

Geotechnical tests on Asteroid Simulant Orgueil

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I. Introduction

In the last 100 years, the global population has more than quadrupled to over seven billion people. At the same time, the demand for food and standard of living has been increasing which has amplified the global water use by nearly eight times from approximately 500 to 4000 km³ yr⁻¹ from 1900 to 2010 [1]. With the increasing concern to sustain the growing population on Earth it is necessary to seek other approaches to ensure that our planet will have resources for generations to come. In recent years, the advancement of space travel and technology has allowed the idea of mining asteroids with resources closer to becoming a reality. During the duration of the internship at NASA Kennedy Space Center, several geotechnical tests were conducted on BP-1 lunar simulant and asteroid simulant Orgueil. The tests that were conducted on BP-1 was to practice utilizing the equipment that will be used on the asteroid simulant and the data from those tests will be omitted from report.

Understanding the soil mechanics of asteroid simulant Orgueil will help provide basis for future technological advances and prepare scientists for the conditions they may encounter when mining asteroids becomes reality in the distant future. Distinct tests were conducted to determine grain size distribution, unconsolidated density, and maximum density. Once the basic properties are known, the asteroid simulant will be altered to different levels of compaction using a vibrator table to see how compaction affects the density. After different intervals of vibration compaction, a miniature vane shear test will be conducted. Laboratory vane shear testing is a reliable tool to investigate strength anisotropy in the vertical and horizontal directions of a very soft to stiff saturated fine-grained clayey soil. [2] This test will provide us with a rapid determination of the shear strength on the undisturbed compacted regolith [2]. The results of these tests will shed light on how much torque is necessary to drill through the surface of an asteroid.

Most of the known asteroids are believed to be left over material during the formation of the solar system that never accreted to form planets [3]. Asteroids can be found in several groups such as Trojan Asteroids, Near Earth Asteroids (NEA's) and the main asteroid belt. The Trojan Asteroids orbit the 4th and 5th Lagrange points of major planets in the Solar System while the NEA's have orbits that are close to and sometimes intersect with Earth's orbit and the Main Asteroid Belt which is found between the orbit of Mars and Jupiter. Gravitational perturbations can alter the orbit of asteroids in the Main Asteroid Belt causing them to move closer to earth causing them to become in the NEA class.

Asteroids typically fall into three broad categories: C-type (carbonaceous); M-type (metallic) and S-type (stony). C-type meteorites can be categorized as CI type or CM type. CI chondrites are a group of rare stony meteorites belonging to the carbonaceous chondrites and can contain between 17% - 22% water [4]. For the sake of the experiment the asteroid simulant Orgueil will be used which is a common CI-type asteroid. CI-type asteroids are of most importance due to the volatiles such as water. CI-type asteroids are the most within our galaxy and are made of carbonaceous clay and silicate rocks. In this experiment Orgueil simulant created by NASA and UCF will be used because of its rich composition in volatiles [5]. Orgueil simulant was created to replicate the Orgueil meteorite which is a carbonaceous chondrite meteorite that fell in southwestern France in 1864. The volatiles found on asteroids can be processed to make propellant fuel H₂ and oxygen which avoids the need to haul fuel from Earth. For example, it takes 226 kg of propellant to send 1 kg of propellant to Mars [6]. With these costs and payloads associated with sending supplies to Mars it makes colonizing space an extremely difficult task. If we could create our own propellant, water, and oxygen from the resources on asteroids it will have multiple benefits that would streamline the idea of colonizing the Moon and Mars such as decreasing the payload for each launch, decreasing the number of launches, reducing dependence on Earth and increasing the distance and length of human exploration missions [6].

NASA's In Situ Resource Utilization (ISRU) program was created to harness and use resources wherever we go in space and to create products and services that would reduce the mass, cost and risk of robotic and human exploration [7]. ISRU's goal is to increase performance and allow new missions to develop without the need to bring everything from Earth which would greatly reduce the direct expense of the mission. ISRU is building toward self-sufficiency of long-duration space bases which would expand our exploration efforts and allow for the commercialization of space.

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Utilizing newly proposed technology, landings can be made on asteroids, and samples can be taken that can be studied for composition and to determine which resources are available. Asteroids moving closer to earth’s orbit can allow spacecraft to land on the asteroid to determine if resources are available to mine. If an NEA is sampled and deemed mineable we can redirect the asteroid into a stable orbit to make it safer to mine since NEAs pass by Earth rapidly and do not return for decades. Mining nearby asteroids could lengthen the exploration mission and reduce initial payload which lowers mission cost.

II. Technical Methods

During my internship at NASA Kennedy Space Center, I was able to measure several geotechnical properties of the Orgueil simulant. In the beginning of the Internship at Kennedy Space Center the Swamp Works lab received a new particle size and shape analyzer. To become comfortable with the equipment several samples of BP-1 regolith were examined with the particle size and shape analyzer.



Figure 1. Microtrac PartAn Mini used to analyze Orgueil simulant

The first geotechnical test conducted on asteroid simulant Orgueil was a particle shape analyzation and grain size distribution using the Microtrac PartAn Mini particle analyzer. The PartAn Mini can evenly disperse fine, cohesive powders for accurate particle size and shape measurements by utilizing compressed air. The PartAn Mini measures from 4 to 4500 microns and can also take an image of the individual particles as they move through the machine. During the particle testing of the simulant close examination of the particles sphericity, length/width ratio, width distribution, length distribution and volume distribution.

Once the particles of the Orgueil simulant has been studied, to better understand Orgueil, the theoretical density was calculated. Density is one of the fundamental properties of matter which is determined by the mass per unit volume. The mass can be calculated by the atomic masses of the elements that make up the simulant Orgueil, while the volume is a physical

arrangement of those elements into crystalline forms. The arrangement of the elements within the granular simulant can cause the simulant’s density to deviate from the theoretical value of a perfect crystal. To determine if the theoretical density was different from the actual density a geotechnical test was preformed to determine the unconsolidated density and the maximum density of Orgueil. This was done by filling the simulant Orgueil in different sized beakers and graduated cylinder’s.

Mineral	Percentage	Density
Coal	5%	1.6 g/cm ³
Smectite	5%	2.35 g/cm ³
Epsomite	6%	1.67 g/cm ³
Pyrite	6.5%	5.01 g/cm ³
Olivine	7%	3.22 g/cm ³
Vermiculite	9%	2.4 g/cm ³
Magnetite	13.5%	5.15 g/cm ³
Serpentine	48%	2.59 g/cm ³

Table 1. Constituents of asteroid simulant Orgueil and the densities

$$Theoretical\ Density\ (\rho_t) = \sum_{n=1}^N \rho_n x_n$$

Figure 2. Formula used to calculate the theoretical density of asteroid simulant Orgueil

$$Density\ (\rho) = \frac{mass}{volume}$$

Figure 3. Formula used to calculate the density of asteroid simulant Orgueil

Once the theoretical and maximum density tests were conducted the asteroid simulant was compacted for different time intervals on a Humboldt vibrating table. The use of the vibrating table will ensure uniform compaction of the regolith. To maximize compaction a 10-pound weight is set on top of a steel plate that is placed on the surface of the regolith. Once compaction is complete a miniature vane shear test will be conducted.

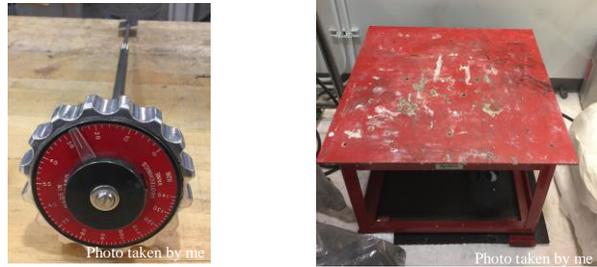


Figure 4. Left: Picture of Humboldt geovane shear soil strength tester Right: Picture of vibrating table used to compact samples

III. Results

Utilizing the Microtrac PartAn Mini we could determine several characteristics of the Orgueil simulant besides just the particle size distribution. We also analyzed the feret width, feret length and the area equivalent diameter. Feret width and length is not a width or length in its actual sense but the common basis of a group of diameters derived from the distance of two tangents to the contour of the particle in a well-defined orientation. Area equivalent diameter is an equivalent diameter corresponding to the diameter of a sphere passing through a sieve of defined mesh size with square or circular apertures.

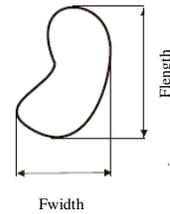


Figure 5. Feret width (Fwidth) and Feret length (Flength)

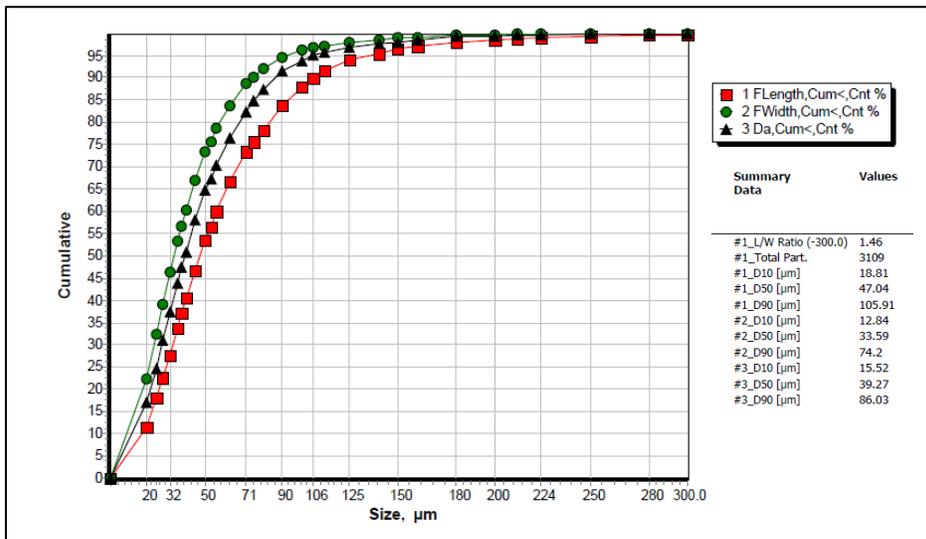


Figure 6. Results from the Microtrac PartAn Particle Analyzer

The figure above is displaying the results from the Microtrac particle analyzer. After analyzing over 3,000 particles from the Orgueil simulant we can notice several trends from the particle size distribution. The first thing that is noticeable is that the Fwidth of the particle is slightly larger than the Flength. The area equivalent diameter (Da) also follows the trend of the Flength and Fwidth. The particles of the Orgueil simulant range from spherical to ellipse shape. If the width and length of a particle are equal then the particle would be a perfect sphere. The size of the particles that make up Orgueil simulant range from 20µm – 300 µm. The average Flength in Orgueil is 47.04µm and the average Fwidth is 33.59µm with an average Da value of 39.27µm. The L/W ratio can range from 1 to infinity

where a value of 1 indicates a perfect sphere. With the value of 1.46, the particle is not a perfect sphere but it is round to ellipse shape which further confirms the data seen in figure 4.

Once the analyzation of particles was completed the density of the Orgueil simulant was the next test conducted. Precompacted densities of the simulant were measured by filling beakers with 100mL, 150mL and 200mL of simulant and recording their respective weights. By weighing the beaker before starting the test and weighing the beaker we could determine the mass to get the unconsolidated density value of 1.036 g/cm³. We could then empty the beaker and re-run the test to obtain more data points. During the density tests, we also determined the maximum density by running the same test in both a 30mL beaker and 250mL graduated cylinder. To determine maximum density the Orgueil simulant was added in small increments (about 15-20 grams) at a time and then compacted manually with a small rubber piece that would fit into the beaker and graduated cylinder. The maximum density for Orgueil simulant was about 1.62 g/cm³ – 1.77 g/cm³. This maximum density coincides with the density obtained by Consolmagno etc. al. at 1.58 g/cm³. Shown below are pictures of the graduated cylinder, beaker and rubber piece used to compact the regolith.

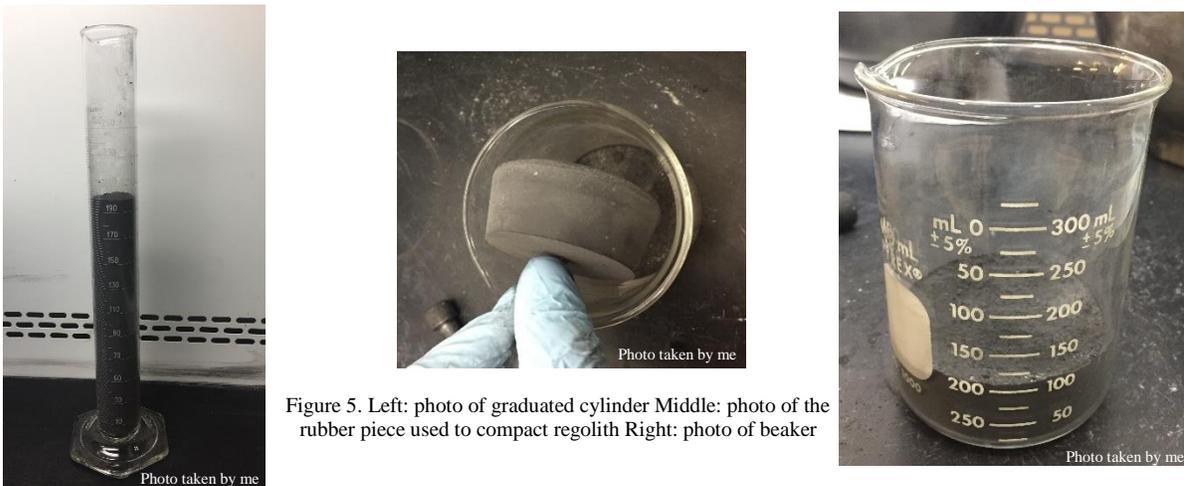


Figure 5. Left: photo of graduated cylinder Middle: photo of the rubber piece used to compact regolith Right: photo of beaker

A vibration experiment was ran where the Orgueil simulant was placed in a cylindrical sample holder about 12 inches tall and compacted with a vibrating table for several different intervals. After each vibrating interval a mini vane shear test was conducted with a geovane soil shear strength tester from Humboldt. Following the procedures and protocols from ASTM D4648/ D4648M-13 [9]. The test was conducted in the center of the sample to avoid any edge effects from the sample holder. Each interval will allow for two tests at the same location. One at the surface and another test below the surface to determine the torque necessary to drill about 4 inches below the surface.

30-minute vibration with 10 lb. weights		
Test Number	Date	Surface/Deep
1	3/1/17	32/54
2	3/1/17	30/50
3	3/1/17	30/42
4	3/2/17	36/43

1-hour vibration with 10 lb. weights		
Test Number	Date	Surface/Deep
1	3/2/17	43/65
2	3/2/17	32/52
3	3/2/17	32/46
4	3/3/17	34/56

2-hour vibration with 10 lb. weights		
Test Number	Date	Surface/Deep
1	3/3/17	34/46
2	3/6/17	32/42
3	3/8/17	32/44
4	3/9/17	32/50

4-hour vibration with 10 lb. weights		
Test Number	Date	Surface/Deep
1	3/14/17	34/42
2	3/15/17	32/46

4-hour vibration with 23 lb. in weights		
Test Number	Date	Surface/Deep
1	3/16/17	30/50
2	3/17/17	34/48

Table 2. The tables shown above are the results of the mini vane shear test at different intervals of vibration. The Surface/ Deep reading will be in kPa units

After examining the results of the compaction tests for the Orgueil simulant, it was noticeable that even though the sample is vibrated through different time intervals the torque necessary to break the surface of the simulant remains the same. I can't convert the readings from the geovane soil shear strength tester because the calibration chart has been misplaced. I am waiting on Humboldt to send NASA KSC a new copy so I can convert the torque

stress to kPa. The only test that shows that the stress increases with the interval of vibration is the 1-hour vibration test 1 result.

Although the test results show that the torque stress does not increase with vibration intervals, we believe that the vibrating table used did not compact the sample as efficiently as hoped. The next thing we would have liked to accomplish was vibrate the sample at the vibrating table in the cryolab at KSC where they can control the frequency at which the sample is vibrated and the sample can be vibrated horizontally and vertically. The vibrating table at the Swamp Works lab only vibrates in the vertical motion which could limit the compacting of the Orgueil simulant.

It is known that in space the asteroids encounter multiple conditions such as thermal cycling and solar winds which could also affect compaction making the torque stress needed to break the surface increase.

IV. Side Experiments

During the end of the internship at Kennedy Space Center we started a project in the cryolab. We placed the same sample holder used in the vibration compaction test in a cryofab (shown in figure 6) and attempted to replicate the conditions an asteroid would encounter in space. To track the temperature of the sample four K-type thermocouples were placed with the sample at different heights. By tracking the temperature of the sample we could monitor the sample to determine the length the thermal cycles need to be. Based on data obtained from asteroid Lutetia, the range of temperatures we are going to try to replicate is a low of -103.15°C and a high of -28.15°C .

The goal of the experiment is to simulate the thermal cycling conditions of a C-type asteroid using the Orgueil simulant. Using liquid nitrogen (LN_2), we cooled the sample down to about -177°C and then turned on a 500 watt halogen lamp to warm the sample to about -28°C at the top of the sample. The bottom of the sample holder had a steel plate to allow a contact point between the sample holder and cryofab allowing it to cool the sample efficiently from the bottom.



Figure 6. Left: The Cryofab used for the thermal cycling experiment
 Middle: The sample holder with the K-type thermocouples
 Right: Temperature meter showing temperatures for the thermocouples

After cooling and heating the sample for two days and examining the data from the thermocouples we could determine several things. The first noticeable thing is when we cover the top of the cryofab with LN_2 inside, the convection from the LN_2 cools the top of the sample at a much faster rate which could assist in shortening the length of the thermal cycle allow for more cycles in a shorter time. Analyzing the graph below we could notice that when the light is turned on the bottom of the sample is heating just as fast if not faster than the top of the sample. Since this is not a response we would expect to see when an asteroid rotates, we needed to alter the set-up to eliminate the heating at the bottom of the sample.

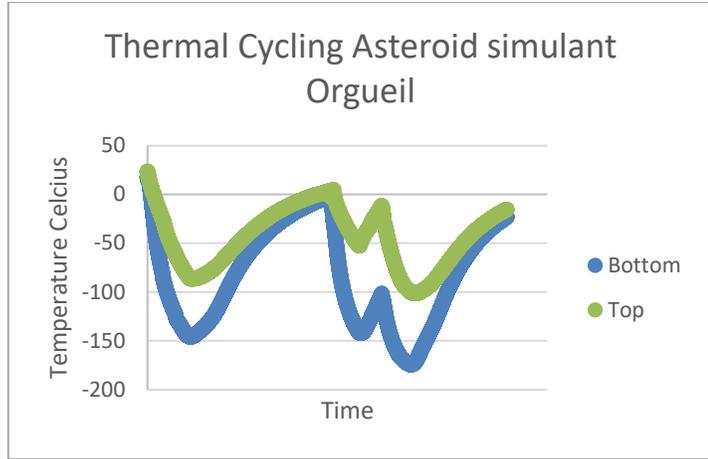


Figure 7. Left: The sample in the cryofab with LN₂ cooling sample
Right: Temperature meter data from cooling and heating the first time



After the first test one, we decided to try and block the light from penetrating into the bottom of the cryofab trying to limit the sample being heated from the top. We placed aluminum foil around the side of the sample holding creating a barrier to block the light. With the alteration of the set-up we decided to cool and heat the sample to determine if we eliminated the sample heating up from the bottom. After running the experiment and analyzing the temperature data, we noticed that we did not eliminate the heating of the sample on the bottom of the cryofab.

Another possible solution to preventing the sample from heating up at the bottom is to use spacers from some insulating material and place the sample holder on top of the spacers so the bottom plate of the sample holder does not touch the surface of the cryofab. We could also keep LN₂ inside the cryofab during the entire duration of the experiment to avoid the walls of the cryofab heating up and possibly find a cylindrical tube that would go under the light preventing any light from shining on the walls of the cryofab.

Figure 8. The second set-up for the thermal cycling experiment where we placed aluminum foil around the sample holder preventing light from shining on the bottom

V. Conclusion

During my internship at Kennedy Space Center I have had the privilege to work alongside NASA researchers on several projects. I enjoyed being a part of a team that is constantly on the forefront of innovation and technological advances. It was a great experience that allowed me to apply some of the concepts learned in the classroom to real projects. The staff at UB was more than pleasant with everyone willing to assist me on any task no matter how trivial. The UB-R1 staff was a very close knit group where you could notice immediately that everyone enjoyed their job and wanted me to get everything out of the internship possible. There was several days where they would organize tours for myself and other interns in UB-R1 taking us to the VAB, Apollo launch pad, Gemini launch pad, Mercury launch pad, the infamous astronaut beach house and the shuttle landing runway. Thank you for the opportunity of a lifetime to spend a semester at Kennedy Space Center.

VI. References

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Appendix

Calculations for the theoretical density

$$\textit{Theoretical Density } (\rho_t) = \sum_{n=1}^N \rho_n x_n$$

Calculations for the unconsolidated density

$$\textit{Density}_{100} (\rho) = \frac{100.8918 \text{ grams}}{100 \text{ mL}}$$

$$\textit{Density}_{100} (\rho) = 1.008918 \text{ g/cm}^3$$

$$\textit{Density}_{150} (\rho) = \frac{156.2 \text{ grams}}{150 \text{ mL}}$$

$$\textit{Density}_{150} (\rho) = 1.0413 \text{ g/cm}^3$$

$$\textit{Density}_{200} (\rho) = \frac{205.4 \text{ grams}}{200 \text{ mL}}$$

$$\textit{Density}_{200} (\rho) = 1.027 \text{ g/cm}^3$$

$$\textit{Density}_{200} (\rho) = \frac{215.6 \text{ grams}}{200 \text{ mL}}$$

$$\textit{Density}_{200} (\rho) = 1.078 \text{ g/cm}^3$$

Calculations for the average unconsolidated density

$$\textit{average unconsolidated density } (\rho) = \frac{\rho_{100} + \rho_{150} + \rho_{200} + \rho_{200}}{4}$$

$$\textit{average unconsolidated density } (\rho) = 1.036 \text{ g/cm}^3$$

Calculations for the maximum density in 300 mL beaker

$$\textit{Density}_{100} (\rho) = \frac{167.0282 \text{ grams}}{100 \text{ mL}}$$

$$\textit{Density}_{100} (\rho) = 1.67 \text{ g/cm}^3$$

$$\textit{Density}_{125} (\rho) = \frac{199.2186 \text{ grams}}{125 \text{ mL}}$$

$$\textit{Density}_{125} (\rho) = 1.59 \text{ g/cm}^3$$

$$\text{Density}_{150} (\rho) = \frac{240.0431 \text{ grams}}{150 \text{ mL}}$$

$$\text{Density}_{150} (\rho) = 1.60 \text{ g/cm}^3$$

Calculations for the average maximum density in 300 mL beaker

$$\text{average maximum density } (\rho) = \frac{\rho_{100} + \rho_{125} + \rho_{150} +}{3}$$

$$\text{average maximum density } (\rho) = 1.62 \text{ g/cm}^3$$

Calculations for the maximum density in 250 mL graduated cylinder

$$\text{Density}_{50} (\rho) = \frac{86 \text{ grams}}{50 \text{ mL}}$$

$$\text{Density}_{50} (\rho) = 1.72 \text{ g/cm}^3$$

$$\text{Density}_{74} (\rho) = \frac{130.4 \text{ grams}}{74 \text{ mL}}$$

$$\text{Density}_{74} (\rho) = 1.76 \text{ g/cm}^3$$

$$\text{Density}_{90} (\rho) = \frac{160.2 \text{ grams}}{90 \text{ mL}}$$

$$\text{Density}_{90} (\rho) = 1.78 \text{ g/cm}^3$$

$$\text{Density}_{110} (\rho) = \frac{198.2 \text{ grams}}{110 \text{ mL}}$$

$$\text{Density}_{110} (\rho) = 1.80 \text{ g/cm}^3$$

$$\text{Density}_{130} (\rho) = \frac{232.3 \text{ grams}}{130 \text{ mL}}$$

$$\text{Density}_{130} (\rho) = 1.79 \text{ g/cm}^3$$

$$\text{Density}_{150} (\rho) = \frac{268.8 \text{ grams}}{150 \text{ mL}}$$

$$\text{Density}_{150} (\rho) = 1.792 \text{ g/cm}^3$$

Calculations for the average maximum density in 250 mL graduated cylinder

$$\text{average maximum density } (\rho) = \frac{\rho_{50} + \rho_{74} + \rho_{90} + \rho_{110} + \rho_{130} + \rho_{150}}{6}$$

$$\text{average maximum density } (\rho) = 1.77 \text{ g/cm}^3$$

Microtrac PartAn Particle Size Analyzer Standard Operating Procedure

1. Turn on equipment before turning on computer software
2. Name of Software is PartAn Mini and Password is atdt47

This particle analyzer will read from 3 μ m to 4500 μ m. Any particle under 3 μ m will not be seen or photographed due to the fact the particle is smaller than a pixel size so it will collect the data but no photo will be taken

To conduct an analysis:

1. Choose SOP based on the particle being analyzed
2. Get material ready for analyzation
3. Use at least 1 mg
4. Type in sample identifier/name
5. Make sure the plastic cover is over the sample so the a/c in lab won't cause particles to go airborne
6. Click start

To change whether the particle is transparent or not go to SOP then click on particle measurement

To check the air pressure in the air-line go to SOP then FEEDER. This will display the amount of pressure in the air-line

To check focus on PartAn Mini:

1. Click on start analysis
2. Choose the glass cleaning SOP
3. Pull the wire out of plastic that is next to computer
4. Click start
5. Place the wire in the funnel
6. Once you see the wire on the computer screen if it is focused then the machine is working properly
7. If out of focus on the computer screen change the position of the image with the arrows on the right
8. Click 1:1 at the top of the screen to magnify the image of the wire and make focusing easier. Turn the key until a sharp focus is obtained
9. Click on FIT at the top line to remove agnification of the wire and view completed focusing