Use of a 3D scanner for shrinkage curve tests

<table>
<thead>
<tr>
<th><strong>Journal:</strong></th>
<th>Canadian Geotechnical Journal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Manuscript ID:</strong></td>
<td>cgj-2017-0700.R1</td>
</tr>
<tr>
<td><strong>Manuscript Type:</strong></td>
<td>Article</td>
</tr>
<tr>
<td><strong>Date Submitted by the Author:</strong></td>
<td>05-Apr-2018</td>
</tr>
<tr>
<td><strong>Complete List of Authors:</strong></td>
<td>Wong, Jonathan; University of Saskatchewan, Department of Civil, Geological and Environmental Engineering; Elwood, David; University of Saskatchewan, Civil and Geological Engineering; Fredlund, Delwyn; Golder Associates Ltd</td>
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<tr>
<td><strong>Keyword:</strong></td>
<td>Shrinkage curve, 3D scanning, Atterberg limits, Index tests, shrinkage limit</td>
</tr>
<tr>
<td><strong>Is the invited manuscript for consideration in a Special Issue?</strong></td>
<td>Not applicable (regular submission)</td>
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Use of a 3D scanner for shrinkage curve tests

by Jonathan M. Wong, David Elwood and Delwyn G. Fredlund

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Abstract

A procedure is proposed for conducting shrinkage limit tests using a 3D scanner. Shrinkage limit tests were conducted on 27 different soils of varying plasticity. In this study only 8 of the shrinkage curves were determined using 3D scanning techniques, while the remaining 19 were taken from literature. An individual specimen was scanned between 30 to 50 times to produce a high-resolution shrinkage curve. Shrinkage curves for each material were obtained by curve fitting a shrinkage model to the measured dataset. The primary intent of the research was to relate the shrinkage curve equation to the plasticity of a given soil. Using linear regression analysis, an empirical correlation was developed to reasonably relate parameter $c_{sh}$ from the shrinkage model to the ratio of the plastic and liquid limits. The shrinkage curves produced based on the model have an average difference of ~1.2% in terms of measured void ratio and predicted void ratio. The method was demonstrated to be robust for materials of low, medium, and high plasticity. The proposed methodology also presents a means of estimating a shrinkage curve in its entirety based solely on the volume of an air-dried sample, the specific gravity and Atterberg limits of the specimen. This effectively reduces the amount of work needed to derive the shrinkage curve and could potentially reduce the time for a shrinkage limit test by half or more.

Keywords: Shrinkage curve, 3D scanning, Atterberg limits, shrinkage limit, index tests, unsaturated soil
Introduction

A soil matrix typically consists of three primary phases: the solid phase (soil particles), the water phase, and the air phase. The volume of water being removed from, or added to, a soil matrix does not necessarily equal the change in overall volume since changes in the soil structure also play a significant role (Haines 1923). The relationship between the soil water content (at and below saturation) and its void ratio is known as the shrinkage curve. The shrinkage curve is particularly important for designing lightweight structures, such as soil cover systems, road pavements, and rail beds. Differential displacements (heave or settlement) in the presence or absence of water can result in damage to the structure, or cracking of the soil mass.

There are many different shrinkage models used to relate the intrinsic water content of a soil sample to a volume quantity. For example, Cornelis et al. (2006) proposed a parametric model to relate moisture ratio with the void ratio of a soil as it dries; Peng and Horn (2007) proposed a model that relates moisture ratio to void ratio, which also accounts for anisotropic shrinkage and swelling of soils; Fredlund et al. (2002) developed a shrinkage model relating gravimetric water content to void ratio. Many more models exist in the soil science discipline, which uses multiple equations to sections of a segmented shrinkage curve (gravimetric water content versus specific volume). Examples of each may be found in Giraldez et al. 1983; MacGarry and Malafant 1987; or Tariq and Dunford 1993. As the method developed by Fredlund et al. 2002 was primarily developed for volume change as it relates to geotechnical engineering, the method will be focus of this paper.

A continuous shrinkage curve equation is obtained by curve-fitting a shrinkage model to discrete measurements of void ratio and gravimetric water content obtained by performing a shrinkage limit test. The equation commonly used to fit the shrinkage data in geotechnical engineering was first proposed by Fredlund et al. (2002):
\[ e(w_i) = a_{sh} \left( \frac{w_i}{b_{sh}} \right)^{c_{sh}} + 1 \] ^{1/c_{sh}} [1]  

where,

- \( a_{sh} \) is the minimum void ratio and is the y-intercept value of the shrinkage curve;
- \( b_{sh} \) is the slope of the inclined-linear portion of the shrinkage curve and can be calculated directly using \( b_{sh} = \frac{a_{sh}S}{G_s} \);
- \( c_{sh} \) is a curve fitting parameter that determines the curvature of the shrinkage curve, \( w_i \) is the gravimetric water content, and \( e(w_i) \) is the void ratio of the soil mass at any selected gravimetric water content \( w_i \), \( S \) is the degree of saturation and \( G_s \) is the specific gravity of the soil.

This shrinkage curve model has three parameters. Parameters \( a_{sh} \) and \( b_{sh} \) each have a physical meaning related to the shrinkage of the soil during drying. However, no physical meaning has been ascribed to parameter \( c_{sh} \), other than it being related to the curvature of a shrinkage curve. If parameter \( c_{sh} \) can be related to plasticity of the soil, then shrinkage curves can be better estimated without the need for carrying out tests other than those needed to determine the liquid, plastic and shrinkage limits of a given soil.

Historically, shrinkage limit tests were conducted using mercury displacement, but this method was withdrawn without replacement in 2008 due to health and safety concerns (ASTM D427-04). Many methods have since been developed, including the wax-dip method (Prakash et al. 2009), the photogrammetry method (Li et al. 2015) and direct measurement. These tests, however, either require a skilled hand to execute or assumptions to interpret the results. For example, the wax-dip method (ASTM D4943-08) is a destructive test that involves the preparation of multiple batches of soil samples at various water contents. The samples are dipped...
into molten wax to preserve the water content during mass-volume measurements. The test assumes that the difference in water content is the only factor affecting the volume of the soil specimen; however, this is hardly the case as sample preparation is an influencing factor. In 2017 April, the wax-dip method was also withdrawn without replacement due to it being out-dated (ASTM D4943-08).

Three-dimensional (3D) scanners have been proposed for measuring the volume of a soil sample at any water content (Wong et al. 2017). A major advantage of applying remote sensing technology (such as 3D scanners or photogrammetry) to shrinkage limit tests is that it results in minimal disturbance of the soil sample without compromising accuracy. The objective of the paper is to illustrate the using of a 3D scanner for shrinkage limit tests propose a test procedure for obtaining the shrinkage curve. The scanning procedure provides a means of measuring the entire shrinkage curve based solely on the volume of an air-dried sample, the specific gravity and the Atterberg limits of the specimen. This effectively reduces the amount of work needed to determine the shrinkage curve.

Methodology

Working Principle

A 3D scanner utilizes “Light Detection and Ranging”, (LiDAR) technology and computer imaging to reconstruct a colored three-dimensional object. The 3D scan involves placing an object on a turntable at a fixed distance from the 3D scanner (Fig. 1). The turntable is connected to the scanner and is programmed to rotate the sample following completion of a given scan. Sample rotation is required to obtain a complete 3D image of the test specimen.

The 3D scanner then uses a computer-imaging program to differentiate between the scanned object and the background. The on-board camera captures an image of the object during
and after illumination by the light module. Both the camera and light modules are shown in Figure 1. The processing unit then compares the two images, and flags the pixels that have a significant change in light intensity (Fig. 2). Pixels that were identified as having significant light change were then used to identify objects of the scanning setup that needed to be removed manually once the LiDAR scan was completed. The colors of these flagged pixels are assigned to a corresponding point in a “point cloud”, thereby reducing the number of objects that need to be trimmed to obtain the sample volume. Identification of pixels of interest is carried out automatically by the scanner software (NextEngine ScanStudio) based solely on the difference in light intensity obtained from the captured images. Objects such as the pedestal or the stabilizing arm for inclined objects were metal or light colours, which resulted in considerable changes in light intensity in the captured images when compared to the soil samples. This procedure is in contrast to conventional LiDAR scanning where the results are filtered based on the time of return, and therefore the distance from the scanner.

The laser module emits a series of laser points to the object upon completion of the imaging process. The sensor picks up the laser points that are reflected off the surface, and calculates the distance between the scanner and the object based on the time between when the light is emitted and returned to the scanner. Multiple 3D coordinates (point cloud) are generated simultaneously as the laser points scan across a surface continuously.

In order to test the scanning methods and the efficacy of the methods used, a metallic calibration puck was used as shown in Fig. 3a. The puck was positioned on an angle using the supplied support arm and plasticine at the base in order to minimize any image shadows. Once the surface of the object has been scanned, the turntable rotates the object until a new surface faces the scanner. This surface is scanned by repeating the previous procedure. The 3D
coordinates of different faces are joined ("stitched") together to form a 3D point cloud based on the surface topography and the overlaps of images (Fig. 3b). The density of the point cloud can be adjusted for different situations by setting the scanning resolution prior to scanning. A high-density point cloud (i.e., more than 11 points per mm$^2$), allows more surficial details to be captured but requires more processing time and computation power than a lower density meshed volume.

When scanning is complete, the 3D point cloud must be further edited prior to being used for the calculation of the overall volume. The edits require the trimming of any background details that may have been scanned despite the image processing described above. Following trimming of the erroneously captured points, the object is then transformed into a water-tight surface mesh (Fig. 3b) based on the point cloud using any conventional meshing software package. Trimming of the scanning unit turntable and pedestal was carried out using NextEngine ScanStudio (supplier provided 3D scanner software). Meshing and surface generation was then carried out using CloudCompare.

The volume of the object can only be computed if the mesh is watertight. Any holes or voids in the mesh will result in an inaccurate calculation of the object volume. The calibration puck used in Figs. 3a and 3b was designed to determine the optimal shape and positioning for 3D scanning and a basis for accuracy calibration of its volume. As can be seen in the meshed surface, that there were considerable errors around the edges, suggesting a need for a different sample shape. The missing data surfaces can subsequently affect the stitching process, and result in a deformed point cloud (Fig. 4). It was found that the scanner requires a clear line of sight to the sample surface to avoid the presence of “holes” in the associated point cloud that result from missing data points or hidden surfaces, and therefore the shape and orientation of the soil sample.
must be considered. Flat surfaces that are parallel to the travel direction of the lasers are often a major contribution to holes and should be avoided. Shapes without a flat top surface, such as bullet shape, should be adopted instead (Fig. 5). In order to minimize the potential for line of sight holes in the point cloud, the sample shape was molded to a rough bullet shape. The molding requires some plasticity of the soil, which is also a requirement for observing shrinkage of a soil. Water content losses during shaping of the sample was minimized by moistening the surface of the tester’s hands with deionized water. Despite efforts to maintain a clear line of sight, some sample surfaces are inevitably out of sight, such as the tip and the bottom of the object (Fig. 6). Small holes (e.g., at the tip), can be patched with a smooth flat surface during the meshing process. The “patch” is generated by averaging the orientation of the micro-surfaces around the holes. Bigger holes, such as the one at the bottom of the object, can be patched with a fabricated surface of specified orientation. The patched surface is only accurate if the base of the soil sample is indeed flat and smooth. Therefore, samples must be prepared in a manner that ensures good contact with the revolving baseplate. The dimensions of tests samples used in this study are shown in Fig. 6. It is important to note that the size of the sample used is dependent on the type and resolution of the 3D scanner used. NextEngine simply suggested that the size of the sample be such that it is completely captured in the line of sight of the 3D scanner. This prevented the need to piece together point clouds during post-processing.

**Calibration**

A calibration study was conducted to determine the accuracy of volumes obtained using the 3D scanner. The 3D scanner was used to measure the volume of a metallic puck (Fig. 3a) with an average diameter of 30.05 mm, height of 10.12 mm, and total volume of 7173.3 mm³. The metallic puck was painted to simulate the color of soil samples to be scanned as part of the main study. The puck was scanned at different mounted positions a total of 12 times. The
average scanned volume (± standard deviation) of the puck was 7820 (± 123.28) mm³, corresponding to a difference of +9.02% with respect to the actual volume. These results indicate the scanner can provide consistent volume measurements but lacks in overall accuracy. Therefore, before or after a shrinkage limit test is completed, an object with known volume and similar dimensions to that of the soil specimen should be scanned. A calibration factor, \( \alpha \), is then obtained using the relationship

\[
\text{Calibration Factor (} \alpha \text{)} = \frac{\text{Scanned volume}}{\text{True volume}}
\]  

[2]

The calibration factor can then be applied to the scan results of the soil sample to determine a more accurate volume. The procedure can be repeated at different water contents to obtain the shrinkage curve.

**3D Scanning Procedure**

The proposed procedure for conducting a shrinkage limit test using a 3D scanner involves five steps; namely, scanner calibration, sample preparation, mass measurements, volume measurements, and drying. The five steps are as follows:

Step 1: The scanner must first be calibrated for accurate volume measurements, as described above, by scanning a solid non-reflective object of similar volume to the soil sample. This allows the determination of the calibration factor (Eq. 2).

Step 2: A soil sample with an initial water content between the plastic and liquid limits is recommended for a shrinkage limit test. The soil specimen is molded into a preferred shape for scanning. The specimen is placed on the platform where it remains until all scanning is complete.

Step 3: While the 3D scan normally takes 15 to 20 minutes and the water content might change during the scanning process (e.g., due to evaporation). Therefore, the mass of the sample...
should be measured twice (once prior to scanning and once immediately after scanning) to obtain an average gravimetric water content that represents the water content of the sample during 3D scanning.

Step 4: The platform in contact with the soil sample is placed on top of the turntable and the desired resolution selected (e.g., 11 points per mm$^2$). Upon completion, the background information of the scan is trimmed, leaving only the point cloud. Meshing software is used to generate a watertight mesh from the point cloud and any existing “holes” are patched. The mesh is then exported for volume calculation. Once the mass of the soil sample is measured after 3D scanning, the sample can be left to air dry prior to taking the next mass and volume measurements.

Steps 3 and 4 are repeated until the volume of the soil sample no longer significantly changes.

Step 5: The soil sample is then oven-dried for 24 h before measuring its dry mass and minimum volume.

In all, approximately 30 to 50 individual scans were completed to construct a complete shrinkage curve using the 3D scanner. Ideally, the scanning was carried out consecutively in order to capture the full range of water contents through the drying phase. It is important to note that this high number of scans was only completed in order to obtain high resolution to the shrinkage curves measured with the purpose to be finding a correlation of the radius of curvature, $c_{sh}$ with the plasticity of a given soil. If a correlation could be found, then it would permit a practitioner or lab technician to construct a complete and accurate shrinkage curve without the need to carry out such a high number of scans.
Once the mass and volume measurements of the entire shrinkage curve have been obtained, the calibration factor (Eq. 2) must be applied to the volume measurements. The specific gravity of the soil (ASTM D854-14) is used to calculate the corresponding void ratios. Gravimetric water content and the void ratio of the soil sample are then calculated from the corrected volume measurements. The dataset can then be fitted with the shrinkage curve equation (Eq. 1).

**Results and Discussion**

The 3D scanner was used to obtain shrinkage curves for a wide range of soil samples (Table 1). In total, 27 soils were used in the evaluation to determine the relationship of $c_{sh}$ with the plasticity of a given soil. Eight of the soils were evaluated using the 3D scanning method described above. In addition, 19 shrinkage curves were obtained from literature (Russam, 1958; Dagg & Russam, 1966; Fredlund et al., 2011; Elwood et al., 2015; and Zhang, 2016¹) and used in this analysis. The shrinkage curves reported by from past studies were obtained using the caliper method.

The results of the 3D scanning method for a low, medium and high plasticity clay are shown below in Figures 7a, 7b and 7c respectively. There is considerable scatter to the data for the low and high plasticity clays, though the data can be fit quite well using Eq. 1 and using linear regression to fit the data by changing $c_{sh}$ since $a_{sh}$ and $b_{sh}$ are known values. It is important to draw the reader’s attention to the scales of the void ratios for each the low, medium and high plasticity clays. Please note that there is considerable variance to the void ration and this may have played a role in the scatter in the low water content range. It is possible that the initial

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¹ Zhang 2016 presented an interpretation of work provided by Marinho 1994.
degree of saturation of the samples may have played a role in the scatter associated with the high
and low plasticity soils.

The primary purpose of the shrinkage curve measurements was to determine whether a
physical meaning of the $c_{sh}$ variable could be related to the material characteristics. The materials
selected were chosen based on their Atterberg limits with the intent of covering a wide range of
plasticity values. The properties of the materials were either obtained from published literature or
physically measured in the laboratory; namely Atterberg limits (ASTM D4318-17), specific
gravity (ASTM D854-14), and particle size (ASTM D7928-17). Shrinkage data for the materials
were obtained using the 3D scanner procedure. The shrinkage curve data was then fitted with the
shrinkage curve equation (Eq. 1). The $c_{sh}$ variable was the only unknown.

Shrinkage curves can be divided into three phases according to Haines (1923). The
phases are: normal shrinkage, residual shrinkage, and zero shrinkage. In the normal shrinkage
phase, the soil is fully saturated, and its overall volume change equals the volume of water
removed or added. Soil volume change is directly proportional to the water volume change until
the water content of the soil drops below its plastic limit (Fredlund et al. 2011; Marinho 2013), at
which point it enters the residual shrinkage phase. Soils in the residual shrinkage phase are
unsaturated. In this phase, the overall volume change of the soil is less than the change in the
volume of water. Soil samples in the zero-shrinkage phase are also unsaturated, and have no
overall volume change despite the removal or addition of pore-water. The beginning of zero
shrinkage phase is marked by the shrinkage limit, which is defined as “the water content below
which further loss of water by evaporation does not result in a reduction of volume” (Peck and
Terzaghi 1948). The three parameters in Eq. 1 ($a_{sh}$, $b_{sh}$, and $c_{sh}$) respectively represent the y-axis
intercept upon complete drying of the sample; the slope of the initial saturation line (i.e.,
typically taken as the slope of the change in void ratio beyond the plastic limit), and the curvature of a shrinkage curve that transitions from a dry soil. The three parameters each represent the geometry of a segment of the shrinkage curve within the zero, normal, and residual shrinkage phases, respectively.

Haines (1923) and Fredlund et al. (2002) suggested a physical property that could be used to quantify the geometry of a shrinkage curve through to the residual shrinkage phase ($c_{sh}$). Haines (1923) suggested that the volume change through the residual shrinkage phase is related to the clay particle-water interactions within the sample. Fredlund et al. (2002) report a difference in $c_{sh}$ values when soil samples are of different plasticity. The term clay activity (activity hereafter) introduced by Skempton (1953) attempted to combine the effect of unify clay fraction and plasticity:

$$\text{Activity} = \frac{\text{Plasticity Index}}{\text{Clay Fraction}}$$

where,

- plasticity index is the difference between the liquid limit (LL, %) and plastic limit (PL, %), and
- the clay fraction is the mass of clay particles within a soil sample (%).

A plot of $c_{sh}$ vs. activity showed no consistent relationship. Atterberg limits, in particular the plasticity index, vary with clay content for soils with a clay fraction of 30% or higher (Seed et al. 1964; Polidori 2007). Plots of $c_{sh}$ with respect to the plastic limit, liquid limit, and plasticity index showed the independence of $c_{sh}$ in the low range of these plasticity variables. However, a power-function relationship was observed when $c_{sh}$ was plotted against the plasticity index on a semi-log scale (Fig. 8). The coefficient of determination was quite low ($R^2 = 0.81$), but the general trend of the curve shows an inverse relationship between $c_{sh}$ and plasticity.
A non-asymptotic relationship with higher $R^2$ values was obtained when the data was plotted as $c_{sh}$ versus the ratio of the plastic and liquid limits (hereafter referred to as plasticity ratio) (Fig. 9). The plasticity ratio has physical meaning in that a plasticity ratio of 0 indicates a high plasticity soil and 1 indicates a completely non-plastic soil. An empirical equation is obtained using a linear regression analysis that relates $c_{sh}$ to the plasticity ratio:

$$c_{sh} = 1.7 + e^{3.3\frac{PL}{LL}}$$

where,

Shrinkage curves created using the $c_{sh}$ values estimated from Eq. 4 were compared to those obtained through linear regression curve-fitting. The shrinkage curves produced based on Eq. 4 resulted in an average difference of ~1.2% in terms of void ratio (measured vs. predicted) and a maximum error of 6% when predicting the void ratio of extremely high plasticity material (i.e., bentonite with a plasticity ratio near to 0). Figures 10 to 12 illustrate the quality of the estimated curves for materials of low, medium, and high plasticity using Eq.4. Figs. 10 to 12 illustrate that the estimation of $c_{sh}$ from Eq. 4 agrees well with curves fitted to the shrinkage data using Eq. 1 and linear regression to fit the measured data for $c_{sh}$ as shown in Figs. 7a to 7c. It is expected that Eq. 4 will provide an accurate prediction of the three tested materials as Eq. 4 is based on data obtained from fitted data. However, when applied to data not physically measured in this study (Zhang, 2016), the results are still considered to be reasonable.

It is important to note that there is no physical meaning to the relationship between the ratio of the plastic and liquid limits. What is important is that the void ratios obtained from Eq.4 provide predictions of the shrinkage curve within the limits of laboratory testing error. Furthermore, when the plasticity and liquid limits are equal, then the value of $c_{sh}$ is 23.9. This value of $c_{sh}$ results in a material that has zero volume change to a water content approximately
equal to the value of $b_{sh}$ irrespective of the degree of saturation of the soil. At a water content, equal to $b_{sh}$, the void ratio increases at a constant rate as defined by $b_{sh}$ suggesting little to no curvature of the shrinkage curve. The lack of curvature is in keeping with shrinkage curve testing of non-plastic soils.

Conclusions

This paper proposed a procedure for conducting shrinkage limit tests using a 3D scanner. Shrinkage limit tests were conducted on 27 different soils of various plasticity using the proposed procedure with shrinkage curves for these materials obtained by curve fitting a shrinkage model to measured datasets. Using a linear regression analysis, an empirical correlation was developed to reasonably relate parameter $c_{sh}$ from the shrinkage model to the ratio of the plastic and liquid limits.

The proposed empirical equation effectively streamlines the process associated with obtaining a shrinkage limit test. Shrinkage limit tests usually require 24 to 48 hours of repetitive scanning and weighing. With the proposed empirical equation, the repetitive scanning and weighing cycles might be replaced by using the Atterberg limits and a single 3D scanning to obtain the minimum void ratio of a dried soil sample. Once the specific gravity of the soil is obtained, parameters $a_{sh}$, $b_{sh}$, and $c_{sh}$ (and, thus, the entire shrinkage curve) can be estimated. This procedure considerably reduces the time required to obtain a shrinkage curve.

Acknowledgements

The authors acknowledge the support of Golder Associates, the Saskatchewan Centre for Excellence in Transportation Infrastructure (SCETI) and Ms. Feixia Zhang (University of Alberta) for their contributions to this research study.
References


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Table 1: Sample materials and properties thereof for shrinkage curves

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<th>Material</th>
<th>Specific gravity</th>
<th>Clay fraction (%)</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>(a_{sh})</th>
<th>(b_{sh})</th>
<th>(c_{sh})</th>
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<td>48</td>
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<td>30/70 London clay/sand&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.67</td>
<td>16.1</td>
<td>24</td>
<td>18</td>
<td>0.45</td>
<td>0.16</td>
<td>13.9</td>
</tr>
<tr>
<td>L40S-SC, 28%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.7</td>
<td>28</td>
<td>43</td>
<td>22</td>
<td>0.42</td>
<td>0.14</td>
<td>7.0</td>
</tr>
<tr>
<td>Janga clay&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.75</td>
<td>40.8</td>
<td>73</td>
<td>28</td>
<td>0.36</td>
<td>0.14</td>
<td>4.9</td>
</tr>
<tr>
<td>Boom clay&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.71</td>
<td>39.2</td>
<td>56</td>
<td>29</td>
<td>0.45</td>
<td>0.16</td>
<td>5.5</td>
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<tr>
<td>L00S, 45.38%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.75</td>
<td>45.38</td>
<td>89</td>
<td>32</td>
<td>0.42</td>
<td>0.15</td>
<td>4.4</td>
</tr>
<tr>
<td>L20S, 39.35%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.73</td>
<td>39.35</td>
<td>73</td>
<td>29</td>
<td>0.44</td>
<td>0.15</td>
<td>4.1</td>
</tr>
<tr>
<td>L30S, 37.57%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.71</td>
<td>37.57</td>
<td>65</td>
<td>26</td>
<td>0.47</td>
<td>0.16</td>
<td>4.4</td>
</tr>
<tr>
<td>L40S, 32.01%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.7</td>
<td>32.01</td>
<td>43</td>
<td>22</td>
<td>0.51</td>
<td>0.18</td>
<td>5.2</td>
</tr>
<tr>
<td>L60S - PP, 24.76%&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.75</td>
<td>24.76</td>
<td>36</td>
<td>19</td>
<td>0.64</td>
<td>0.21</td>
<td>7.4</td>
</tr>
<tr>
<td>Blue clay&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.75</td>
<td>36.79</td>
<td>63</td>
<td>27</td>
<td>0.60</td>
<td>0.21</td>
<td>6.3</td>
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<tr>
<td>HD bentonite&lt;sup&gt;a&lt;/sup&gt;</td>
<td>2.8</td>
<td>48.93</td>
<td>402</td>
<td>45</td>
<td>0.55</td>
<td>0.18</td>
<td>3.0</td>
</tr>
</tbody>
</table>

<sup>a</sup> Zhang 2016; <sup>b</sup> Fredlund et al. 2011; <sup>c</sup> Dagg & Russam 1966; <sup>d</sup> Elwood et al. 2015; <sup>e</sup> Russam, 1958

The materials have been only designated by the test name and percentage of clay fraction. A specific clay mineral or site source has not been provided.
Figure 1 3D Scanner and Set-up

Figure 2 Area to be trimmed based on light intensity

Figure 3a Metallic calibration puck

Figure 3b Point Cloud (left) and Mesh (right) of Metallic Puck

Figure 4 Deformed scan due to image shadows

Figure 5 Optimal sample shape and potential image shadows

Figure 6 Holes and Patched Area due to Line of Sight Errors

Figure 7a Raw shrinkage curve data for a low plasticity soil

Figure 7b Raw shrinkage curve data for a medium plasticity soil

Figure 7c Raw shrinkage curve data for a high plasticity soil

Figure 8 Relationship between csh and Plasticity Ratio

Figure 9 Relationship between csh and Log Plasticity Index

Figure 10 Estimated shrinkage curve for a low plasticity soil

Figure 11 Estimated shrinkage curve for a medium plasticity soil

Figure 12 Estimated shrinkage curve for a high plasticity soil
60x45mm (300 x 300 DPI)
Figure 2 Area to be trimmed based on light intensity

159x155mm (300 x 300 DPI)
Figure 4 Deformed scan due to image shadows

64x48mm (300 x 300 DPI)
Figure 5 Optimal sample shape and potential image shadows

48x34mm (300 x 300 DPI)
Figure 6 Holes and Patched Area due to Line of Sight Errors

57x38mm (300 x 300 DPI)
Figure 8 Relationship between $c_{sh}$ and Plasticity Ratio

$100\times117$mm (300 x 300 DPI)
Figure 9 Relationship between $c_{sh}$ and Log Plasticity Index

$\log c_{sh} = 5.3P^{-0.79} + 2$

$R^2 = 0.81$

117x160mm (300 x 300 DPI)
Figure 10 Estimated shrinkage curve for a low plasticity soil

79x72mm (300 x 300 DPI)
Figure 11 Estimated shrinkage curve for a medium plasticity soil

Material: Kaolinite
Liquid limit: 59%
Plastic limit: 36%
Saturation = 100%

Fitted Curve
(Fredlund et al., 2002)
\( a_{sh} = 0.36 \)
\( b_{sh} = 0.14 \)
\( c_{sh} = 9.0 \)
\( G_s = 2.60 \)

Estimated Curve
\( a_{sh} = 0.36 \)
\( b_{sh} = 0.14 \)
\( c_{sh} = 8.6 \)
\( G_s = 2.60 \)

Max Difference: 0.4%
@ \( w = 14\% \)
\( R^2 = 1.00 \)
Figure 12 Estimated shrinkage curve for a high plasticity soil

Material: Sodium Bentonite
Liquid limit: 751%
Plastic limit: 100%

Fitted Curve
(Fredlund et al., 2002)

\[ a_{sh} = 6.05 \]
\[ b_{sh} = 2.57 \]
\[ c_{sh} = 2.5 \]
\[ G_s = 2.35 \]

Estimated Curve

\[ a_{sh} = 6.05 \]
\[ b_{sh} = 2.57 \]
\[ c_{sh} = 3.21 \]
\[ G_s = 2.35 \]

Max Difference: 5.95%
@ \[ w : 257\% \]
\[ R^2: 1.00 \]

Saturation = 100%