EXPERIMENTAL RESULTS FOR THE COMPACTION AND CONSOLIDATION OF LUNAR REGOLITH CONTAINING DISCRETE WATER ICE IN 1 ATM PRESSURE – A REFERENCE FOR LUNAR TESTS. N. Barnett[1], Z. Gong, J. Lee, H. Jin, B. Ryu, T. Ko, J. Oh, A. Dempster and S. Saydam[2], [1]University of NSW Sydney, nicholas.barnett@unsw.edu.au, [2]University of NSW Sydney, s.saydam@unsw.edu.au.

Overview: This abstract provides the outcomes of the consolidation and compaction experiments performed on lunar regolith simulant containing 0%, 1%, 5%, 10%, 15%, 20% and 25% discrete water ice particles under two continuous overburden loading conditions at 1 atmospheric pressure. The results provide a reference for future work testing the compaction and consolidation in lunar environmental conditions.

Introduction: The impact of the consolidation of the regolith on lunar infrastructure could pose issues if development occurs on areas of the Moon that could contain lunar volatiles, with small volumes of discrete water ice potentially resulting in instability issues. In such cases, consolidation can lead to uniform, tilt or distortion, or non-uniform settlement of infrastructure. Uniform consolidation can result in the infrastructure being lower than the surrounding infrastructure and can cause disturbances in connections or integration with other infrastructure or equipment [1]. Differential consolidation across the infrastructure can result in either tilting or distortion consolidation, which can make the infrastructure unserviceable, or non-uniform settlement, resulting in structural problems such as cracks due to the uneven loading of the infrastructure [1]. In any of these cases, the consolidation effect can result in damage to infrastructure and uneven heights or angles between either connected or surrounding infrastructure.

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Methodology: To ensure the compaction and consolidation experiments behave in a representative manner of the lunar regolith, a regolith simulant that has a similar mineralogy and particle size distribution of lunar regolith is to be used. Lunar water ice is most likely to be located in the lunar polar conditions, able to support long-term water ice, with the topography dominated by lunar highlands [2]. For this reason, Korean Lunar Simulant 1 (KLS-1), was used [3]. KLS-1 has been developed to match the mineralogy and particle size distribution of Apollo 14 highland lunar regolith sample 14163, with physical, chemical and mechanical properties comparative to the Apollo regolith samples and other lunar simulants [3].

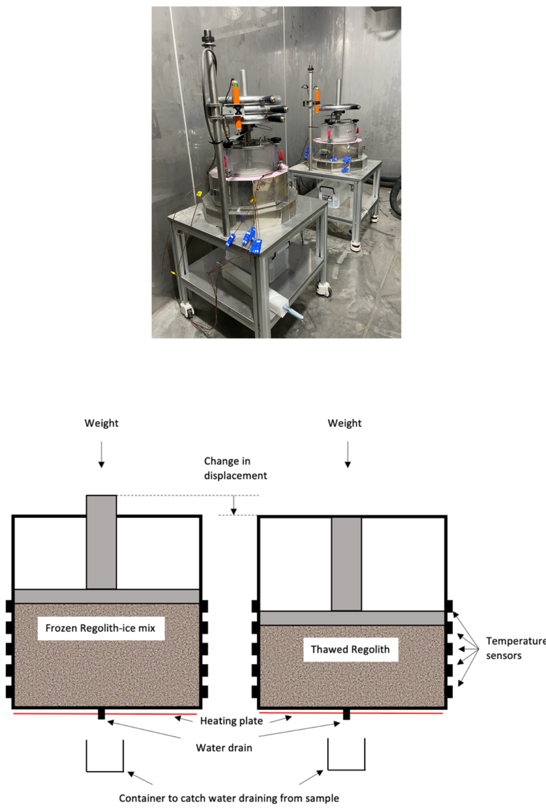


Figure 1: (top) Photo and (bottom) test setup of consolidation testing apparatus.

The ASTM D4546-21 Oedometer test (Figure 1) is used for the geotechnical investigation to measure the consolidation properties of soil. It is used to determine the rate and size of soil settlement when subjected to a vertical load. The test provides an intuitive assessment of the one-dimensional vertical displacement of a cylindrical soil sample subjected to a vertical load under radial constraints [4, 5]. The apparatus uses an acrylic mould with a height-to-diameter ratio of about 0.53-0.67 to remediate side friction between the specimen and the side wall [4, 5]. The outer mould is covered with heat-insulating material to control the direction of heat conduction. A heating plate is located at the base of the mould which heats the sample one-dimensionally from the bottom up.

Two test systems were run in parallel, with one testing overburden weight of 33.4 kg (10.4 kPa) and the second testing overburden weight of 13.4 kg (4.2 kPa).

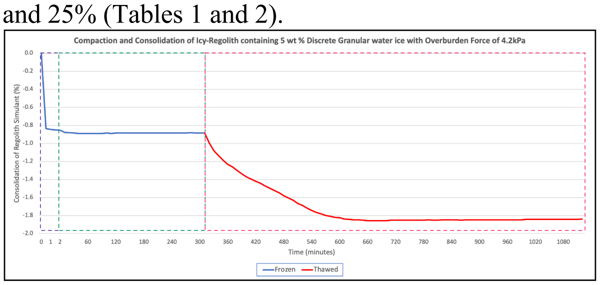
Preparation of icy regolith mix: One-dimensionaly frozen water ice was crushed and sieved to have a particle size <850 µm. Sieved water ice was homogeneously mixed with KLS-1 regolith simulant that was pre-cooled to -15 degC.

Icy regolith mix was placed in the pre-cooled to -5 degC ASTM D4546-21 Oedometer, with the test chamber filled to a maximum depth of 135 mm. After every 20 mm of the mix was added into the chamber, the icy regolith was flattened using a 2.7 kg weight (0.8 kPa equivalent) for 10 seconds. Once the chamber was filled to the desired depth, filter paper was placed on top of the icy regolith, with the height of the icy regolith taken in 3 locations (every 120°), to ensure the icy regolith height was even.

To commence the tests, weights of 13.4 kg and 33.4 kg were added as overburden forces, equivalent to 4.2 kPa and 10.4 kPa respectively.

The icy regolith mix remained at temperatures <-5 degC until compaction rate was <0.04 mm per 30 min. The icy regolith mix was heated to >1 degC for the long-term consoliation for a minimum of 12 hours and until the consolidation rate of the regolith was <0.01 mm per hour.

Results: Tests were run with icy regolith mix concentrations containing 0%, 1%, 5%, 10%, 15%, 20% and 25% (Tables 1 and 2).



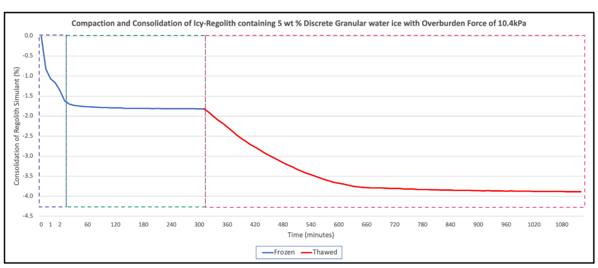


Figure 1: The compaction and consolidation tests for icy regolith containing 5 wt % discrete granular water ice.

Tests yielded three separate consolidation phases (Figure 2): (1) compaction of the frozen icy regolith after the placement of each additional force; (2) long-term compaction of the frozen icy regolith; and (3) consolidation of the thawed regolith. Results from each of these three phases provide the impact of human activities on the lunar regolith in varying manners and have been separated to compare the impact of each phase: (1) stepping or a vehicle passing over the regolith; (2) impact of an object remaining stationary on the frozen regolith; and (3) impact of an object remaining stationary on thawed regolith.

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

Table 1: 4.2 kPa overburden results.

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

Table 2: 10.4 kPa overburden results.

Conclusion: The tests provide an initial view as to the consolidation and density behaviour of regolith simulant. Due to time restraints, the number of tests conducted and the timeframe for each test observing the long-term consolidation were limited. Further testing on the long-term consolidation of lunar simulants and how differing lunar simulants behave when similar tests are performed are necessary to provide an improved understanding of the consolidation of the lunar regolith.

References: [1] Budhu, M. (2015), *Soil Mechanics Fundamentals*. [2] Lemelin, M. et al (2022), *Compositional Maps of the Lunar Polar Regions Derived from the Kaguya Spectral Profiler and the Lunar Orbiter Laser Altimeter Data.* PSJ **3**(3). [3] Byung-Hyun, R. et al. (2017), *Development and Geotechnical Engineering Properties of KLS-1 Lunar Simulant.* JAE **31**(1). [4] Monden, H. (1969), *One-Dimensional Consolidation Affected by Side Friction.* Soils and Foundations **9**(1). [5] Yao, W. et al. (2023), *Effect of Height-to-Diameter Ratio on the Compression Test Results of Remodeled Loess and Its Mechanism.* Buildings, 2023. **13**(176).