UNCONFINED COMPRESSIVE AND SHEAR STRENGTHS, YOUNG'S MODULUS, SEISMIC VELOCITIES, AND ELASTIC PROPERTIES OF A MURCHISON METEORITE INDIVIDUAL.

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Introduction: As relatively high spatial resolution imagery (and related spectral and other optical property data) of asteroids become available, features resulting from geologic processes are becoming more evident; spacecraft interactions with asteroid surfaces are also increasing. Consequently, physical properties of asteroid lithologies are becoming useful in constraining modelling of asteroids' geologic histories and current mission surface interactions. We have begun measuring unconfined strengths (compression and shear), seismic velocities (compression and shear), and related static (e.g. Young's modulus) and dynamic elastic constants for carbonaceous chondrites (together with density, microporosity, coefficient of restitution, and consideration of sample details such as veining and brecciation that may influence mechanical properties). Study of relatively recent falls is prioritized to minimize terrestrial weathering effects.

Murchison Meteorite: The Murchison meteorite is a CM2 chondrite (fell Sept. 28, 1969); many specimens were collected before long local exposure. The studied individual is an ~ 9 mm-thick sawn slab (sample ME2640, Field Museum) showing no obvious weathering. The slab is relatively uniform in lithology with bulk density of 2.4 g/cm^3; grain density and microporosity were determined by He pycnometry as 2.94 g/cm^3 and 18.3%, respectively. These fall in the range previously measured for Murchison individuals [1], but the microporosity is at the low end of those previously measured (18.7 – 24.9%) although the grain density is typical. Relatively cryptic brecciation textures are present in the slab as often described for Murchison [e.g. 2] with visible clasts up to ~1 cm size.

Methods: Unconfined compressive and shear strengths were performed following the procedures of [3] & [4], respectively, excepting as limited by sample availability. Compressive tests were done on cuboids of 2:1 length to cross section side ratio; cuboids were cut (dry) using a wire saw with ~0.15 mm kerf. A Test Resources (Model 313Q) electromechanical press with 5 & 50 kN load cells compressed the samples to failure; displacement was measured with an Epsilon 3542 extensometer. Samples were outgassed overnight in vacuum (to reduce potential effects from absorbed water) before testing at ambient conditions. The shear strength measurements were conducted using the same press in a direct shear guillotine fixture; sample cubes of 2.5 and 5 mm-size were measured. After testing video and pre-test static imagery are examined to see if any apparent flaws localized failure; cuboid failure fragments are also recovered.

Seismic velocities were measured using ultrasonic transducers (e.g., 13 mm Olympus V103 & 153) in an alignment jig following procedures outlined in [5] as practical; samples were measured without couplant using only contact pressure for wave coupling (applied pressure was monitored using a force meter and never exceeded ~200 N). Measurements were repeated with three different operators to explore reproducibility.

Compressive Strengths: Figure 1 shows the compressive strength for six cuboids with lengths of 7.2 to 18.1 mm. Measured strengths ranged from 34 to 121 MPa; the smallest samples probably exceeded the representative sampling limit, but the two weakest samples were of intermediate size. The 12.2 mm-long sample failed on a hairline vein and the 11.2 mm-long sample had multiple peaks in its stress curve. The three strongest samples of 83 to 121 MPa may be most representative of Murchison's compressive strength when unfractured.

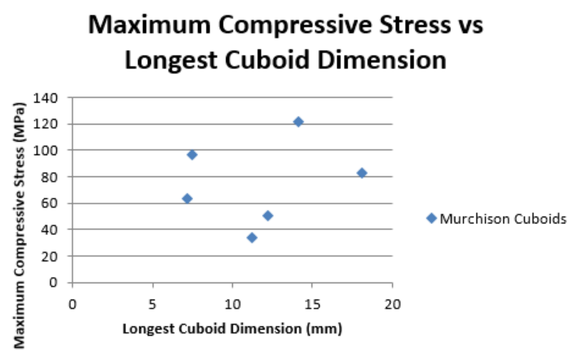

Figure 1: Ultimate compressive strengths for six Murchison cuboids of 2:1 length to cross section side ratios. The two largest cuboids required use of the 50kN load cell; others measured with 5kN load cell.

Shear Strengths: The direct shear strength tests (Fig. 2) showed a relatively narrow range of 29 to 35 MPa for the four ~5 mm cube sizes; the lower and more variable values of the four ~2.5 mm cubes are the result of the smaller test sample size violating the empirically established criterion of selecting sample dimensions such that they exceed the average/largest sample grain by a factor of ten (Murchison is a mixture of a relatively fine-grained matrix with coarser grained weak inclusions of ~0.5 mm size).

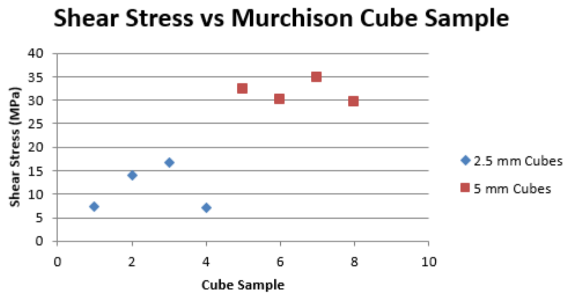

Figure 2: Ultimate shear strengths of eight Murchison samples; note that the 2.5 mm sample cubes were too small to adequately represent Murchison's strength in this test setup.

Young's Modulus: Young's moduli for Murchison (shown in Figure 3) were calculated from uniaxial strain/displacement (during uniaxial compression) data using the linear portion of the axial stress-strain curve [e.g. 3]; these values are from the six samples tested for uniaxial compressive strength. The static Young's moduli range from 9.7 to 13.6 GPa for the three strongest Murchison samples.

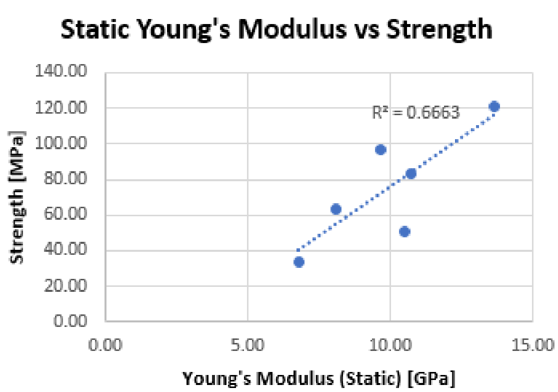

Figure 3: Static Young's modulus values plotted vs. compressive strength for six Murchison cuboids.

The moduli and strength data correlate particularly if the cuboid that failed on a hairline vein is removed from consideration.

Seismic Velocities: All cuboids measured for shear and compressive strengths that were of sufficient size had seismic velocities measured in three orientations (Figs. 4 & 5 show compression (P wave) and shear (S wave) results, respectively). The observed range of P wave velocity was 3,040 to 3,400 m/s; the longest cuboid dimension was often the slowest suggesting that the smallest cuboids may have been showing the "rod effect" [5], although total variation was only ~5% and the velocities were within the range measured across the slab before subsampling. Most cuboids showed no velocity anisotropy with up to ~5% possible.

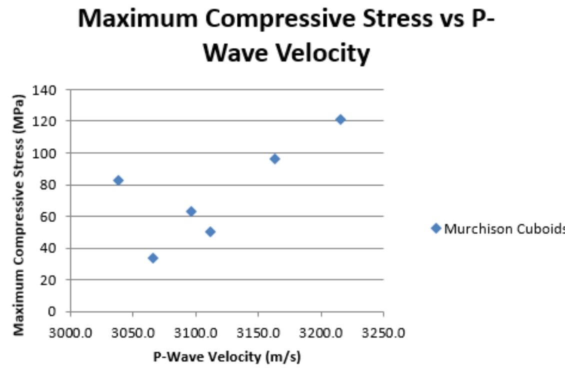

Figure 4: P wave velocities along cuboid long axes versus their respective compressive stresses; a weak correlation is observed.

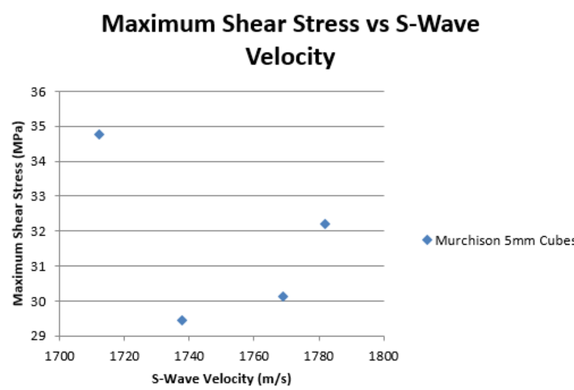

Figure 5: S wave velocities showed no correlation with shear stress in the 5 mm-diameter cuboids.

For Murchison the seismic velocities yield dynamic Poisson's ratios, shear moduli, bulk moduli, and Young's moduli of 0.21 – 0.28, 6.9 – 8.4 GPa, 11.8 – 14.2 GPa, and 17.6 – 20.8 GPa, respectively.

Discussion: The measured Murchison compressive strength range of 83 – 121 MPa is higher than some of the few available literature values, but is similar to one Sutter's Mill value (80 MPa – [6]) which is also a CM2. The higher value could also reflect the low microporosity of the studied sample, indicating the need for common measurements of physical properties to aid in interpretation. Finally, Murchison's brecciation remains to be understood on most scales.

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References: [1] Macke, R.J. et al. (2011) *MAPS, 346*, 1842-1862. [2] Metzler K. et al. (1992) *GCA, 56*, 2873-2897. [3] ASTM International D7012-04 (2004). [4] ASTM International D5607-16 (2016). [5] ASTM D-2845 (1995). [6] Jenniskens, P. et al. (2012) *Science, 338*, 1583-1587.