AFM MEASUREMENTS OF ASTEROID-RELEVANT PARTICLE ADHESION.

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Introduction: Our scientific goal is to experimentally model asteroid surfaces, specifically by understanding the cohesive forces that act at the nanoscale as a glue to hold rubble piles/strengthless bodies [1] together and influence particle motion. Characterizing the adhesive values, or "stickiness," of asteroid materials is essential because adhesion plays a key role in the structures of asteroids, in their evolution, and in surface features. By understanding material surface properties such as adhesion and cohesion, we can examine the processes that form asteroids, develop models that predict their evolution and history, and better model their current behavior.

Asteroid surface and internal structures are predominantly determined by remote observations. Imagery of asteroids helps us to define upper limits to rubble pile asteroid diameters and gives more defining factors of their surfaces. The cores of rubble pile asteroids are not fully understood, but imagery from sample return missions has suggested that the surfaces of rubble piles asteroids are boulder-like with finer regolith acting as a glue to hold the boulders in place. Many small bodies in our solar system have low bulk densities that are much less than the densities of their meteorite equivalent, which leads to the interpretation that the parent bodies must be very porous. While these observations are in line with some modeling work [2][3], these predictions have not been experimentally tested in labs or explored fully through sample return missions. It is difficult to perform these experiments in a simulated asteroid environment especially due requirements of a low-gravity, vacuum environment, and due to the many physical effects that shape asteroid surfaces.

To validate these models and acquire more accuracy and precision in the measurements, laboratory measurements are needed. Atomic Force Microscope (AFM) measurements uniquely allow for high resolution imaging of surfaces, especially on the nanometer-scale, but more importantly for this work, can be used to acquire force-distance measurements that allow the study of mechanical properties of materials and surfaces [4].

Experimental Methods and Initial Results: AFM cantilevers are often made of silicon, in a rectangular or "V" shape, but can be customized with coatings and with desired tips. For this study we used tips of different shapes, including the standard pyramidal shape (gold-coated silicon) to understand the AFM operation and to take initial measurements, and then silicon spheres to begin to look at the effects of tip size and shape (2µm and 15µm spheres) on the interactions.

In our initial experiment we used three samples, each of different grain sizes of JSC-1 simulant: a 125-250 µm sample, a 75-125 µm sample, and a less than 45 µm sample (Figure 1). Each sample was attached to a silicon substrate by sprinkling a random distribution of particles to coat an adhesive surface and then mounted in the AFM. On each sample we selected 2-3 grains of representative sizes, acquiring about 100 curves in a 3 µm by 3 µm region on each grain. We then screened the curves into "normal" and "abnormal" categories, based on the which curves looked standard, with a clear interaction signal due to adhesive forces, and others that are difficult to interpret due to effects such as cantilever vibrational oscillations or high signal-to-noise ratios. Abnormal signals will be interpreted in future work. For the analysis on the "normal" curves we extract the adhesive force from the force curves using calibrated cantilever spring constant values, and the root-mean-square voltage measurement, V_{rms}, values using the formula from Ohler [5]. Those values are then converted to an adhesive force based on the strength of the "pull-off" force between the grain and tip. For the measurements with the standard tip and the regolith simulant samples we observed that the < 45 µm sample showed the highest tip-grain adhesion values and also had a larger distribution of forces.

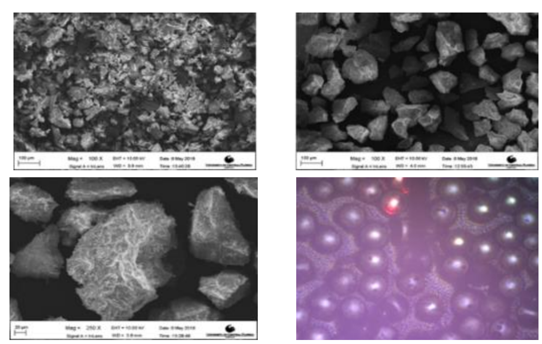

Figure 1. SEM images of the < 45 µm sample (top left), the 75-125 µm sample (top right), a 250X magnification SEM image of the 75-125 µm sample displaying the smaller particles on the surface of a rock (bottom left), and an optical AFM image of the spherical glass beads (bottom right).

Particularly of interest for this work is the "colloidal probe technique," which typically uses a spherical AFM probe tip (because of its well-defined geometry and symmetry) to study surface forces and particle-particle interactions [6]. We will use this technique, both with spherical tips and by attaching regolith simulant grains to the cantilever. With these methods we measure regolith simulant grain-to-grain adhesion forces under a variety of experimental conditions.

The first step with this technique included reproducing sphere-to-sphere interactions by attaching a 45 µm sphere to a tipless cantilever and then measuring the adhesive force between the tip and the sphere samples at ambient conditions and at 15% humidity. Because surface contamination and adsorbed water are known to affect measured adhesion results, we use simulants and tips that have been stored in dry chambers with desiccant and we control the humidity by using dry nitrogen flow in the AFM experiments. We also performed "sphere-to-rock" measurements using the 2µm, 15µm, and 45µm SiO_2 sphere tips on the different regolith samples. We observed larger forces with the 15µm (Figure 2) and 45µm tips and the <45µm sample than the other samples in both ambient conditions and at 15% humidity. The 2µm tip showed the largest forces in the 75-125µm regolith sample. These measurements will be compared with basic granular adhesion models to interpret the results.

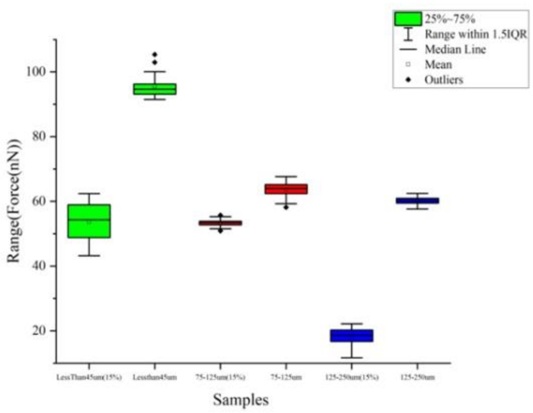

Figure 2. Box Plots showing the 15µm tip measurements across the different regolith samples at 15% humidity and ambient conditions. As shown, we observe the largest forces on the <45µm samples at both humidity levels, and decreases in force with increasing sample size.

Ongoing Work: To further our investigation, we will begin performing grain-to-grain contact measurements. To achieve this objective, we attach a sample grain, such as a JSC-1 lunar simulant grain, an SiO_2 sand grain, or another representative minerology, to the cantilever using the technique as described by Gan [6]. With all of these experiments, we will perform measurements on several representative grains on the surface, taking a minimum of 25 force curves on each grain. We will attempt to vary both the sample grain size and the relative surface roughness. With multiple, repeated contacts, we can both reproduce the locations of contact and vary them along the surface. We will then analyze the force curves, extracting the adhesion forces and energy dissipated through the interaction by using our in-house analysis software, as done for the previous sphere-sphere grains. We will compare how the force is distributed over the surface, and effects of particle size, composition, and surface structure. We will present initial results of these experiments.

To further explore these effects and test other methods, we have also begun a collaboration to evaluate the possibility of performing experiments in vacuum.

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