the shear stress at a given depth exceeded the shear strength of the bed at the same depth.
- Rapid titling of the beds resulted in the generation of excess pore water pressure which, at a given elevation, was of the same order of magnitude as the normal effective stress and thus, affected the shear strength of the beds. Slope failure was triggered when the excess pore water pressure became equal to the normal effective stress at a given elevation in the bed.
- During failure, the soil mixture showed complete loss of integrity. The failure plane was parallel to the bottom of the tank and located at 0.4 to 2.5 cm from the bed surface.
- Liner drained residual strength envelopes of tested mixtures were successfully defined at a vertical stress range from 0.03 to approximately 0.18 kPa. The drained residual friction angle of the beds, Φ', generally decreased with increasing clay content in the mixtures, but bentonite was much more effective in reducing Φ' than

kaolinite. The partially drained (total stress) failure envelopes obtained for the tested mixtures were also linear within the tested stress range with zero cohesion intercept.
- For beds of the same composition and age, the total friction angle, Φ_T, was determined to be lower than Φ', which was attributed to the higher excess pore pressure generated within the beds during rapid tilting in comparison with that induced in response of slow tilting. Experimental results demonstrated little variation of both Φ' and Φ_T with bed age in the tailings/kaolinite beds, whereas increasing the time for consolidation from 3 to 12 days, resulted in 2.1° degrees gain in frictional resistance in the tailings/bentonite beds.

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