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

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ABSTRACT

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