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Experimental Insights on the Densification of Regoliths by Thermal Cycling

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Abstract

A range of processes are implicated in the formation and modification for planetary regoliths, but the individual contributions of each mechanism are unknown. In this work we investigate the role of thermal cycling, perhaps the most ubiquitous process occurring on airless bodies, in regolith evolution. We demonstrate experimentally that thermal cycling can cause granular compaction in unconsolidated granular materials, but that initially compact materials remain unmodified over the range of parameters tested. Our results tentatively suggest that thermal cycling induced regolith compaction will reach a saturation density (over a timescale determined by insolation parameters) that will remain unchanged unless by another modification process.

1. Introduction

Regoliths are a common feature on rocky and airless bodies. Consisting primarily of fragmented granular debris, they serve as the interface between space and the interior of a body. As such, they are continuously formed and modified by a range of frequent small-scale processes and infrequent large-scale events [1], the signatures of which are likely recorded in the regolith. Our current understanding of regolith evolution does not include individual inputs from modification processes, which hampers efforts to interpret remote sensing datasets that are sensitive to regolith properties.

Thermal cycling by insolation is advocated as one of the processes responsible for forming and modifying regoliths on rocky bodies [2-4]. The non-stochastic nature of this process makes it suitable for theoretical and laboratory testing, but few studies have investigated the effect of thermal cycling in the context of regolith evolution [4]. Here, we perform experiments examining the influence of thermal cycling on regolith simulant fines and other granular media.

2. Experimental Methods

We perform a suite of experiments to test the effects of thermal cycling on granular materials at the Simulated Planetary ICes and Environments Laboratory (SPICE Lab) at the Weizmann Institute of Science. Using a PID loop, we impose sinusoidal temperature variations on samples in a radial heating configuration. T-type thermocouples continuously monitor and log sample temperatures and a DSLR camera captures images at designated intervals, which are then used to analyze each experiment. We vary the cycle temperature range (ΔT), number of cycles (n_{cycles}), atmospheric pressure, sample material, sample container, and initial compaction state.

3. Results and Discussion

The experiments carried out in this study demonstrate several important concepts with respect to regolith compaction stemming from thermal cycling. First, we show that ΔT is positively correlated with the extent of densification of initially uncompact samples (Fig. 1), which is consistent with previous work [4-5]. Across the solar system and on a single body, ΔT can vary widely, dictated primarily by the object's topography and orbital parameters. Our results suggest that porosity may be observably higher in regions where the temperature fluctuations are small, such as in permanently shadowed craters on the Moon where water ice is known to persist [6].

We also demonstrate that the degree of compaction varies for dissimilar types of granular materials (Fig. 1). The thermal expansion and contraction of spherical granular materials have been shown to result in the reconfiguration of grains into more optimally packed arrangements [5]. In the case of planetary regoliths, which are often angular and irregularly shaped, it is possible to substantially alter the packing arrangement through this same process (Fig. 2). The significant density changes observed in our uncompacted regolith trials reflect this concept.

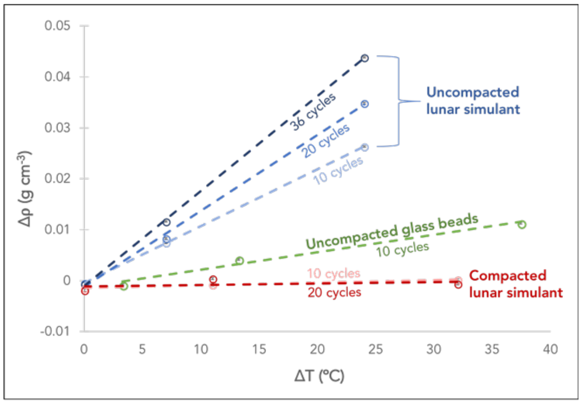

Figure 1: Change in density for thermally cycled materials over a range of temperatures and n_{cycles}. Dashed lines are linear fits to the data. Points at ΔT=0 are control experiments with no temperature oscillations.

Experiments in initially uncompacted samples were also shown to increase in density with each progressive thermal cycle, although samples did not reach saturation density, similar to previous work [4-5]. Experiments with initially compacted (porosities approximately 10% lower than uncompacted samples) lunar regolith simulant showed no changes over twenty cycles for a range of temperatures (Fig. 1). We interpret this as an indication that these samples exceed the aforementioned saturation density and were not able to rearrange to a less dense matrix in the experimental conditions.

Density and grain connectivity is known to influence the thermophysical properties of regolith [7]. Examples of this can be seen on the Moon, around "cold spots," which are regions of low thermal conductivity surface soil surrounding recent impacts [7-8] that appear to fade over a 150 kyr timescale [9]. These features will act as a natural laboratory for future work as we incorporate experimental results into a comprehensive model for thermally induced changes in regolith.

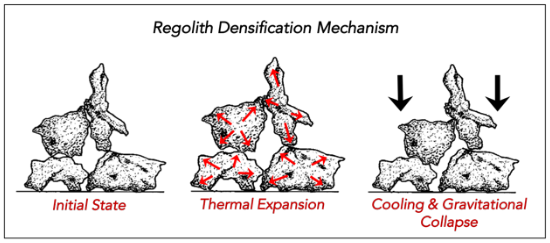

Figure 2: Cartoon of regolith densification via the thermal cycling mechanism. The irregular shapes of regolith permit significant changes in packing arrangement.

4. Summary and Conclusions

Thermal cycling of uncompacted regolith simulants and granular materials leads to sample densification that increases as a function of ΔT and n_{cycles}. Conversely, initially compact regolith simulants remain unchanged by the same thermal cycling process during the course of our experiments. We suggest this behavior implies that thermal cycling densification is irreversible by the same process. If regoliths are continuously approaching or reach their saturation density through this modification process, then the contribution of thermal cycling to regolith evolution may be modeled, estimated and validated with remote sensing datasets.

Acknowledgements

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