A SIMPLE ANALYSIS OF POROSITY AND PORE SPACE SATURATION EFFECTS ON CRATER VOLUME.
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Introduction: Impact experiments into porous sandstone were carried out within the framework of the MEMIN research group [1,2]. Among several other aspects of the cratering process, MEMIN is also focused on the effects of porosity and pore space saturation on crater dimensions, and the implications they potentially have for planetary-scale cratering. Here, a simple strength scaling approach is applied to calculate crater volumes in non-porous materials, and compare and quantify how porosity and pore-space saturation have influenced MEMIN crater volumes.

Cratering experiments: Experiments were carried out at the facilities of the Ernst Mach Institute, Freiburg, Germany, using two different two-stage light-gas guns. Smaller steel spheres weighing 67 mg were accelerated to ~5 km/s and impacted into dry sandstones and sandstones saturated with water to 50% and 90%. Larger steel and iron meteorite spheres weighing 4.1 and 7.3 g were accelerated to between 2.5 and 5.3 km/s into dry and 50% saturated targets. As target material, Seeberger sandstone was used. Average porosity was calculated to 23.1±0.5%. Uniaxial compressive strength (UCS) was measured on uncased cylindrical samples (74x160 mm) in a uniaxial loading frame, giving a value of 36.3±1.7 MPa. The amount of pore space saturation was determined by weight. 50% saturation was achieved by submerging targets in tap water und atmospheric pressure, 90% was achieved by placing the submerged targets in a vacuum chamber. Crater volumes were determined using a 3D laser scanner.

Calculation of crater volumes: The experiments are well within the strength-dominated regime of cratering where gravity effects are negligible. A general equation for the crater volume in the strength regime is given in [3]:

$$V \sim m/\rho * (\rho U^2/Y)^{3\mu/2} * (\rho/\delta)^{1-3v} \quad (1)$$

where V is the crater volume, m is the projectile mass, ρ is the target density, U is the projectile velocity, Y is a measure of target strength, δ is the projectile density and μ and v are scaling exponents. For most small scale impact experiments on brittle materials in the strength regime, crater volume is assumed to be proportional to the impact energy, therefore μ=2/3. Here, we also assume v to be ~1/3, thus simplifying equation (1) to:

$$V = K * 0.5mU^2/Y \quad (2)$$

where K is a constant that must be determined.

In Fig. 1, several experimental impact campaigns [4-7] using strong, brittle materials are shown in a diagram of crater volume plotted against the kinetic energy of the projectile. Least square fits of the datasets show exponents of ~1, confirming the applicability of energy scaling. To determine the constant K, the strength Y of the materials must be known. The only UCS value published is that of the basalt dataset (300±63MPa). Using this value, we find K=1.15±0.25 (for Y in units of MPa and V in units of cm³, or Pa and m³, respectively). In spite of the lack of other reported strengths, the value for K appears acceptable for the experimental data, as shown in Fig. 1, where lines of equal strength calculated from equation (2) are plotted. Ice UCS is in the order of a few MPa [5], and [5] suggest that a decrease in ice temperature from 257 to 81°K increases its strength by at least a factor of two. Granite strengths of 100 MPa are also common [8].

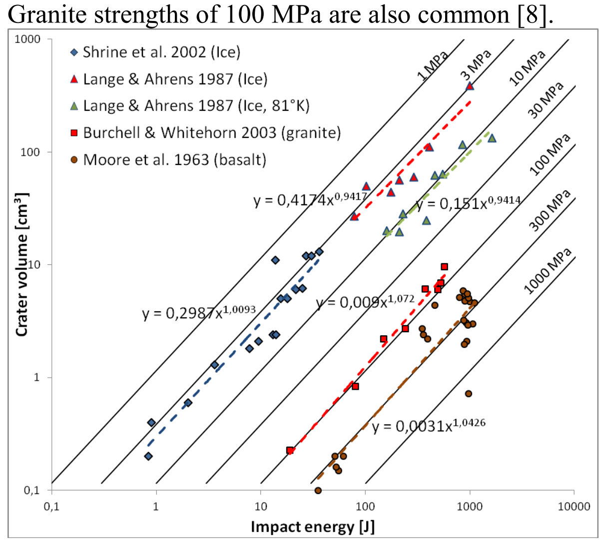

Fig. 1: Crater volumes of experimental impacts into non-porous, brittle materials can be scaled to the impact energy of the projectile. Black lines show crater volumes as calculated in (2) for different strengths.

Comparison to MEMIN data: MEMIN data are plotted in Fig. 2, together with lines of equal strength from equation (2) using K=1.15. Although the sandstone has a UCS of 36 MPa, crater volumes are smaller than would be expected for their strength and lie near the 100 MPa line. This is due to the 23% porosity in the sandstone that dampens the shock wave and reduces cratering efficiency as the shock wave loses energy crushing the pore space cavities [e.g. 9,10]. Saturating the pore space with water counteracts the effects of porosity, as can be seen as a general increase in crater volume with increasing saturation in Fig. 2. Water is much less compressible than air during shock deformation, and water reduces the impedance mismatch between the quartz grains and voids. Surprisingly, the two experiments with 90% saturation slightly exceed the volume expected for 36 MPa strength (Fig. 2), although this is within the margin of error. More importantly, UCS decreases with increasing saturation to ~20-25 MPa, therefore the calculated, “non-porous” crater volume for 90% saturation should actually be higher. In this case, the reduction in volume may be caused by the remaining unsaturable pore space and the impedance mismatch between quartz and water.

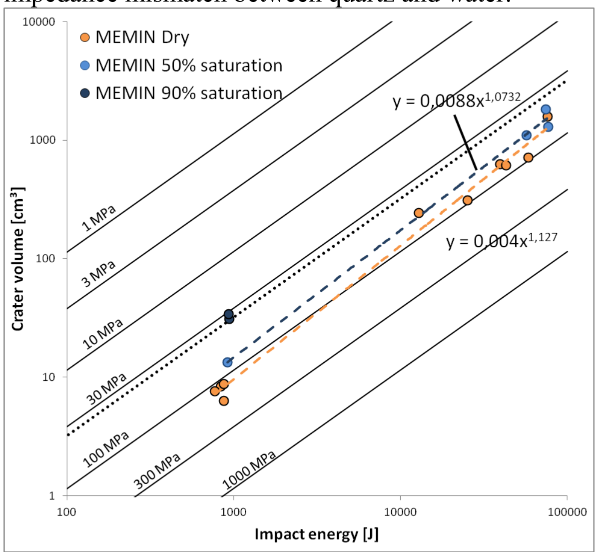

Fig. 2: Crater volumes of porous and saturated MEMIN experiments are compared to crater volumes of non-porous materials (solid black lines). The dotted line shows volumes expected for a non-porous material with a strength of 36 MPa (the strength of dry MEMIN sandstone). MEMIN craters are smaller due to porosity. Increased saturation counteracts the effect of porosity.

Quantifying porosity effects: In order to quantify the amount by which porosity reduces crater volume, MEMIN crater values were normalized to the volume of their non-porous counterparts calculated with equation (2). Dry MEMIN sandstone craters formed with small projectiles have only 25-30% of the expected “non-porous” volume, while craters formed with large projectiles lie at 40-65%. This discrepancy may be due to different spall behavior for larger target rocks, or possibly caused by scale-dependant strength effects, as suggested by [11] to explain scaling exponents >1. The fit for the MEMIN data in Fig. 2 has an exponent of ~1.13. Perhaps this reflects a weaker total UCS for larger crater volumes.

Pore space saturation increases crater volume. 90% saturated targets produced craters with 60% of the expected non-porous volume (with an estimated UCS of 20 MPa), showing that in this case, maximum pore space saturation did not completely counteract porosity effects.

The normalized crater volumes are plotted against their porosity in Fig. 3. Data from impact experiments into sintered glass bead targets [12,13] are additionally plotted. The glass bead targets had varying strengths and porosities, and thus give an opportunity to compare data over a wider parameter range. Non-porous volumes were calculated with equation (2) and K=5, which was fit using the least porous glass bead targets (~5-10% porosity) as references. A trend was fitted to the data, where the normalized volume $V_N=2.3e^{-0.1n}$, with n as porosity (Fig. 3). The dry MEMIN craters have higher normalized volumes in comparison to the fitted curve, i.e., porosity has less of an effect on volume reduction in sandstone than in sintered glass beads. This may be due to some change in material properties, e.g. increased tensile strength that could increase the volume of spalled material relative to the transient crater. Also, it is possible for the scaling exponent to vary with porosity, as suggested in [14].

Outlook: MEMIN experiments on high and low-porosity rocks are planned in the near future and will help to better constrain and quantify porosity effects.

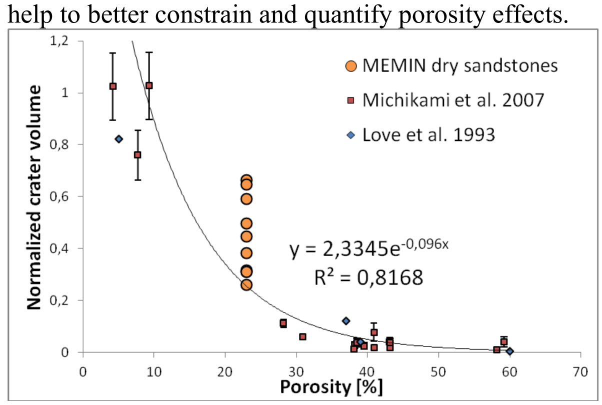

Fig. 3: The reduction of crater volume relative to the volume calculated for non-porous materials in (2) is plotted against the porosity. Increased porosity reduces crater volume and a roughly exponential rate.

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