# RATE-DEPENDENT STRENGTH AND THE SCALING OF IMPACT CRATERS.

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**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 $10^2$ $s^{-1}$, 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, 3, 4]. Dynamic compressive strength and fragmentation in brittle materials is not widely implemented in numerical impact simulations, particularly those used in planetary science [5, 6].

In this study, we use the results of high strain rate mechanical tests [2, 3, 4] to develop a semi-empirical approach to account for rate-dependent shear and tensile strength in numerical impact simulations. We benchmark our model against experimental impact craters from the MEMIN research unit [7], with the aim of demonstrating that rate-dependent strength is required to explain the dimensions of laboratory-scale impact craters. Furthermore, we show how rate-dependent strength affects impact crater scaling for small, strength-dominated craters, without influencing scaling in the gravity regime.

**Methods:** We implement our model of rate-dependent strength in the iSALE shock physics code [8 and refs. therein] as a modification of the ROCK strength model [9] (*Fig. 1*). The model is a generalized form of the universal scaling relationship for uniaxial compressive and tensile strength of [1]. First, we define a maximum dynamic strength envelope, $Y_{dynm}$, on the basis that: a) rock strength during ductile deformation (i.e. high pressures and temperatures) is independent of rate, and b) the coefficient of friction, μ, must always be positive. The strength of the material is given by:

$$Y_{dyn} = (1 - E)Y + EY_{dynm}, \qquad (1)$$

where $Y$ is the static strength. $E$ is the "dynamic strength parameter":

$$E = \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}^{\frac{2}{3}} \frac{Y}{Y_{dynm} - Y}, \qquad (2)$$

where $\dot{\varepsilon}$ is the strain rate and $\dot{\varepsilon}_0$ is the characteristic strain rate in the material. $\dot{\varepsilon}_0$ can be calculated from mechanical and microstructural properties [e.g., 1], or determined from the results of high strain-rate mechanical testing [e.g., 2, 3, 4]. For rocky materials, it typically has a value between ~150 and ~350 $s^{-1}$.

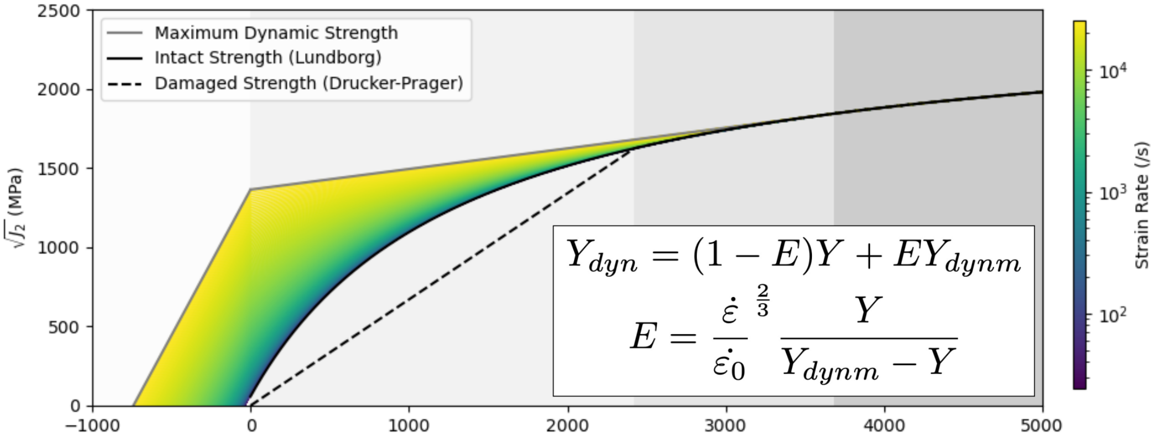

*Figure 1: Implementation of rate-dependent strength in pressure (P) vs. the square-root of the second invariant of the deviatoric stress tensor (√J₂) space. The static strength of the material is defined by "intact" and "damaged" strength envelopes [5]. Here, we define a maximum dynamic strength envelope and the "dynamic strength parameter", E, which determines the magnitude of strength modification.*

An important consideration is whether rate-dependency applies only while the rock remains partially intact or whether it applies equally to intact and damaged material. We consider two end-member implementations. The first implementation, RATEDAM, applies rate-dependent strength only to the intact strength envelope (i.e., Y in *Eq. 1 & 2* is the intact strength). The fully damaged strength envelope is assumed to be rate independent. The second implementation, DAMRATE, applies rate-dependent strength equally to damaged and intact material (i.e., Y in *Eq. 1 & 2* is the strength modified by damage).

**Results:** We benchmark our rate-dependent strength model against laboratory impact experiments from the MEMIN research unit [7] using laboratory measured strength values as material inputs. We find that while rate-independent strength can reproduce crater dimensions in some lithologies, it produces much larger craters than observed in other lithologies. Introducing rate-dependency acts to limit crater size (*Fig. 2*) such that all MEMIN experiments can be reproduced using laboratory-measured strength properties.

More generally, we investigated the effect of rate-dependent strength on π-group crater scaling [10]. We find that rate-dependent strength is responsible for a ~30-50% reduction in cratering efficiency, $\pi_V$, in the strength-regime compared to simulations without rate-dependency. Additionally, as expected, we find that rate-dependent strength has no effect on crater scaling in the gravity regime (*Fig. 3*).

**Discussion:** Our results demonstrate that rate-dependent strength has an important effect on the scaling of impact crater dimensions in the strength-regime. Our rate-dependent strength model is an important development due to the need to accurately ground-truth numerical impact models against laboratory scale experiments. It shows that laboratory measured strength values can be directly used as inputs for constitutive models in numerical impact simulations.

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**References:** [1] Kimberley, J. et al. (2013) *Acta Materialia*, 61:9, 3509-3521. [2] Rae, A. S. P. et al. (2020) *JGR: Planets*, 125:10. [3] Rae, A. S. P. et al. (2022) *Tectonophysics*, 824, 229221. [4] Padmanabha, V. et al. (2022) *Rock Mech. Rock Eng.* [5] Holsapple, K. A. (2009) *Planetary and Space Science*, *57*(2), 127-141. [6] Jutzi, M., et al. (2015) *Asteroids IV*, 679-699. [7] Kenkmann et al. (2018) *MAPS*, 53:8, 1543-1568. [8] Wünnemann, K. et al. (2006) *Icarus*, 180:2, 514-527. [9] Collins, G. S. et al. (2004) *MAPS*, 39:2, 217-231. [10] Holsapple, K. A. (1993). *Ann. Rev. Earth and Planetary Sciences*, *21*, 333-373.

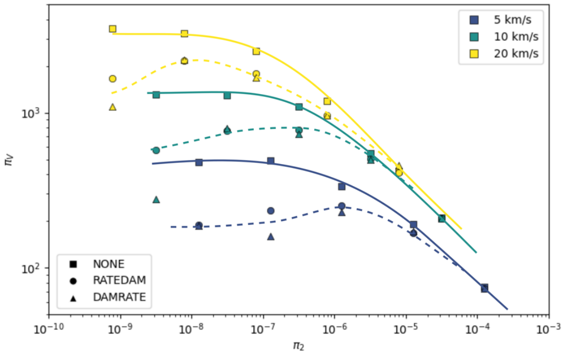

*Figure 3: Dimensionless π-group scaling with and without rate-dependent strength. Solid lines show scaling with rate-independent strength, dashed lines show scaling with rate-dependent strength.*

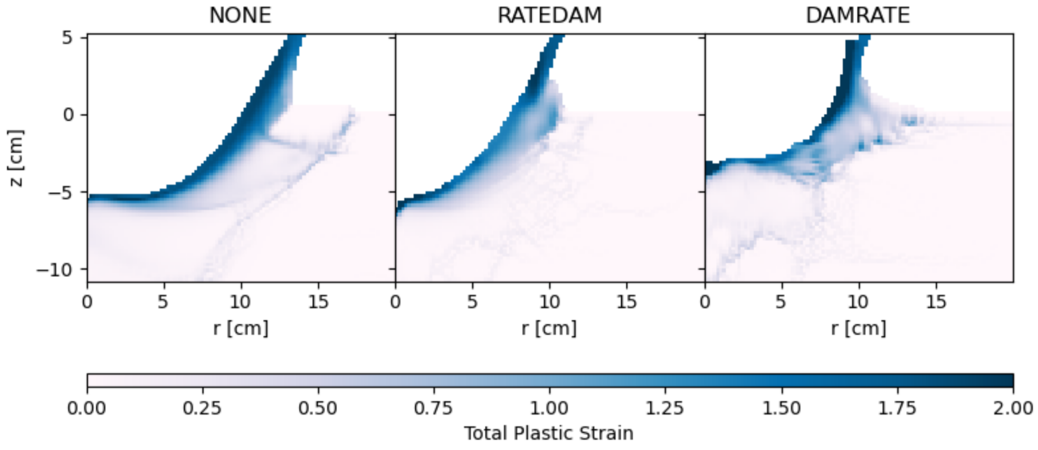

*Figure 2: Comparison of transient crater size using rate-independent and -dependent strength models. Rate-dependent strength always leads to smaller crater sizes for the same projectile properties and quasi-static strength parameters.*