The Case for Using Fines Void Ratio

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ABSTRACT
Generally in geotechnical engineering, the relationships of compressibility, hydraulic conductivity and shear strength are plotted as functions of total void ratio. However, for oil sands and other tailings containing both fines and sand, it has been found that the sand does not significantly influence the compressibility, hydraulic conductivity and shear strength of sandy, fluid fine tailings. The sand only functions as filler material that displaces the fines matrix. In plotting the relationships, the fines void ratio, therefore, should be used not the total void ratio. Test results proving the case for using fines void ratio not total void ratio is included using a Soil Structure Behaviour Diagram.

RÉSUMÉ
Généralement en génie géotechnique les relations de la compressibilité, la conductivité hydraulique et la résistance au cisaillement sont tracées en fonction de l'index de vide total, mais pour les sables bitumineux et d'autres résidus contenant à la fois de fines et de sable, il a été constaté que le sable n'a pas d'influence significative sur la compressibilité, la conductivité hydraulique et la résistance au cisaillement de résidus fins fluides de sable. Le sable ne fonctionne que comme matériau de remplissage qui déplace la matrice de fines. En traçant les relations, l'index de vide de fines, par conséquent, devrait être utilisé et non l'index de vide total. Les résultats des essais prouvant le cas de l'utilisation de l'index de vide fines et non l'index de vide total est démontré à l'aide d'un Diagramme de Comportement de la Structure du Sol.

1 INTRODUCTION

Regulatory and closure commitments compel oil sands companies to dewater and reclaim fluid fine tailings (FFT) deposits. To achieve undrained strengths sufficient to support reclamation, significant dewatering and treatment of the FFT may be required. Companies are having difficulty in meeting this requirement and are adding flocculants to the FFT and using thickeners or centrifuges to increase the solids content. As the tailings stream contains sand as well as fines, the underflow from thickeners and centrifuges flowing to a dedicated disposal area contains sand as well as fines. The amount of sand varies depending on the thickening process and usually affects the measured properties of the tailings feed. Analyses and modeling of the long-term behaviour of the tailings feed is based on the results of large strain consolidation and standpipe tests. The material relationships needed in modeling are void ratio as a function of effective stress, hydraulic conductivity as a function of void ratio and shear strength as a function of void ratio. Generally with most materials the void ratio used is the total void ratio which is a function of the solids content. As discussed below when a slurry is formed by mixing two different soils together, such as oil sands sand and clay-shale fines that have particle size distributions (PSD) that are completely different, the resulting slurry is a gap graded slurry that has unique properties. Oil sands tailings is such a material and, depending on the fines content and solids content, the fines void ratio may have to be used instead of the total void ratio. The objective of the paper is to examine oil sands tailings test data especially the Atterberg limits to define if and when fines void ratio should be used.

It was found, when plotting the relationships for the Atterberg limits, hydraulic conductivities and shear strengths, the fines void ratio should often be used not the total void ratio. In these cases the sand acts as an internal surcharge in the fines matrix and has some effect on the effective stress during self-weight compressibility, but once the effective stress is over 1 kPa, its effect is negligible. Therefore, for compressibility purposes, the fines void ratio should also be used for plotting the relationships for compressibility. As the sand content changes in the tailings feed, the properties change as a function of fines solid content not total solids content.

2 THE OIL SANDS ORE

Over the 4,800 km² Athabasca oil sands mining area (Government of Alberta 2011) the properties of the ore can change substantially by mass (55 to 80% sand (>45 µm), 5 to 34% fines (<45 µm), 4 to 18% bitumen and 2 to 15% water). Typical deposits of average grade oil sands ore contain 72% sand, 12% fines, 11% bitumen and 5% water. Figure 1 is a geological section through the oil sands McMurray Formation which is mined for bitumen. Figure 2 shows a PSD of the sand layers containing bitumen which contain almost no fines; if the whole deposit was like this, there would be no fine tailings. Figure 2 also shows the PSD of a typical clay-shale seam in the oil sands McMurray Formation. The fines in the tailings come from these indurated clay-shale discontinuous seams and layers in the oil sands.

Figure 3 is a photograph of a section in the Upper McMurray Formation showing typical clay-shale layers. The clay-shale layers are less frequent in the lower parts of the deposit, but still make up a significant part of the ore. These dense but weak clay-shale materials are broken up during the mining process, and the larger more indurated pieces are screened out as reject material. In the bitumen extraction process the clay-shale pieces are further broken down into clay lumps and aggregates, and some clay lumps are dispersed into small clay booklets and flakes. The amount of dispersion depends on the extraction process. The sodium hydroxide dispersing agent in the Clark Hot Water Extraction process used in oil sands extraction plants effectively disperses much of the clay aggregates into clay flakes smaller than 2 µm, which have large active clay surfaces.

Elevation, m	Depth Below Surface, m	Unit	Lithology
306 298	127 135	B	shale and sandy shale
293	140	C	interbedded rich oil sands and shales
	149	D	rich oil sands with various amounts of shales which reduce in frequency with depth
	158	E	
		F	shale
270	160 163	G	

Figure 1. Stratigraphy of the McMurray Formation

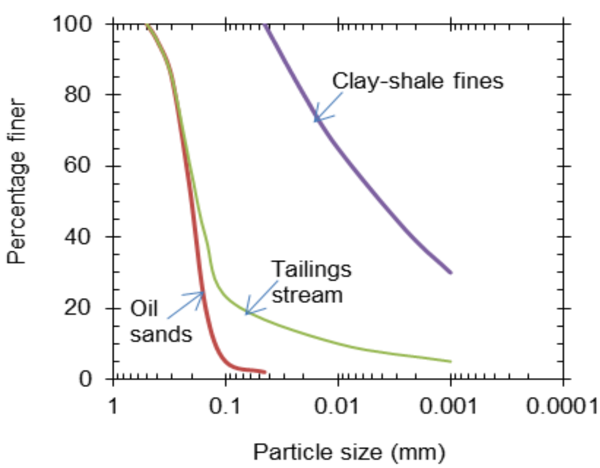

Figure 2. PSD of oil sands ore, clay-shale inclusions and resulting tailings stream

The PSD of the oil sands layers contains almost no particles finer than 0.1 mm, and the PSD of the clay-shale contains no material coarser than 0.05 mm. The mixing of these two different geological deposits makes a gap graded tailings stream PSD (Figure 2) that contains little material between 0.1 and 0.05 mm. Although the sand content and clay-shale content varies in the tailings stream, the gap graded PSD remains. Such gap graded slurries have unique properties, and it is with such materials that the fines void ratio or clay void ratio, not the total void ratio, must be used for material relationships in modeling.

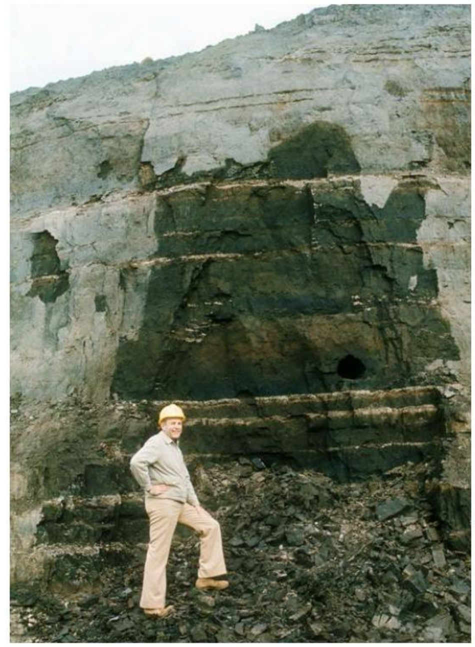

Figure 3. Section in the Upper McMurray Formation

3 THE SOIL STRUCTURE BEHAVIOUR DIAGRAM

The Soil Structure Behaviour Diagram (SBD) pictures slurry properties over a complete range of solids contents and fines contents or clay contents (Scott and Cymerman 1984; Chalaturnyk and Scott 2001). Figure 4 illustrates the construction layout of a typical SBD in a ternary construction. The SBD is characterized by three apexes denoting water, sand and fines or clay. Based on percentages by mass, the three axes represent: (a) the solids content which is directly related to total void ratio plotted on the left hand side, (b) the fines content or clay content plotted along the base, and (c) the fines-water ratio (FWR) which is directly related to the fines void ratio or the clay-water ratio (CWR) which is directly related to the clay void ratio plotted on the right hand side. The parallel horizontal lines depict slurries with constant solids content and are designated as constant solids-water ratio lines. Straight lines drawn from the water apex to the base describe constant sand-fines ratio lines or constant coarse-clay ratio lines. Straight lines drawn from the sand apex to the right hand side signify constant FWR lines or constant CWR lines. For simplicity, in this paper, fines content not clay content will be used in the SBD except where specifically noted. The Alberta oil sands industry has traditionally used the 45 µm size as the boundary between fines and sand. The SBD has to be developed separately for each slurry type and for clayey slurries; clay content instead of fines content is best used. A slurry with a certain amount of water, fines and sand plots as a point on the diagram.

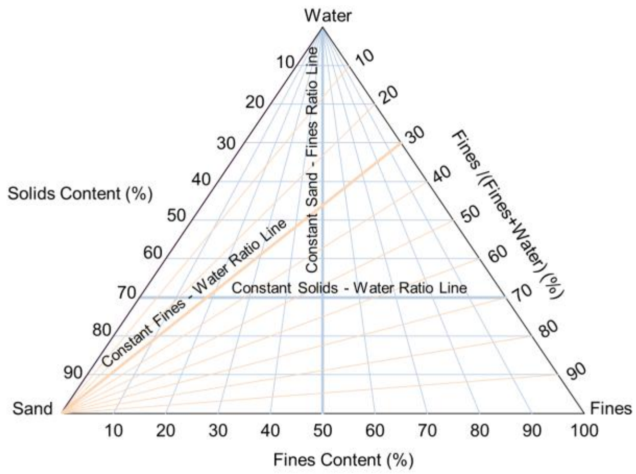

Figure 4. The Soil Structure Behaviour Diagram

Figure 5 illustrates the characteristics of oil sands tailings. The SBD shows boundaries between different types of engineering behaviour as the solids content and fines content of the material is varied. The matrix boundary or sand boundary distinguishes between a sand matrix (below the line) and a fines matrix (above the line). A sand matrix is one in which the coarse sand grains barely touch one another, that is, the sand void ratio is at a maximum and the fines are present in the pore space between the sand grains. In the fines matrix the sand grains do not touch one another, but are suspended in the fines matrix. The intercept of the sand boundary on the solids content axis is the maximum void ratio of the sand, which has to be obtained by a minimum density index test (ASTM D4254 2014). The minimum void ratio of the sand on the solids content axis is obtained by a maximum density index test (ASTM D4253 2014). The boundaries are then simply calculated at different fines contents. As the sand is at its densest state at the minimum void ratio, saturated slurries cannot exist below this line.

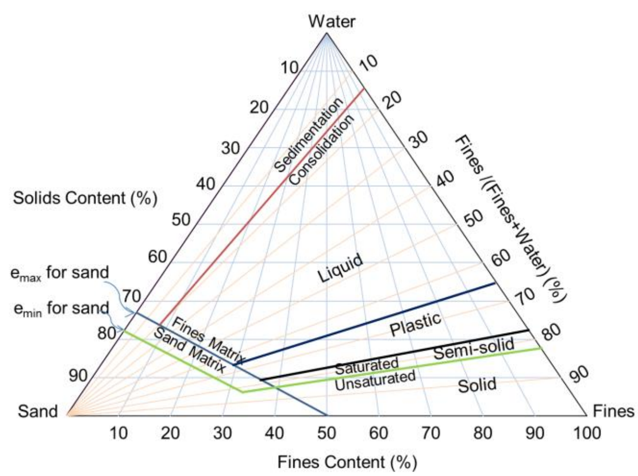

Figure 5. Typical characteristics of oil sands tailings

The sedimentation-consolidation boundary differentiates between the sedimentation region (above the line) and consolidation area (below the line). The sedimentation-consolidation boundary follows a 15% fines-water ratio line for the particular oil sands tailings used in this example. The boundary between the tailings liquid state and plastic state is defined by plotting equal undrained shear strengths (~2 kPa), which closely approximate the liquid limit for slurry mixes. The boundary between the plastic state and the semi-solid state is the plastic limit with a shear strength approximately 100 times that of the liquid limit. Finally, the saturated-unsaturated boundary which is the boundary between the semi-solid state and solid state pertains to the shrinkage limit for fines contents falling in the fines matrix, whereas in the sand matrix, it denotes the minimum void ratio of the sand.

The key feature of the SBD is the understanding of the fines/fines+water ratio (FWR) lines which are lines of constant tailings behaviour in the fines matrix part of the SBD where the sand has limited effect on tailings behaviour. In the sand matrix, constant soil behaviour lines would be parallel to the sand matrix boundary because soil behaviour is governed by the sand void ratio and the fines only fill the voids in the sand matrix. Figure 5 shows that all these boundaries fall on constant FWR lines which indicates that the FWR or fines void ratio control the tailings characteristics in the fines matrix region.

4 CONSISTENCY LIMITS

4.1 Oil Sands Tailings

The consistency of slurries is defined by the Atterberg limits, liquid limit, plastic limit and shrinkage limit. The Atterberg limits are not only used for slurry soil classification, but there is also a close relationship between the limits and properties of a slurry such as compressibility, permeability and strength. It is, therefore, valuable to determine whether these consistency limits are a function of total void ratio or fines void ratio.

Liquid limit and plastic limit tests were performed on two samples of fine tailings with different amounts of sand added to change the solids content or total void ratio (Sorta et al. 2013). The fines tailings were mature fine tailings (MFT) taken from the Albian Muskeg River mine tailings pond from depths of 7.5 m (AL7.5) and 15 m (AL15). The coarse tailings were Albian beach sand: the coarse portion of extraction tailings that segregated while the tailings were discharged into a large tailings containment. The fines content (< 45 μm) of the two MFTs were 99 and 91%, respectively, and the clay size content (< 2 μm) were 57 and 38%, respectively, as determined by dispersed hydrometer tests. The beach sand contained 5% fines and no clay size. Liquid limit and plastic limit tests (ASTM D4318 2010) were performed on nine mixed samples of AL7.5+sand and seven mixed samples of AL15+sand at fines contents from 20 to 99%. Shrinkage limit values were determined by the Casagrande method (Holtz and Kovacs 1981)

Figure 6 is an SBD containing the AL7.5 Atterberg limit values. The liquid limit values fall on a FWR of about 64%, the plastic limit values fall on a FWR of about 80% and the shrinkage limit values fall on a FWR of about

85%, indicating that the Atterberg limits are functions of the FWR or fines void ratio. When the plastic limit and shrinkage limit tests crossed below the sand boundary, they tended to become parallel to the boundary as the sand void ratio controls the limits in this region. The sand boundary in this figure was not determined from a minimum density test on the beach sand, but taken from that of a typical uniform fine sand, so its position may be slightly in error.

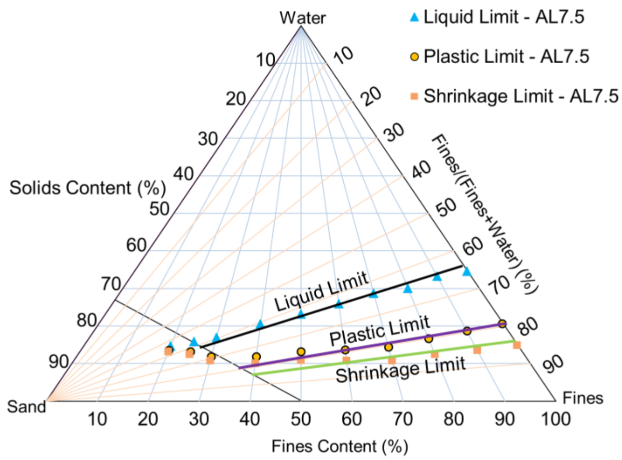

Figure 6. Atterberg limits of AL7.5

Figure 7 is a similar SBD containing the AL15 liquid, plastic and shrinkage limit values. The limit values fall on FWRs of ~68, ~79 and ~83%, respectively. For the plastic and shrinkage limits, as the sand content increased above 50% the sand had much more influence and the FWRs were higher.

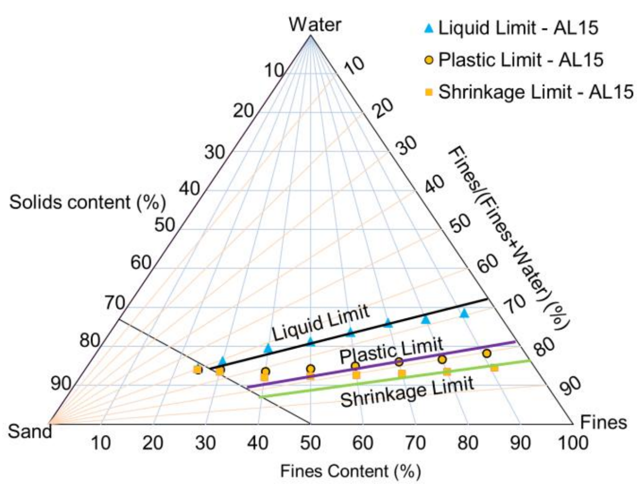

Figure 7. Atterberg limits of AL15

Figure 8 is the SBD for both samples, but using a clay/clay+water ratio (CWR) axis instead of an FWR axis. Straight lines drawn from the sand-silt apex to the right hand side then signify constant CWR lines. The liquid limit values despite the different clay size amounts tend to plot on a same CWR of about 50%. The plastic limit values tend to group around a CWR of about 68%. For consistency the sand boundary is also plotted on this figure. It should, of course, be a sand-silt boundary which would be lower, but this has not been determined.

These results confirm that these consistency limits are functions of fines void ratio or clay void ratio, not total void ratio.

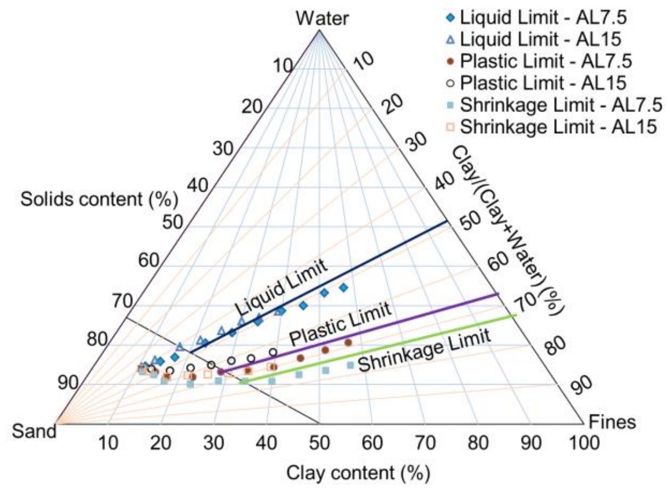

Figure 8. Atterberg limits as a function of CWR

4.2 Other Slurries

Soil mixtures of clay weathered from marl and limestone and sand from a beach on the Arabian Gulf had liquid and plastic limits determined for mixtures from 10 to 100% clay (Azam 2003). Figure 9 shows these test results on an SBD with a CWR as the right axis. The actual liquid and plastic limit measurements are shown on the SBD. The liquid limit values plot on a CWR of 40%, and the plastic limit values plot on a CWR of about 65%, indicating that these soil mixtures in the clay matrix are functions of clay void ratio not total void ratio.

The boundary between the coarse material (sand + silt) matrix and the clay matrix is also shown. As with the oil sands tailings, when the test results are below this boundary the soil mixture values tend to become parallel to the boundary which indicates that they start to become functions of the coarse material void ratio in this region.

Coussot (1992) also performed a series of liquid limit and other tests on mixtures of fines and sand. The liquid limit test results are shown on an SBD in Figure 10. The liquid limit values plot on a FWR of 40%. Although the plastic limit values are not shown, they plotted on a FWR of 66%. The boundary between the sand matrix and fines matrix was not determined, but based on the liquid limit test results, the sand appears to have a maximum void ratio at a solids content of about 66%.

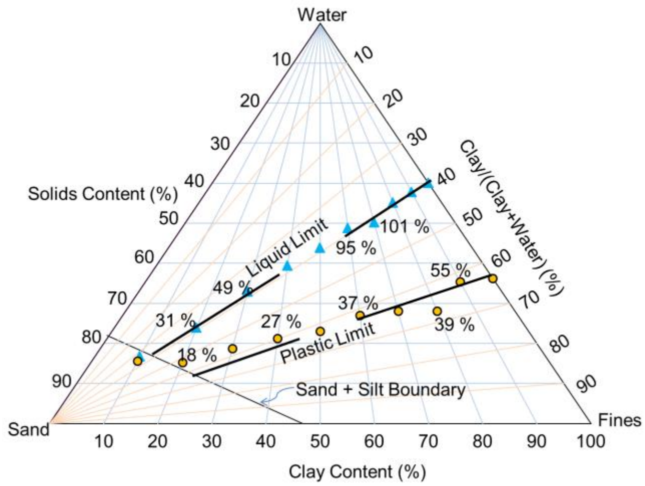

Figure 9. Atterberg limits for Middle East sand and clay mixtures (after Azam 2003)

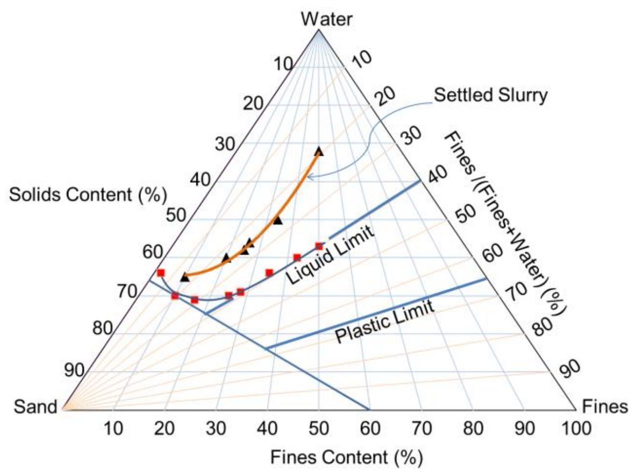

Figure 10. Yield stress limits (after Coussot 1992)

5 COMPRESSIBILITY

On the SBD, straight lines drawn from the water apex to the base describe constant sand-fines ratio lines. These lines represent slurries with constant grain size distribution or constant fines content, but varying solids content. The compressibility measurements in a large strain consolidation test fall on one of these lines. Figure 11 shows the results of 10 large strain consolidation tests on various samples of oil sands tailings ranging from MFT to paste to composite tailings. The vertical effective stresses to reach the various solids contents are shown on the figure. Curves for effective stresses of 50 and 200 kPa are drawn through the test results. Although the various tailings will have different compressibilities depending on their chemical treatment, their compressibility under the same effective stress is fairly well defined by the fitted curves. Above a fines content of about 50% the curves generally follow a constant FWR line. Therefore, above a fines content of 50% the fines void ratio controls the compressibility. At fines contents below 25% the compressibility at high effective stresses appears to be a function of the sand void ratio. These results for the effective stresses of 50 and 200 kPa are only an approximation, and separate SBDs should be drawn for each separate tailings material.

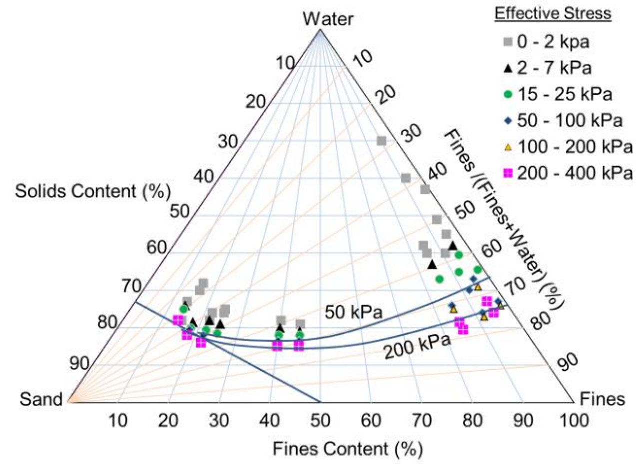

Figure 11. Compressibility of different oil sands tailings

6 HYDRAULIC CONDUCTIVITY

Figure 12 shows the constant hydraulic conductivity test results (Sorta et al. 2013). In the fines matrix these constant values fall on FWR lines, which shows the fines void ratio controls the hydraulic conductivity and the sand in the tailings has little effect.

7 UNDRAINED SHEAR STRENGTH

Measured undrained shear strengths at the liquid limits for tailings AL7.5 are shown in Figure 13 (Sorta et al. 2012). The undrained shear strengths are around 2 kPa as determined by many authors. As for other properties, the undrained shear strengths at low solids contents in the fines matrix are a function of fines void ratio and the sand in the tailings has little effect.

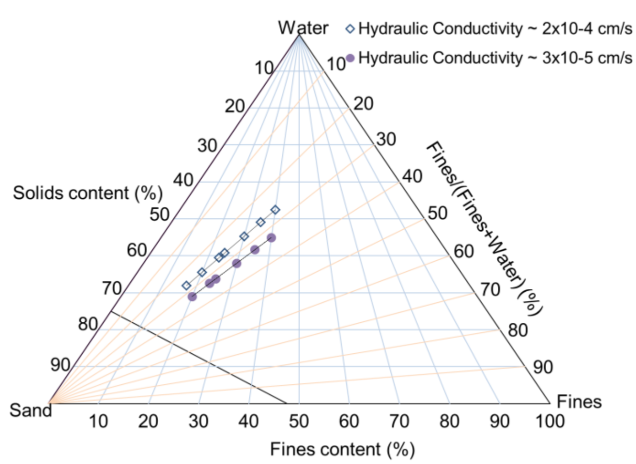

Figure 12. Hydraulic conductivity (after Sorta et al. 2013)

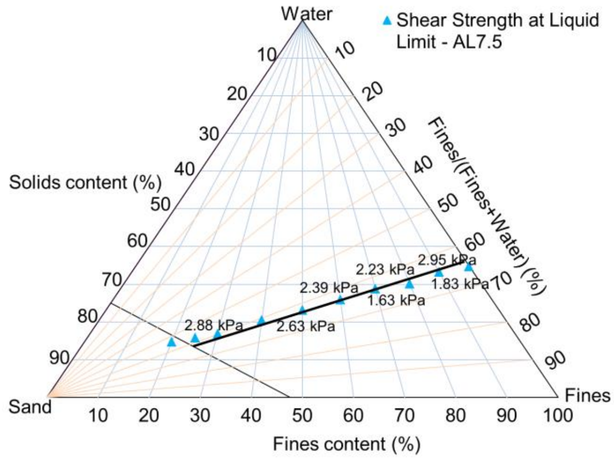

Figure 13. Shear strength at liquid limit (after Sorta et al. 2012)

Figure 14 shows undrained shear strengths during consolidation for six samples of oil sands tailings ranging from desanded paste to non-desanded paste to composite tailings. The increase in undrained shear strength with an increase in solids content is shown with a best fit curve drawn through an undrained shear strength of 20 kPa. At fines contents above 50%, the 20 kPa strength falls on a FWR of about 72% which is about halfway between the liquid limit and the plastic limit. Below a fines content of 50%, the sand has an increasing influence on the undrained shear strength and below a fines content of 25% at high solids contents the strength appears to be a function of the sand void ratio.

These two sets of data indicate that for slurries at and above the liquid limit, the undrained shear strength throughout the fines matrix region is a function of the fines void ratio. As slurries approach the plastic limit the sand begins to have an influence on the undrained shear strength; this influence increases as the sand content increases.

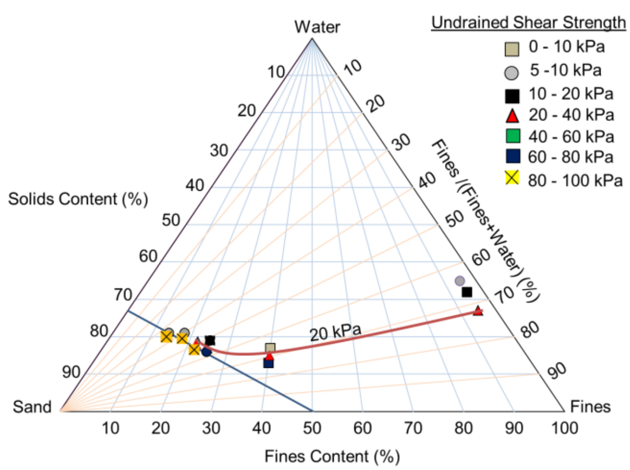

Figure 14. Undrained shear strength of different oil sands tailings

8 CONCLUSION

The key feature of the SBD is the understanding of the FWR lines, which are lines of constant tailings behaviour in the fines matrix part of the SBD where the sand has limited effect on tailings behaviour. The oil sands tailings characteristics boundaries shown in Figure 5 fall on constant FWR lines, indicating that the FWR or fines void ratio control the tailings characteristics in the fines matrix region.

In the sand matrix, constant soil behaviour lines would be parallel to the sand matrix boundary because soil behaviour is governed by the sand void ratio and the fines only fill the voids in the sand matrix.

For oil sands tailings, the liquid limits, plastic limits and shrinkage limits all fall on FWR lines, indicating that the Atterberg limits are functions of the FWR or fines void ratio. When the plastic limit and shrinkage limit tests cross below the sand boundary, they tend to become parallel to the boundary as the sand void ratio controls the limits in this region.

Above a fines content of about 50%, the compressibility curves generally follow a constant FWR line. Therefore, above a fines content of 50%, the fines void ratio controls the compressibility. At fines contents below 25%, the compressibility at high effective stresses appears to be a function of the sand void ratio.

In the fines matrix at low solids contents, the hydraulic conductivity values fall on FWR lines, which show that the fines void ratio controls the hydraulic conductivity in this region and the sand in the tailings has little effect.

For slurries at and above the liquid limit, the undrained shear strength throughout the fines matrix region is a function of the fines void ratio. As slurries approach the plastic limit for fines contents less than 50%, the sand begins to have an influence on the undrained shear strength; this influence increases as the sand content increases.

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