THE FLUID BEHAVIOR OF REGOLITH ON DRY AIRLESS BODIES. D. Y. Wyrick[1], R. Patterson[1], A. Murphy[1], R. Baillie[1], and H. Başağaoğlu[1], [1]Southwest Research Institute (6220 Culebra Road, San Antonio, TX; dwyrick@swri.org).

Introduction: Common to all solid planetary bodies is surface regolith, unconsolidated material typically comprised of dust and broken rock fragments. Planetary bodies with atmospheres (Earth, Venus, Mars, Titan) have regolith surfaces that are also subject to aeolian and fluvial erosional processes that serve to round individual grains, creating an unconsolidated material with well-rounded grains of high sphericity. This inherent roundness of the grains exerts a fundamental control on the macroscale behavior of the unconsolidated material. Additionally, common sources of erosion also serves to sort grains by size, often creating sediments that are well sorted and uniform in grain size.

Less well understood is the behavior of regolith materials on airless bodies, where minimal erosional processes keep individual grains at a high degree of angularity. Apollo samples of lunar regolith material show heterogeneous lithic fragments ranging from dust to boulder-scale in size. Erosional processes on the moon (and other airless bodies) consist primarily of macro- and micro meteorite impacts, which produce different erosional effects. Micrometeorites (<1 mm) impact the surface of planetary bodies millions of times a day, creating small impact melts called agglutinates (10s µm to mm in scale) that often entrain other lithic fragments and volatile gases. These include solar wind ions such as hydrogen and helium which, because of lack of an atmosphere, can be imbedded several hundredths of a micrometer into the regolith subsurface. Impacts by larger meteorites serve as another major factor in regolith material behavior, as they can either directly fuse unconsolidated material into rock at high pressures (regolith breccia) or serve as an erosional mechanism through seismic shaking of the body from impact.

Motivation: Regolith mass wasting on small airless bodies is expressed in several ways. Ponding is common in areas of low topography [1], where smooth, flat areas of regolith material is thought to occur from impact seismic shaking, similar to liquefaction processes on Earth. On many small bodies, regolith material appears to collect in topographic lows, with a smooth, often featureless, terrain. Less well understood are the gully formations that appear on airless bodies such as Helene and Vesta. The observed gullies on Vesta are narrow (30 m wide), with an average length of 900 meters and are confined inside impact craters [2]. These features are steep-walled, with material showing angles of repose well above that of dry sand (~30°). Scully et al. [2] suggest the gullies form from transient water from impacts, however they rely upon terrestrial analogs of wet versus dry granular flow, all of which suffer from the systemic bias of water and wind erosion on Earth that would not be found on Vesta.

Similar gully formations have been observed on Helene, a small icy moon of Saturn [3]. The grooved formations on Helene occur primarily near topographic divides and appear to cut into a broad, slightly lower albedo surface, with fairly regular spacing of 125 – 160 m. Other geomorphic features suggest that material has traveled several kilometers concentrated along linear, downslope pathways, implying an advective transport process as opposed to diffusive mass wasting process that would produce a smoother surface. Helene, unlike Vesta, is made primarily of porous water ice, with a dusty regolith likely sourced from Saturn's E-Ring. Umurhan et al. [3] invoke electrostatically charged particles and van der Waals forces to explain the deeply incised channels and angles of repose <30°. To date, neither research group has explored the role of grain size and shape distribution on the dynamic and static behavior of the regolith on airless planetary bodies.

Grain sphericity and size distribution influence a material's overall porosity and may in turn influence the materials' bulk behavior and resultant geomorphic expression. On the moon, near-surface regolith has a high porosity (50%) in the top 15 cm [4]. This high porosity reflects the main emplacement process – ejecta fallout – on airless planetary bodies. However, at depths of >15 cm, penetration resistance increases rapidly, with resistance reaching greater than 1000 kPa within 50 cm of the surface [5].

Previous work: It was noted in previous testing of the JSC-1A simulant that when the material was gently deposited, the individual angular grains tend to lock with one another. In this way, large angles of repose are achievable, in some cases nearly 90°. As additional material is deposited, the material begins to increase in overburden pressure, compacting grains and decreasing porosity. A proposed hypothesis is that the regolith grains foliate under increasing normal stress, allowing individual grains to rotate 90° to the normal stress and align along the shear stress direction [5]. For these highly angular and non-spherical grains, this foliation may rotate grains such that their long axis is aligned perpendicular to the normal stress and parallel to the

shear stress. This is expressed by the simulant material being very strong in the normal direction, perpendicular to the long axis of the grains, and very weak in the shear direction, where grains are individually aligned in a favorable orientation. After the simuland regolith fails and mobility is achieved, the unconsolidated material acts much like a fluid, following the downslope gradient. Once it reaches the topographic level where it runs out of kinetic energy, the regolith simulant appears to revert back to its high angle of repose, with the grains once again locking into place. Over time, as more material is emplaced on the surface, buried regolith materials are put under increasing lithostatic normal pressures, which in turn may increase the grain foliation that leads to slope failure. The general dynamics of these materials may be described from a geomechanical perspective as strain hardening/strain softening behavior. Alternatively, this material may be described from the fluid dynamics perspective as a non-Newtonian, Bingham-fluid flow.

Results: Experimental tasks have begun to compare grain shape and size to mechanical behavior. Grain size and shape distributions are compared to the Apollo lunar sample returns that were extensively characterized during the 1970s and whose records are finally publically available in electronic format [6]. Apollo 17 core sample of regolith sample #79002, taken near the Van Serg crater, was used as the fiducial regolith sample in our experiments, as it best fits the average grain size range from that mission [7].

Fig1: Fine grained pumice on left (44-74 µm) constructs a much higher angle of repose cone, with slopes reaching upwards of 80°, whereas the glass beads on the right (45-90 µm) construct flatter angles of repose of ~30°.

Two main types of unconsolidated materials have been procured for the density and repose experiments: spherical glass beads and pumice grit, each with grain sizes ranging from <40 µm to 1.4 mm. These represent the end members on the grain sphericity range. Density and angle of repose testing has begun on the various sediments, with preliminary results pointing to confirmation that grain shape does indeed have an effect on the geophysical behavior of the bulk material. In early testing, materials with the same grain size distribution have remarkably different constructional cone angles of repose. The pumice grit (44-74 µm) constructs a much higher angle of repose cone, with slopes reaching upwards of 80°, whereas the glass beads (45-90 µm) constructs a flatter cone, with angles of repose around 30° (Fig 1). These tests confirm that the microscale characteristic of grain shape has a macroscale geomechanical effect on angle of repose under Earth's atmospheric pressure.

Larger particle size (>2 mm) experiments have begun, with material selection determined based on material behavior using dry, unfired clay shapes under Earth's atmospheric pressure. The dry, unfired clay shapes were found to best mimic the small-scale edge erosion that regolith particles would be subjected to under turbulent conditions. These experiments are two-dimensional (2D) in nature and are designed to determine the effect of grain shape on angle of repose and porosity. Similar to the microscale observations, grain shape has a direct effect on the rotating angle of repose. Rolling drum angle of repose experiments show circles (Figure 2A) easily rolling over each other to reach a low angle of repose, whereas star-shapes (Figure 2C) achieve a high angle of repose due to their interlocking configurations.

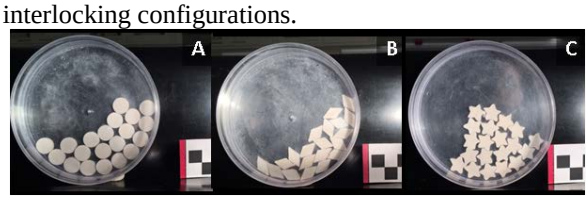

Fig 2: Centimeter scale 2D shapes in rolling drum angle of repose testing. (A) circles settle to a low angle of repose; (B) rhomboid shapes show low porosity and low angle of repose; and (C) star-shape settle at a high angle of repose, with interlocking grains.

Future work: Numerical modeling has begun, using a fluid dynamics approach to modeling unconsolidated materials. Utilizing a lattice-Boltzmann approach, we are currently incorporating arbitrary shaped particles as well as incorporating non-Newtonian flow (e.g., Bingham fluids) to the simulations.

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