Ceres Regolith Simulant Material Property Testing

SUBMITTED BY:

Nicole Becker, Dustin Holley, Allie Lerman, Selim Odok,
Max Ofsa, Mark Puppo, Surahbi Srivastava, Todd Stefan,
Raeven Waters

AEROSPACE AND OCEAN ENGINEERING DEPARTMENT
VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
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FACULTY ADVISOR: Dr. Olivier Coutier-Delgosha
LAB TEACHING ASSISTANT: Viswajit Talluru

Abstract

The dwarf planetoid Ceres is the interest of space agencies like NASA for the unique geomorphology available. Questions concerning the early formation of planets in our solar system as well as the potential migration of Ceres from the outer solar system could be better understood from the exploration of this planetoid. Currently there are no available samples of Ceres surface to perform testing upon. Therefore, spacecraft hardware and proposed mission applications require the use of regolith simulants as an analog. This experiment outlines the procedures to test Ceres-like simulants for compressive, impact, and tensile strength. Using guidance from other simulant studies, two primary procedures are used in sample creation. The first sample intends to account for the dry sublimated surface of Ceres while the second sample is intended to mimic the frozen clay-like subsurface found immediately under the dry crust. We report the physical properties of these two sample types and compare their differences. The intent of this experiment is to provide base properties that may be used as guidelines for the creation of spacecraft intended to travel to Ceres.

Introduction

Ceres, a dwarf planet in the Main Asteroid Belt, is largely unexplored. The Dawn mission orbited Ceres in 2015 to gather general information about its structure and composition. The 2021 RASC-AL competition, hosted by NASA, challenges students to design a human mission to Ceres, requiring two crew members to land on its surface by 2050. To plan such a mission, more information is needed to address how equipment and crew members can safely interact with the dwarf planet's surface. Based on information gathered by Dawn, Ceres regolith can be modeled and tested on Earth. Knowledge gained from material and structural testing of Ceres regolith influences aspects of mission design such as lander design, payloads brought to Ceres, and crew interactions on the surface of Ceres.

To obtain a better understanding of the surface of Ceres, a series of experiments were performed on Ceres regolith simulant to obtain various physical properties of the material. These properties include tensile modulus of elasticity, compressive modulus of elasticity, and impact energy. For the samples in tension and compression, the Instron Universal Testing System was used to output sample displacement as load applied is increased. From these measurements along with the dimensions of the samples, the stress at each measurement is obtained with the following equation:

$$\sigma = \frac{F}{A} \tag{1}$$

In which, σ is the normal stress in Pa, F is the normal force in N, or load, on the sample either compressive or tensile, and A is the cross sectional area of the object to which the force is acting perpendicular in m^2 [1]. Additionally, the strain can be calculated from the displacement at each measurement with the following equation:

$$\epsilon = \frac{\delta}{L} \tag{2}$$

In which ϵ is the normal strain on the sample, δ is the measured displacement in mm, and L is the initial length of the sample in mm. Once the values for stress and strain are obtained, the modulus of elasticity is found. This is performed by plotting the stress versus strain, giving a graph with an initial section showing a linear relationship between strain and stress. The slope of this linear region is the modulus of elasticity as described by the equation below:

$$\sigma = E \cdot \epsilon \tag{3}$$

In which σ is the stress in Pa, ϵ is the strain, and E is the modulus of elasticity in Pa. This process can be applied to tension or compression, leading to the calculation of the compressive modulus of elasticity and the tensile modulus of elasticity. The modulus of elasticity, or Young's modulus is a material property which characterizes a material's resistance to deformation [2].

In addition to the modulus of elasticity, the fracture energy and impact resistance is found using the Charpy method. This method involves striking notched samples with a swinging hammer [3]. The Instron Impact Pendulum was used to obtain fracture energy. This measurement is equivalent to the minimum energy required to break a sample of a specific size and is obtained from the following equation:

$$E_f = E_0 \times \left(1 - \frac{h_{mr}}{h_0}\right) \tag{4}$$

In which E_f is the fracture energy in J, E_0 is the potential energy of the hammer before the release in J,h_0 is the vertical position of the hammer before the release in m, and h_{mr} is the vertical position of the hammer at the maximum rise after the impact in meters [3]. The impact resistance is the fracture energy divided by the width of the sample. By determining this parameter, more accurate predictions related to interactions with Ceres' surface are made. This informs the design of a Ceres lander system, crew interaction with the surface, and anchoring systems needed to mitigate microgravity.

Literature Review

As true Ceres soil samples do not currently exist, research was conducted on the creation, composition, testing, and validity of possible Ceres regolith simulants. It is theorized that Ceres regolith is composed of a mixture of Magnetite, Water Ice, Carbonates, Magnesium Serpentines, and Ammonia-bearing Phyllosilicates [4]. From this, an actual simulant composition can be determined and made.

The primary reference used in the design of this experimental study was that which created and tested simulant of Phobos' surface [5], an asteroid-moon of Mars suspected to be similar in composition to Ceres. Like Ceres, no samples of Phobos' surface exist on Earth. This paper discusses methods used to develop a Phobos simulant via the use of remote spectroscopy and angle of repose measurement to provide constraints on its mineralogy. The paper then describes methods of shear strength, compression, and tensile strength testing to be used on these simulants. The paper concludes by describing a number of other important values to be used when creating asteroid simulants.

Secondarily referenced experiments were the *"Investigation of the Mechanical Properties of Some Martian Regolith Simulants"* [6], *"Very Weak Carbonaceous Asteroid Simulants I"* [7], *"Lunar surface: Dust dynamics and regolith mechanics"* [8], and *"Measuring the Fidelity of Asteroid Regolith and Cobble Simulants"* [9]. All four papers describe the mechanical properties needed to be maintained in order to properly construct regolith samples, with the last expanding more on the parameters used by NASA in order to evaluate the validity of samples in testing. These papers were also useful in providing reference values for this experimental study, particularly those relating to Phobos Simulants PCA-1 and PGI-1, as well as C-class asteroids [5,8].

Sample Composition

Based on surface composition data gathered by the Dawn spacecraft, Ceres regolith composition by weight is hypothesized as 50% magnetite, 20% water, 16% carbonates, 8% magnesium-serpentines, and 6% ammonia-bearing phyllosilicates [10-12]. Due to safety and temperature limitations, the regolith simulant could not match the hypothesized Ceres regolith composition exactly. Mineral composition of the regolith simulant is specified in Table 1. The largest difference between the simulant and true regolith composition is related to ammonia-bearing phyllosilicates. Since these minerals are often toxic and unstable unless kept at low temperatures, they were not used in the regolith simulant. The exclusion of ammonia-bearing phyllosilicates is not expected to significantly alter the physical properties of the simulant.

Table 1. Ceres Regolith Sample Composition by Percent Weight.

Component	Weight Percentage (%)
Serpentine (antigorite/lizardite)	48.0
Magnetite	13.5
Vermiculite	9.0
Olivine	7.5
Pyrite	6.5
Epsomite	6.0
Coal, Sub-bituminous	5.0
Attapulgite	5.0

Sample Preparation Procedure

A standard preparation procedure was established and used for all tested samples. First, the regolith simulant was sifted to remove any large particles. This was done to standardize particle size and promote bonding between particles. Water was used as the bonding agent for all samples. For every 170 g of regolith sifted, 34 g of water was added creating a 5:1 simulate to water ratio. The regolith and water were mixed until a smooth, paste-like consistency was achieved. To eliminate any air pockets present, the mixture was placed in a vacuum chamber for 20 minutes. Following removal from the vacuum chamber, the mixture was packed into a standard ASTM aluminum mold specific to the mode of testing for the sample. The mold was then placed back in the vacuum chamber for another 20 minute period. After removal from the vacuum chamber, dry samples were left in the mold to air dry for 24 hours. Once air dried, they were baked on a 70℃ hotplate for 1 hour enclosed in a fume hood. For cold samples, after coming out of the vacuum chamber for a second time, they were placed in a -62℃ freezer for 24 hours. At the conclusion of the 24 hour period, they were transferred to the lab for testing using a cooler filled with dry ice.

Testing Procedure

The following procedure was followed for each individual sample. Although time was not a factor for dry samples at room temperature, cold samples had to be taken out of the cooler one at a time and tested quickly to maintain the samples' cold internal temperature.

Before testing, each sample's relevant dimensions were recorded:

- Tensile: width, thickness, and gauge length
- Compression: diameter and length
- Impact: width and thickness

After these measurements were taken, a dry sample was immediately tested. A cold sample, however, was subsequently submerged in liquid nitrogen for 1-2 minutes. During this time, if a compression test was to be performed, the testing instrument's compression platens were compressed onto a layer of dry ice to bring their temperature below room temperature. After submersion, the temperature of the cold sample was recorded using a Fluke T3000 FC Wireless K-Type Temperature Module. The cold sample was then immediately tested.

Two instruments were used for this experiment. For tension and compression tests, an Instron 5969 Dual Column Universal Testing System was used. The tensile rate and compression rate were both left constant at 2 mm/min. When testing a sample, the test was stopped after a noticeable drop in load and/or the sample failed. The compression platens and tensile grips were cleaned of sediment after each test. For Charpy impact tests, an Instron CEAST 9050 Impact Pendulum was used. A V notch was cut into each sample at the desired impact point to control the fracture location.

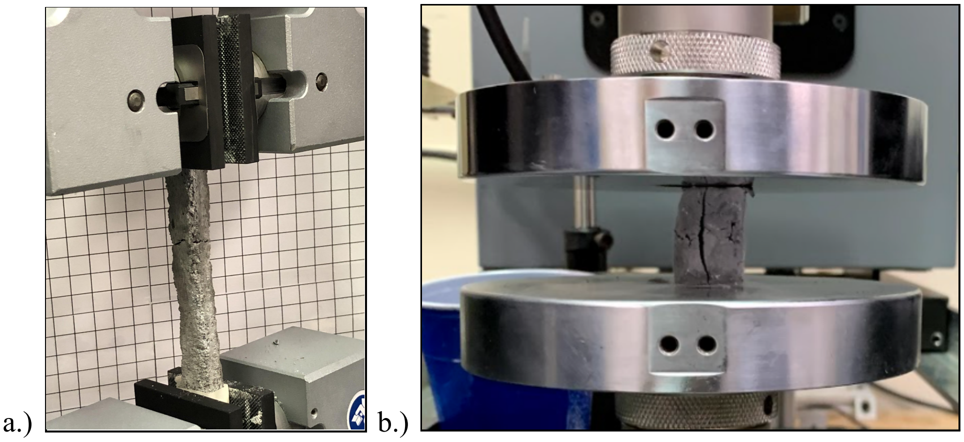
a.) b.)

Figure 1. a) Dry tension sample with fracture after testing. b) Cold compression sample with fracture after testing.

Dry Samples

Compression Samples

Compression, tension, and Charpy impact testing was completed and the results were analyzed. Compression tests were completed on fifteen dry cylindrical samples that were tested over a two day testing period. Sixteen samples were made in total, but only 15 survived. Eight of the most viable samples were chosen to analyze and are shown on Figure 2, however all sample data can be seen on Figure 3. The load-displacement graphs were generated by the Instron. From the load-displacement graphs, the stress-strain graphs were produced using Equations 1 and 2. The average peak stress for dry compression samples was 1.82 MPa. Using the linear section of the stress and strain graphs, the Young's Modulus was computed. The average Young's Modulus for the dry compression tests was 129.20 MPa. The peak stress values and Young's Modulus values are shown in Table 2.

Table 2. Peak Stress and Young's Modulus for dry compression samples. Sample names are denoted for their assigned sample number and day, (D3-Day3)

Sample	Peak Stress (MPa)	Young's Modulus (MPa)
2-D3	0.82	38.90
3-D3	1.97	64.90
4-D3	2.17	177.80
7-D3	1.26	67.90
3-D1	2.08	50.20
4-D1	2.21	84.10
5-D1	1.92	487.3
8-D1	2.14	62.70
Average	1.82 ± 0.515	129.20 ± 138.72

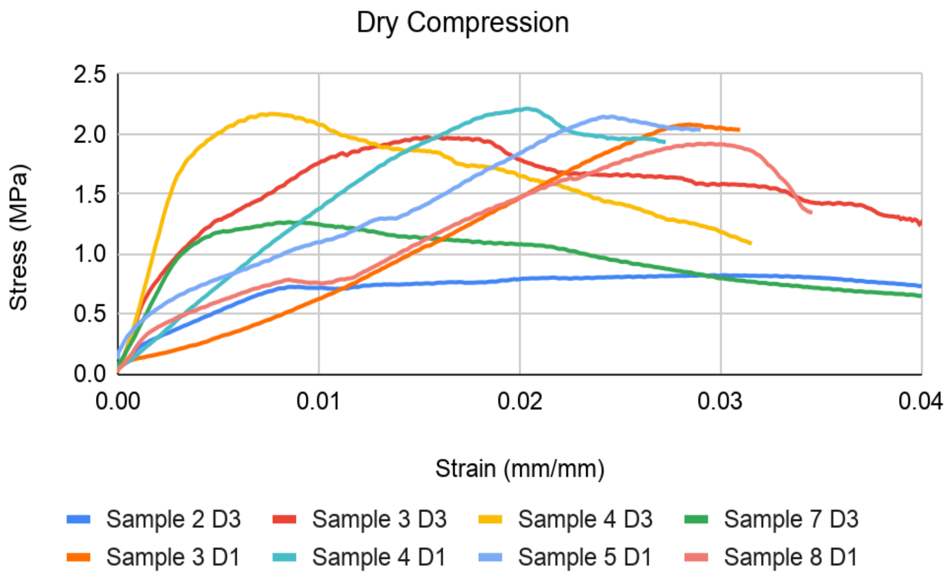

Figure 2. Stress-Strain plots for eight most consistent dry compression samples.

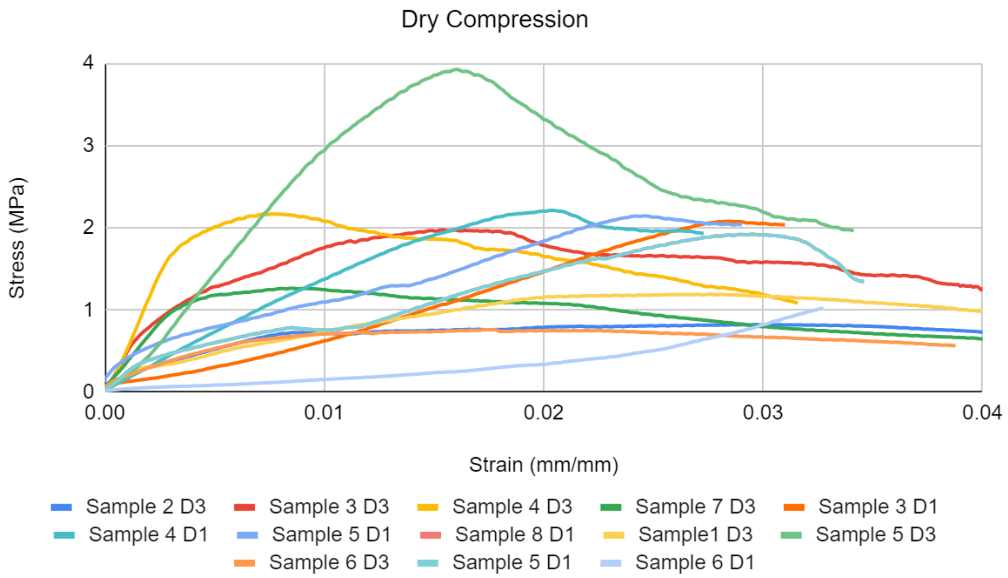

Figure 3. Stress-Strain plots for all dry compression samples.

<u>Tension Samples</u>

Using the Instron tensile testing configuration, 7 samples were successfully tested. The dogbone samples were significantly more brittle and fragile than the compression samples, therefore while 16 samples were made, only 7 of them made it to the test stand. The samples broke as a result of handling during the measurement period and the installation of the samples to the machine. Of the samples tested, 5 samples were recognized as the most viable and consistent for analysis. The stress-strain plots for these samples are shown in Figure 4. Of the most viable samples, the peak stress was 0.10 MPa, shown in Table 3. This stress is significantly smaller than the peak stress for the compression tests.

Table 3. Peak Stress among dry tensile samples

Sample	Peak Stress (Mpa)
1-D3	0.11
2-D3	0.16
3-D3	0.07
2-D1	0.04
3-D1	0.13
Average	0.10 土 .038

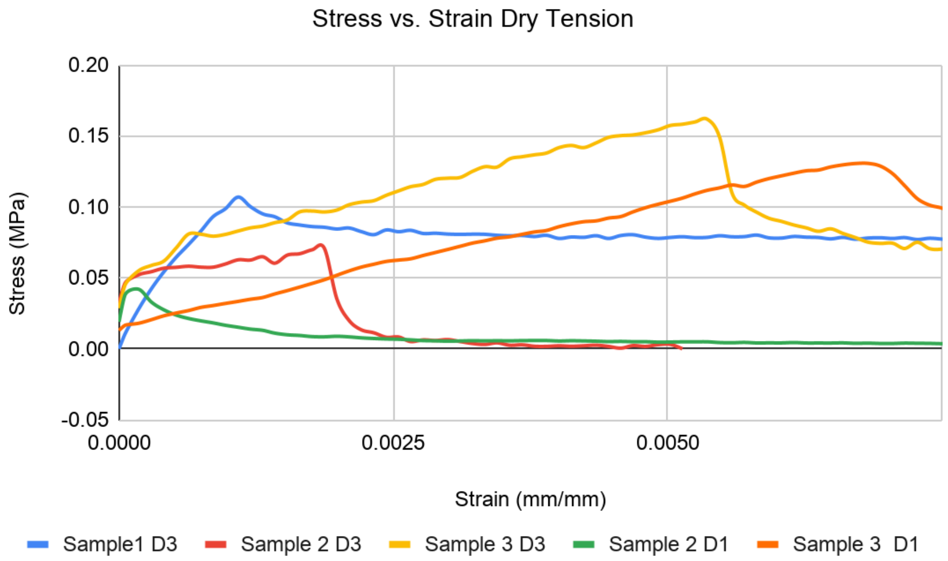

Figure 4. Stress-Strain for 5 most viable samples.

<u>Charpy Samples</u>

The rectangular, V-notch charpy impact sample samples were tested using the Charpy impact pendulum. Six out of the eight samples made were successfully tested. The width and thickness were recorded before the tests were performed. For the mission, the most important material characteristics from the Charpy impact test were the absorbed energy and the impact energy. These characteristics are shown in Table 4 along with the REL, RE, Impact Velocity and Impact Angle. The absorbed energy was

2.74% with an impact energy of .148 J. All available data was analyzed because there weren't significant outliers.

Table 4. Charpy impact test results of 6 dry samples.

Sample	Width (mm)	Thickness (mm)	Absorbed Energy (%)	REL (J/m)	RE (kJ/m^2)	Impact Energy (J)	Impact Velocity (m/s)	Impact Angle (°)
1	14.00	13.43	2.74	12.88	1.03	0.148	3.55	-144.10
2	13.46	13.38	3.21	15.10	1.21	0.174	3.76	-143.30
3	14.03	13.36	2.64	12.38	0.99	0.142	3.55	-144.30
4	14.14	13.77	4.18	19.63	1.57	0.226	3.76	-141.65
5	13.45	14.58	1.96	9.20	0.74	0.106	3.55	-145.65
6	13.69	13.88	1.70	7.97	0.64	0.092	3.76	-146.15
Average	13.80 ± 0.35	13.73 ± 1.21	2.74 ± 1.44	12.86 ± 6.77	1.03 ± 0.54	0.148 ± 0.078	3.65 ± 0.1	-144.19 ± 2.54

Cold Samples

In a manner similar to the dry samples, compression, tensile, and Charpy tests were conducted on the cold samples prepared and analyzed. Each of these tests enabled us to determine and understand the average Young's Modulus, peak stress, and behavior when impacted. The primary purpose of conducted cold samples was to simulate the behavior of the regolith in the low temperatures present on the surface of Ceres.

Compression Tests

A total of 16 compression samples were prepared of which only 4 were selected as they presented viable data points. The reduction in the sample size is a result of the inability to maintain a cold environment which caused samples to not only be destroyed before testing, but also weaken during testing. The four samples tested were able to completely undergo the compression tests and lead to reliable results. The peak stress and the calculated Young's modulus for each sample was found and is present in Table 5.

Table 5. Compression test results. The peak stress and the Young's modulus were calculated based on the test results.

Sample	Peak Stress (MPa)	Youngs (MPa)
1	21.454	2249.490
4	16.607	654.093
5	24.212	1114.034
7	19.713	550.966
Average	20.497 ±2.337	1142.146 ± 553.672

The average peak stress of the samples was found to be approximately 20.5 MPa and the Young's Modulus was calculated to be 1142.15 MPa. The stress-strain plots obtained for these samples are shown in Figure 5.

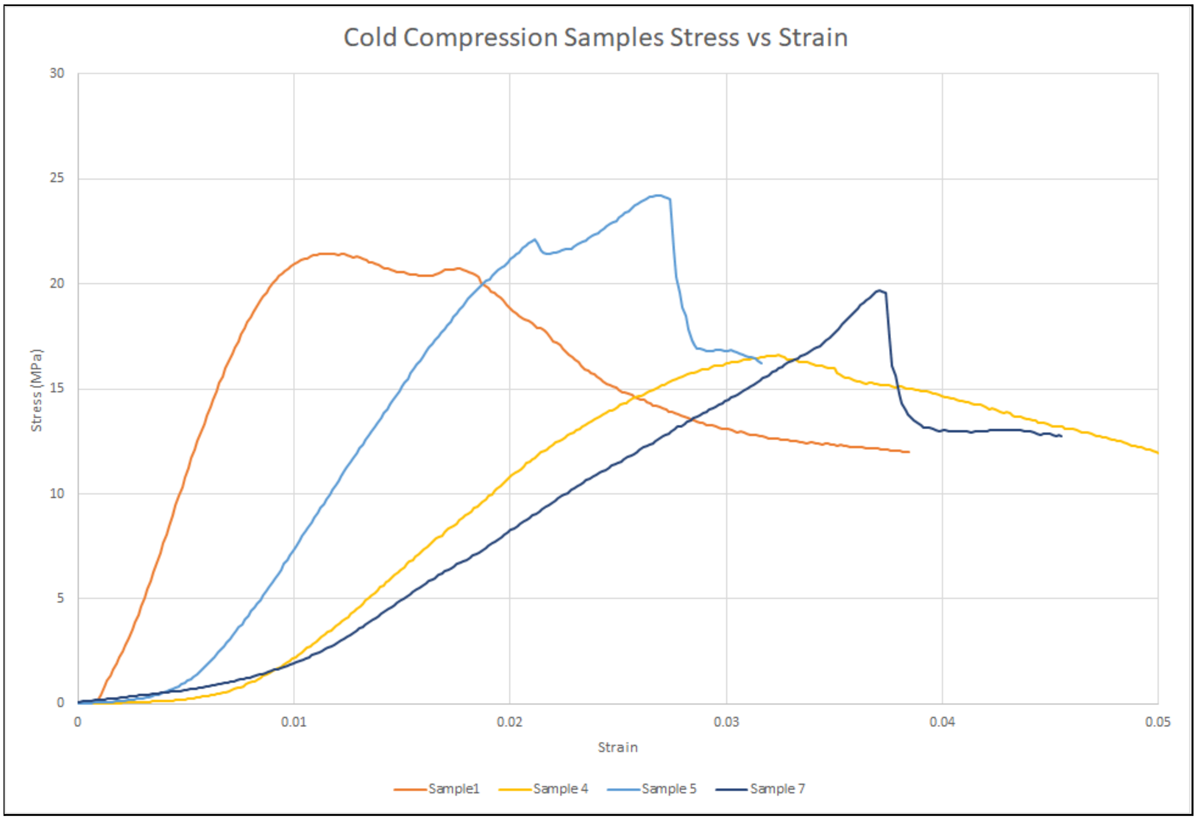

Figure 5. Stress-Strain plots for Cold Compression tests. All tested samples follow a similar trend as they first withstand the stress and then fracture.

Tension Test

There were multiple samples prepared for the tensile test of which only 8 samples were chosen for testing. This was because other samples either broke or sustained cracks before the test. Testing these samples would skew the results. Of the 8 tensile tests conducted, only four were selected to present viable data which is present in Table 6.

Table 6. Compression test results. The peak stress was calculated based on the test results.

Sample	**Peak Stress (Mpa)**
1	0.061
4	0.069
5	0.065
7	0.074
Average	0.067 ±0.0042

The average peak stress sustained by the tensile samples was 0.067 MPa. The stress-strain plots for these samples are present in Fig 6.

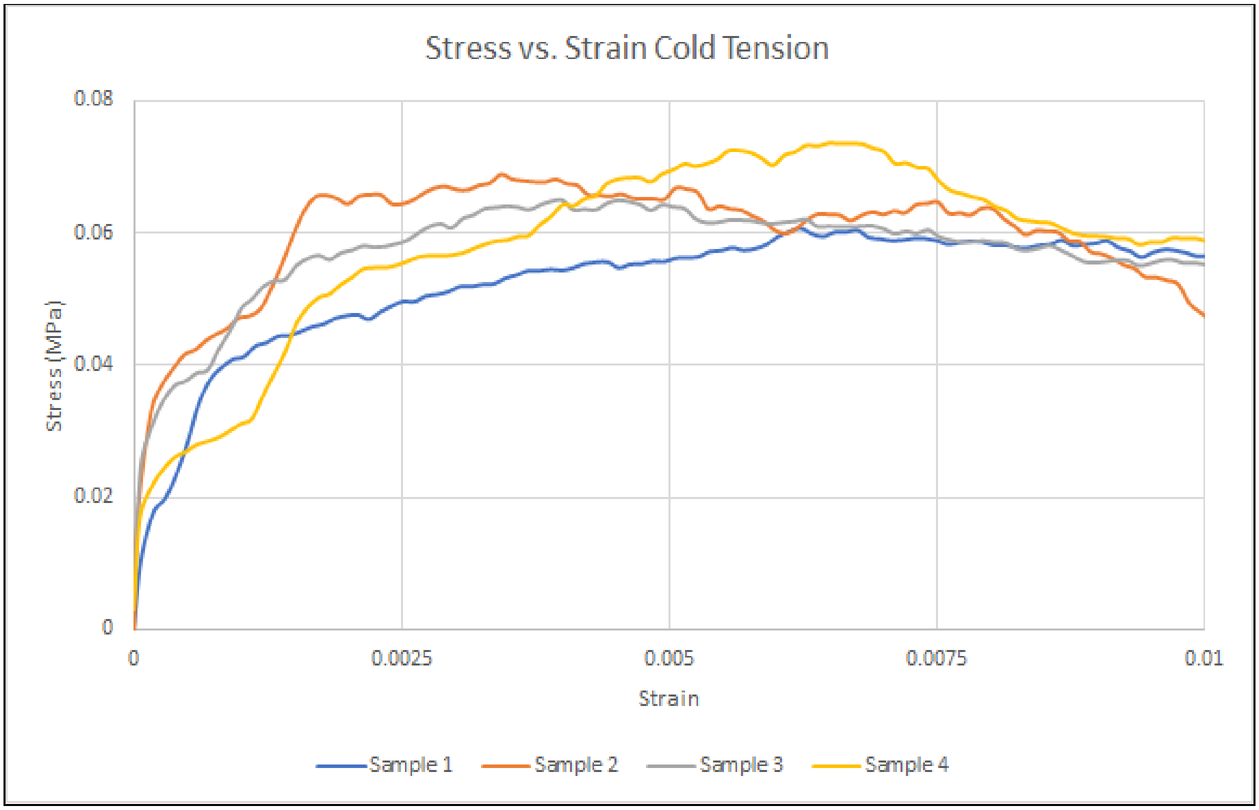

Fig 6. Stress-Strain plots for Cold Tensile tests. All tested samples follow a similar trend as they first withstand the stress and then fracture.

Based on these tests, it can be hypothesized that regolith is vulnerable to tensile stress. However, this data is also from a very limited sample size and to solidify the hypothesis into a conclusion, a larger sample size is required.

Charpy Test

A total of 7 samples were tested and considered to have viable data for the Charpy test. The dimensions of these samples along with the percentage absorbed energy, REL, RE, impact energy, and impact velocity are present in Table 7.

Table 7. Cold Charpy test results. The tests were performed with samples having extremely low temperatures to simulate the behavior of the regolith on the surface of Ceres.

Sample	**Width (mm)**	**Thickness (mm)**	**Absorbed Energy (%)**	**REL (J/m)**	**RE (kJ/m^2)**	**Impact Energy (J)**	**Impact Velocity (m/s)**	**Impact Angle (°)**	**Sample Temperature (°C)**
1	14.11	13.20	5.61	26.37	2.11	0.303	3.76	-139.23	-37
2	14.29	13.39	4.03	18.93	1.51	0.218	3.76	-141.90	-43
3	14.26	13.12	4.01	18.84	1.51	0.217	3.76	-141.85	-51
4	14.11	12.74	4.12	19.33	1.55	0.222	3.76	-141.75	-37
5	13.54	12.99	4.58	21.53	1.72	0.248	3.55	-140.95	-48
6	12.89	13.36	5.79	27.19	2.18	0.313	3.55	-138.95	-51
7	13.10	12.85	3.66	17.17	1.37	0.198	3.55	-142.55	-43
Average	13.76 ± 0.87	13.09 ± 0.35	4.54 ± 1.25	21.34 ± 5.85	1.71 ± 0.47	0.246 ± 0.067	3.67 ± 0.1	-141.03 ± 2.08	-44 ± 7

Based on the test results, we can observe that in general, the sample absorbed approximately 4.54% of the impact energy which would be about 0.246 J. The Charpy tests were conducted at fairly low temperatures to mimic the behavior of the regolith on Ceres' surface. Similar to the case of dry samples, no significant outliers were identified for this set of data.

Literature Result Comparisons

The most interesting result from the experiment came from the outcome of the frozen samples, which had an order of magnitude higher of a compression strength and an order of magnitude lower of a tensile strength. Upon reviewing the literature, none of the comparison studies froze their samples, which makes comparing this outcome difficult. Further complicating this, the results were generally highly variant due to the high porosity of the samples and the low sample size of the experiment.

The results of the dry samples are quite comparable to those of the other regolith simulants, though the peak tensile strength appears to be quite weaker. More samples tested for all procedures would presumably result in more reliable averages.

Revisions and Future Work

Dry samples, intended to be representative of the dry sublimated surface of Ceres, are significantly fragile. If future investigators would like to test these materials, this team advises the use of a Brazillian disk test for tensile testing [13]. Additionally, attempting to record the amount of dust created from tool interaction on solid samples would likely be helpful in determining applications for work on Ceres.

Due to the nature of this experiment, cold temperatures were difficult to maintain for testing requisite samples. Further testing suggested for cold samples, intended to represent the frozen immediate sub-surface of Ceres, would include more precise environmental controls for the testing apparatus and colder testing temperatures to better represent Ceres.

Additional testing of general abrasivity and angle of repose are suggested to add even more scope to the expected conditions on Ceres surface. The significant ferrous material and lack of eroding properties likely means the regolith on Ceres is highly abrasive and therefore would need to be mitigated for most engineering applications. Angle of repose testing will reveal the expected flow of loose material on Ceres.

Potential Applications

The results of this experiment can be used to extrapolate systems proposed to go to Ceres. From the results present a nominal anchoring system could be derived to be used on Ceres surface by a vehicle landing system. A value for soil cohesion can be estimated from the compression loaded samples of this experiment. This data would allow a system like a helical anchor, such as those used in construction on Earth, to be developed with some level of confidence of success.

For drilling and tool interaction the charpy results can help determine the mechanical strength of equipment that would be needed to interact with Ceres surface. Given the concrete-like results of this material, we would suggest using Earth based concrete techniques and tools as the base architecture for any proposed equipment.

Conclusion

The tested simulant provides a base set of results to be used by the community as guidelines for Ceres surface applications. The results of this experiment revealed a very strong compressive material, especially when frozen. The behavior of the material was similar to that of concrete and other brick like materials. High porosity in the sample material leads to significant variance in the results and advises healthy factors of safety when designing spacecraft hardware for interaction. More sample creation and testing would limit these variances to an acceptable range of values. Ceres regolith is likely abrasive in nature and should be accounted for in the creation of any equipment. We recommend further study of this simulant to verify the results in this paper, specifically in regards to frozen sample testing as comparisons are limited.

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References:

[1] 12.3 stress, strain, and elastic modulus - university Physics Volume 1. (n.d.). Retrieved May 12, 2021,from https://openstax.org/books/university-physics-volume-1/pages/12-3-stress-strain-and-elastic-modulus

[2] Modulus of Elasticity. (n.d.). Retrieved May 12, 2021, from https://www.instron.us/en-us/our-company/library/glossary/m/modulus-of-elasticity

[3] Experimental Methods Course Manual - Appendix 4 - impact strength testing. (n.d.). Retrieved May 12, 2021, from http://www.dept.aoe.vt.edu/~aborgolt/aoe3054/manual/app4/index.html

[4] Rivkin, A. S., Li, J., Milliken, R. E., Lim, L. F., Lovell, A. J., Schmidt, B. E., . . . Cohen, B. A. (2010). The surface composition of Ceres. The Dawn Mission to Minor Planets 4 Vesta and 1 Ceres, 95-116. doi:10.1007/978-1-4614-4903-4_7

[5] Landsman, Z. A., Schultz, C. D., Britt, D. T., Peppin, M., Kobrick, R. L., Metzger, P. T., & Orlovskaya, N. (2021). Phobos regolith simulants PGI-1 And PCA-1. Advances in Space Research, 67(10), 3308-3327. doi:10.1016/j.asr.2021.01.024

[6] Delage, P., Karakostas, F., Dhemaied, A., Belmokhtar, M., Lognonné, P., Golombek, M., . . . Banerdt, B. (2017, July 10). An investigation of the mechanical properties of SOME Martian regolith Simulants with respect to the surface properties at the Insight Mission landing site. Retrieved May 12, 2021, from https://link.springer.com/article/10.1007/s11214-017-0339-7

[7] Avdellidou, C., Di Donna, A., Schultz, C., Harthong, B., Price, M. C., Peyroux, R., . . . Delbo', M. (2020). Very weak carbonaceous asteroid simulants i: Mechanical properties and response to hypervelocity impacts. Icarus, 341, 113648. doi:10.1016/j.icarus.2020.113648

[8] Colwell, J., Batiste, S., Horányi, M., Robertson, S., & Sture, S. (2007, June 26). Lunar surface: Dust dynamics and regolith mechanics. Retrieved May 12, 2021, from https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2005RG000184

[9] Metzger, P. T., Britt, D. T., Covey, S., Schultz, C., Cannon, K. M., Grossman, K. D., . . . Mueller, R. P. (2019). Measuring the fidelity of asteroid regolith and cobble simulants. Icarus, 321, 632-646. doi:10.1016/j.icarus.2018.12.019

[10] Prettyman, T. H., Yamashita, N., Ammannito, E., Ehlmann, B. L., McSween, H. Y., Mittlefehldt, D. W., Marchi, S., Schorghofer, N., Toplis, M. J., Pieters, C. M., Castillo-Rogez, J. C., Raymond, C. A., Russell, C. T., "Elemental Composition and Mineralogy of Vesta and Ceres: Distribution and Origins of Hydrogen-Bearing Species," Icarus, Vol. 318, January 2019, pp. 42-55. Available: https://www.sciencedirect.com/science/article/abs/pii/S0019103517308643.

[11] Castillo-Rogez, J. C., Neveu, M., Scully, J. E. C., House, C. H., Quick, L. C., Bouquet, A., Miller, K., Bland, M., Cristina De Sanctis, M., Ermakov, A., Hendrix, A. R., Prettyman, T. H., Raymond, C. A., Russell, C. T., Sherwood, B. E., Young, E., "Ceres: Astrobiological Target and Possible Ocean World," Astrobiology, Vol. 20, November 2020, pp. 269-291. Available: https://www.liebertpub.com/doi/pdf/10.1089/ast.2018.1999.

[12] Neveu, M., Desch, S. J., Castillo-Rogez, J. C., "Aqueous Geochemistry in Icy World Interiors: Equilibrium Fluid, Rock, and Gas Compositions, and Fate of Antifreezes and Radionuclides," Geochimica et Cosmochimica Acta, Vol. 212, September 2017, pp. 324-371. Available: https://www.sciencedirect.com/science/article/abs/pii/S0016703717303721?casa_token=Wr5vwF-4FaUAAAAA:KDbmV_vb8eJkfqNPLwnCU0LjzckKxnYOnL-s2Y6DG6-rAUqaW_8Pi1GnzCRGGsDI-sHxCIWAQA.

[13] Li, D., & Wong, L. (2012, May 15). The Brazilian disc test for Rock Mechanics Applications: Review and new insights. Retrieved May 10, 2021, from https://link.springer.com/article/10.1007/s00603-012-0257-7