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Introduction: In September 2023, NASA’s OSIRIS-REx mission returned to Earth a sample from asteroid (101955) Bennu, a carbonaceous B-type asteroid [1,2]. The sampling mechanism penetrated ~50 cm into the subsurface of Bennu [3], consistent with pre-launch numerical simulations for near-cohesionless regolith [4,5] and low-gravity experiments: both generate loose material which can easily be mobilized [6]. Bennu is a rubble pile held together by a combination of gravity, friction, and cohesion that may also control its bulk shape [3,7,8]. Identifying the relative magnitudes of these forces offers a way to help understand the stability and evolution of Bennu’s shape due to external forces (like YORP spin-up), and to develop hazard-mitigation strategies for Bennu and other near-Earth asteroids. Understanding the cohesive forces in a range of particle sizes can help us to understand how the surface and subsurface cohesion lend to the overall strength of Bennu.

To accomplish this, we plan to directly measure the cohesive force between sample particles. The following overview focuses on the particle-particle nanoscale atomic force microscopy (AFM) cohesion testing to estimate the strength of asteroid Bennu. Here we present our testing protocol and initial results from testing a Bennu-like simulant.

Cohesion Testing: We plan to directly measure the cohesive force between sample particles using AFM (Fig. 1a). As discussed in [9], we seek to mitigate the influence of humidity (physiosorbed terrestrial water, leading to capillary bridges with a ~100x stronger cohesion than dry cohesion [10,11,12,13]), which has adversely affected cohesion measurements. Particle-to-particle measurements are conducted inside of an AFM that can perform a vertical approach displacement. One particle is attached to a tipless AFM cantilever (Fig. 1b, c) and another to a substrate. The cantilever arm is lowered, allowing the particles to touch, until zero force is registered. The cantilever is then raised, and the particle separation force is measured. All testing will be performed in a well-sealed and ultra-high purity (UHP; 99.9999%) nitrogen gas purged chamber to help reduce the relative humidity. Before testing, the particles will be heated to just under 100 °C to help evaporate any free water. All particles will be stored in a nitrogen-purge desiccator prior to testing. We will test a range of particle sizes (Fig. 2) and obtain the statistical distribution of cohesive/adhesive forces between different particle pairs. It is expected that ~40 particles (or 20 pairs) will be tested. The cohesive force is governed by the amount and composition of asperities, or roughness contact points [14], and the chemistry of the particle's surface. Given this, we will perform several measurements on different areas of the two contacting particles. In addition, we will attempt to extract the roughness power spectrum through contact AFM profilometry and optically via the Depth from Defocus method with the Keyence VHX-7000 Digital Microscope to produce 3D topographic models of particle surfaces.

Initial Simulant Results: Prior to obtaining the returned samples, we tested the experimental protocol on a Bennu-like CM simulant to understand the effects of humidity on our samples [15]. Initial force versus displacement curves were obtained on the simulant (Fig. 3). The measured cohesive force was 3.2 x 10^-9 N. The work of adhesion is determined by the cohesive force divided by 2πR where \( R = (R_1 \times R_2) / (R_1 + R_2) \), and \( R_1 \) and \( R_2 \) are the radii of the particles [16]. The total work of adhesion of the test performed in Fig. 2 is 2.72 x 10^-4 J/m². The measured cohesive force and work of adhesion presented here were acquired in a UHP nitrogen environment with minimal effects of water. If water was present, we would observe higher cohesive values due to the higher surface tension of water. This test thus demonstrates the feasibility of our procedure to measure the cohesion of Bennu particles in a moisture-free environment.

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Fig. 1: (a) Schematic of test. (b-c) Progressive zoom of particle attached to AFM tip. Yellow scale bar in (b) is 80 µm and red scale bar in (c) is 40 µm.

Fig. 2: Image of the aggregate sample OREX-803024-0 which shows a range of particle sizes similar to the particles which will be used for cohesion testing.

Fig. 3: Sample force vs. displacement curve for a trial cohesion test on the Bennu-like CM simulant.