Determination of Shrinkage of Fine-Grained Soils using 3D Scanning Technology

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Dedication

To my grandparents, Mr. Gopilal Joshi and Mrs. Dalli Devi Joshi.

Acknowledgement

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I am immensely indebted to my parents, Mr. Bishnu Prasad Joshi and Mrs. Suna Devi Joshi, and all my family members for providing the love and the motivation in every day of my life.

Abstract

Shrinkage Limit is the moisture content parameter in fine grained soil which is related to the volume stability of the soil. The conventional method, ASTM Standard D427-04 that uses mercury has been replaced by wax method, ASTM Standard D4943-02 that uses wax and water or MT-92 that uses spray coating. This modification has certainly minimized safety concerns of the laboratory technicians by avoiding the use of the health hazardous substance, mercury (Hg) but it is not really an economic and convenient method. This thesis proposes a 3D scanning method of determining the shrinkage limit of fine grained soils. The 3D scanning method involves the use of a calibrated 3D scanner to obtain the 3D model of soil samples and the CREO or the SOLIDWORKS software to determine the volume of the 3D model. The experimental and the statistical results demonstrate that values for Shrinkage Limit of soils calculated by Spray Coating Method and 3D Scanning Method can be thoroughly correlated.

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List of Abbreviations

3D	3 Dimensional
ASTM	American Society for Testing and Materials
g	Gram
in	Inch
lb	Pound
LL	Liquid Limit
ml	Milliliter
mm	Millimeter
MT	Material Testing
PL	Plastic Limit
SL	Shrinkage Limit

1. Introduction

One of the Atterberg Limits is the Shrinkage Limit which is the limiting moisture content of the soils below which the reduction in water content does not cause any reduction in the volume of the soil. It is the characteristic soil property related to the volumetric stability of the soil in the field subjected to shrinkage. In laboratory settings, the shrinkage limit is calculated by determining the moisture content and the initial volume of the standardized sample size of moist soil compared to the final oven-dry volume of the sample. The key part of the shrinkage limit test is the determination of the volume of the dried sample, and there have been several methods developed for it.

The mercury displacement method was replaced by wax method (or spray coating method) to address the health issues. The replacement of mercury by wax definitely accounts for the primary concern of engineers, the safety issue but these new methods are also time consuming and tedious. Therefore, the need for a new method that incorporates economic and convenience concerns of engineers is inevitable. This thesis is the study of a quick, convenient and economic method to calculate shrinkage limit of fine-grain soils, taking advantage of recent progress made on 3D scanning (and 3D printing) technology.

The shrinkage limit tests performed in the laboratory are inconvenient and inefficient economically because of the multiple steps and materials required to calculate the volume of the dry samples. The 3D scanning method simplifies practice of the volume determination. The 3D scanner is calibrated as recommended by the manufacturer. The volume calculation is verified by using the soil samples available in the laboratory. Then shrinkage limit of the Bentonite clay, and 20% sand with Bentonite mixture is calculated for further comparative analysis.

1.1 Conventional Method: Spray Coating Method

The spray coating method is very similar to the wax method which requires the determination of the volume of the oven-dry soil sample coated with waterproofing spray by the water displacement method. The inner diameter and the inner height of the shrinkage can is measured by using the sliding Vernier’s Calipers. The average of the three readings each is used to determine the volumetric capacity of these cans, which is also the initial volume of the wet soil sample. The chosen soil type is mixed with tap water to form a paste with water content preferably above the liquid limit. The mass of the empty can is also recorded, and then the inner surface is coated with a thin layer of petroleum gel (Vaseline) to prevent adhesion of the soil. The mass of the can with the Vaseline is also recorded, which is neglected if the change is really small. The wet soil sample is placed in the can making sure that no air bubbles or the voids are included in the wet soil mass. The filled can is struck off with a straightedge and wiped clean before recording the mass of the can with the wet sample. These are then allowed to dry in the air initially to check if early cracks are detected, two of them are placed in the oven for 3 hours and two are air-dried at room temperature for 24 hours. The mass of each dry sample with can is also recorded. The samples are the sprayed with the waterproofing coating, and the mass of the dry soil with coating is recorded. If the change is really small, the additional mass and thus volume is neglected. The water proof sample is then placed slowly in the beaker filled with tap water, and the volume of the water overflown into the pan measuring cylinder is also recorded. This overflown volume of the water is equal to the volume of the dry soil sample. The moisture content (w) of each sample is calculated by using the following equation.

$$w = \frac{W - W_o}{W_o} \times 100 \quad \text{[Equation 1]}$$

Where, W = Mass of Moist Soil = Mass of [can & moist soil – empty can] (lb or g)

W_o= Mass of Dry Soil= Mass of [can& dry soil – empty can] (lb or g)

The values obtained for the water content, weights, and the volumes are then used to determine the shrinkage limit of each sample by using the equation below. The shrinkage limit obtained for each sample is recorded to compare it with the value obtained from the proposed method (3D scanning method).

$$SL_{sm} = w - \frac{V_o - V_{sm}}{W_o} \times 100 \quad \text{[Equation 2]}$$

Where, SL_{sm}= Shrinkage Limit by Spray Coating method

w= Moisture Content (%)

V_o= Volume of Wet Sample (ml)

V_{sm}= Volume of Dry Sample by Water Displacement Method (ml)

W_o= Mass of Dry Soil Sample (g)

The shrinkage limit values for oven dry against air dry conditions, for pure Bentonite against the 20% sand mixed Bentonite are organized to evaluate for the theoretical expected and practically experienced results. For example, it is known from experience and theory that the clay is expected to have higher water content and higher shrinkage than the sand-mixed-clay.

1.2 Proposed Method: 3D Scanning Method

The 3D scanning model follows the same standards for the preparation of the sample and finding the weight and initial volume values for the wet soil samples. This method, however, differs from conventional methods in the determination of the volume calculation of the dry soil sample. It is very simple and involves only one step, minimizing all the human errors and multiple instrumental errors. The dried soil sample is placed on a calibrated turntable of the 3D scanner, scanned as non-textural object, and modeled as a 3D entity to obtain volume using the software that has been developed for analyzing 3D designs. The minor inner cracks are automatically filled, the broken pieces can be separately scanned and the volume can be determined by the method of superposition if required. The volume calculation after calibrating the scanner is really fast, can be done within few seconds. The accuracy and precision is very high, and can be controlled/adjusted. In this research, the EinScan SE Desktop 3D Scanner has been used to scan the object, and different software like the Meshmixer by Autodesk is used to model the 3D object and CREO by PTC is used to find the volume and the SOLIDWORKS by Dassault Systems to verify the volume. The same equations are then applied to calculate the shrinkage limit of the soil samples and further analysis. The sample calculations have been shown in the Appendix.

2. Experimental Results and Discussions

The readily available dry standard samples from previous shrinkage limit tests in the laboratory were used in the calibration of the 3D scanner and determining the steps to obtain the volume from the software. The different features available in the 3D scanner as well as the software were applied in these steps to adjust the fineness of the 3D scanned object and accuracy of the volume being determined. The sample without any cracks and uniform surface area were chosen to assure the reliability in the calibration course. The volumes of these samples obtained by the conventional water displacement method and the proposed 3D scanning method have been listed in Table 1.

Table 1: of Volume of the Samples by Water Displacement vs. 3D Scanning Method

Sample No	Volume of Water Displaced (ml)	Volume by 3D Scanning Method (mm^3)	Volume by 3D Scanning Method (ml)
6	14.0	15664.80	15.66
9	15.0	15479.85	15.48
11	14.8	15234.30	15.23
12	15.5	15629.25	15.63

The results show that the volume obtained by these two different methods for each sample is very close numerically as seen from Figure 1. The volume obtained by displacement was observed to be lesser than that by the 3D scanning method, probably due to the absorption of some water when the dry soil sample was sunk in the beaker of water during the displacement method. The software displays the volume in cubic millimeter with high accuracy, up to 1/100th value. The parallax error while reading the value of the water level from the calibrated measuring cylinder can be a possible source of error in the conventional method.

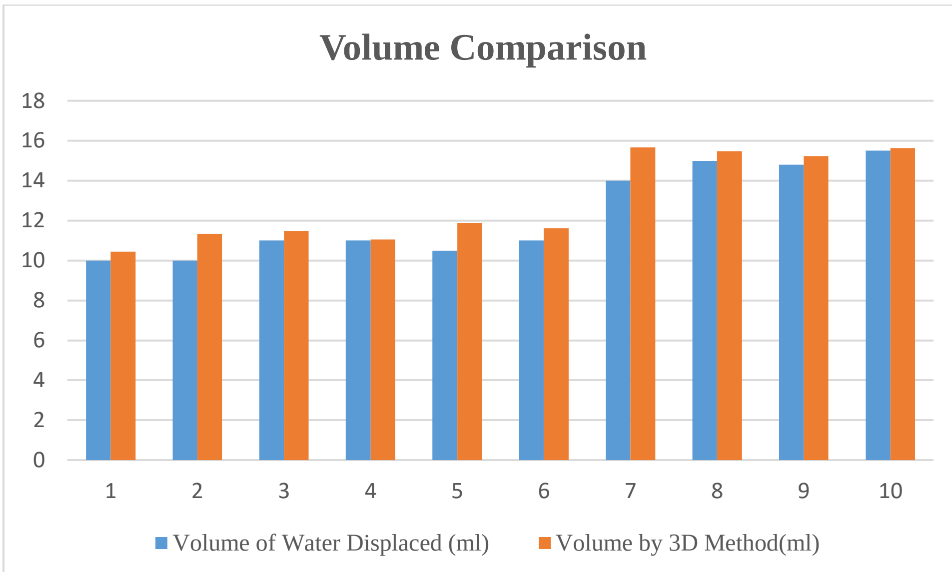

Figure 1: Volume of Dried Soil Samples by two Different Methods

The Table 2 presents the moisture content (%), volume of dry sample by water displacement method (ml) as well as 3D scanning method (mm^3 and ml), and the Shrinkage Limit (%) for each sample by these two different methods for each sample prepared by using the pure Bentonite clay. The percentage difference in the numerical values of SL and volume by these two different methods are also listed in the table. The values of volume and shrinkage limit obtained are very close numerically. The percentage difference for volume ranges from 0.46% (Can 4) to 12.57% (Can 2) and for SL ranges from 1.70% (Can 4) and 32.32% (Can 2). The volumes for the oven dry samples (Can 1 and Can 2) are lower than those for air dry samples (Can 3 and Can 4) as expected for both the methods. This justifies the theoretical and experienced implication that the shrinkage limit will be greater for the dry oven sample, and verified by the experimental results as observed in Table 2 and Figure 2.

Table 2: Volume and SL comparison in Bentonite by Conventional and Proposed Method

Sample	Moisture Content (%)	Volume of Water Displaced (ml)	Volume by 3D Method (mm^3)	Volume by 3D Method (ml)	SL_{sm} (%)	SL_{3D} (%)	$\Delta\%_{vol}$	$\Delta\%_{SL}$
Can 1	69.70	10.0	10438.40	10.44	27.20	30.13	4.29	10.22
Can 2	60.00	10.0	11341.60	11.34	21.92	30.37	12.57	32.32
Can 3	60.00	11.0	11484.60	11.48	21.31	24.37	4.31	13.36
Can 4	55.56	11.0	11050.40	11.05	17.96	18.27	0.46	1.70

The shrinkage limits obtained by spray coating method and the 3D scanning method are plotted in horizontal bar graph in Figure 2, allows to comprehend the resemblance between these two methods.

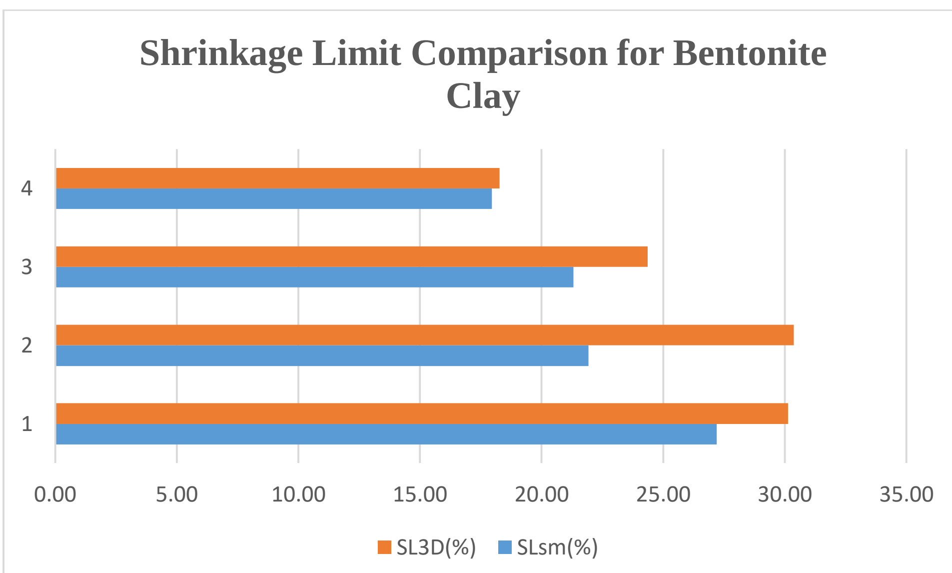

Figure 2: Shrinkage Limit of Bentonite clay by two Different Methods

The pattern follows for the volume and SL of different samples of 20% Sand and Bentonite mixture, but due to the presence of the sand the dry oven samples (Can 1 and

Can 2) were really cracked. The water displacement method is not convenient to get the volume of such cracked samples. Without the 3D scanning method, these samples would be wasted. However, the 3D scanner can be used even for such cracked samples, and saves the time and effort in getting the SL and volume of oven dry samples.

Table 3: Volume and SL comparison in 20% Sand and Bentonite by Conventional and Proposed Method

Sample	**Moisture Content (%)**	**Volume of Water Displaced (ml)**	**Volume by 3D Method (mm^3)**	**Volume by 3D Method (ml)**	**SL_{sm} (%)**	**SL_{3D} (%)**	$\Delta\%_{vol}$	$\Delta\%_{SL}$	
Can 1	57.14	-	10908.60	10.91	-	22.80	-	-	
Can 2	51.43	-	10404.42	10.40	-	15.90	-	-	
Can 3	55.56	10.5	11891.56	11.89	14.88	23.40	12.43	44.52	
Can 4	57.14	11.0	11613.00	11.69	18.48	22.34	5.42	18.92	

The comparison of the volume and SL in (Table 3) of the air-dry samples (Can 3 and Can 4) show the anticipated trend like in the Bentonite samples. The percentage difference for volume ranges from 5.42% to 12.43% and for SL ranges from 18.92% to 44.52% for Can 3 and Can 4 respectively. All these data and results support that the proposed 3D scanning method is more reliable, quick and economic in determining the volume of dry soil samples, and then shrinkage limit. The accuracy and the efficiency as evidenced by the experimental results conceives that the 3D scanning method can be used in replacement of conventional spray coating method or wax method.

The human errors like parallax error, misreading and misreporting of the data in the experimental procedure as well as the instrumental errors such as weighing and volumetric instruments at the multiple steps involved in conventional methods can be easily avoided by one step based 3D Scanning method. The 3D scanning methods can be improved to minimize the instrumental errors by adjusting the lighting of the lab, distance of the sample from scanner, speed of the turntable, and the scope of the scanning light projected from the scanner. The accuracy and the precision in modeling the 3D scanned object, and then obtaining the volume (and other parameters such as surface area, dimensions, etc.) can be customized as required.

3. Conclusion and Recommendation

The recent technological development in 3D scanning and 3D printing tools/techniques can be applied in geotechnical researches to replace the conventional methods which are tedious and inconvenient. The volume calculation by water displacement method can be replaced by the 3D scanning method, which simplifies many associated tests in the laboratories. The experiments that compared and contrasted the determination of the shrinkage limit of fine grained soils as explained above signifies the convenience, the accuracy, and the economic aspect of 3D scanning methods over the conventional methods. More samples can be analyzed with the variation of the mixture contents by amount and soil type to ensure the reproducibility of the test results. The 3D scanning method is not only suitable to obtain the results in the laboratory but also to preserve the models in a database in economic and safer way. These 3D-modeled objects (samples) can be printed whenever required.

It is recommended to study and compare the results obtained with a higher number of turntable rotations while scanning the samples. The solid and smooth objects (whose volume can easily calculated theoretical geometry) can be scanned to understand any discrepancies occurring during the 3D modeling, subsequent extraction of volume by the software such as CREO or SOLIDWORKS.

4. List of References

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5. Appendices

A. Sample Calculations [Bentonite Can 1]

A1 Moisture Content of the Soil

$$w = \frac{W - W_o}{W_o} \times 100$$

W = Mass of [can & moist soil – empty can] = Mass of Moist Soil = 0.056 lb = 25.40 g

W_o= Mass of [can& dry soil – empty can] = Mass of Dry Soil = 0.033 lb = 14.97 g

$w = \frac{25.40 - 14.97}{14.97} \times 100$ = 69.70 %

A2 Volume of Wet Soil Sample

The volume of wet or moist soil sample is same as the volume of standard calibrated can volume. Because it was repeatedly used the shape/volume might have changed. Therefore three measurements were taken with digital Vernier's Calipers for the average inner diameter (D) and the average depth (h) to find the volume.

$$V_o = \frac{\pi D^2 h}{4}$$

$$V_o = \frac{\pi * 1.642^2 * 0.472}{4} in^3 = 0.998 in^3 = 16360.521 mm^3 = 16.36\, ml \approx 17.60\, ml\ (Standard)$$

A3 Volume of Dry Soil Sample by Spray Coating Method

The spray coating was applied to the dried soil sample to make it water-proof and the change in weight was negligible, so the volume of coating spray was neglected to find the volume of the dry soil sample by the volume displacement method. The volume of water displaced by the dry soil sample when placed in the beaker containing 80 ml of water is considered the volume of dry sample.

V_{sm}= 10 ml

A4 Volume of Dry Soil Sample by 3D Scanning Method

The 3D Scanned soil samples were made solid using the MESHMIXER software by AutoDesk, which were then analyzed using the CREO by PTC and the SOLIDWORKS by Dassault Systems to find the volume. The inner cracks were filled and the bottom surface was extrapolated to be roughly smooth in this process.

V_{3D}= 10438.40 mm^3 = 10.44 ml

A5 Shrinkage Limit by Spraying Method

$$SL_{sm} = w - \frac{V_o - V_{sm}}{W_o} \times 100$$

$SL_{sm} = 69.70 - \frac{16.36-10}{14.97} \times 100 = 27.20$ %

A6 Shrinkage Limit by 3D Scanning Method

$$SL_{sm} = w - \frac{V_o - V_{3D}}{W_o} \times 100$$

$SL_{3D} = 69.70 - \frac{16.36-10.44}{14.97} \times 100 = 30.13$ %

A7 Percentage Difference

The percentage difference with respect to the conventional spray coating method for the volume and shrinkage limit (SL) were calculated using the following equations.

$$\Delta\%_{vol} = \frac{|V_o - V_{3D}|}{\frac{V_o + V_{3D}}{2}} \times 100$$

$$\Delta\%_{SL} = \frac{|SL_{sm} - SL_{3D}|}{\frac{SL_{sm} + SL_{3D}}{2}} \times 100$$

$$\Delta\%_{vol} = \frac{|10 - 10.44|}{\frac{10 + 10.44}{2}} \times 100 = 4.29\ \%$$

$$\Delta\%_{SL} = \frac{|27.20 - 30.13|}{\frac{27.20 + 30.13}{2}} \times 100 = 10.22\%$$

B. Lab Apparatus and Sample Preparation

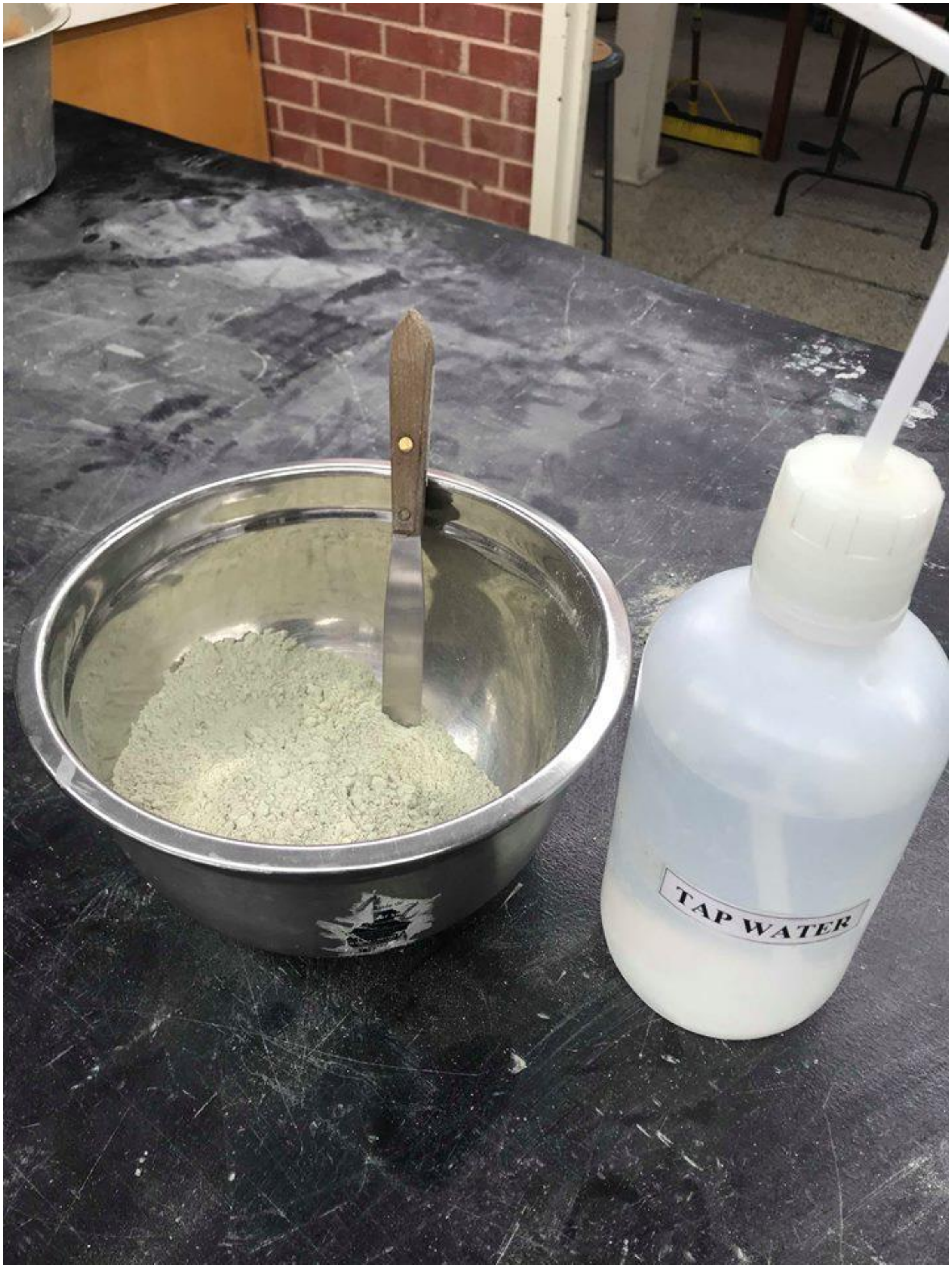

Image B1: Bentonite Clay, Tap Water and Instruments used in Sample preparation

Image B2: The Wet Samples being Air-Dried in the Lab

Image B3: The Wet Samples being Oven-Dried in the Lab

Image B4: The Oven-Dried Samples being cooled to Room Temperature

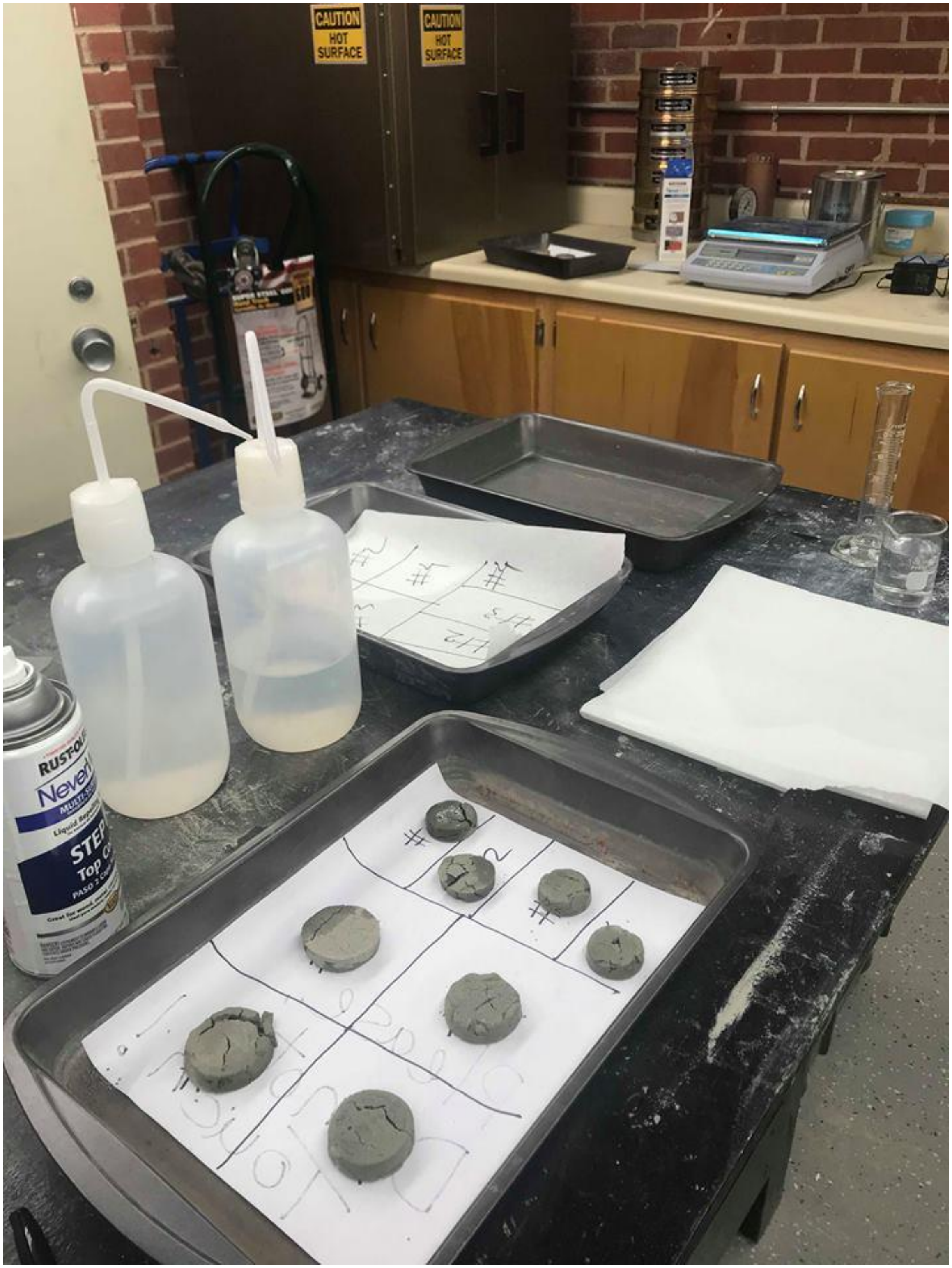

Image B5: The Dried Samples being prepared for Water-proofing by Spray Coating

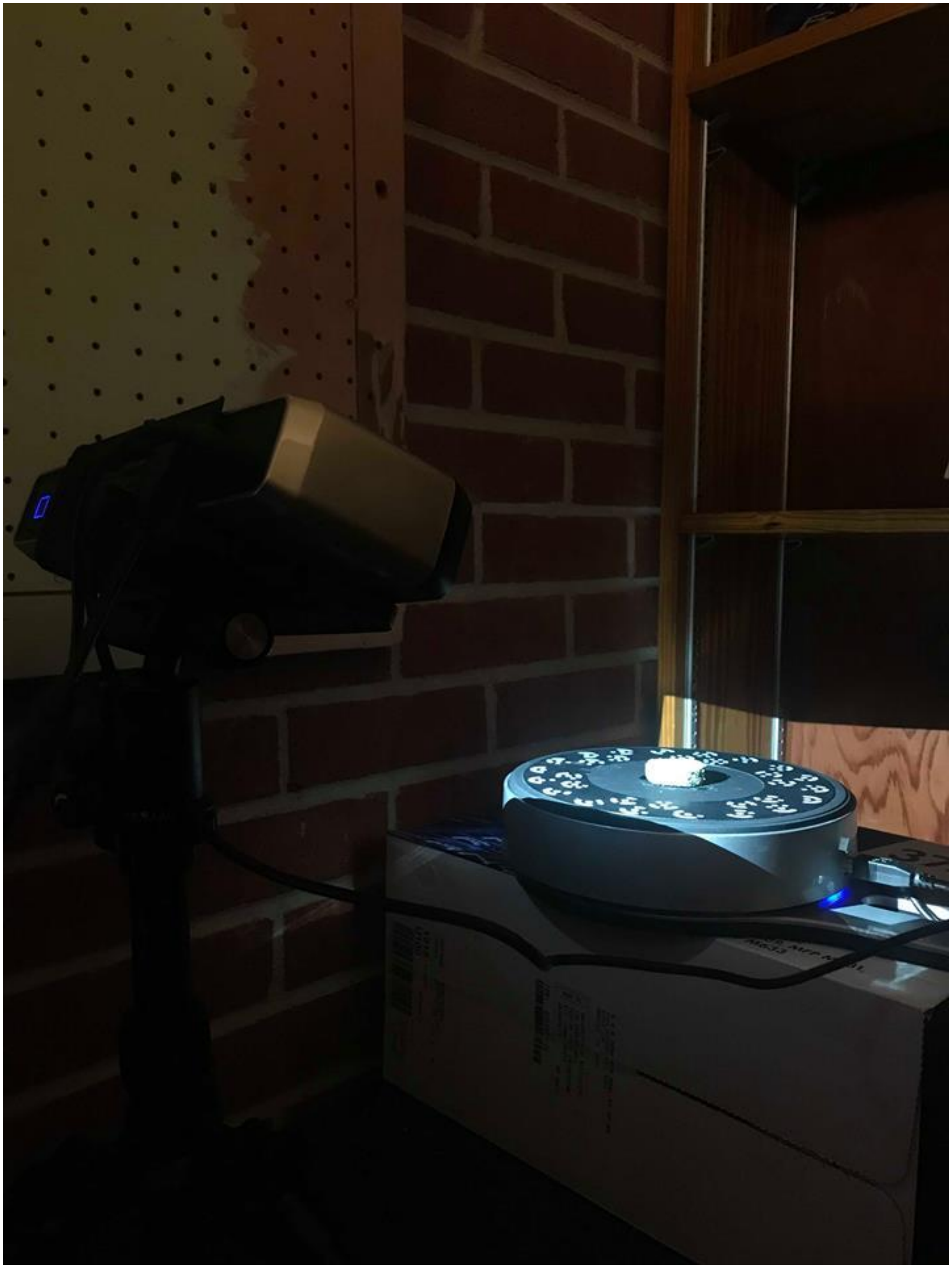

Image B6: The Dried Sample undergoing 3D scanning on turntable

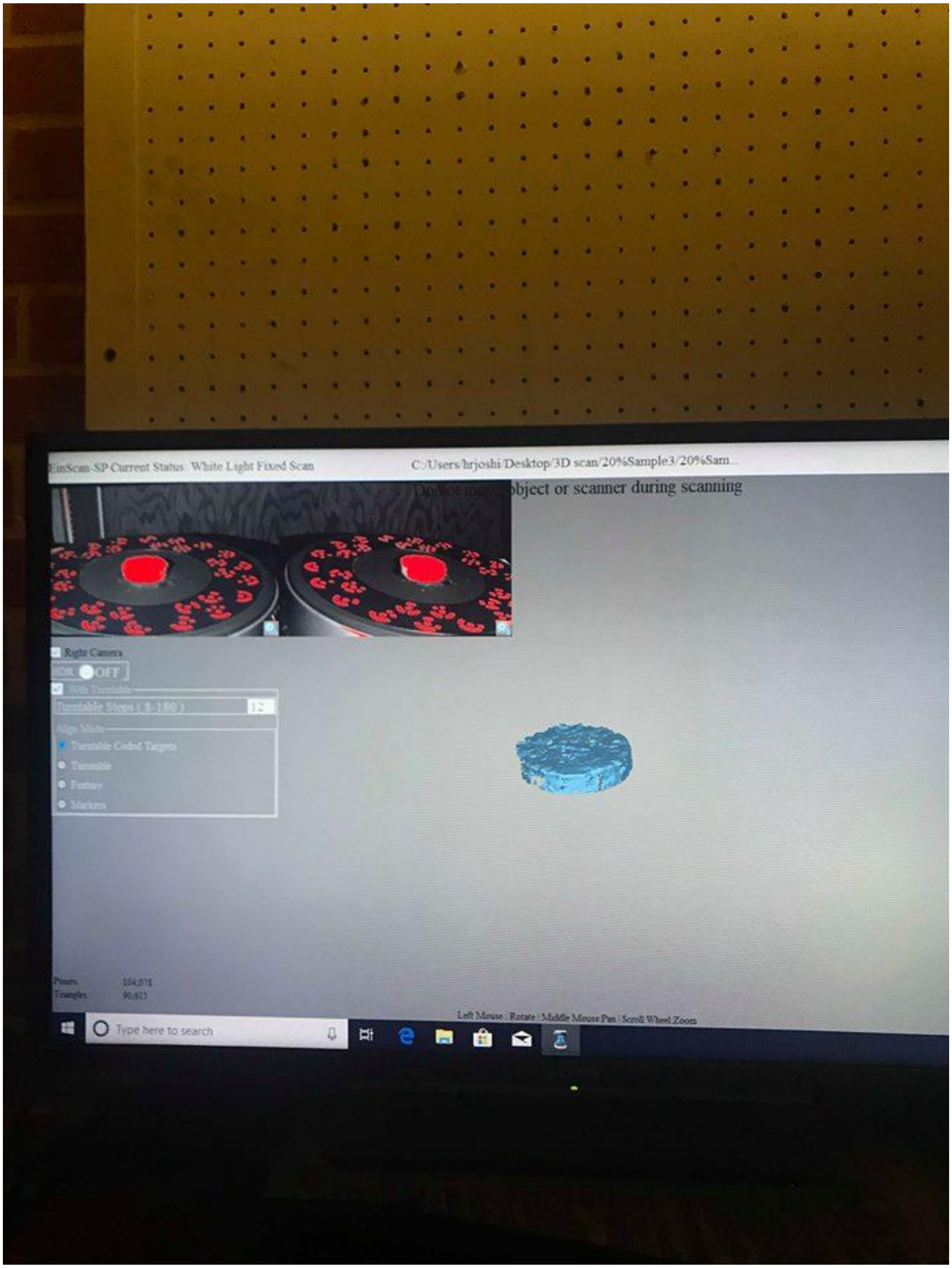

Image B6: The Dried Sample undergoing 3D scanning On-screen View

C. Volume Calculation in CREO by PTC

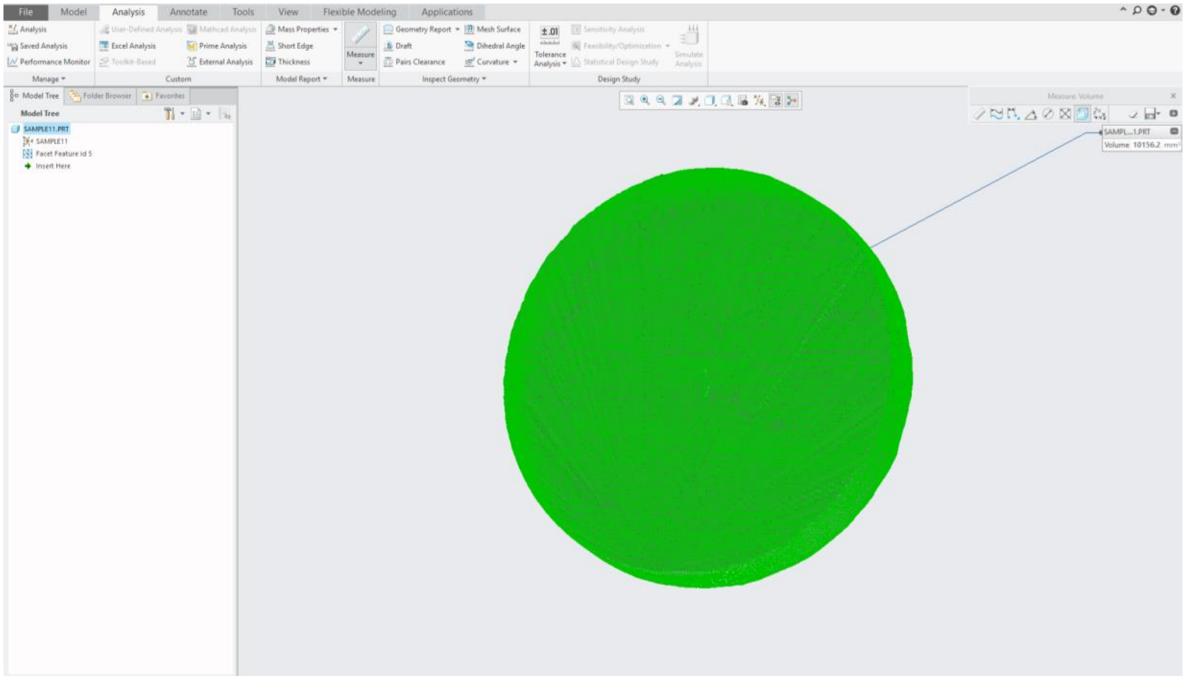

Image C1: The Volume of 3D Soil Sample 6 displayed by the CREO

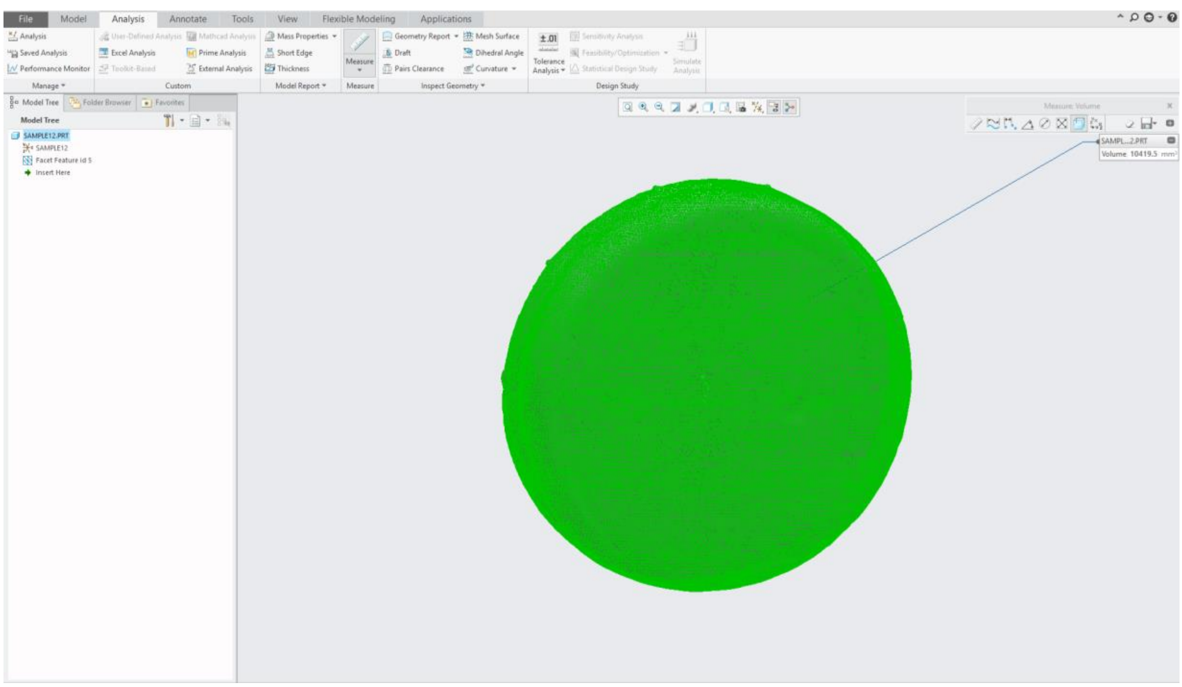

Image C2: The Volume of 3D Soil Sample 9 displayed by the CREO

D. Excel Worksheet for Data Collection and Result Calculations

	Inner Diameter (in)			Depth (in)			Average Diameter (in)	Average Depth (in)	Volume of Can (in^3)	Volume of Can (mm^3)	Volume of Can (ml)	Mass of Empty Can (lb)	Mass of Glycyrinced Can (lb)	Mass of Can + Wet Soil (lb)	Mass of Can + Dry Soil (lb)	Mass Wet Soil (lb)	Mass Dry Soil (lb)	Mass Dry Soil (gm)	Mass of Water (lb)
	D1	D2	D3	H1	H2	H3													
Can1	1.625	1.647	1.653	0.483	0.462	0.47	1.642	0.472	0.998	16360.521	16.36	0.045	0.045	0.101	0.078	0.056	0.033	14.969	0.023
Can2	1.634	1.641	1.653	0.466	0.455	0.465	1.643	0.462	0.979	16044.746	16.04	0.045	0.045	0.101	0.08	0.056	0.035	15.876	0.021
Can3	1.641	1.656	1.649	0.489	0.49	0.491	1.649	0.490	1.046	17141.696	17.14	0.045	0.045	0.101	0.08	0.056	0.035	15.876	0.021
Can4	1.655	1.651	1.648	0.487	0.49	0.488	1.651	0.488	1.046	17138.699	17.14	0.045	0.045	0.101	0.081	0.056	0.036	16.329	0.02

Image D1- Data and Preliminary Results for Bentonite Samples

	Inner Diameter (in)			Depth (in)			Average Diameter (in)	Average Depth (in)	Volume of Can (in^3)	Volume of Can (mm^3)	Volume of Can (ml)	Mass of Empty Can (lb)	Mass of Glycyrinced Can (lb)	Mass of Can + Wet Soil (lb)	Mass of Can + Dry Soil (lb)	Mass Wet Soil (lb)	Mass Dry Soil (lb)	Mass Dry Soil (gm)	Mass of Water (lb)
	D1	D2	D3	H1	H2	H3													
Can1	1.625	1.647	1.653	0.483	0.462	0.47	1.642	0.472	0.998	16360.521	16.36	0.045	0.045	0.1	0.08	0.055	0.035	15.876	0.02
Can2	1.634	1.641	1.653	0.466	0.455	0.465	1.643	0.462	0.979	16044.746	16.04	0.045	0.045	0.098	0.08	0.053	0.035	15.876	0.018
Can3	1.641	1.656	1.649	0.489	0.49	0.491	1.649	0.490	1.046	17141.696	17.14	0.045	0.045	0.101	0.081	0.056	0.036	16.329	0.02
Can4	1.655	1.651	1.648	0.487	0.49	0.488	1.651	0.488	1.046	17138.699	17.14	0.045	0.045	0.1	0.08	0.055	0.035	15.876	0.02

Image D2- Data and Preliminary Results for 20% Sand mixed with Bentonite Samples