

**DYNAMIC STRENGTH AND FRAGMENTATION DURING HIGH-RATE BRITTLE FAILURE.** A. S. P. Rae<sup>1</sup>, T. Kenkmann<sup>2</sup>, G. S. Collins<sup>3</sup>, M. H. Poelchau<sup>2</sup>, V. Padmanabha<sup>4</sup>, F. Schäfer<sup>5</sup>. <sup>1</sup>Department of Earth Sciences, University of Cambridge, Downing Street, Cambridge CB2 3EQ, UK, aspr2@cam.ac.uk. <sup>2</sup>Institute of Earth and Environmental Sciences – Geology, Albert-Ludwigs Universität Freiburg, Albertstrasse 23b, 79104 Freiburg, Germany. <sup>3</sup>Department of Earth Science and Engineering, Imperial College London, SW7 2BP, UK. <sup>4</sup>Department of Civil Engineering, Indian Institute of Technology Guwahati, Guwahati, India. <sup>5</sup>Fraunhofer Institute for High-Speed Dynamics, Ernst-Mach-Institut (EMI), Ernst-Zermelo-strasse 4, 79104 Freiburg, Germany.

**Introduction:** During impact cratering, target materials are subjected to extreme deformation conditions. Brittle deformation under these conditions, where strain rates can exceed  $10^1$  to  $10^2$  s<sup>-1</sup>, is rate-sensitive. Typically, rocks are stronger when deformed at high strain-rate conditions [1]. This occurs because fracture propagation has a limited velocity; at high loading rates, the weakest flaws in a material are not able to cause failure before other, increasingly strong flaws are activated. This results in significant changes to mechanical properties and causes fragmentation of the target material [2]. Dynamic compressive strength and fragmentation in brittle materials is not currently implemented in numerical impact simulations.

In this study, we present results of high strain rate mechanical tests to determine the characteristic strain rate for rate-dependent brittle failure and dynamic strength increase, and the fragment size and shape distributions that result from failure at these conditions. We investigated a variety of rock types and considered whether the fragment characteristics can be used as

diagnostic indicators of loading conditions during brittle failure. In addition, we use numerical impact simulations to assess the significance of dynamic strength increase and compressive fragmentation during impact cratering at a variety of scales.

**Methods:** Mechanical data and samples were obtained using a hydraulic loading frame and a Split-Hopkinson Pressure Bar (SHPB). The hydraulic loading frame achieves strain rates from  $10^{-5}$  s<sup>-1</sup> to  $10^{-4}$  s<sup>-1</sup>, while the SHPB achieves strain rates from  $10^1$  s<sup>-1</sup> to  $10^2$  s<sup>-1</sup>. As sample materials, we chose a variety of igneous, metamorphic, and sedimentary rocks in order to investigate differences between target types and material properties.

From the mechanical experiments, the strain-rate dependency of strength was calculated and samples were generated for microstructural analysis. We focussed our microanalysis on the distributions of fragment size and fragment shape as functions of strain rate. Numerical impact simulations in this study were

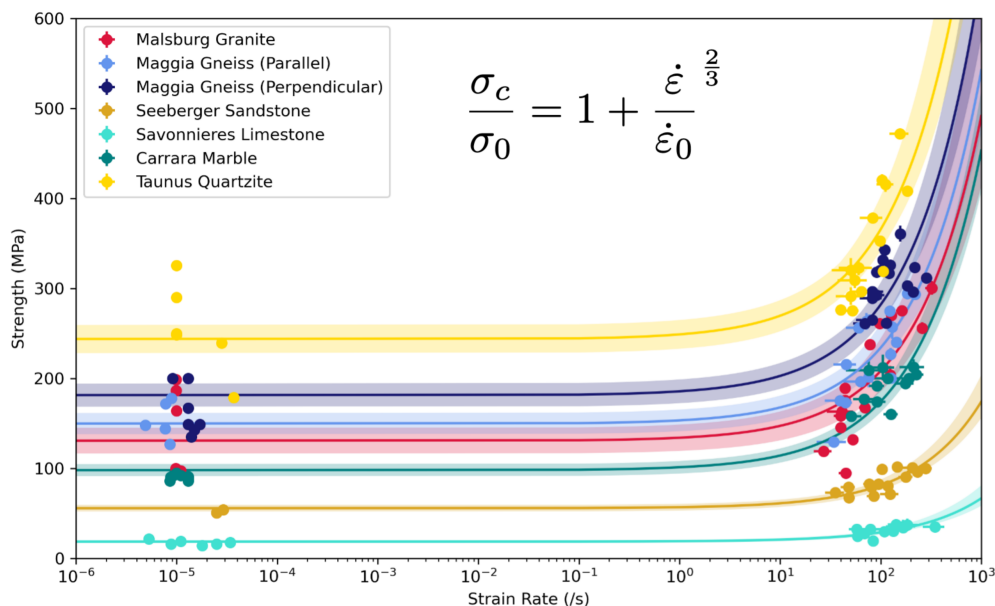


Figure 1. Rock strengths from quasi-static and dynamic testing. Each lithology follows the universal scaling relation (inset) of [1], where each material possesses a unique characteristic strength,  $\sigma_0$ , and strain rate,  $\dot{\epsilon}_0$ . In all tested lithologies, strength dramatically increases at strain rates  $> \sim 10^1$  s<sup>-1</sup>.

conducted using the iSALE shock physics code [3 and refs. therein].

**Results:** We find that the characteristic strain rates of rocks, where the dynamic strength is twice the quasi-static strength, ranges between  $\sim 150$  and  $\sim 350 \text{ s}^{-1}$  depending on lithology (Fig. 1).

Fragment size analysis demonstrates an inverse power-law relationship between fragment size and strain rate for dynamic failure under uniaxial compression. The relationship can be expressed in a generalised form (Fig. 2):

$$\frac{\bar{s}}{s_0} = k \frac{\dot{\epsilon}}{\dot{\epsilon}_0}^{-\mu},$$

where  $\bar{s}$  is the average fragment size and  $\dot{\epsilon}_0$  is the strain rate.  $\dot{\epsilon}_0$  and  $s_0$  are the characteristic strain rate and characteristic length scale given by:

$$s_0 = \frac{K_{IC}^2}{\sigma_0^2},$$

where  $K_{IC}$  and  $\sigma_0$  are the mode-I fracture toughness and uniaxial compressive strength, respectively. The parameter  $k$  varies as a function of porosity (or a related property) and  $\mu$  has a value of  $\mu = 1.93 \pm 0.14$  for all rocks.

Unlike fragment size, we find that fragment shape is independent of strain rate under dynamic uniaxial loading.

**Discussion:** Numerical impact simulations demonstrate that strain rates are sufficiently high to produce rate-dependent effects in all planetary impacts (impact velocities from  $\sim 5$ -20 km/s) where impactor diameters are  $\sim 100$  m or smaller. Rate-dependent strength and fragmentation therefore plays an important role in small planetary impacts and laboratory impact experiments. Based on the results of this study, we are developing a semi-empirical approach to account for rate-dependent shear strength in numerical impact simulations. An important development due to the need to accurately ground-truth numerical impact models against laboratory scale experiments.

An additional implication of this study is that fragment size may be used as a diagnostic indicator of the strain rate at failure during impact loading while fragment shape cannot be used. However, our experiments only used uniaxial compressive loads, it is uncertain how truly triaxial stress states may affect fragmentation behaviour.

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**References:** [1] Kimberley, J. et al. (2013) *Acta Materialia*, 61:9, 3509-3521. [2] Rae et al. (2020) *JGR: Planets*, 125:10. [3] Wünnemann, K. et al. (2006) *Icarus*, 180:2, 514-527.

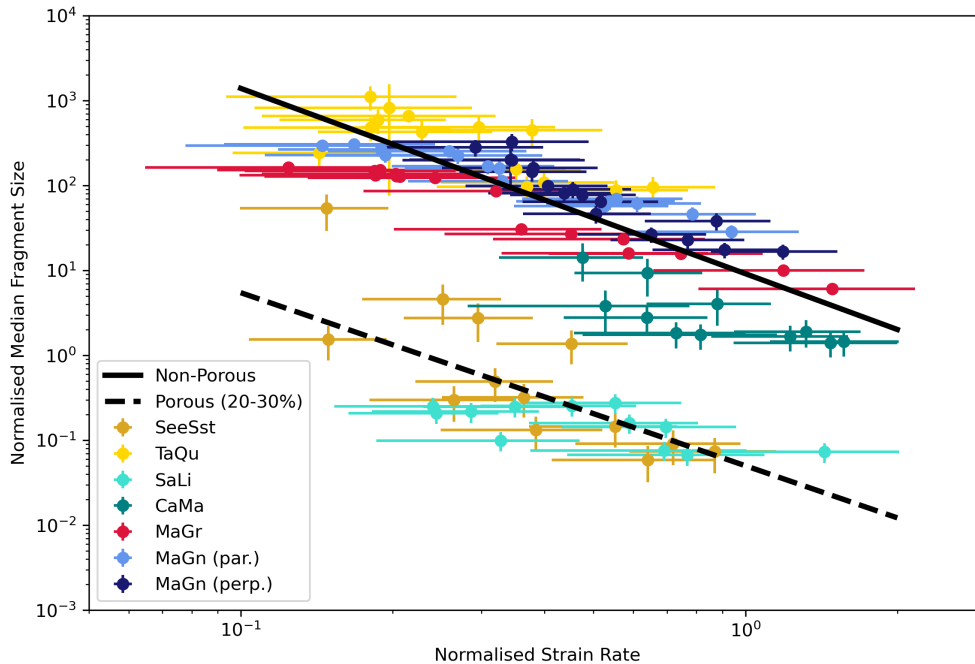


Figure 2. Scaled empirical fragmentation relationship for uniaxial compressive failure. The exponent,  $\mu$ , of the relationship remains the same, while the constant,  $k$ , varies between porous and non-porous rocks.