BENNU SAMPLE PHYSICAL PROPERTIES FROM MULTI-SCALE MEASUREMENTS OF STRENGTH AND INDENTATION HARDNESS.

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Introduction: NASA's OSIRIS-REx mission to Bennu [1], a carbonaceous asteroid, returned samples to Earth on September 24, 2023. A series of tests will be performed to determine the physical and thermal properties and the effects of nano-sized inclusions on the micro-scale properties of the returned sample [2]. These collected data will test a subset of mission hypotheses related to the formation, geological evolution, and fundamental nature of Bennu and its parent body (see chapter 3 in [2]), formulated through analysis of remote sensing data. Strength results will help us understand the evolution of Bennu's surface in response to impacts, thermal fracturing, and mass wasting [2]. Strength and energy absorption values will help determine if the energetic events (sample collection and return) possibly influenced the sample [3]. Elasticity and strength results will help inform asteroid deflection strategies, such as the recent DART mission, by providing quantities needed to calculate momentum and energy transfer during collisions. The following overview focuses on a subset of these tests: the nano- and micro-scale mechanical tests, with preliminary results from tests with analog materials.

Nano- and Micro-scale Testing Program: We plan to perform (i) nano- and micro-scale indentation, (ii) compression testing, and (iii) cohesion testing [4]. Here, we present an overview of the indentation and compression testing. As part of preparations for sample return, we performed tests on carbonaceous chondrite materials, which can act as analogs to Bennu material based on infrared remote sensing data analysis [5,6,7]. Two practice materials were indented: a 30-µm section, prepared at NASA's Johnson Space Center (JSC) of the Lonewolf Nunataks 94102 (LON 94102) meteorite (Fig. 1, a-c), and a 50-µm section, also prepared at JSC, of a Bennu-like CM terrestrial simulant, similar to [8] but with a higher total porosity of ~54%. Compression tests were performed on the CM simulant.

Preliminary results of indentation testing: Instrumented nanoindentation, consists of pushing a diamond Berkovich tip into the surface of a material and recording the force vs. displacement response, allows for the properties of the returned rocks (on a scale down to ~5–10 nm) to be elucidated thanks to phase separability [9]. Micro-indentation is the same style of test with larger forces and penetration depths, yielding a more homogenized response. The modulus (*M*) and hardness (*H*) of the indented material(s) are determined using the Oliver and Pharr model [10].

Nano-scale indentation tests were performed on LON 94102, using a force-controlled testing protocol with a max force of 8 mN. A collection of measurements on and around a stiff particle (Fig. 1c) resulted in the force vs. displacement curves (Fig. 1d). Most of the indents on the particle had shallow footprints around 150 nm deep, giving an *M* and *H* of 183.2 ± 44 GPa and 12.5 ± 3.56 GPa, respectively. Indents on the clay matrix (Fig. 1e) were deeper, for the same maximum force, due to the compliant behavior of the clay, resulting in wider footprints and an *M* and *H* of 46.7 ± 7.3 GPa and 2.67 ± 0.61 GPa, respectively.

Micro-indentation was performed on the CM simulant. These indents reached depths of ~2.9 µm at 8 gram-force, yielding an *M* of 18.22 ± 5.93 GPa and *H* of 0.49 ± 0.14 GPa. Our results are consistent with findings from other heterogeneous materials including cements and organic-rich source rocks [9,11,12].

Preliminary results of compression. Compressing a particle between two rigid metallic platens is a common technique for quantitative determination of particle-scale strength [13]. The scale of this test will be on the order of a few hundred µm to mm, depending on the size distribution of particles in the allocated aggregate. The micro-indenter will compress the sample with a "flat punch" probe with controlled displacement up to a max depth. The output of each test is a force vs. displacement curve (Fig. 2a). XCT scans will show if there are large pre-existing flaws within the particles that could concentrate stresses as singularities and nucleate cracks. In our test with the CM simulant, the average particle diameter in Fig. 2b was 0.95 mm and the max force (Fig. 2a) was 186 mN, yielding a splitting tensile strength of 184 kPa. The test resulted in fragmentation of the main specimen into several smaller pieces (Fig. 2c), all of which were recoverable for future analysis.

Outlook for Bennu sample analysis: Preliminary examination of the returned rocks has confirmed the carbonaceous nature of Bennu and revealed the samples to be heterogeneous in nature [14]; therefore, the response to any excitation on larger scales of the sample is a combination of the effects across multiple material phases on smaller scales.

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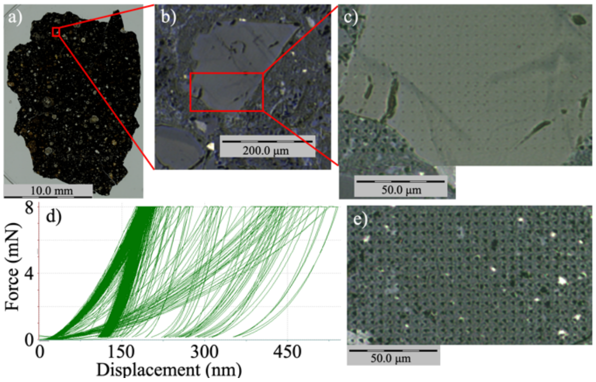

Fig. 1: (a-c) Progressively magnified view of LON 94102 meteorite thin section with 405 indents performed on embedded stiff particle (c), resulting in (d) collection of force vs. displacement curves. (e) 400 indents in the fine-grained clay matrix.

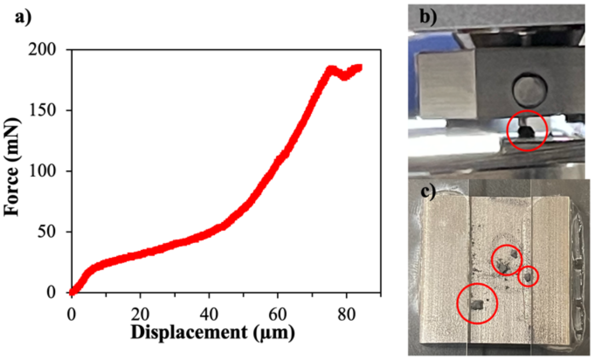

Fig. 2: (a) Force vs. displacement curve from compression of simulant sample. (b) Simulant sample inside of compression testing machine, outlined by red circle. (c) Smaller fragments of simulant sample formed during compression tests, outlined by red circles.