Segregation Related to Centrifuge Modelling of Oil Sands Tailings

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ABSTRACT
Settling column and centrifuge tests are conducted on oil sands tailings composed of fines-coarse fraction at various sand-fines ratio and different maximum size of sand. Based on the tests results, segregation boundaries on ternary diagram are established. The effects of applying centrifugal acceleration that is many times earth gravitational acceleration on segregation boundaries are investigated. The undrained shear strength of fines-sand mixture at various sand-fines ratio is established. Applicability of formulas that relate acceleration level, shear strength and unit weights to maximum particle size of sand that remain in the slurry is evaluated.

RÉSUMÉ
Les essais de colonnes de décantation et d'essais en centrifugeuse ont été effectués sur les résidus de sables bitumineux composés de fractions fines à grossières comprenant différents pourcentages de sable fins et grossiers. Les résultats obtenus ont permis d'établir la ségrégation des limites sur les diagrammes ternaires. Les effets de l'application de l'accélération centrifuge, souvent considérée comme l'accélération gravitationnelle, sur la ségrégation des limites ont été étudiés. Le non drainage du mélange de sable fins contenant différents pourcentage de fines et la résistance au cisaillement ont été établis. L'applicabilité des formules qui lient la vitesse d'accélération, la force de cisaillement et l'unité de poids à la taille maximale des particules de sable contenues dans la boue a été évaluée.

1 INTRODUCTIONS

The sedimentation and self-weight consolidation of matured fine tailings (MFT) is slow process that may take over a decade. Devising any reclamation scheme or understanding the sedimentation and self-weight consolidation behavior of MFT involves laboratory experimental studies. Large and small scale stand pipe tests have been used as common methods for studying the sedimentation and self-weight consolidation behavior of MFT or fines-sand mixtures (Caughill et al., 1993; Jeeravipoolvarn et al., 2009; Scott et al., 1986; Suthaker et al., 1997). The consolidation parameters (void ratio-effective stress and void ratio- permeability relation) are usually determined from large strain consolidation tests combined with settling column tests (Jeeravipoolvarn etal., 2008b; Pollock, 1988; Scott et al., 2008). These testing methods are well documented and useful in quantifying the consolidation parameters and in understanding sedimentation and self-weight consolidation behavior of slurry. However, the methods may require many months or years to complete. The settling column tests also fail to represent the field (protype) stress conditions.

Alternatively, centrifuge has been used during the past decades to study sedimentation/self-weight consolidation behavior and to measure consolidation parameters of slurries and soft soils. Unfortunately, centrifuge has not been widely utilized for studying the sedimentation /self-weight consolidation behavior and for examining different reclamation schemes or for measuring consolidation parameters of oil sands tailings. Probably one of the reasons centrifuge modelling is not widely used in oil sands tailings industry is the concern of segregation related to centrifuge testing. MFT is a high water content material that is composed of fine and coarse particles plus residual bitumen. Subjecting this material to a centrifugal acceleration that is many times earth gravity acceleration level without increasing the carrying capacity of the clays may prompt and enhance segregation. The purpose of the study presented in this paper is to examine segregation related to centrifuge tests in MFT and fines-sand mixtures by defining segregation boundary using ternary diagram based on centrifuge and settling column tests. This diagram was developed by Scott and Cymerman (1984). The applicability of Weiss (1967) and Cardwell (1941) formulas which predicts maximum grain size that remain in suspension for oil sands tailings will also be examined.

2 CENTRIFUGE MODELLING

2.1 Modelling Principle

Centrifuge modelling is based on stress similarity between field (protype) and laboratory model. In centrifuge test, model of size (1/N) of protype is used. Protype stress is achieved by increasing the acceleration in the centrifuge by N time's earth gravitational acceleration thereby achieving stress similarity between protype and model is maintained (Eq. [1]).

$$\sigma_m = h_m * a_m * \gamma = \frac{hp}{N} * (N * g) * \gamma = \sigma_p \qquad [1]$$

Where h_m is model height, a_m is acceleration in the model, hp is protype height, N is linear scale (h_p/h_m or relative acceleration ($r\omega^2/g$)), g is earth gravitational acceleration and γ is unit weight of the material

In modelling sedimentation/self-weight consolidation of slurries/soils a beam type centrifuge is commonly used. In beam centrifuge, sedimentation and self-weight consolidation is simulated by placing one dimensional sedimentation/consolidation model at the end of centrifuge arm and then rotating the sample in a horizontal plane at acceleration level of N times earth gravitational acceleration (N*g).

Due to the short drainage path in the model, sedimentation/self-weight consolidation phenomena that may take many years under field conditions can be simulated within a few hours using the centrifuge. Significant reduction in testing time and capability to reproduce field stress condition makes the centrifuge a powerful and attractive method for modelling sedimentation and self-weight consolidation.

2.2 Centrifuge modelling of slurries and soft soils

Quite a number of centrifuge tests have been conducted on slurries material in a past. The objectives of the tests were: studying sedimentation/self-weight consolidation behavior, evaluating different reclamation schemes, verifying theories and evaluating consolidation parameters. For example, Beriswill et al., (1987); Townsend and Bloomquist, (1984); and Selfridge et al., (1986) used centrifuge to model sedimentation and self-weight consolidation of slurries. Centrifuge has been used by Mikasa and Takada, (1984); Scully et al., (1984); Croce et al. (1985) and Eckert et al., (1996) to validate large strain consolidation numerical model. Towensend et al., (1986, 1989) and Theriault et al., (1995) uses centrifuge for evaluation of different disposal options. Centrifuge was also used to measure consolidation parameters (Mcvay, et al., 1987 and Takada and Mikasa 1986).

2.3 Centrifuge modelling and Segregation

The problem of segregation related to centrifuge modelling has been acknowledged in centrifuge tests (for example, Mikasa and Takada 1984; Takada and Mikasa, 1986 and Towensend et al., 1986).

Mikasa and Takada (1984) recognized segregation related to centrifuge modelling and used a "*soft soil*" with an initial consistency that did not allow any particle segregation. The selected initial water content was based on their experience but without clearly established pre-test criteria. However, they used post test criteria to verify segregation did not occur in their tests by examining the shape of void ratio effective stress curve at the end of self-weight consolidation. Takada and Mikasa, (1986), in their centrifuge test, used a sample with an initial water content that was twice or less than twice the liquid limit of the clay to prevent particle segregation under high centrifugal forces. The selection criterion was based on past experiences on similar slurries. Townsend et al., (1986) studied the problem of segregation related to centrifuge modelling and recommended a further study as it hampers the applicability of centrifugal modelling for sand/clay suspensions.

Review of past centrifuge tests reveals that most researchers (such as Croce et al. (1985), Mcvay, et al., (1987) and Townsend et al., (1989)) recognize segregation related to centrifuge tests and then try to prevent the potential for segregation in their model tests by using a low water content sample, low centrifugal acceleration or stage loading procedures. There seems no well established guideline in selecting samples that do not segregate during the centrifuge tests. The purpose of this study and paper is to establish pre-test guidelines for selecting a non-segregating material for centrifuge tests.

3 MATERIALS AND EXPERIMENTS

3.1 Materials Descriptions

The materials used for this study are: Albian MFT from 7.5m depth (Albian_7.5), Albian MFT from 15m depth (Albian _15), Albian thickener underflow tailings (Albian_TUT), Syncrude MFT (Syncrude) and Syncrude cyclone overflow tailings (Syncrude_COT). The characteristics of these tailings are summarized in Table 1. Albian MFTs were used to define a segregation boundary by preparing fines-sand mixture at various solids and fines content whereas Syncrude MFT, Syncrude_COT and Albian_TUT were used to define segregation boundary solids content for an existing sand percentage in the samples.

Albian beach sands were used in preparing fine-sand mixture. The effect of sand grain size on segregation boundary were investigated by preparing beach sands of particles passing sieve No. 10 (2mm), No. 40 (0.425 mm) and No.60 (0.25 mm).

Table 1. Characteristics of materials

	Characteristics					
	Fines	Bitumen	LL[1]	PL[2]	Clay	CFR[3]
Samples	[%]	[%]	[%]	[%]	[%]	[%]
Albian_7.5	99	1.0	53	26	57	58
Albian_15	91	7.0	40	22	38	42
Albian_TUT	70	3.5	35	17	36	51
Syncrude	98	4.5	53	26	56	57
Syncrude_COT	92	2.5	42	19	46	50

[1] liquid limit, [2] plastic limit, [3]Clay-fines ratio

The fines content are the mass of solids passing sieve No 325 (0.045mm) divided the mass of solids and the bitumen content is mass of bitumen to mass of solids.

3.2 Settling Column Tests

Settling column tests were conducted on tailings composed of fines-sand mixture for a purpose of defining segregation boundary on the ternary diagram. In theses test series, fine-sand mixture at various solids and fine content were prepared and filled in settling column of 1L capacity. After letting sedimentation and consolidation to take place for one month, the samples solid content profiles were determined by measuring the water content profile. Segregation index was then calculated from the solids content profile using Equation 2. For a particular solid content, segregation index versus fines content were plotted and the segregation boundary point was taken as the fines content corresponding to 5% segregation index.

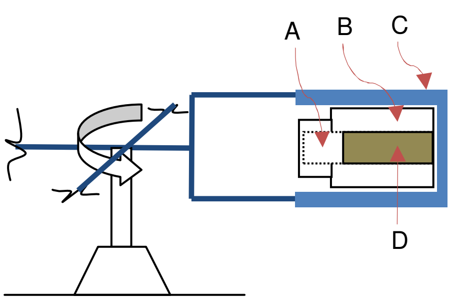
$$SI = \frac{\sum \left|(s_i - s_{ave}) * (H_i - H_{i+1})\right|}{s_{ave}} x100 \qquad [2]$$

Where SI is segregation index, s_i solid contents at slice i, s_{ave} is the average solid content over the total height of the sample after one month and $H_i - H_{i+1}$ is the normalized height of slice i.

3.3 Centrifuge Test

3.1.1 Description of Centrifuge

The centrifuge used for this study is a bench top centrifuge. It has four arms that can be used to spin four samples at a time. Each arm has a round metal bucket that accommodates 750 ml centrifuge bottles. For centrifuge tests, samples were prepared in 6.3 cm diameter and 10 cm height plastic cylinders and placed inside the 750 ml centrifuge bottle. The centrifuge bottle containing the samples is then placed in the centrifuge bucket and spun to the desired acceleration level and time. Figure 1 shows a schematic test setup on one arm of the centrifuge.



A= plastic cylinder, B= 750 ml centrifuge bottle, C=Metal bucket, D= specimen

Figure 2. Centrifuge test set up

3.1.2 Centrifuge Tests

Centrifuge tests, like settling column tests, were carried out by preparing fines-sand mixture at various solids and fines content. After mixing the fines-sand mixture to the desired solid and fine content, the samples were poured into plastic cylinders of 6.3 cm diameter. The height of the samples varies from 3.3cm to 8.3 cm, depending on the centrifugal acceleration level used in centrifuge tests.

Before running the centrifuge tests, the samples were left to stand for one night. After one day of waiting time, the samples were spun to the desired acceleration for a period of 14 to 62 minutes. After the end of centrifuge tests, the samples in the plastic cylinder were subsampled into five to seven layers and the solid and fine content of each layer were determined. The segregation index was computed from the solid content profile using Equation 2. The segregation boundary for particular solids content was determined from a plot of fines content versus segregation index for a segregation index corresponding to 5% (fines capture index of 95%).

In centrifuge tests, the heights of sample were selected on the basis that each model tests represents 5 m of pond in the field (Eq. [3]). The spinning time in centrifuge for each model is equivalent to 30 days in protype time. Centrifuge spinning times were calculated using Equation 4. During centrifuge model test a centrifugal acceleration level of 60 to 150 time earth gravitational acceleration were used. In computing the centrifugal acceleration ($a=r\omega^2$), the radius was taken from the center of rotation to mid height of the sample

$$h_m = \frac{h_p}{N} \qquad [3]$$

$$t_m = \frac{t_p}{N^x} \qquad [4]$$

Where t_m is model time (spinning time in centrifuge), tp is prototype time, 30 days, N is the ratio of centrifugal acceleration to earth, g is earth gravity acceleration, and x is a time exponent (1.6 to 2).

3.4 Shear Tests

The undrained shear strength of the fine-sand mixes was measured using the vane shear testing apparatus. The apparatus had a measuring capacity of 0.5 - 1000 Pa. The tests were carried out according the ASTM standard for laboratory vane shear tests (ASTM D4648 – 05). Samples for shear tests were prepared together with the centrifuge test samples. Undrained shear strength were determined after 1, 2, 4 and 24 hour then at various days. The one day undrained shear strength was used to correlate shear strength with fines void ratio and to evaluate the applicability of formulas that relate shear strength with the slurry maximum grain carrying capacity.

4 RESULTS AND DISCUSSIONS

4.1 Settling Column Tests Results

The results of settling tests are summarized by plotting segregation boundary on ternary diagram (Figure 2). The boundaries for Albian MFTs are established at vary solids and fines content. For the other tailings used in the study, boundaries are established only for existing sand contents in the test samples.

As shown in Figure 2, segregation boundaries vary with the tailings compositions and source though Azam and Scott (2005) suggested near 28% of fines-water ratio (fines/ (fines + water)) for all oil sand tailings. The segregation boundary of Albian MFT at 7.5 m depth lies above the boundary of Albian MFT at 15 m. The difference in the segregation boundary may be associated with the percentage of clays in the fines. Albian MFT at 7.5 m depth has a clay-fines ratio of 58% but Albian MFT at 15 m depth has a clay-fines ratio of 42% (Table 1). Segregation boundary points of Syncrude, Syncrude_COT and Albian_TUT are close to the segregation boundary of Albian MFT at 7.5 m as the percentage of clays-fines ratio is closer to Albian MFT at 7.5 than Albian MFT at 15 m depth. In addition to the significant clay-fines ratio (CFR) difference, other possible reasons for the variation of the boundary between Albian tailings are variation in bitumen content, fines mineralogy, and extraction methods.

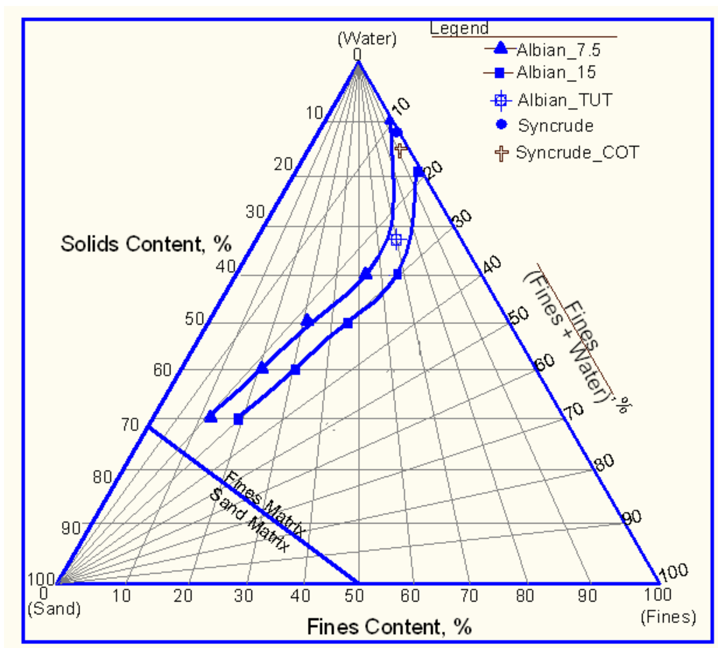


Figure 2. Segregation boundaries from settling column tests

4.2 Centrifuge Tests Results

Segregation boundaries from centrifuge tests are shown in Figure 3. Similar to settling column tests, the boundaries for Albian MFT are established at varies solids and fines content; but for the other tailings only at existing sand contents of the as received fine tailings. The boundaries shown in Figure 3 for Albian MFT at 7.5 m depth (Albian_7.5) are at an acceleration of 60, 80, 100 and 150 times the earth gravitational acceleration. Segregation boundaries of Albian MFT at 15m depth (Albian_15) are at 60 and 100 times the earth gravitational acceleration. Segregation boundaries shown in Figure 3 for Albian_7.5 and Albain_15 are based on addition of beach sand finer than the No 10 sieve (2mm).

The segregation boundaries determined from centrifuge tests are a function of tailings composition, source and acceleration levels. The difference in the segregation boundary between tailings is exhibited more in centrifuge tests than in settling column tests. Difference in segregation boundary for different tailings (for the same acceleration level) may be due to variation in water chemistry, fines mineralogy, composition and oil extraction methods. Like settling column tests, segregation boundaries of tailings with high clay-fines ratio lies above the boundary of tailings having low clay-fines ratio.

As shown in Figure 2 and 3, the segregation boundaries from settling and centrifuge tests are different. This variation is due to the application of high centrifugal acceleration in centrifuge tests without first increasing the carrying capacity of clay fractions. In centrifuge model tests, as the centrifugal acceleration is applied, the weight of individual grains increases proportional to the applied acceleration level but the fines carrying capacity remains unchanged. Fines-sand mixture that is non-segregating in settling column test (under earth's gravity level) becomes segregating mixtures under these higher acceleration levels in the centrifuge. The area bounded by centrifuge and settling column segregation boundary shown on the ternary diagrams refers to tailings compositions that become segregated materials as a result of applying high centrifugal force via the centrifuge.

Effects of maximum sand size on the centrifuge segregation boundary were investigated by using Albian MFT from 15 m depth. The effects of maximum size of sand on segregation boundary are shown in Figure 4. Figure 4 show that, fines-sand mixture with a maximum particle size of 2 mm requires more fines to carry the sand particles than fines-sand mixture with maximum particle of sand size of 0.25 mm. At relatively low solids content, the segregation boundary is governed by the maximum particle size of sands in fines-sand mixture. But at lower fines and high solids content, it appears that grain size distribution of sand has more effect than the maximum grain size of the sand. The grain size distribution of beach sand passing the 0.25 mm is poorly graded as compared to sands passing sieve No 10 (2 mm) (Figure 5).

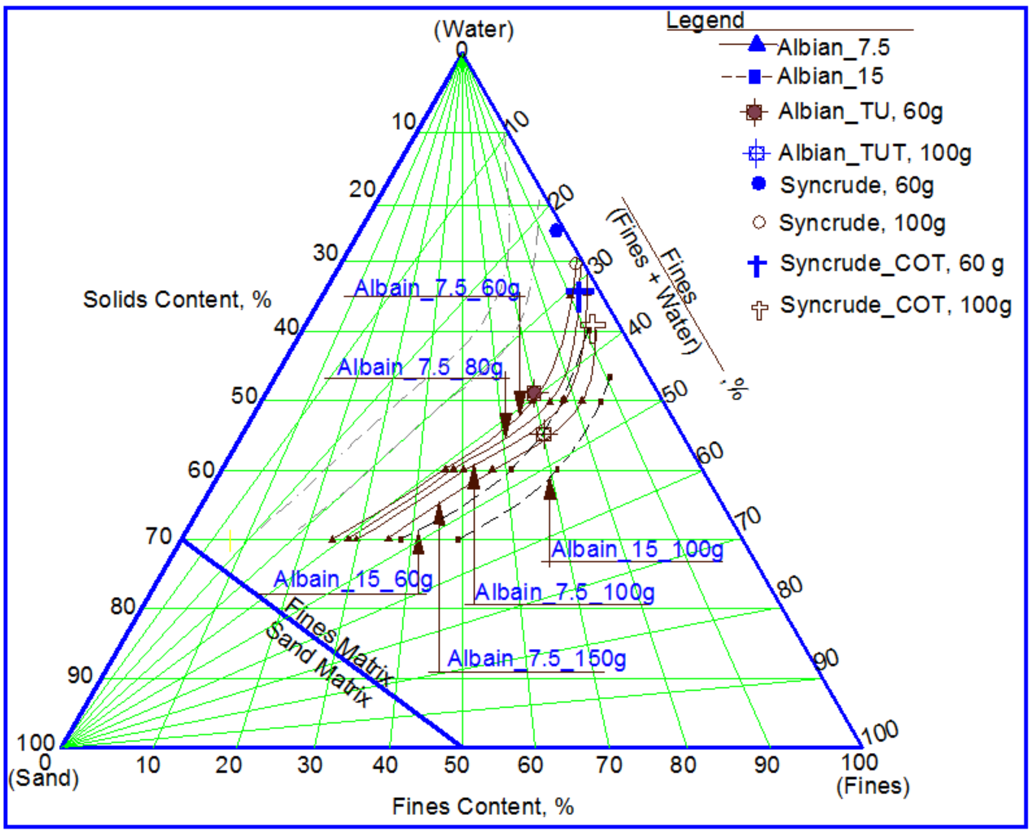


Figure 3. Segregation boundary from centrifuge tests

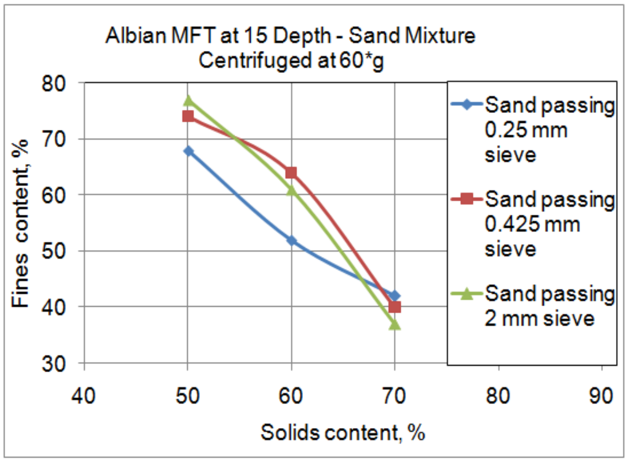


Figure 4. Effect of maximum grain size of sand on segregation boundary

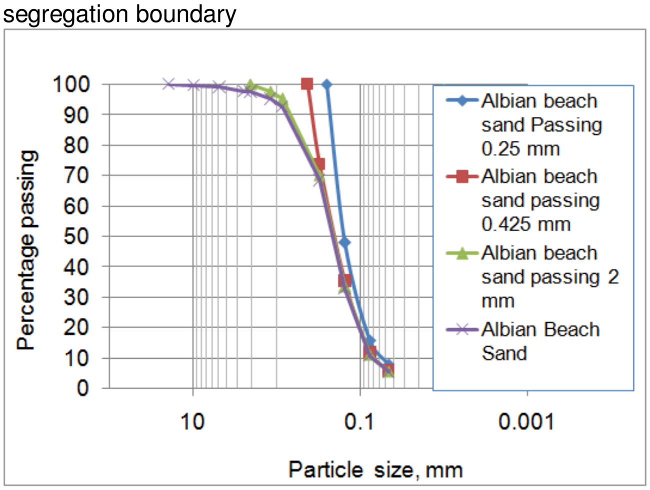


Figure 5, Grain size distribution of beach sand

4.3 Shear Tests Results

The tests results of undrained shear strength of samples that were prepared with the centrifuge test samples are summarized in Figure 6. The shear strengths shown in Figure 6 are the undrained shear strength after one day following sample preparation. The strength of fines-sand mixture are plotted as a function of fines void ratio and the relation is best described using a power relation between shear strength and fines void ratio (or linear relation in log strength versus log fines ratio plot) (Figure 6). The fines voids ratio is used instead of void ratio or solid contents because the strength of fines-sand mixture varies with the percentage of fines contained in a sample at the same solids content (void ratio).The fines void ratio is computed from solids and fines content using Equation 5. The variation between shear strength of different tailings (for the same fines void ratio) may be associated with the variation in the percentage of clays relatives to fines and bitumen content.

$$e_f = \frac{e * G_f}{f * G_s} \quad [5]$$

Where e_f is fines void ratio, e is void ratio, G_f specific gravity of fines; f is percentage of fines, and G_s specific gravity of solids.

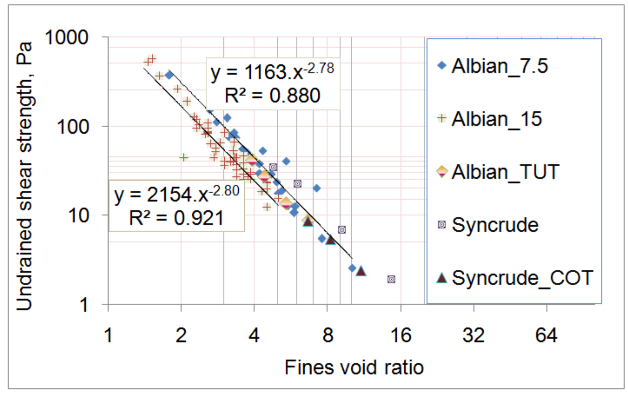


Figure 6. Shear strength of fine tailings and fines-sand mixtures.

A typical plot of undrained shear strength of fines-sand mixtures as a function of time is shown in Figure 7. The results are the undrained shear strength measured after, 1hr, 1 day, 4 days and 6 days following sample preparation. As it shown in the Figure 7, most of the change in shear strength occurred after one day of sample preparation. This change in shear strength, without change in water content, is due to the development of bonds between the particles. The change in shear strength in one day relative to the one hour shear strength varies from 20 to 140% with a general trend of increasing with fines void ratio (Figure 8). The carrying capacity of the fines fraction is a function of the shear strength. As there is significant strength changes in one day, letting samples rest for at least one day before a centrifuge tests reduces the potential of segregation in centrifuge tests.

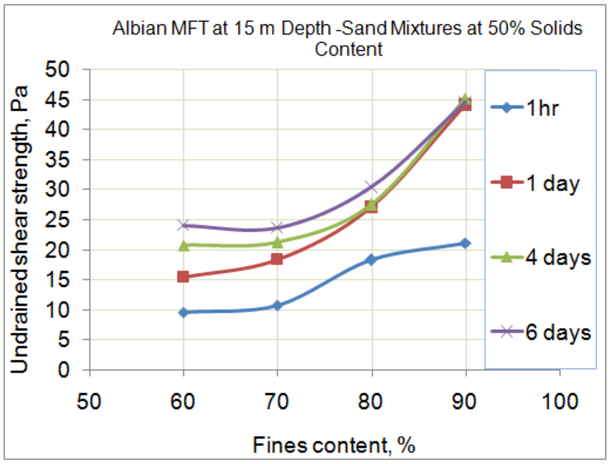


Figure 7. Shear strength development in fines-sand mixtures as function of time

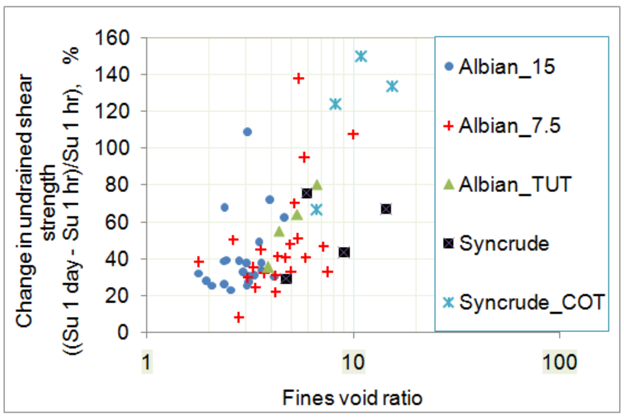


Figure 7. Change in shear strength in one day relative to shear strength after 1hr sample preparation

The effect of applying centrifugal acceleration on segregation boundaries can be seen from ternary diagrams of Figure 2 and Figure 3.The ternary diagram is a convenient tool for defining the segregation boundary. It is used to identify at what solids and fines content fines-sand mixture will behave as a segregating or non-segregating materials. Another approach in the literature that corresponds with defining the segregation boundary is determining the maximum size of sand that remains in suspension. In this approach the formulas by Wisse (1967) and Cardwell (1941) are most applicable. The Cardwell (1941) and Weiss (1967) formula that estimates maximum particles diameter of sand that remain in suspension (slurry) is given by Equation 6.

$$D = \frac{m * C_s}{(\rho - \rho_s) * g}$$

[6]

Where Cs is shear strength of slurry, ρ is the density of particles, ρ_s is the density of slurry, g earth gravitational acceleration, m is constant, 6 for Cardwell and 1.5 for Weiss.

In evaluation of segregation using the above formulas the measured undrained shear strength after one day of sample preparation and acceleration levels in the centrifuge and settling column tests used to compute the maximum diameters of particles that remains in suspensions. As there is a linear relation between strength and fines void ratio, the fines void ratio (or fines-water ratio) can be related to maximum size of sand. Fines-water ratios (FWR) can be computed from fines void ratio using Equation 7.

$$FWR = \frac{e_f}{e_f + G_f}$$

[7]

Where e_f is fines void ratio and G_f specific gravity of fines.

Fines-water ratio (fines/(fines + water)) that supports 2 mm of sand based on data from settling column tests and centrifuge tests using the formulas of Cardwell (1941) and Weiss (1967) are summarized in Table 2. The fines-water ratios corresponding to segregation boundary from settling and centrifuge test results are also listed in Table 2.

Table 2. Fines-water ratio for supporting 2 mm sand in a suspension

Methods	Fines-water ratio (FWR),%					
	Albain_7.5			Albain_15		
	1*g	60*g	100*g	1*g	60*g	100*g
Settling Col.	24	-	-	30	-	-
Centrifuge	-	41	45	-	45	50
Cardwell	23	55	63	32	60	64
Weiss	32	66	68	45	70	75

For Albian MFT at 7.5 m depth (Albian_7.5), Cardwell (1941) formula estimated that at 23% fines-water ratio, the slurry can support 2 mm sand under earth gravitational acceleration (Table 2). This is in close agreement with settling columns test result in which the FWR (fines/(fines + water) parallel to segregation boundary of 24% (Figure 2). According to Cardwell formula, for supporting 2 mm diameter of sand, a FWR of 55% at 60*g and 63% at 100*g are required. But, as shown in centrifuge segregation boundary (Figure 3, for Albian MFT at 7.5 m depth), the slurries can support 2 mm sand at FWR of less than 45%.

For Albian MFT at 15 m depth Cardwell (1941) formula estimates that a FWR of 32% is needed for carrying 2 mm sand at earth gravitational acceleration level. This is a close to the settling column test results for FWR of 30% segregation boundary. At high acceleration levels, FWR of 60% and 64% are required to support sand of 2 mm particle size at 60*g and 100*g respectively. As shown in Figure 3, FWR of less than 53% can support 2 mm sand at 100*g. Hence the formula of Cardwell (1941) provides a good in estimate of the maximum particles of sand that remain in suspension under earth gravitational acceleration field but it is conservative in estimating maximum size of sand that remains in suspension during centrifuge tests. Weiss (1967) formula is conservative for both earth gravitational and elevated acceleration fields.

5 CONCLUSIONS

Based on the measured test results from the settling column, centrifuge and shear tests the following conclusion can be made.

- Segregation boundaries from settling and centrifuge tests depend on tailings source compositions and other chemical and physical process. The boundaries are not the same for different oil sand tailings.
- Application of centrifugal acceleration many times earth gravitational acceleration without increasing the carrying capacity of fines affects the segregation boundary of fines-sand mixture. Hence centrifuge boundaries from settling and centrifuge tests are not the same.
- The area bounded by static (settling column test) and centrifuge segregation boundary on the ternary diagram refers to composition of tailing that can be affected by centrifuge testing.
- The significant shift of segregation boundary of centrifuge tests from settling column test limits the compositions of materials that can be used for centrifuge tests and the ranges of consolidation parameters that can be derived from centrifuge tests.
- Shear strength of fines-sand mixture is better related to fines void ratio than void ratio or solids contents.
- Letting fines-sand mixture to rest for one day before centrifuge tests reduces the potential of segregation in centrifuge modelling.
- The equations of Cardwell (1941) and Weiss (1967) that predicts maximum particle size that remain in slurry are both conservative under high acceleration level.

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