Consistency based correlations for tailings consolidation

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ABSTRACT
The main objective of this investigation was to analyze the consolidation behavior of tailings in conjunction with soil consistency that captures physicochemical interactions. Based on published data, the large strain consolidation behavior of six fine-grained soil slurries was examined. It was found that normalized void ratio (e/e_L) best describes volume compressibility whereas liquidity index (LI) best explains the hydraulic conductivity. In both cases, power laws were found to be the best-fit equations. Additional data over the entire range of sedimentation, transition, and consolidation are required to validate the observed relationships.

RÉSUMÉ
L'objectif principal de cette enquête était d'analyser la conduite de consolidation de tailings dans la conjonction avec la consistance de sol qui capture les actions réciproques physicochemical. Basé sur les données publiées, la grande conduite de consolidation d'effort de six sol grained parfait slurries a été examinée. Il a été constaté que le rapport nul normalisé (e/e_L) décrit le mieux la compressibilité de volume alors que l'index (LI) de liquidité explique le mieux la conductivité hydraulique. Dans les deux cas, les lois de pouvoir ont été trouvées pour être les équations appropriées-meilleures. Les données supplémentaires sur la gamme d'enitre de sédimentation, transition et consolidation sont tenues de valider les rapports observés.

1 INTRODUCTION

The extraction of energy (oil and uranium) and material (metal and mineral) resources from the earth generates enormous amounts of tailings slurry. The tailings are contained in a disposal area with perimeter dykes constructed from the coarser fraction of the slurry. The slow settling rates of the fines and the high standing toxic waters offer unique challenges pertaining to the management of the containment facilities for a number of decades beyond mine closure (Edil and Fox 2000). Numerous tailings dam failures in various parts of the globe have been reported to result in massive contaminant releases causing acute public distress over the conventional practice of tailings disposal (Morgenstern and Scott 1995).

To minimize the environmental footprint, the fluid tailings need to undergo an efficient consolidation, that is, at a rapid rate and up to a high degree (Concha and Burger 2003). According to Azam et al. (2009), the solid-liquid separation behavior of mine tailings is governed by both physicochemical factors (derived from colloid-liquid-additive interactions) and applied loading (due to internal granular surcharge or upper layer deposition). Given the long time required to conduct laboratory tests and the use of complex mathematical modeling tools, there is a need to develop a quick and easy method to predict field performance of slurry tailings.

The main objective of this investigation was to analyze the consolidation behavior of tailings in conjunction with soil consistency that captures the physicochemical interactions. Based on published data, the large strain consolidation properties: volume compressibility (void ratio versus effective stress) and hydraulic conductivity (void ratio versus hydraulic conductivity) of selected slurry tailings were correlated with soil consistency.

2 BACKGROUND

Consolidation refers to change in soil volume resulting from the dissipation of excess pore pressure that, in turn, is provoked by the vertical stresses (Terzaghi et al. 1996). The rate of excess pore pressure dissipation is influenced by the excess pore pressure gradient and the hydraulic conductivity of the material. Classical consolidation theory is unsatisfactory to describe the self-weight settling behavior of fined grained slurries. To account for large settlements in soft soils such as tailings for which compressibility and hydraulic conductivity are non-linear, Gibson et al. (1967) developed the non-linear finite strain consolidation theory. This theory is based on the continuity of mixtures, the Darcy-Gersevanov fluid migration relationship through a soil matrix, and the Terzaghi principle of effective stress for vertical equilibrium (Been and Sills 1981). The consolidation test is necessary to determine the relationships between effective stress (σ'), void ratio (e), and hydraulic conductivity (k) of slurries. Generally, such a test may take up to two to three months to complete and require a lot of sophisticated laboratory instruments (Morris et al. 2000). Denoting the empirical constants by a, b, c and d, the constitutive equations for volume compressibility and hydraulic conductivity obtained from the consolidation test can be respectively written as follows:

$$e = \mathrm{c}\ \sigma'^{\,\mathrm{d}} \qquad [1]$$

$$k = \mathrm{a}\ e^{\,\mathrm{b}} \qquad [2]$$

The purpose of this research is to develop consistency-based relationships describing tailings consolidation.

3 RESEARCH METHODOLOGY

Six types of fine grained materials were investigated: (i) cyclone overflow oil sands tailings from Syncrude Canada Ltd. (Jeeravipoolvarn et al. 2008); (ii) coal wash tailings from Coal Valley Mine of Luscar Sterco Ltd. (Qiu and Sego 2001); (iii) desanded oil sand tailings from Syncrude Canada Ltd. (Lord and Liu 1998); (iv) Georgia kaolin (Znidarcic et al. 1986); (v) laterite ore slurry from Nonoc mine, Philippines provided by Dynatec Inc. Canada (Azam et al. 2009); (vi) Speswhite fine china clay (Znidarcic et al.1986). first, these materials were classified according to the Unified Soil Classification System. Second, the large strain consolidation data were plotted in the form of void ratio versus effective stress and void ratio versus hydraulic conductivity. Third, the void ratio in both of these relationships was replaced with consistency-based parameters: liquidity index (LI), solidity index (SI) and normalized void ratio (e/e_L). Each of these parameters was plotted as a function of effective stress and hydraulic conductivity to obtain the new correlations.

Assuming that the degree of saturation (S) equals 100% in slurries and using the specific gravity (G_s) of soil solids, the slurry water content (w) during the test was obtained according to the following equation:

$$w = e\,S / G_s \qquad [3]$$

Denoting liquid limit by LL and plastic limit by PL, this water content was scaled using the liquidity index of soils as per the following equation:

$$LI = (w - PL) / (LL - PL) \qquad [4]$$

The solidity index was defined by converting the water content as well as the liquid and plastic limit values in Equation [4] to solids contents (s) according to the following equation:

$$s = 1/(1+w) \qquad [5]$$

Finally, the normalized void ratio (e/e_L) was defined using e_L that pertained to the void ratio at the liquid limit.

4 GEOTECHNICAL INDEX PROPERTIES

Table 1 summarizes the geotechnical index properties of the selected materials. The slurry tailings covered a wide range of specific gravity from 1.94 (for the coal wash tailings) to 3.16 (for the laterite ore slurry). Likewise, the water adsorption capacity of the slurries showed large variation as indicated by the liquid limit and plasticity index. Overall, the investigated tailings were classified as clays with high plasticity (CH), clays with low plasticity (CL), and silts with high plasticity (MH).

Figure 1 plots the investigated slurry tailings on the Cassagrande's plasticity chart. Most of the soils plotted on both sides of the A-line: clays above the line and silts below the line. The laterite ore slurry exhibited very high liquid limit (83%) owing to the presence of large amount of clay minerals and cementitious substances. With the exception of coal wash tailings and Georgia kaolin, all of the materials plotted in the high water content zone, that is, at a liquid limit above 50%.

The variability in the geotechnical index properties of the tailings is attributed to the variable solid-liquid interactions. Derived from the geological background (mineralogical composition of the solids) and the mining operation (chemical composition of the pore fluid), these interactions govern the consolidation behavior of fine-grained slurries (Carrier and Beckman 1984).

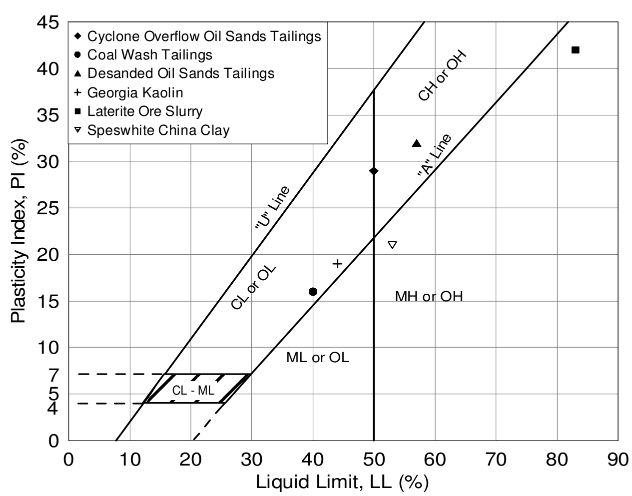


Figure 1. Investigated materials on the plasticity chart

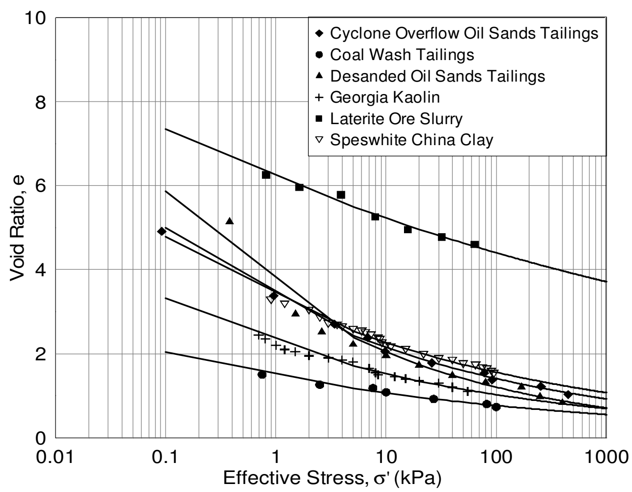
Table 1. Geotechnical index properties of the investigated materials

Slurry type	Specific gravity, G_s	Liquid limit, LL (%)	Plasticity index, PI (%)	USCS symbol	Reference
Cyclone overflow oil sand tailings	2.53	50	29	CH	Jeeravipoolvarn et al. 2008
Coal wash tailings	1.94	40	16	CL	Qiu and Sego 2001
Desanded oil sand tailings	2.65	57	32	CH	Lord and Liu 1998

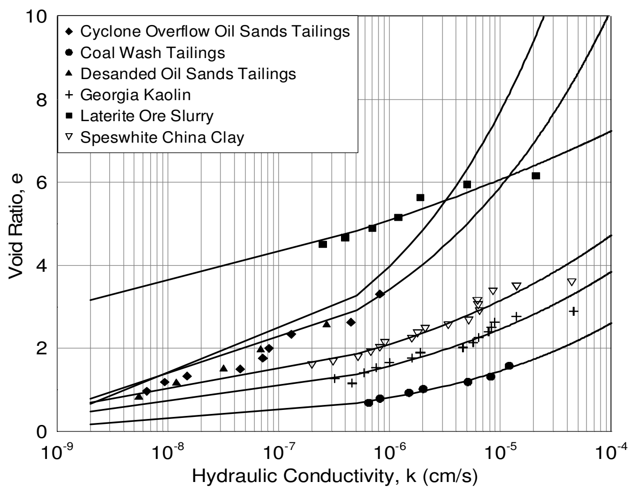
Georgia kaolin	2.60	44	19	CL	Znidarcic et al. 1986
Laterite ore slurry	3.16	83	41	MH	Azam et al. 2009
Speswhite china clay	2.66	53	21	MH	Znidarcic et al. 1986

5 LARGE STRAIN CONSOLIDATION

Figure 2 gives the large strain consolidation data for the investigated materials in the form of void ratio versus effective stress (Figure 2a) and void ratio versus hydraulic conductivity (Figure 2b). As expected, the void ratio of all of the materials was found to decrease with increasing effective stress and appear to converge at high effective stress. This is because the physicochemical interactions were predominant at low effective stress and gradually reduced with increasing effective stress. An opposite trend was observed in the void ratio versus hydraulic conductivity relationships. Overall, the variation in the tailings consolidation behavior should be attributed to variation in geological characteristics, ore beneficiation processes, and field disposal practices (Morris et al. 2000). These factors influence the complex physicochemical phenomena at the solid-liquid phase boundary.



(a) Volume compressibility



(b) Hydraulic conductivity

Figure 2. Large strain consolidation behaviour

6 VOLUME COMPRESSIBILITY CORRELATIONS

Figure 3 gives the volume compressibility correlations in the form of liquidity index versus effective stress (Figure 3a), solidity index versus effective stress (Figure 3b), and normalized void ratio versus effective stress (Figure 3c). Table 2 summarizes the best-fit equations and the associated R^2 values. The data for the investigated materials were analyzed using 99% confidence level. Most of the data were found to be within the limits of this confidence interval. Furthermore, all of the curves followed negative slopes and power laws were found to best describe the correlations. Azam et al. (2009) reported that the best-fit correlations for slurry dewatering are in the form of bi-power laws because such constitutive relationships cover the entire settling process: sedimentation, transition, and consolidation.

Two trends were observed in the liquidity index versus effective stress curve: (i) a steep slope at low effective stresses of up to 5 kPa and a corresponding LI = 2.5 and (ii) a flat slope for σ’ = 5 – 1000 kPa and LI = 2.5 – 0.5. This is similar to soils generally encountered in geotechnical engineering practice. Soils behave like viscous fluids when LI > 1.0, that is, when the physicochemical interactions are quite predominant. Conversely, if LI < 1.0, soils behave like plastic materials with physicochemical interactions quite subdued. Similar trends were observed for the SI versus σ’ and e/e_L versus σ’ correlations. These results are also corroborated by the findings of Morris et al. (2000)

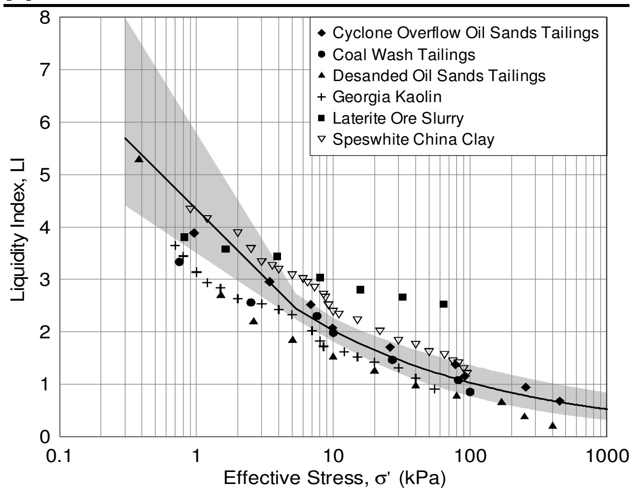
Based on R^2 values, it could be summarized that the normalized void ratio is strongly correlated with effective stress, followed by the liquidity index with effective stress, and then by the solidity index with effective stress.

Morris (2003) observed that the correlation between e/e_L and effective stress for fine-grained materials is statistically stronger than other correlations. This is because the effective pore size governs the consolidation behavior of slurries. According to Mitchell and Soga (2005), the void ratio at the liquid limit (e_L) is almost the same for all clays. Therefore, this void ratio is quite useful for normalizing the void ratio data directly obtained from the large strain consolidation test.

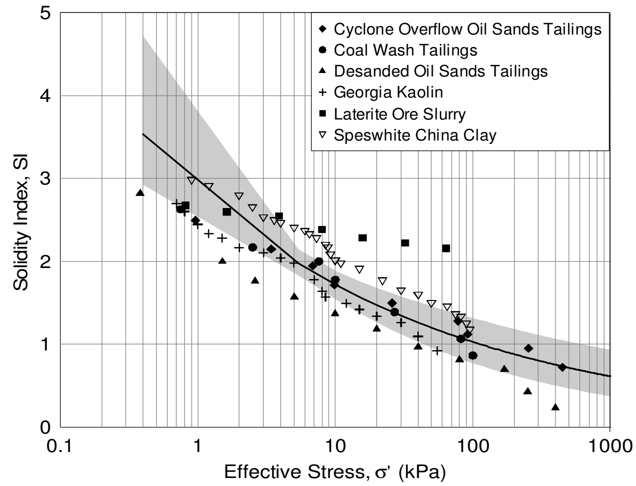
The volume compressibility correlations indicate that the margin of error would be less for tailings deposited in containment facilities. According to Qiu and Sego (2001), the effective stress generally operative in such deposits ranges from 1 kPa (freshly deposited material at the top) to about 100 kPa (for old deposition at the bottom). For mining operations such as thickening of slurries, the observed correlations need to be validated using additional data from such processes. Overall, the new consistency based correlations are best applicable for tailings with measurable effective stresses, that is, at least 1 kPa.

Table 2. Volume compressibility correlations

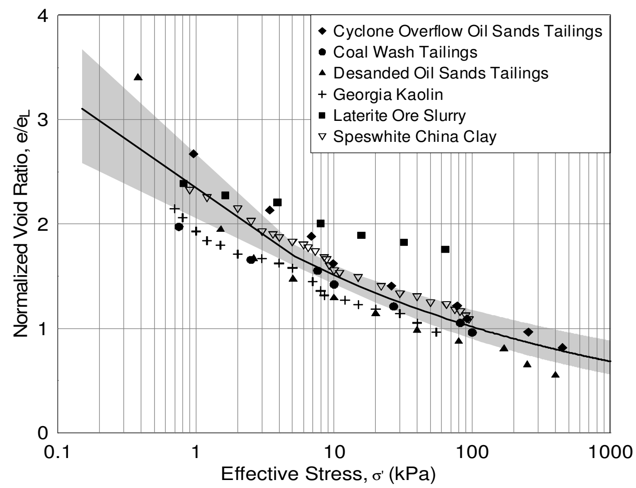
Equation No.	Correlations	R^2
[6]	$LI = 4.0\,\sigma'^{\,-0.29}$	0.75
[7]	$SI = 2.9\,\sigma'^{\,-0.22}$	0.71
[8]	$e/e_L = 2.2\,\sigma'^{\,-0.17}$	0.80



(a) Liquidity index versus effective stress



(b) Solidity index versus effective stress



(c) Normalized void ratio versus effective stress

Figure 3. Volume compressibility correlations

7 HYDRAULIC CONDUCTIVITY CORRELATIONS

Figure 4 shows the hydraulic conductivity correlations in the form of liquidity index versus hydraulic conductivity (Figure 4a), solidity index versus hydraulic conductivity (Figure 4b), and normalized void ratio versus hydraulic conductivity (Figure 4c). Similar to the volume compressibility correlations, all of the consistency-based parameters were found to increase with increasing hydraulic conductivity and power laws were found to best describe the correlations.

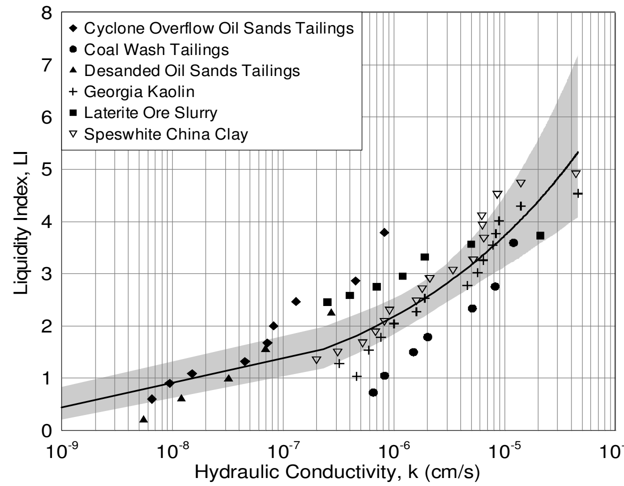
Table 3 summarizes the best-fit equations and the associated R^2 values. The data for the investigated materials were analyzed using 99% confidence level. The hydraulic conductivity correlations generally showed more scatter in data with an associated lower R^2 values. This can be attributed to several factors affecting the hydraulic conductivity of slurries such as the variation in flow velocity with time, the hydraulic gradient, the initial solids content, and the clay content (Suthaker and Scott 1996). The systemic errors in the determination of hydraulic conductivity during testing were further studied by Olsen et al. (1985), who suggested that flow through slurries is time-dependent and can be due to one or more of the following reasons: (i) undissolved air in the equipment and/or specimen; (ii) equipment compliance depending on fabrication material and applied gradients; (iii) inertia required to move the pore fluid; and (iv) time-dependent changes in pore space distribution. Using identical equipment and test conditions for oil sand tailings, Suthaker and Scott (1996) showed that the last reason is the most likely cause of the observed hydraulic conductivity. These authors concluded that the transient phenomenon is repeatable and the initial conditions retainable.

Irrespective of the scatter in the hydraulic conductivity data, two trends were clearly visible in the consistency based correlations: a steep slope for $k = 10^{-4}$ to 10^{-7} cm/sec and a flat slope for $k = 10^{-7}$ to 10^{-9} cm/sec. As described earlier, this because the constitutive relationships had to include the entire settling process: sedimentation, transition, and consolidation (Azam et al. 2009). Based on statistical correlation coefficient, the liquidity index and the solidity index were found to correlate well with hydraulic conductivity in comparison to the normalized void ratio. Carrier and Beckman (1984) and Morris et al. (2000) also showed that the liquidity index strongly correlates with their "normalized" hydraulic conductivity for fine-grained soils.

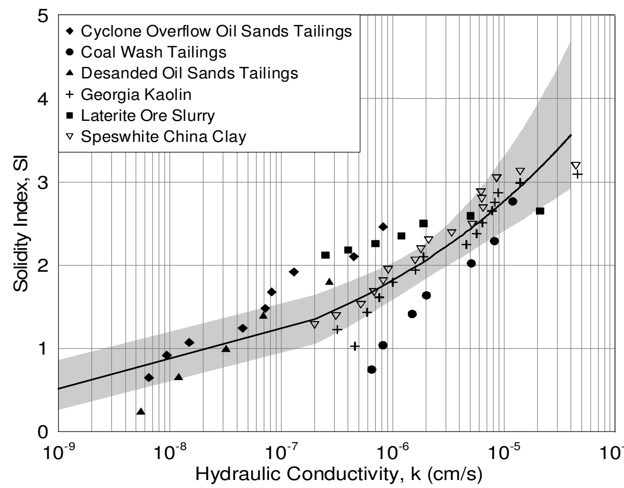
The consistency based hydraulic conductivity correlations are statistically inferior to those obtained for volume compressibility. Clearly, additional data over the entire range of sedimentation, transition, and consolidation are required to validate the observed relationships.

Table 3. Hydraulic conductivity correlations

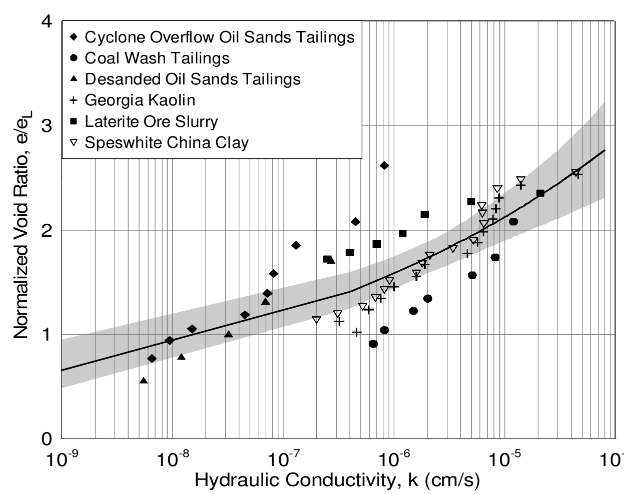
Equation No.	Correlations	R^2
[9]	$LI = 55.0\ k^{0.23}$	0.70
[10]	$SI = 22.7\ k^{0.18}$	0.70
[11]	$e/e_L = 9.2\ k^{0.13}$	0.66



(a) Liquidity index



(b) Solidity index



(c) Normalized void ratio

Figure 4. Hydraulic conductivity correlations

8 SUMMARY AND CONCLUSIONS

The consolidation behavior of fine-grained tailings is governed by inherent material properties. These characteristics are derived from the geological background (mineralogical composition of the solids) and the mining operation (chemical composition of the pore fluid). The geotechnical index properties capture the solid-liquid interactions at the phase boundaries and can be used for preliminary assessment of slurry dewatering. Based on published data, the large strain consolidation behavior of six fine-grained soil slurries was examined. It was found that the normalized void ratio (e/e_L) best describes volume compressibility because the void ratio at the liquid limit (e_L) is almost the same for all clays. Conversely, the liquidity index (LI) was found to best explain the hydraulic conductivity. In both cases, power laws were found to be the best-fit equations. Additional data over the entire range of sedimentation, transition, and consolidation are required to validate the observed relationships.

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