Experimental results for the compaction and consolidation of regolith containing discrete water ice in 1 atm pressure

A reference for lunar tests

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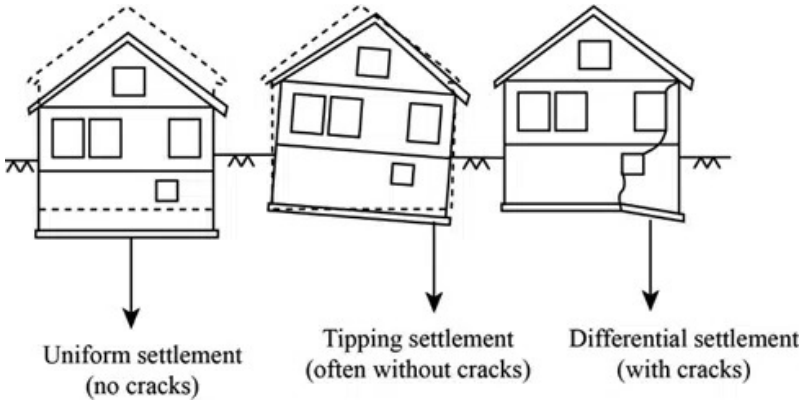
Impact of Soil Compaction & Consolidation

- Environmental damage
- Building or infrastructure damage
- Regolith instability
- Reducing the volume of lunar regolith



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Impact of Regolith Compaction and Consolidation – Apollo missions

- **40 degrees** off vertical: Apollo lander tip-over point. (Cheatham, 1966)
- An angle beyond **12 degrees tilt**, the astronauts might not be able to launch themselves off the surface. (Mueller, 2020)
- Compaction difference of **0.12m** between nearby footpads and **0.16m** for opposing footpads result in tilt angle of 1 degree.

Mission	Penetration Depth of Each Apollo Lander Footpad (cm)				Tilt from Vertical (degrees)
	-Y	+Y	-Z	+Z	
Apollo 11	2.5-7.5	2.5-7.5	2.5-7.5	2.5-7.5	4.5
Apollo 12	10	1-2	1-2	1-2	4
Apollo 14	2-4	15-20	2-4	15-20	7
Apollo 15	Several centimetres each				11
Apollo 16	8-10	Minimal penetration			2.5
Apollo 17	No data available				No data available

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Background – Lunar Ice Concentration

- In 2009, water ice was detected in the Cabeus crater plume, with a calculated concentration of 5.6 ± 2.9% by mass in the regolith at the impact site. (Colaprete et al., 2010)
- Li et al. (2018) determined that Moon Mineralogy Mapper (M3), “spectra may be indicative of 30 wt% ice or higher if it is mixed intimately with regolith.” (Li et al., 2018)*

* The accuracy of the M3 measurement is questionable

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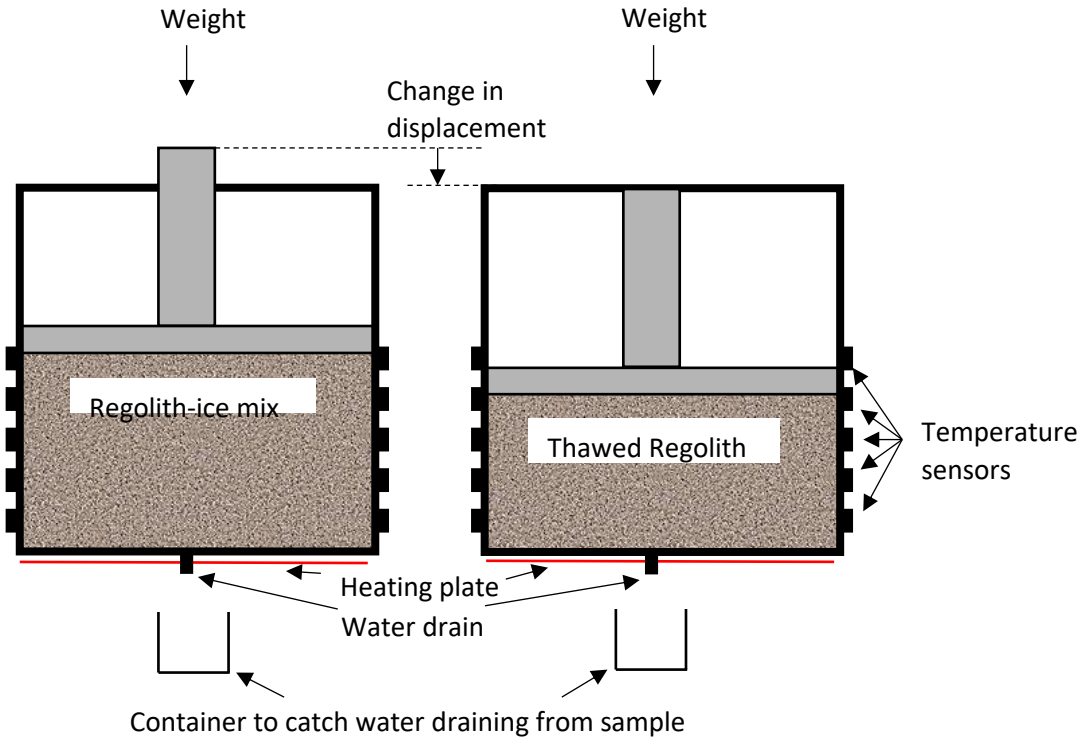
Aim

To measure the compaction of frozen and consolidation of thawed icy lunar regolith, containing water content between 0% and 25% of the total mass of the regolith-water mix (0-25% wt).

ASTM D4546-21 Oedometer Test

Used to test freezing and thawing of terrestrial soils.



Testing Procedure

Distilled water 1-dimensionally frozen to -15degC.

Ice is crushed and blended to fine particles.

Strained ice using 850um sieve.

KLS-1 and ice manually mixed to make a uniform blend.

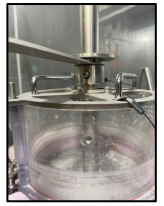
Test apparatus cooled to -10degC.

KLS-1 cooled to -10degC.

Regolith-ice mix loaded into test apparatus. A load of 2.7kg applied every 2cm to compact mix evenly.

Test apparatus filled to a depth of 110mm with mix.

A representative sample of mix taken to check water content.



Top of the regolith height is measured in 3 distinct locations.

Test apparatus cap installed and displacement sensor setup.

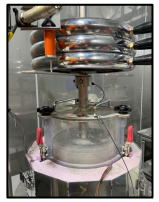
Displacement and temperature recorded with timestamp.

Weights were added to tests at a rate of 10kg every 30seconds.

Test remains at -5 to -10dgC and were observed until settling ceased.

Base plate and room heated to 20degC.

Test observed until consolidation ceased and temperature sensors >0degC.



Final sensor displacement is recorded.

Weights and test apparatus cap are removed.

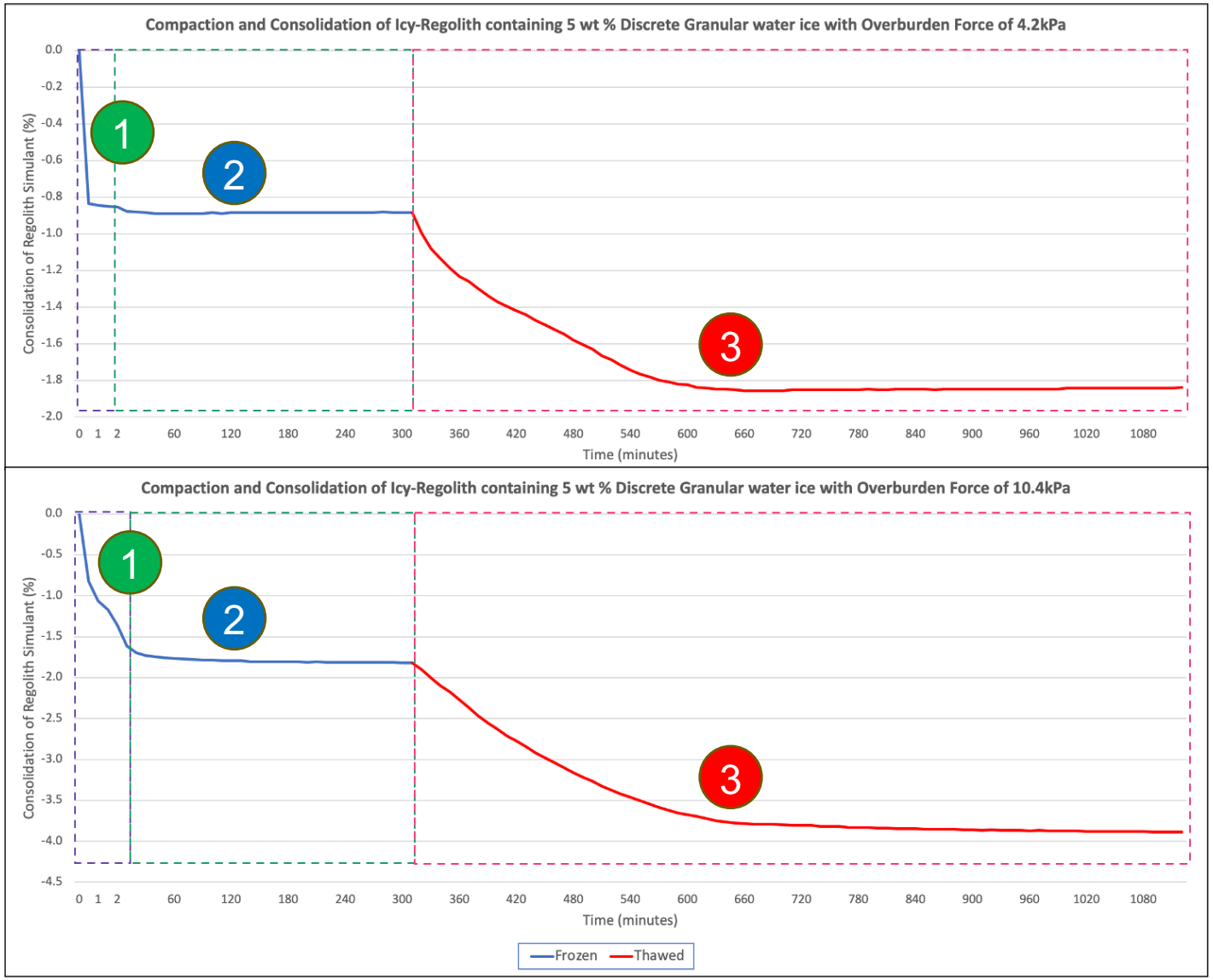
The height of the mix is measured in 3 distinct locations.

A representative sample of mix taken from each test to check water content.

Water captured in container under test apparatus measured.

Results

1. Compaction after placement of weight
2. Long-term compaction of frozen icy regolith
3. Long-term consolidation of thawed regolith



Results – 4.2 kPa Loading

Water Ice (wt %)	Compaction-Consolidation of test sample compared to initial sample height (%)			
	1.0 kPa	4.2 kPa	4.2 kPa Long term Frozen	4.2 kPa Long term Thawed
0	0.00	-0.08	-0.12	-0.50
1	0.00	-0.24	-0.24	-0.36
5	0.00	-0.84	-0.89	-1.84
10	0.00	-0.75	-1.01	-7.66
15	0.00	-0.06	-1.33	-9.00
20	0.00	-0.15	-1.05	-45.61
25	0.00	-0.02	-1.54	-53.29

Initial compaction not affected by water content

Long-term compaction and consolidation generally increased with water ice content

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Results – 10.4 kPa Loading

Water Ice (wt %)	Compaction-Consolidation of test sample compared to initial sample height (%)					
	1.0 kPa	4.2 kPa	7.2 kPa	10.4 kPa	10.4 kPa Long term Frozen	10.4 kPa Long term Thawed
0	0.00	-0.30	-0.63	-0.75	-0.77	-0.90
1	0.00	-0.84	-1.39	-1.76	-2.12	-2.45
5	0.00	-0.82	-1.06	-1.18	-1.82	-3.98
10	0.00	-0.68	-1.27	-1.84	-2.97	-10.95
15	0.00	-0.05	-0.45	-0.95	-3.52	-25.74
20	0.00	-0.26	-0.41	-0.71	-3.83	-50.75
25	0.00	-0.03	-0.13	-0.40	-4.63	-55.69

Initial compaction not affected by water content

Long-term compaction and consolidation generally increased with water ice content

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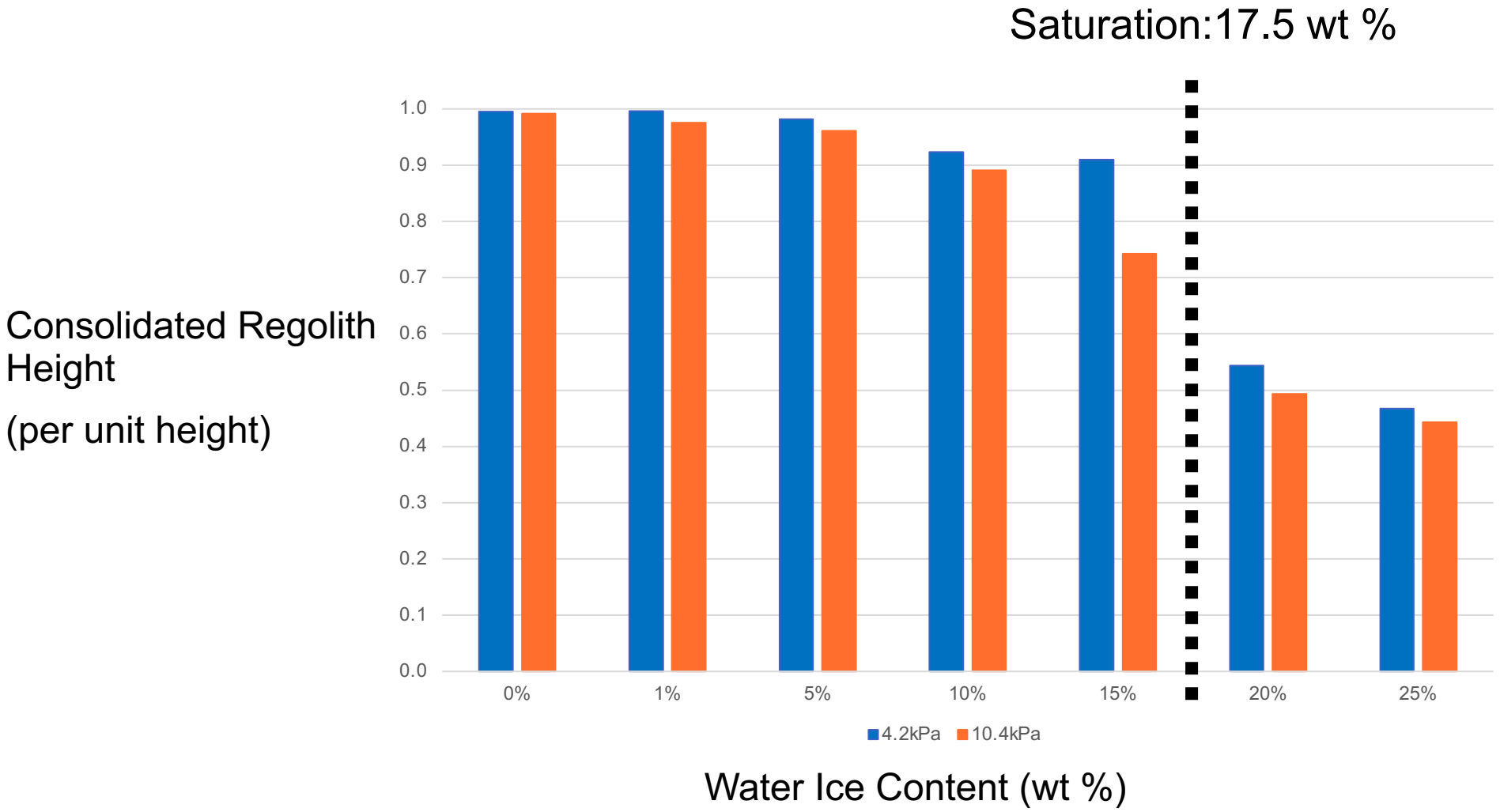
Results – Regolith Consolidation



Conclusion

Provides an initial view as to the consolidation behaviour of regolith under load and findings to aid the design of tests in dirty thermal vacuum chambers.

Further testing is required to:

- Validate the findings
- Analyse the long-term impact of consolidation
- Determine the impact across varying simulants
- Compare these results against against tests performed in lunar conditions

Question that still need to be answered:

How does the melted water impact the consolidation compared to sublimated water?

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Questions?