Investigation of Properties of Icy Lunar Regolith at Cryogenic Temperatures on the Moon

By

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Team Members

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    - Zach Zody, MSc Graduate student, Petroleum Eng.
- Undergraduate Students:
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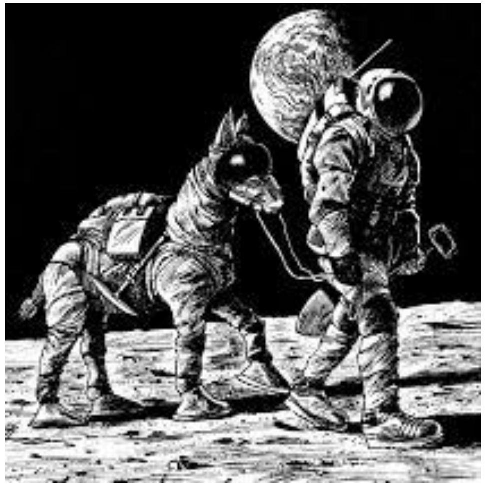
- Subcontractors: Steve Nieczkoski & Brad Blair, Thermal Space Ltd.

Research Objective(s) and Technical Approach

Material Characterization while Drilling on Lunar/Martian Surface

Main Objective: Estimate properties of the icy lunar regolith for the development of an intelligent drilling system for exploration/mining activities on the Moon.

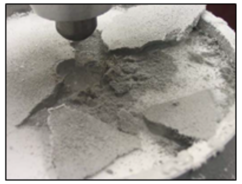
- Use on the surface of the Moon for the real-time characterization of the formation.
  e.g. properties of the loose/compacted/frozen regolith, volcanic boulders, etc.
- Measure water contents in the icy lunar regolith. Find a "water well" on the Moon. "Oil of space" for life requires, inexpensive source of propellants, etc.



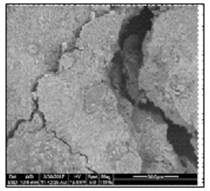
Where is the Water?

Material Characterization | Full-scale Drilling tests | Data Analysis and Programming

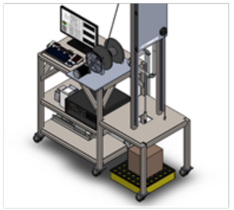
Physical Property Tests



Indentation Tests

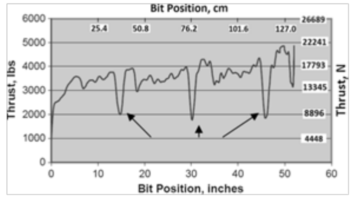


Selection of Equivalent Rocks



Design of the Instrumented Drill &

Full-scale Drilling Test

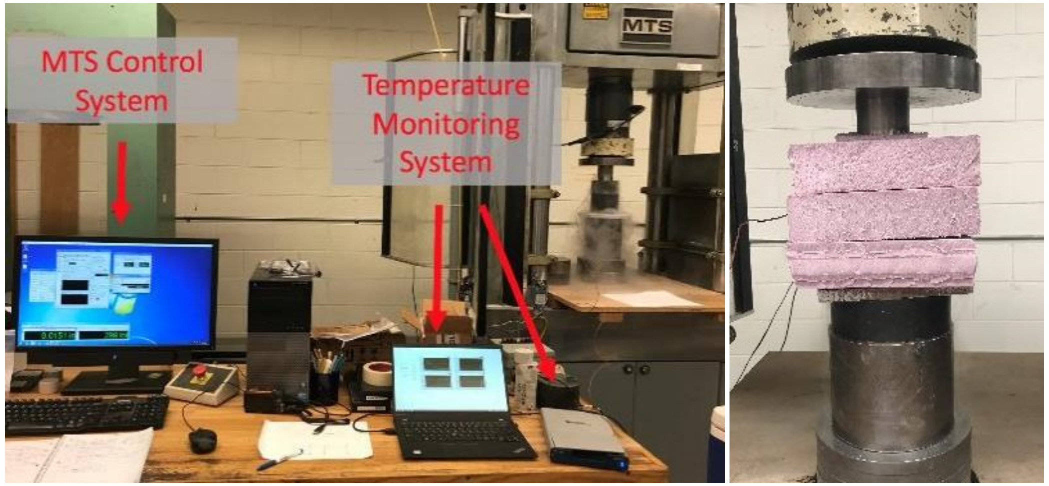


Pattern Recognition, Artificial Intelligent Systems

Intelligent Exploration Drilling System for Material Characterization While Drilling

Drill into the Moon!

Modified Testing Systems for Material Characterization



- A modified 100t capacity MTS press testing system.
- Monitor real-time temperatures in specimens.
- Liquid nitrogen is used to simulate cryo-environments.
- Insulation is used to hold pre-designed cryo-conditions.

* **Strength Tests**

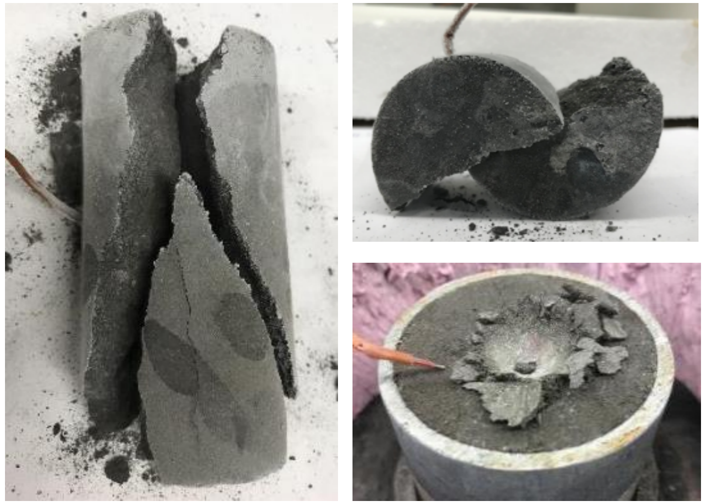
- Uniaxial Compressive Strength (UCS) Tests
- Brazilian Tensile Strength (BTS) Tests
- Punch Penetration Tests

* **Testing conditions/Range of Variables:**

Temperatures: -190 Celsius to -130 Celsius

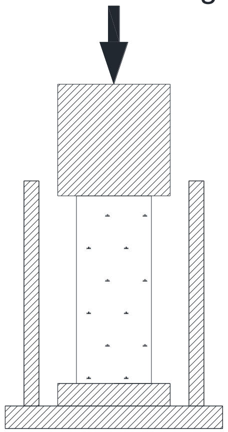
Water Contents: 3% to 9%

Regolith: CSM-CL, JSC-1a, CSM-MC, and LHS-1

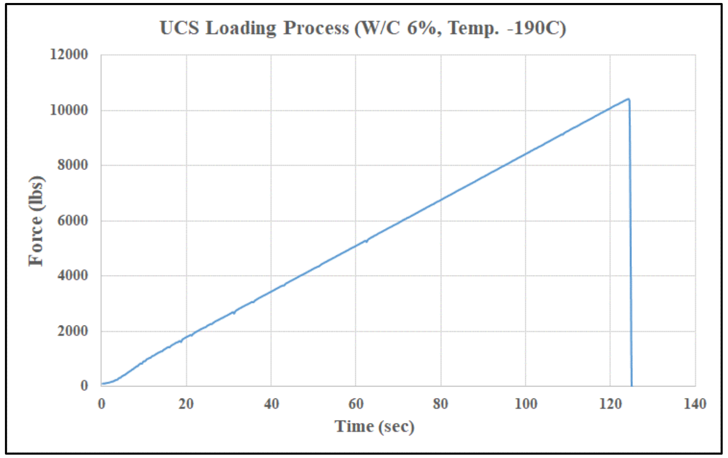


Geo-Mechanics Tests and Data Analysis

Uniaxial Compressive Strength (UCS) Tests

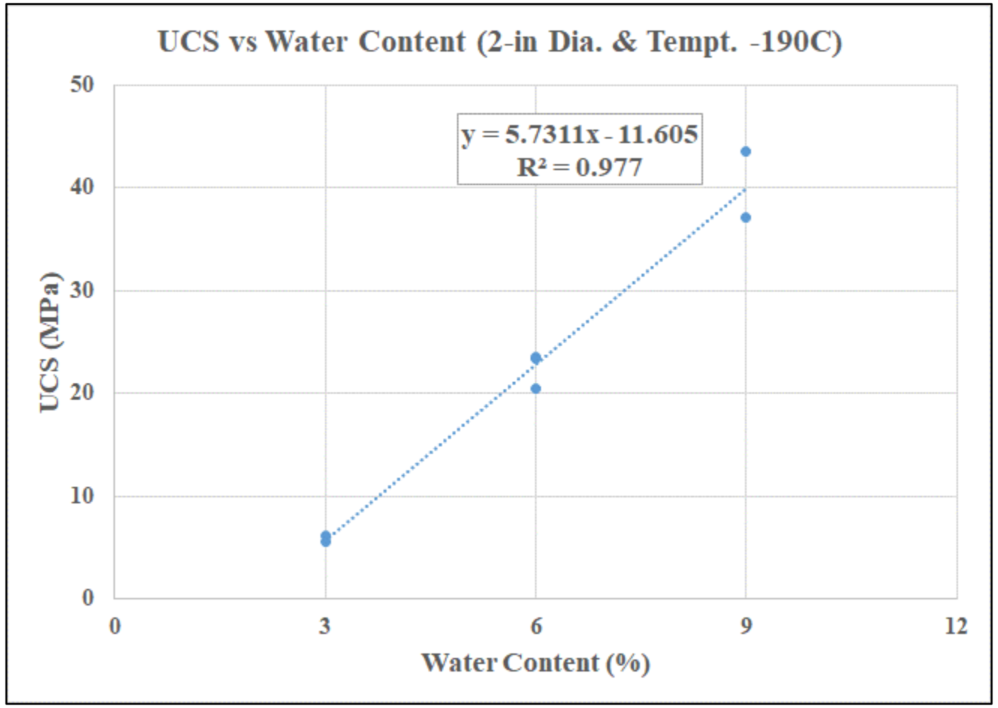


- Sample Preparation protocol, batches at pre-designed W%
- A modified proctor compaction system to cast specimens
- Two stage freezing, casting and to -20°C, → testing at -190°C
- Length: ~5-in & Diameter: ~2-in based on ASTM guidelines
- Thermocouple in the sample for temperature monitoring
- Density: ~1.8 to 2 g/cc



Geo-Mechanics Tests and Data Analysis

UCS vs. Water Contents (3%, 6%, 9%)

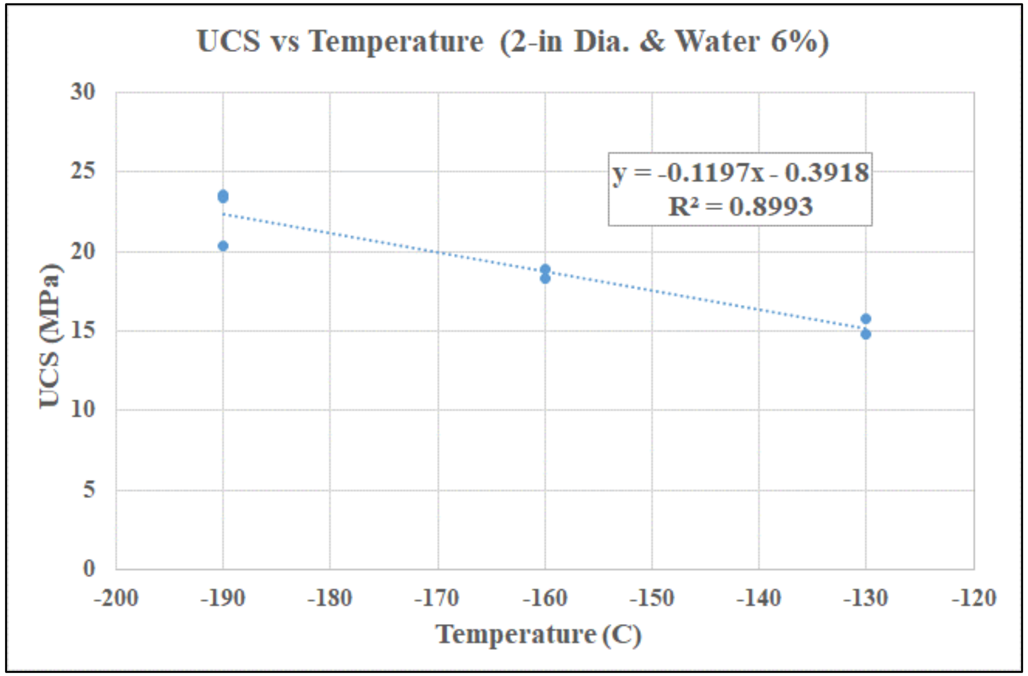


Hardness category	Typical range in unconfined compressive strength (MPa)	Strength value selected (MPa)	Field test on sample	Field test on outcrop
Soil*	< 0.60		Use USCS classifications	
Very soft rock or hard, soil-like material	0.60–1.25		Scratched with fingernail. Slight indentation by light blow of point of geologic pick. Requires power tools for excavation. Peels with pocket knife.	
Soft rock	1.25–5.0		Permits denting by moderate pressure of the fingers. Handheld specimen crumbles under firm blows with point of geologic pick.	Easily deformable with finger pressure.
Moderately soft rock	5.0–12.5		Shallow indentations (1–3 mm) by firm blows with point of geologic pick. Peels with difficulty with pocket knife. Resists denting by the fingers, but can be abraded and pierced to a shallow depth by a pencil point. Crumbles by rubbing with fingers.	Crumbles by rubbing with fingers.
Moderately hard rock	12.5–50		Cannot be scraped or peeled with pocket knife. Intact handheld specimen breaks with single blow of geologic hammer. Can be distinctly scratched with 20d common steel nail. Resists a pencil point, but can be scratched and cut with a knife blade.	Unfractured outcrop crumbles under light hammer blows.
Hard rock	50–100		Handheld specimen requires more than one hammer blow to break it. Can be faintly scratched with 20d common steel nail. Resistant to abrasion or cutting by a knife blade, but can be easily dented or broken by light blows of a hammer.	Outcrop withstands a few firm blows before breaking.
Very hard rock	100–250		Specimen breaks only by repeated, heavy blows with geologic hammer. Cannot be scratched with 20d common steel nail.	Outcrop withstands a few heavy ringing hammer blows but will yield large fragments.
Extremely hard rock	> 250		Specimen can only be chipped, not broken by repeated, heavy blows of geologic hammer.	Outcrop resists heavy ringing hammer blows and yields, with difficulty, only dust and small fragments.

- ➢ Cryogenic temperature was controlled at -190 C
- ➢ Changing water contents significantly affect UCS at the preset cryogenic temperature.
- ➢ Consistent with literature

Geo-Mechanics Tests and Data Analysis

UCS vs. Cryo-Temperatures (-190 C, -160 C, -130 C)

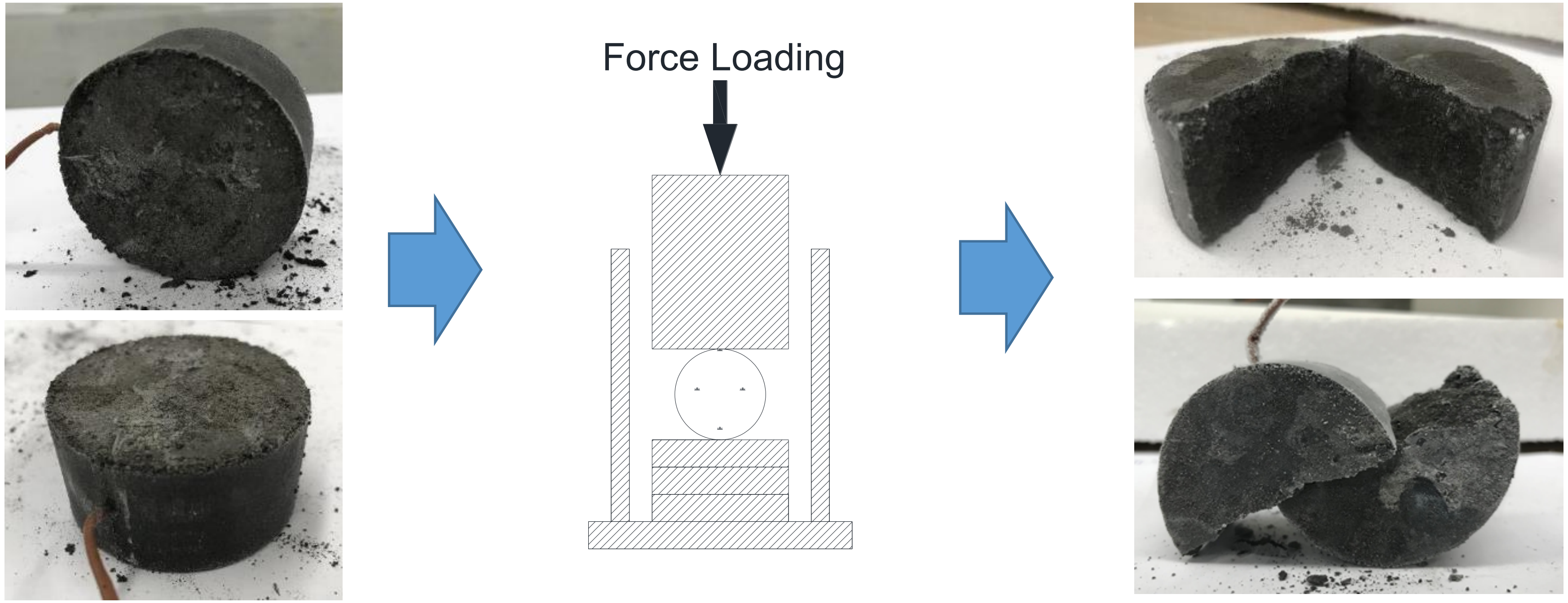


Diameter	Temperature	Water Content	UCS
(inch)	(Celsius)	(%)	(MPa)
2	-190	6	23.31
2	-190	6	20.38
2	-190	6	23.54
Average			22.41
2	-160	6	18.84
2	-160	6	18.27
Average			18.56
2	-130	6	14.75
2	-130	6	15.78
Average			15.27

- Water content was controlled at 6%
- Changing cryo-temperatures moderately affect UCS with a constant water content

Geo-Mechanics Tests and Data Analysis

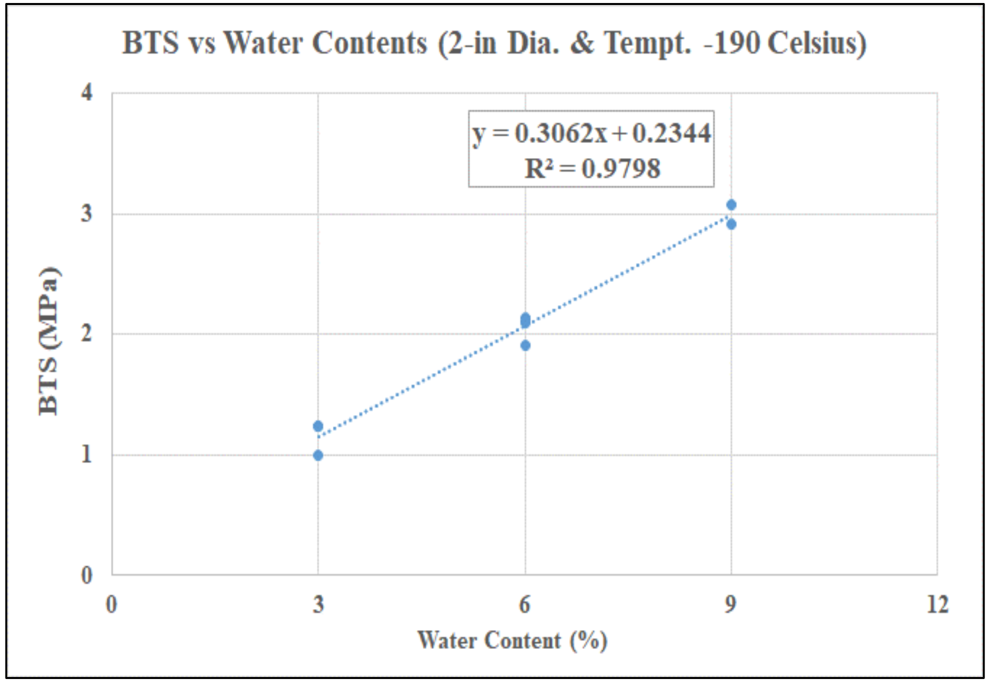
Brazilian Tensile Strength (BTS) Tests



- Sample prep protocol → A modified proctor compaction system to cast specimens.
- Length: ~1-in & Diameter: ~2-in based on ASTM guidelines;
- Single split failure mode: the samples were uniform and the edge effect was minimal, meaning that the results are valid.

Geo-Mechanics Tests and Data Analysis

BTS vs. Water Contents (3%, 6%, 9%)



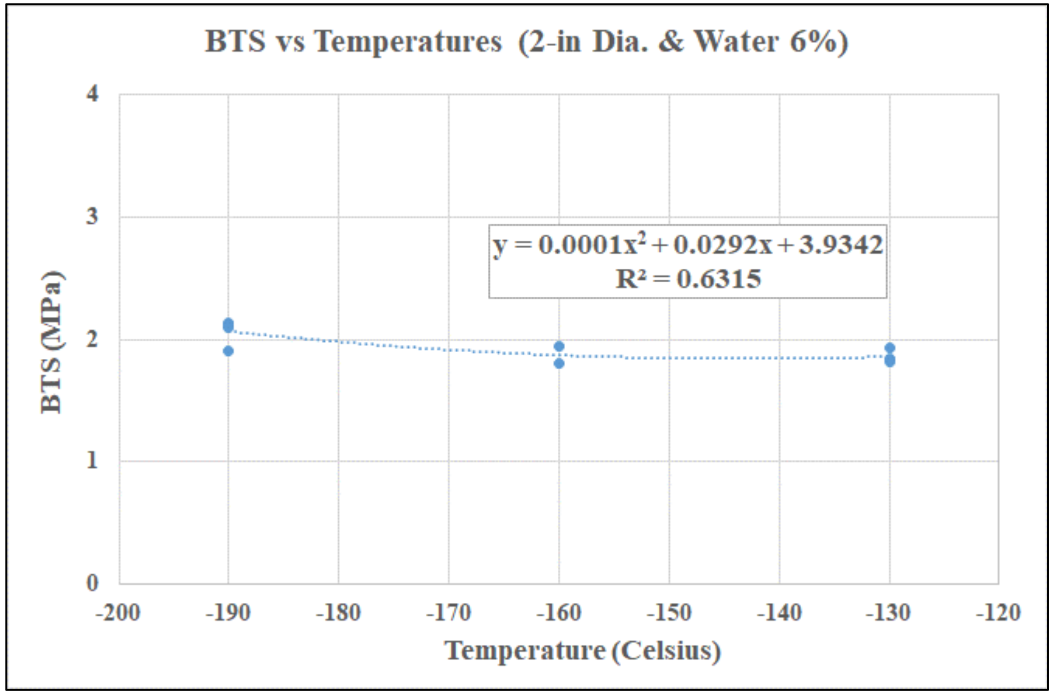
Temperature	Water Content	Diameter	BTS
(Celsius)	(%)	(inch)	(MPa)
-190	3	2	1.24
-190	3	2	1.23
-190	3	2	1.00
Average			1.16
-190	6	2	1.90
-190	6	2	2.14
-190	6	2	2.10
-190	6	2	2.12
Average			2.06
-190	9	2	2.92
-190	9	2	3.08
Average			3.00

- Cryogenic temperature was controlled at -190 Celsius.
- A linear correlation is observed.
- Changing water contents <u>significantly</u> affect BTS at the preset cryogenic temperature.

THERMAL SPACE

Geo-Mechanics Tests and Data Analysis

BTS vs. Cryo-Temperatures (-190 C, -160 C, -130 C)

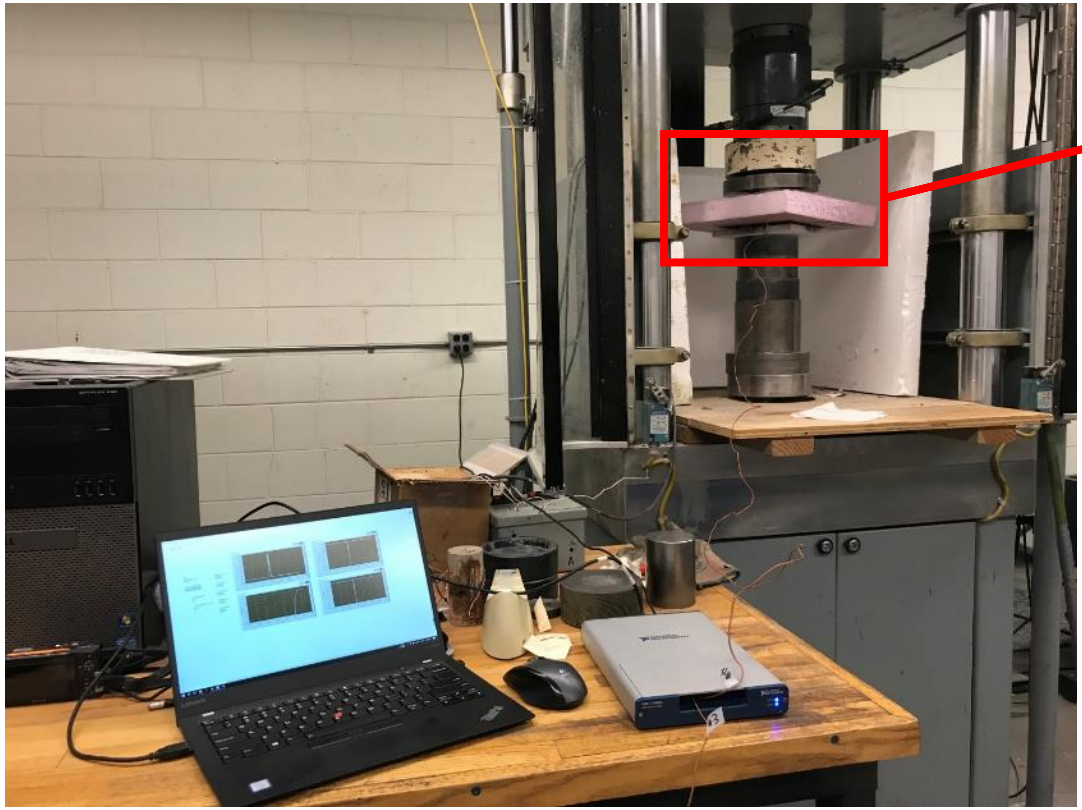


Temperature	Water Content	Diameter	BTS
(Celsius)	(%)	(inch)	(MPa)
-190	6	2	1.90
-190	6	2	2.14
-190	6	2	2.10
-190	6	2	2.12
Average			2.06
-160	6	2	1.80
-160	6	2	1.94
Average			1.87
-130	6	2	1.84
-130	6	2	1.93
-130	6	2	1.81
Average			1.86

- Water content was controlled at 6%.
- Changing cryo-temperatures slightly affect UCS with a constant water content.

Geo-Mechanics Tests and Data Analysis

Punch Penetration Tests



- The Punch Penetration test was used to predict performances of mechanical cutting machines in the process of indentation
- Penetrating 0.25 inches into the sample and output data include:
  - Max load.
  - Brittleness index
  - Peak slope index (peak load).
  - Average slope index (average load).
  - Energy slope index (energy consumption).

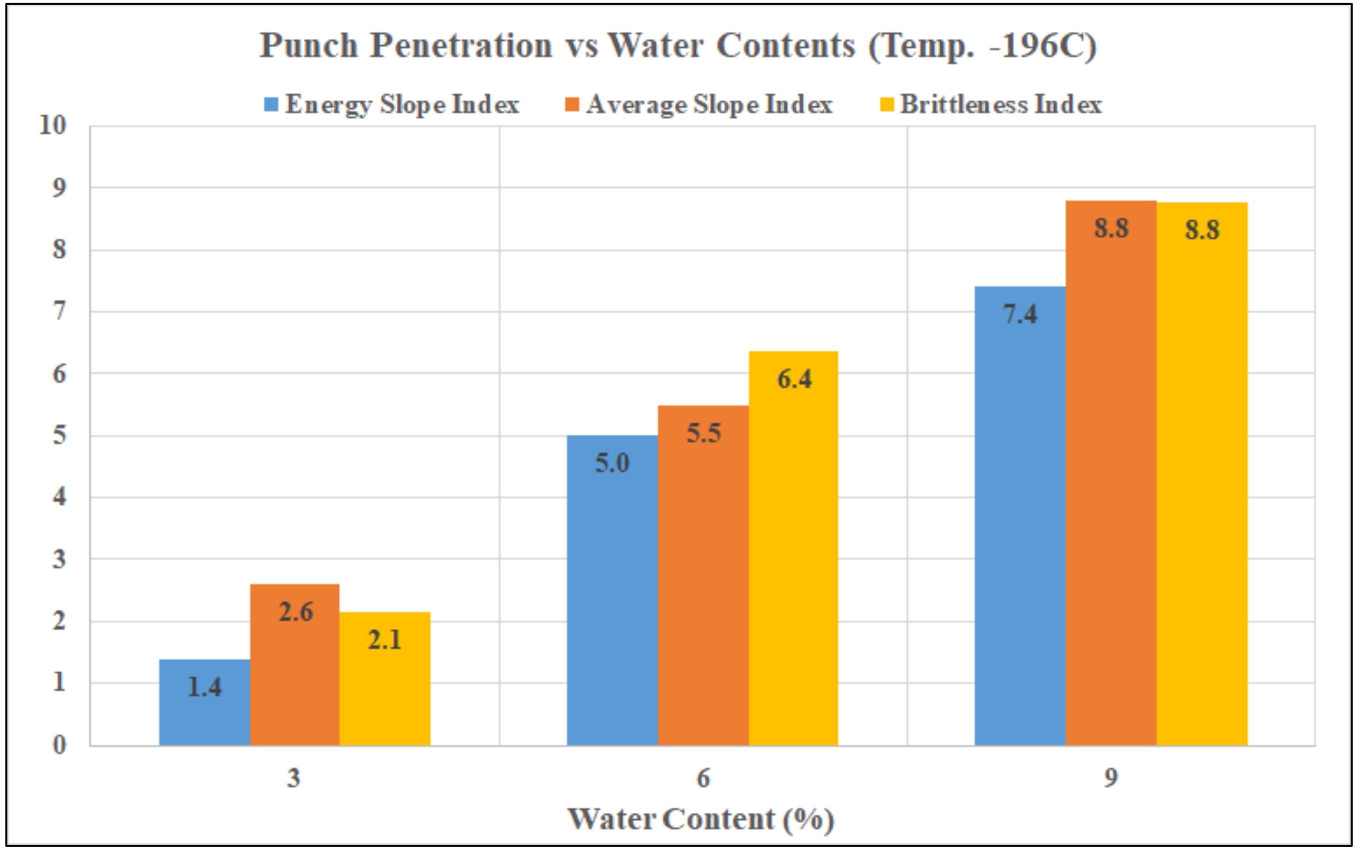
Geo-Mechanics Tests and Data Analysis

Punch Penetration Tests - Summary

Summary of Punch Penetration Tests for NASA Project								
#	Water Content (%)	Temperature (Celsius)	Penetration Rate (mm/s)	Max Load (kN)	Indices (kN/mm)			
					45 degrees Index	Peak Slope Index	Average Slope Index	Energy Slope Index
1	3	-196	0.076 (0.003 in/s)	13.624	3.5	2.1	2.6	1.4
2	6	-196	0.076 (0.003 in/s)	40.336	7.0	6.6	5.5	5.0
3	9	-196	0.076 (0.003 in/s)	55.615	9.1	9.0	8.8	7.4
4	6	-130	0.076 (0.003 in/s)	31.649	5.6	5.0	4.7	4.4
5	6	-160	0.076 (0.003 in/s)	34.764	5.6	6.3	5.3	4.6

Geo-Mechanics Tests and Data Analysis

Punch Penetration Tests – Changing Water Contents



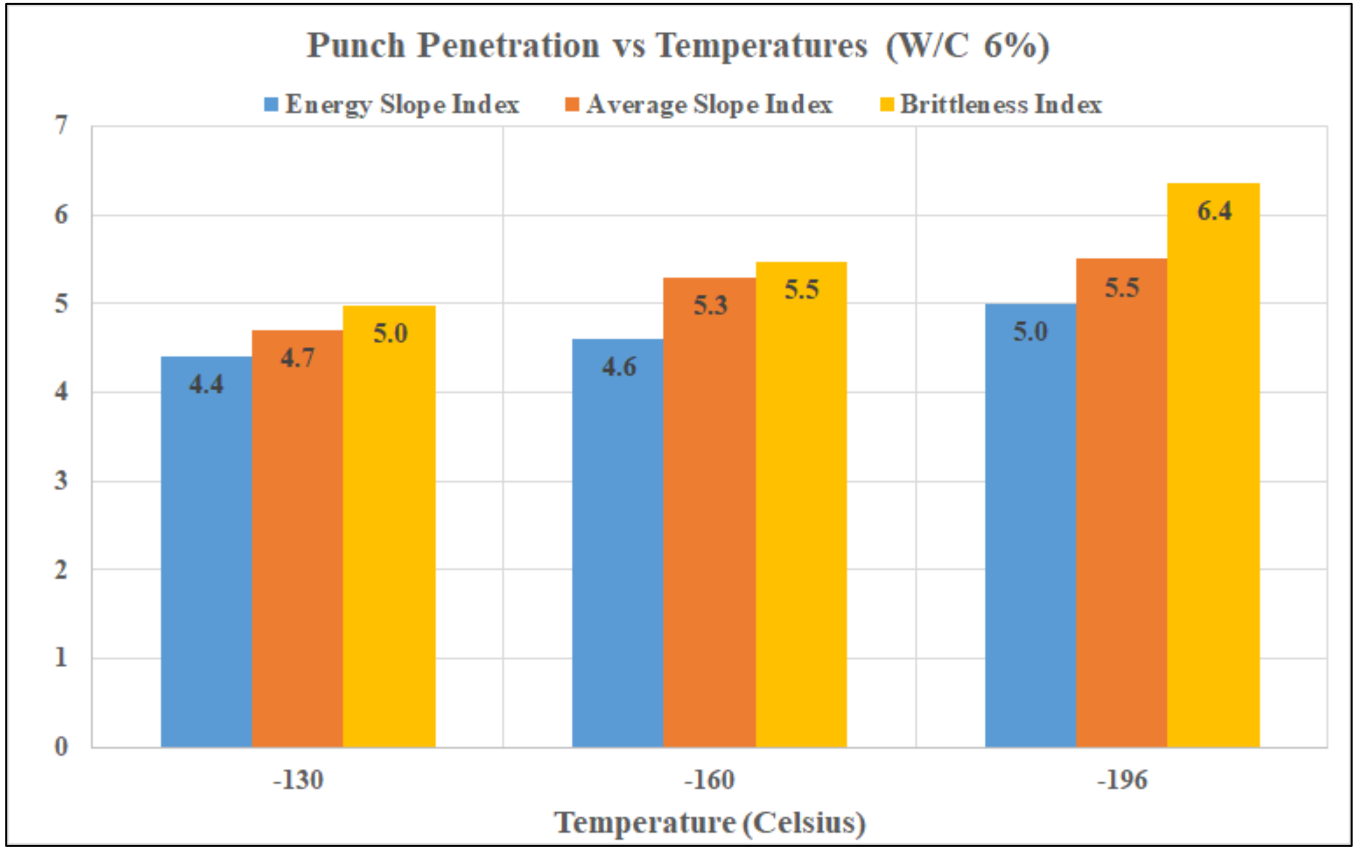
Brittleness index (kN/mm)	Brittleness class
≥ 40	Very high brittle
35- 39	High brittle
30 -34	Medium brittle
25-29	Moderate brittle
20 - 24	Low brittle
≤19	No-brittle (ductile)

Less than < 19 ⇨ **Not Brittle**

Energy slope index (energy consumption); Average slope index (average load); Brittleness Index

Geo-Mechanics Tests and Data Analysis

Punch Penetration Tests – Changing Cryo-Temperatures



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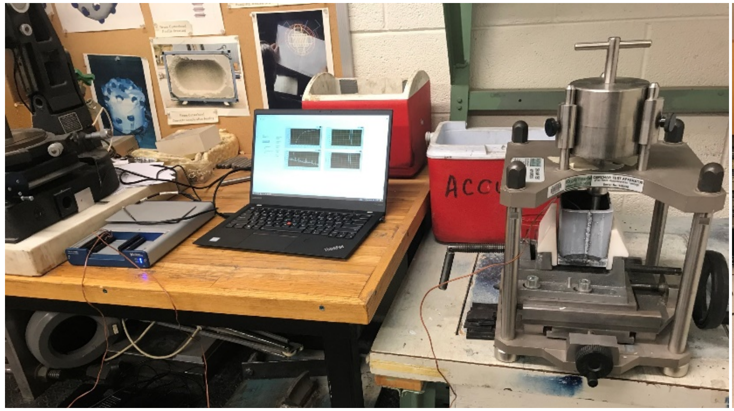
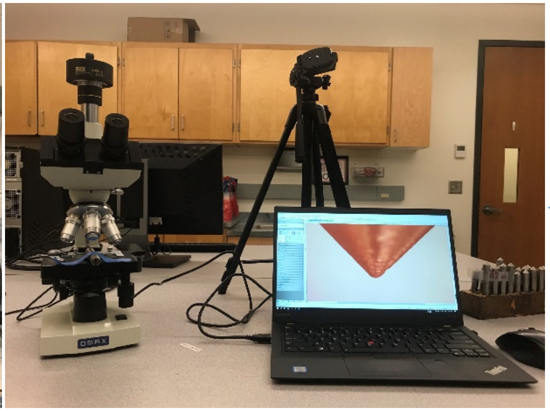
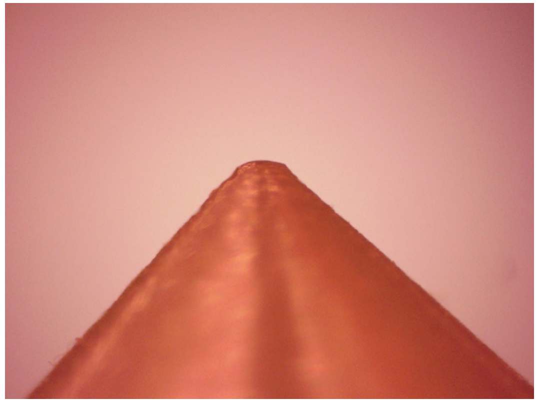
Energy slope index (energy consumption); Average slope index (average load); Brittleness Index

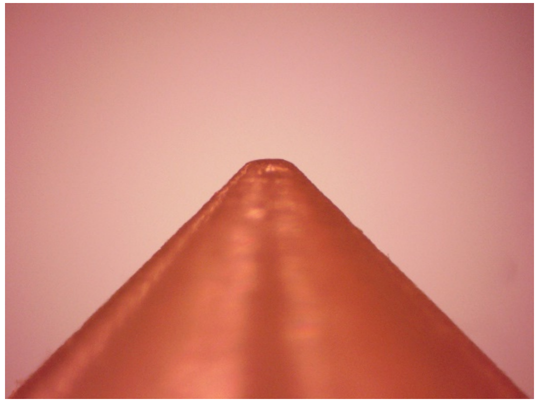
Geo-Mechanics Tests and Data Analysis

Cerchar Abrasivity Index (CAI)Tests









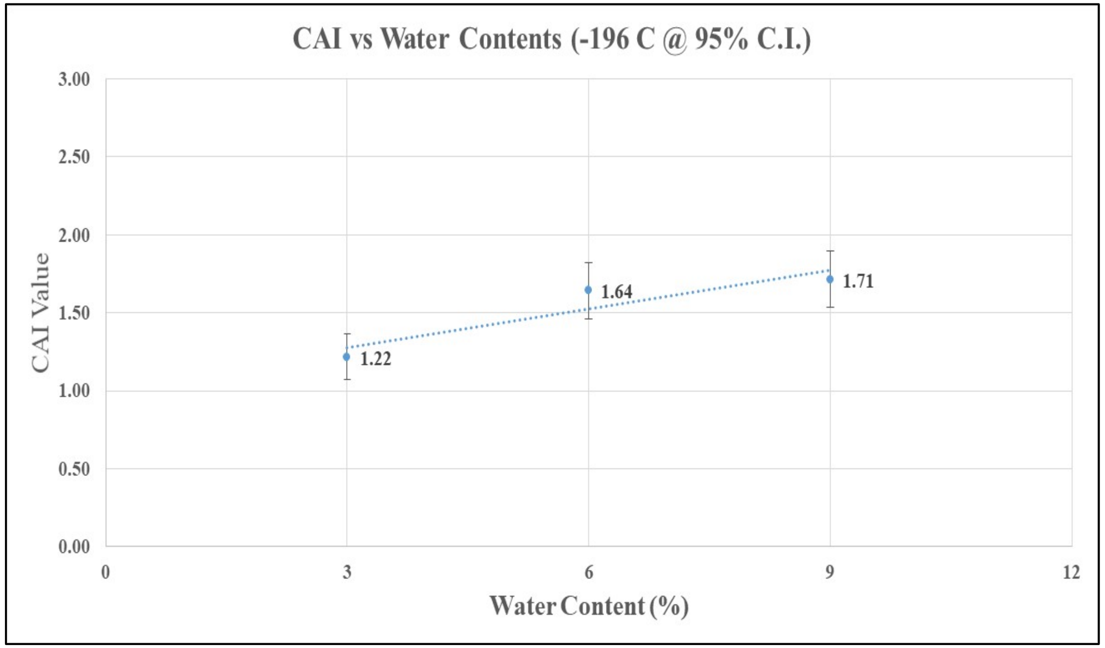
- ➢ The CAI tests were performed to evaluate the abrasiveness of icy lunar regolith.
- ➢ Testing conditions/Range of Variables:

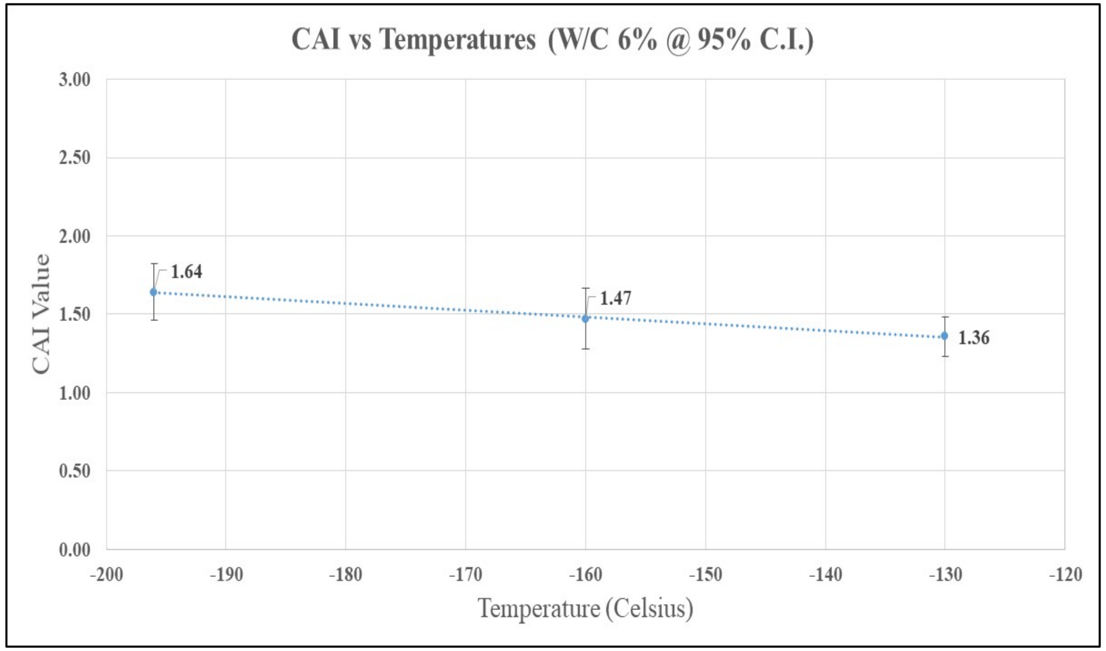
Temperatures: -190 Celsius to -130 Celsius;

Water Contents: 3% to 9%.

Geo-Mechanics Tests and Data Analysis

Cerchar Abrasivity Index (CAI)Tests





- ➢ CAI results are not strongly sensitive water content and temperatures

Table 2 Classification of CAI

Mean CAI	Classification
0.1–0.4	Extremely low
0.5–0.9	Very low
1.0–1.9	Low
2.0–2.9	Medium
3.0–3.9	High
4.0–4.9	Very high
≥5	Extremely high

Project Status and Achievements

- Results suggest that icy lunar regolith at cryogenic temperatures show UCS that range from soft rock to moderately hard rock.

- The UCS, BTS, and Punch Penetration results of the icy lunar regolith are more sensitive to changing water content than changing temperatures at cryogenic temperature conditions.

- This allows for estimation of the water content while drilling since drilling parameters are sensitive to material strength which follows water content.

- CAI results are not strongly sensitive to water content and temperature. Classifies as low abrasivity at all conditions tested.

- Additional geo-mechanics tests are ongoing
    - Higher and lower ice content
    - Additional abrasion testing
    - Additional indentation
    - Additional forms of icy regolith

Thank You!