SENSITIVITY OF SHRINKAGE CHARACTERISTICS OF SURFACE DEPOSITED PASTE TAILINGS TO PLACEMENT WATER CONTENT

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ABSTRACT

Paste tailings, whose particle size typically ranges from that of silty sand to sandy silt, are mine tailings that have been sufficiently dewatered to allow plug flow transport through a pipeline, minimizing segregation and bleed water upon deposition on surface. After surface deposition, evaporation may substantially dewater the paste. Therefore, understanding the shrinkage characteristics of the paste is needed to determine the final "desiccated state", namely the paste’s density, degree of saturation, void ratio, and shear strength, which are important to the overall stability of the deposited stack.

The degree of saturation of the paste immediately after placement is usually less than 1. Previous research on the shrinkage characteristics of compacted silt indicates that the shrinkage curve moves farther away from the saturation line as the initial water content or degree of saturation of the soil decreases, suggesting that the final void ratio is affected by the initial conditions of the soil sample. To better understand the affect of varying water content (initial void ratio) on the final density of paste tailings, shrinkage tests adapted from ASTM 4943-02 were performed on four different mine tailing types of varying mineralogy. Results of the shrinkage tests from all samples indicate that a higher initial void ratio produces a higher final void ratio upon complete drying of the paste. This is counter to the traditional notion of the Shrinkage Limit, as determined by ASTM 4943-02 (Determining the Shrinkage Factors of Soils by the Wax Method), for which the Shrinkage Limit is considered to be an index property of the material. This paper presents a preliminary analysis of the factors contributing to the variation in final void ratio from the shrinkage limit and The significance of these results is discussed in terms of the stability of a tailings stack.

RÉSUMÉ

Collez les produits de queue, dont la dimension particulaire s'étend typiquement de celle du sable silty à la vase arénacée, sont des produits de queue de mine qui ont été suffisamment asséchés pour permettre le transport d'écoulement de prise par une canalisation, ségrégation réduisante au minimum et saignent l'eau lors du dépôt sur la surface. Après le dépôt extérieur, l'évaporation peut sensiblement assécher la pâte. Par conséquent, l'arrangement des caractéristiques de rétrécissement de la pâte est nécessaire pour déterminer l'"état desséché" final, à savoir la densité de la pâte, le degré de saturation, le rapport vide, et la résistance au cisaillement, qui sont importantes pour la stabilité globale de la pile déposée.

Le degré de saturation de la pâte juste après le placement est habituellement moins de 1. La recherche précédente sur les caractéristiques de rétrécissement des sols compactés indique que la courbe de rétrécissement éloigne plus loin de la ligne de saturation pendant que la teneur en eau dégrada la saturation du sol diminue, suggérant que le rapport vide final soit affecté par les conditions initiales de l’échantillon de sol. Pour comprendre mieux l’affection de la teneur en eau variable (rapport vide initial) sur la densité finale des produits de queue de pâte, des essais de rétrécissement adaptés d'ASTM 4943-02 ont été réalisés sur quatre types différents d'équéutage de mine de minéralogie variable. Les résultats des essais de rétrécissement de tous les échantillons indiquent qu’un rapport vide initial plus élevé produit un rapport vide final plus élevé sur le séchage complet de la pâte. C'est à l'opposé de la notion traditionnelle de la limite de rétrécissement, comme déterminé par ASTM 4943-02 (déterminant les facteurs de rétrécissement des sols par la méthode de cire), pour lequel la limite de rétrécissement est considérée comme une propriété d'index du matériel. Cet article présente une analyse préliminaire des facteurs contribuant à la variation du rapport vide final de la limite de rétrécissement et la signification de ces résultats est discutée en termes de stabilité d'une pile de produits de queue.

1. INTRODUCTION

Paste or thickened tailings, whose particle size typically ranges from that of silty sand to sandy silt, are mine tailings that have been sufficiently dewatered to allow plug flow transport through a pipeline, minimizing segregation and bleed water upon deposition on surface (Cadden et al., 2000). The rate of desiccation through evaporation, leads to densification and strength gain of each newly deposited layer of paste, playing an important role in the management of tailings impoundment (Simms et al., 2006). In particular, understanding the shrinkage characteristics of the material is needed to estimate the final void ratio, degree of saturation, and shear strength, all important parameters with regards to the overall stability of the deposited stack.
The degree of saturation of the paste immediately after placement is usually less than 1. The amount of desaturation that occurs during evaporation directly affects the acid generating potential of the paste stack (Simms & Grabinsky, 2006). Typically, a degree of saturation of 85% or greater is desired in order to limit oxidation of acid generating tailings (Aubertin et al, 2004). However, strength and stability of the stack is dependent on achieving sufficient densification through drying. Desiccation may lead to crack development which facilitates oxygen ingress and increases acid generation. Hence, an optimal balance needs to be stricken between the two main objectives (Simms and Grabinsky, 2004).

Previous research on the shrinkage characteristics of compacted silt, as shown in Figure 1, indicates that the shrinkage curve moves farther away from the saturation line as the initial water content or degree of saturation of the soil decreases, suggesting that the final void ratio is affected by the initial conditions of the soil sample (Fredlund & Rahardjo, 1993). Drying tests on paste tailings have shown a similar behaviour, with the final void ratio achieved showing a dependency on the initial water content.

To better understand the affect of varying water content (initial void ratio) on the final density, a series of large and small scale drying tests were performed in the laboratory on three types of mine tailings (Gold, Silicate 1, and Silicate 2), with varying mineralogies. Modified shrinkage tests based on ASTM 4943-02 (Shrinkage Factors of Soils by the Wax Method) were also performed on the aforementioned tailings as well as on copper tailings, that contain some degree of plasticity, used for comparison purposes.

The aim of the large and small scale drying tests was to characterize the rate of evaporation, to note shrinkage and crack development, and to determine the final “desiccated state” in terms of density, void ratio, and degree of saturation. The aim of the shrinkage testing was to determine whether or not the guidelines listed in the ASTM standards produce an accurate representation of the shrinkage of limit of a material when dealing with non-plastic mine tailings.

The results presented will focus primarily on the volume change of each sample over time, correlating the data with the evaporation, matric suction, void ratio, degree of saturation, and the onset of crack development, in order to pinpoint any differences that varying initial water content mixes may produce.

2. MATERIALS TESTED

The experiments were performed on four types of tailings: gold tailings, two separate forms of non-plastic silicate based tailings, and copper tailings. The tailings properties are presented in Table 1.

Table 1: Tailings Properties

<table>
<thead>
<tr>
<th>Tailings Type</th>
<th>Gold*</th>
<th>Silicate 1</th>
<th>Silicate 2</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity, Gs</td>
<td>2.98</td>
<td>2.76</td>
<td>2.76</td>
<td>3.14</td>
</tr>
<tr>
<td>D90, D50, D10 (microns)</td>
<td>150, 25,</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A, 7, 3</td>
</tr>
<tr>
<td>PL, LL, SL (%)</td>
<td>20, 23, 20</td>
<td>18, 19.5, 18</td>
<td>17, 18.5, 17</td>
<td>20, 31, 20</td>
</tr>
<tr>
<td>Pumping water content (gravimetric)</td>
<td>38%</td>
<td>55%</td>
<td>55%</td>
<td>35%</td>
</tr>
<tr>
<td>Mineralogy</td>
<td>Silicates (80%), Pyrite (6%), Calcite (5%), Ankerite (4%)</td>
<td>Quartz (49%), Microcline (28%), Plagioclase (11%), Chlorite (5%), Mica (5%)</td>
<td>Quartz (58%), Microcline (14%), Plagioclase (12%), Chlorite (8%), Mica (6%)</td>
<td>Pyrite (40%), Kaolinite (15%), Carbonates (15%), Quartz (15%), Minor Minerals (5%)</td>
</tr>
</tbody>
</table>

*Data based on testing performed by Crowder (2004)

3. LARGE SCALE DRYING TESTS

3.1 Test Setup

The procedures and methodology used in the large scale drying test follows that presented by Simms et al. (2006).

Tailings were deposited in a 10 cm deep by 1 m by 2 m layer in a box with an initial gravimetric water content specified in Table 1 (i.e. the as-pumped water content used on site), and then dried for three weeks (Simms & Grabinsky, 2006). A schematic of the experimental set-
up is shown in Figure 2. Details with regards to
equipment setup (i.e. heat dissipation and tensiometer
suction probes, moisture probes, heat lamps, etc...) may
be found in Simms et al. (2006).

Figure 2: Schematic of large test set-up (Simms et al.,
2006)

3.2 Results

3.2.1 Gold Tailings

Two large tests were conducted by Simms and Grabinsky
(2005), one in which there was no wind, and one with
wind. A summary of the relevant data from those tests is
presented below.

Average values of the depth of the tailings and the depth
of the tailings plus bleed water are shown on Figure 3.
Two plots of void ratio are also shown, one assuming one
dimensional strain and the other accounting for lateral
strain due to cracking. Crack growth initiated
approximately at the same time as vertical settlement
ceased, at about day 9, and stopped by day 11. Crack
surface area was about 3% of total surface area. To
estimate crack volume, it was assumed that cracks
extended to the bottom of the tailings, and had constant
length and thickness with depth.

The decrease in void ratio to approximately 1.05 due to
bleeding alone is slightly higher than observed in bench-
scale tests, which is about 1.00. The final calculated void
ratio of 0.83 is slightly higher than the void ratio achieved
through drying in water retention curve (WRC) tests,
using the axis-translation technique in a Tempe cell,
performed on site (0.80). This difference is expected due
to the probable presence of macro-voids in the large-
scale test that would not influence the strain
measurements (Simms & Grabinsky, 2006).

The second large test produced similar results, with the
average thickness decreasing from 10.5 to 7.8 cm by day
6. The rate of strain was quicker due the comparatively
faster evaporation rate.

A comparison of final crack patterns for both tests is
shown in Figure 4.

Figure 3: Volume change of gold tailings during large
scale drying test (Simms et al., 2005)

Test 1        Test 2

Figure 4: Comparison of large-scale drying test densities
for Gold Tailings (Simms and Grabinsky, 2006)

3.2.2 Silicate Tailings

Final calculated void ratios for the Silicate 1 and 2 tailings
were 0.78 +/- 0.04 and 0.60 +/- 0.02, respectively (Simms
& Grabinsky, 2005). The surface of the Silicate 1
displayed a higher crack density than Silicate 2, as
observed in Figure 5.

Figure 5: Comparison of large-scale test crack densities
of Silicate tailings (Simms and Grabinsky, 2005)

In terms of suction, Silicate 2 displayed an earlier onset of
development, occurring at about the 2nd to 3rd day of
drying, compared with that of Silicate 1 which saw a rapid
rise in suction at about the 5th day.
4. SMALL SCALE DRYING TESTS

4.1 Test Setup

One small scale test for each silicate material was performed by Simms and Grabinsky (2005). The tests were conducted under the same environmental conditions as the large scale tests. Setup details for each test are outlined in Simms and Grabinsky (2005).

In addition to the small scale tests, another drying test was performed, using the Silicate 1 tailings, in which a Konica Minolta Vivid 700 3D laser scanner was used to take daily images of the drying surface so as to monitor any shrinkage occurring at or near the tailings surface. The sample was placed in a clear plastic cylinder, 0.14 m in diameter with a height of approximately 0.24 m. Two heat dissipation sensors were installed, to monitor matric suction, at the bottom of the cylinder and at a sample depth of approximately 5 cm. A tensiometer was also installed at a sample depth of 5 cm. Daily height measurements were obtained using a digital micrometer, and volumetric water content readings were obtained using a ThetaProbe from Delta Technologies (Cambridge, UK).

4.2 Test Results

4.2.1 Gold Tailings

The results of the small column evaporation test are shown in Figures 6 and 7. The experiment had an initial drying rate of approximately 10 mm/day. Based on data from the heat dissipation sensors, suctions reached a value of approximately 300 kPa before water was added to rewet the soil to a degree of saturation of about 85% on day 10. Thereafter, the pattern of evaporation follows very closely to the initial rate of drying after the soil began to desaturate, on day 5 of the initial drying stage. Final void ratio upon drying was calculated at 0.91.

4.2.2 Silicate 1

No bleed water was observed during the Silicate 1 small-scale test. Suction data presented in Figure 8 indicates non-uniform drying of the sample given that matric suction at the top of the sample developed some three days before a significant increase in the suction at the bottom of the sample was recorded (Simms & Grabinsky, 2005).

Significant horizontal shrinkage away from the side of the bucket was noticed for the Silicate 1 tailings. At the surface of the sample, the average distance from the tailings to the interior of the container was 1 cm (Simms & Grabinsky, 2005). The calculated void ratios in Figure 9 (final void ratio near 0.90) assume no horizontal shrinkage. If it is assumed that the horizontal separation measured at the surface was uniform with depth, a final void ratio of 0.60 would be achieved. Separation from the side of the container started on day 3, and stopped noticeably increasing by day 5 (Simms & Grabinsky, 2005).
Results of the secondary cylinder test on the Silicate 1 tailings, using the laser scanner served to confirm the results of the initial small scale test. The test showed that shrinkage along the sides of the cylinder began at about day 4 of drying (Figure 10) and was fully developed by day 6 (Figure 11). Based on data from the tensiometer located near the tailings surface, matric suction began to spike on day 4, further connecting an increase in suction with horizontal shrinkage from the sides of the cylinder. It should also be noted that horizontal shrinkage began to occur at about the same time in which rate of vertical settlement began to decline. Only a 1.2 % overall decrease in the height was observed after day 6.

The tensiometer recorded a suction value of 78 kPa on day 9 before cavitation occurred. Unfortunately, the heat dissipation sensors installed in the sample malfunctioned and no suction data was obtained from them. As presented in Figure 12, the final void ratio was calculated at 0.76. It should be noted that by week 3 of the test, the degree of saturation continued to linearly decrease even though the amount of evaporation had leveled off.

Upon initial drying of the silicate 2 material, some bleed water was observed at the surface, but had evaporated by the end of the second day. The heat dissipation sensor data, presented in Figure 13, for the top and bottom of the sample, indicates relatively uniform drying throughout as compared with that of Silicate 1.

Figure 14 compares the rate of evaporation and vertical settlement with the calculated average degree of saturation and void ratio. Silicate 2 undergoes greater shrinkage, and consequently maintains a higher degree of saturation for a longer period of time than the Silicate 1 tailings. Significant horizontal shrinkage away from the side of the bucket was noticed for the Silicate 1 tailings, but not for the Silicate 2. The final void ratio for the Silicate 2 tailings was calculated at 0.5.
5. SHRINKAGE TESTING

5.1 Test Procedures

Shrinkage tests were performed on the silicate and copper tailings only. Results were then compared to those obtained by Crowder (2002), who had previously conducted shrinkage tests on the gold tailings. The shrinkage test procedures were adapted from ASTM 4943-02, The Standard Test Method for Shrinkage Factors of Soils by the Wax Method. The only deviation from the standard procedures was that the tailings were dried in water content tins as opposed to the shrinkage dishes specified in the ASTM.

Three test samples, mixed to gravimetric water contents of 45, 37.5, and 25 %, were created for each tailings type and placed in water content vessels coated in vacuum grease to prevent sticking of the paste to the sides of the tin and to promote uniform drying of the sample. The samples were air dried to achieve a state as close to complete drying as possible, and then coated in yellow beeswax ($G_s = 0.97$). The buoyant weight of each coated sample was measured using a bucket filled with water and a lab scale, allowing the determination of final void ratio, density, saturation, and shrinkage limit based on phase relationships provided in the ASTM.

5.2 Results

The average shrinkage limit (SL) values obtained for each tailings type is presented in Table 2. It should be noted that the tests on the copper tailings produced some variability in SL results.

Table 2: Shrinkage Limit Results

<table>
<thead>
<tr>
<th>Tailings Type</th>
<th>Initial Gravimetric Water Content (%)</th>
<th>Silicate 1</th>
<th>Silicate 2</th>
<th>Copper</th>
<th>Gold*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>45</td>
<td>21.7</td>
<td>16.8</td>
<td>24.14</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td>37.5</td>
<td>18.3</td>
<td>17.8</td>
<td>22.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>19.3</td>
<td>16.2</td>
<td>16</td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>19.8</td>
<td>16.9</td>
<td>20.72</td>
<td>20</td>
</tr>
</tbody>
</table>

*SL based on Initial Gravimetric Water Content ~ 32 %

Final gravimetric water contents for all specimen data presented in above ranged from 0.5% to 2%. Therefore, near complete drying was attained.

Figure 15 plots the final void ratio versus the initial void ratio for all of the samples tested. The dotted line represents the line of minimum void ratio, given that during drying, one does end up with a final void ratio greater than the initial. The results show that the higher the initial void ratio (i.e. the higher the water content) upon placement, the higher the final void ratio upon total drying of the samples.
6. INTERPRETATION OF RESULTS

Figure 16 correlates the initial gravimetric water content of each tailings sample for each type of test conducted with the final calculated void ratio.

The data displays a good correlation between gravimetric water content and void ratio for the Gold and Silicate 1 tailings. As the initial mixing water content decreases, so does the final void ratio of the sample upon ultimate drying.

The relationship is less obvious for the Silicate 2 and Copper tailings. However, if we remove the Silicate 2 data obtained from the large and small scale drying tests, merely using the data obtained from shrinkage testing, then the correlation changes from 0.073 to 0.871. As to why the drying test samples end up with lower void ratios at higher water contents is uncertain, but it may bring into question the validity of the ASTM shrinkage testing method as a tool for determining the shrinkage limit of non-plastic materials.

The copper tailings also display a high variability in final void ratio. Again, the reason is uncertain. Though one hypothesis may be that, given the relatively high percentage of kaolinite (15%) as compared with other minerals present, electrostatic forces may have an as of yet undetermined effect on the settling properties and alignment of the particles, thereby affecting the final void ratio. Further research is needed by performing large-scale drying tests on the copper tailings to better understand its drying characteristics.

Alternatively, the void ratio phenomena witnessed may simply be a result of air entrapment. If one assumes a constant volumetric fraction of the pore space is occupied by air, then higher water contents at mixing will result in a higher volume of entrapped air.

Simms & Grabinsky (2005) also noted that interpretation of void ratio data is complicated by the presence of cracks, rendering volume change measurements difficult. Any future testing needs to incorporate methods to accurately measure the decrease in volume due to desiccation cracking.

7. CONCLUSIONS

Some of the conclusions based on the testing regime are summarized below.

It appears that horizontal shrinkage for the gold tailings accelerated after the majority of vertical settlement had occurred. The Silicate 1 small cylinder test supports this assumption given that the height of the sample decreased by only 1.2 % following day 6 of drying (i.e. when major horizontal shrinkage first appeared).

The Silicate 1 tailings undergo more horizontal shrinkage during drying than the Silicate 2 material, as evidenced by cracking in the large scale tests and by separation from the sides of the container in the small scale tests. Further, in the small test the Silicate 1 tailings developed a steep gradient in suction with depth, while suctions in the corresponding test for the Silicate 2 material were uniform with depth. This last result is possibly due to differences in the measured soil-water characteristic curves.

The final void ratio achieved by drying depends on the mixing water content, and appears to be material specific. However, some variability in the shrinkage test data suggests that the ASTM method for determining shrinkage limits may not apply to non-plastic materials such as mine tailings. If the engineering design is sensitive to the final void ratio achieved by drying, this phenomenon must be investigated further.

References


