DYNAMIC STRENTH MEASUREMENTS ON GRANITE AND BASALT. K.R. Housen
Applied Physics, The Boeing Co., MS 2T-50, P.O. Box 3999, Seattle WA 98124. kevin.r.housen@boeing.com.

Small samples of rock, like those used in laboratory collision experiments, are known to be much stronger than bodies that are meters to hundreds of meters in size [1]. Specifically, the impactor energy per unit target mass needed to shatter the target decreases dramatically with increasing target size. This occurs because the strength of rock, like many other geological materials, depends strongly on the duration or rate of loading. In small impacts, where the loading rates are high, the material is quite strong and requires a high energy per unit mass to shatter it. In large impacts, the loading rates are low, the material is relatively weak and the energy per unit mass for shattering is correspondingly reduced.

Thus, the interpretation and extrapolation of lab collision experiments to asteroid collisions is directly connected to the relationship between strength and strain rate. In fact, the scaling of collisional outcomes with event size is directly related to the rate-dependence of strength [1,2]. Therefore, one may gain insights into the scaling of collisional outcomes by studying the strain rate dependent strength of rock.

Measurements of the dynamic strength of rock have been reported previously [3-5]. However, the materials used were generally not the same as those used in collision experiments. In the present study, strength measurements are made on the same granite [1] and basalt [6] used in previously documented collision experiments.

Experiments: The dynamic tensile strength is measured here using a dynamic version of a conventional Brazilian, or splitting test, in which a cylindrical sample is compressed along a direction perpendicular to the cylinder axis. This loading condition produces a state of nearly uniform tension that splits the specimen across its diameter. The tensile strength is calculated as $2F/\pi DL$, where F is the compressive force at failure, D is the specimen diameter and L is its length.

The dynamic Brazilian test is performed in a Split Hopkinson Pressure Bar, schematically shown in Figure 1. An impactor strikes the input bar, generating a compressive wave that loads the specimen in the configuration of a standard Brazilian test. Part of the compression wave is transmitted through the specimen into the output bar. A strain gage on the output bar measures the compressive loading from which the load at failure is calculated using the standard Hopkinson Bar analysis methods.

A strain gage on the specimen directly measures the loading strain rate, as the standard methods for calculating specimen strain in a Hopkinson Bar test do not apply in this case. Thus, each test produces a value of the tensile failure strength and the loading rate.

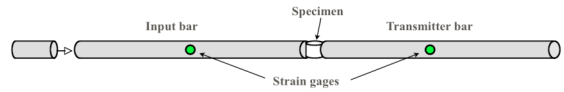

Fig. 1. Hopkinson Bar configuration. All bars are 2011-T3 aluminum, 2.54-cm in diameter.

The specimens were cylinders of either Georgia Keystone granite or Columbia basalt 1.9 cm in diameter and 0.8 cm in length. The experiments were recorded with high-speed video at rates to 120K pics/s to assure that the specimens broke cleanly across the diameter.

Tests were also conducted at low strain rates on a servo-hydraulic test machine. In addition to tests at strain rates of ~10^{-5}/s, two tests were run using basalt at rates up to the highest that the machine would run at (~0.1/s).

Results: The measured tensile strengths for the basalt and granite coupons are shown in Figure 2. The basalt data show a definite, albeit small increase in strength at low strain rates in which the tensile strength is proportional to the 0.029 power of the strain rate. In the parlance of Weibull flaw size distributions (number of flaws activated at strain less than ε is proportional to ε^m), this corresponds to a Weibull exponent of m~100. Beyond a strain rate of ~10/s, the strength increases dramatically. Although there are not enough data points at high strain rates to properly define a power-law slope, the present data suggest a strain rate exponent as large as 0.4-0.5, or a Weibull exponent of m=3-4.5. This is considerably smaller than the values of m=6 to 9 typically quoted for granite and basalt. Experiments at higher strain rates would be needed to study this further.

Another interesting feature of Figure 2 is that, while the quasi-static strength of the basalt is larger than that of the granite by a factor of ~3, the dynamic strengths of the two materials are in much closer agreement. This explains the experimental observation that the threshold energy/target mass for shattering of Georgia Keystone granite is just slightly smaller than that of Columbia basalt [6]. This also illustrates the pitfalls of using quasi-static strength measurements to infer the results of dynamic events such as collisions.

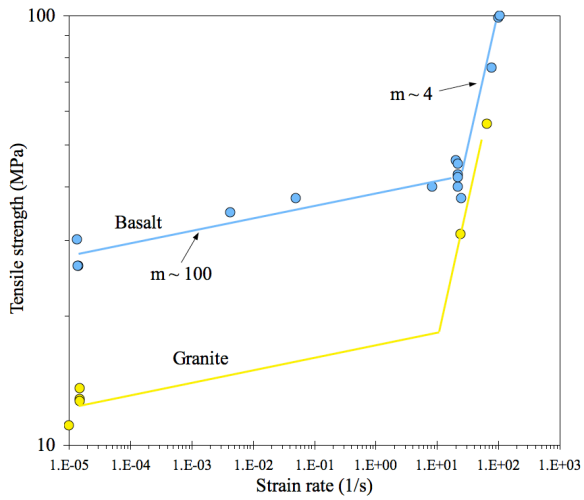

Figure 2. Dynamic tensile strength data for Georgia Keystone granite and Columbia basalt.

The rapid increase of strength at strain rates above ~10/s is similar to the trend that has been observed in numerous studies of the dynamic strength of concrete. Figure 3 compares the present data for basalt and granite to data for concrete [7]. The strength measurements are shown as the ratio of the dynamic tensile strength to the quasi-static strength. The results for concrete show a trend very much like that observed here, i.e. a weak but definite initial dependence on strain rate, with a sharp rise at higher loading rates.

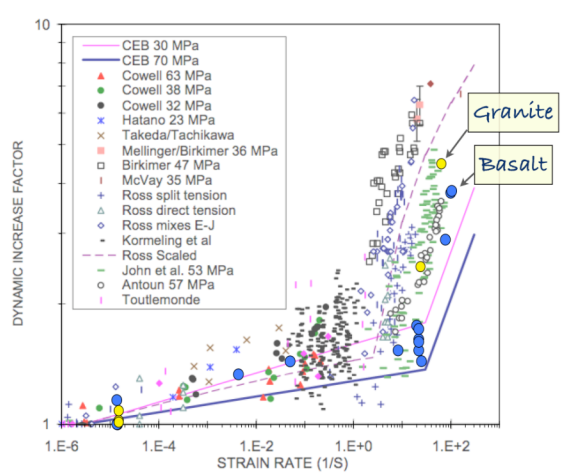

Figure 3. Data for granite and basalt compared to that for concrete.

In addition to having data from collision experiments with the same granite and basalt studied here, direct (visual) measurements of the flaw size distribution have been made for the Georgia Keystone granite [1] and are shown in Figure 4. The figure shows the number of flaw traces (expressions of a 3D flaw on a 2D surface of observation) larger than a given size. Dashed lines indicate slopes for Weibull exponents of m=100 and m=4.

For the specimen corresponding to the data shown in Figure 4, the largest flaw size was just over 1 mm, so the flaw size distribution must steepen near a size of 1 mm. At low strain rates, only the larger flaws are activated before failure occurs. Therefore, the large value of m seen in Figure 2 for low strain rates is consistent with a steep slope in the flaw size distribution for mm-size flaws.

The slope of the flaw distribution is consistent with m=4 for flaw sizes of several tens of microns. However, crack growth models [2] suggest that these flaws should not be activated until strain rates exceed 10^3 to 10^4/s, well beyond the maximum strain rates reached here. Therefore, the steep slope shown in Figure 2 for strain rates >10/s is currently at odds with the measured flaw size distribution.

Further study of this question should help illuminate the connection between the dependence of collisional outcomes on size scale, the strain rate dependence of strength and the distribution of flaw sizes. This will put scaling laws for collisions, as well as numerical models that depend on data such as that shown in Figures 2 and 3, on firmer ground.

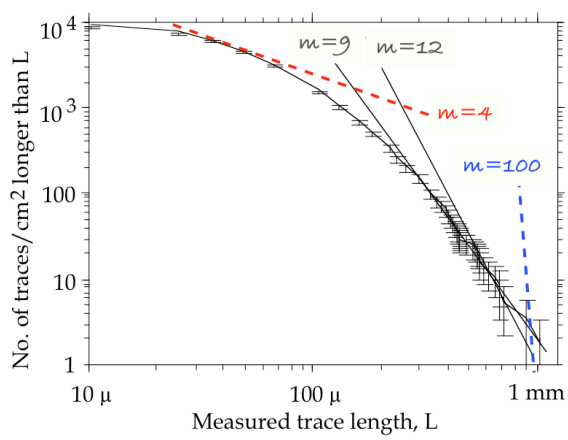

Figure 4. Flaw size distribution for Georgia Keystone granite [1].

References: [1] Housen and Holsapple (1999), Icarus, 142, 21-33. [2] Housen and Holsapple (1990), Icarus, 84, 226-253. [3] Grady and Lipkin (1980) *GRL*, 7, 255-258. [4] Cohn and Ahrens (1981) *JGR*, 86, 1794-1802. [5] Ai and Ahrens (2004), *M&PS*, 39, 167-348. [6] Housen and Voss (2000), *LPSC 31*, abst. 1495. [7] Malvar and Crawford (1998) 28th DDESP Seminar, Orlando FL (available on the web).