Recent studies have indicated that cratering on small bodies in the solar system may be very different from craters formed on planar surfaces (1, and references therein). The curvature of the cratering surface has been shown to affect final crater diameter. As collisional evolution work progresses, e.g., analyses of asteroids Gaspra (2), Ida (3), and Ida's moon Dactyl, as well as the Stickney crater on Phobos (4), reliable predictions for crater diameters formed by impacting projectiles are required. We compare Holsapple and Schmidt (5) crater scaling laws (strength regime), derived primarily from impacts into semi-infinite targets, to results from high-velocity laboratory cratering experiments using spherical, strong cement mortar targets (1, 6). We find that strength scaling underestimates crater size by about a factor of 2. We also use our 2D numerical code (7) to model cratering impacts (under the same initial conditions) into both a sphere and the planar surface of a cylinder (axial symmetry). The crater diameter calculated by the code was larger for the curved-surface case (by ~40%), in agreement with experimental results (1).

Figure 1 shows a series of crater diameters measured from laboratory impact experiments into spherical, strong cement mortar (1, 6) targets. To compare these results to scaling predictions, we combine data for competent rock (8) with the crater strength scaling equations of Holsapple and Schmidt (5), and obtain an equation for crater diameter ($D_c$):

$$D_c \left[ \frac{\rho_t}{m_i} \right]^{1/3} = 1.6 \left[ \frac{Y}{\rho_i v_i^2} \right]^{-0.28},$$

where, $\rho_t$ is the target density, $m_i$ the impactor mass, $\rho_i$ impactor density, and $v_i$ the impact velocity. The strength $Y$ in Eq. 1 is interpreted to be the yield strength of the material (8). In uniaxial tension, Grady and Kipp (9) showed that the dynamic tensile strength $\sigma_d$ is proportional to the strain rate $\dot{\varepsilon} (v_i/d$, where $d$ is projectile diameter) of the impact event. Dynamic strength relations have been determined for a variety of materials, and the particular constants are given in (7). For strong cement mortar, we use $Y = \sigma_d = 1.15 \times 10^7 \dot{\varepsilon}^{0.34}$ (erg/cm$^3$), giving an average value of $Y = 7 \times 10^8$ erg/cm$^3$. Crater diameters determined from Eq. 1 using the experiment conditions of (1, 6) are also shown in Figure 1. It appears that scaling underestimates the final diameters typically by a factor of 2. The differences were not solely due to curved surface effects, however. We used Eq. 1 to calculate crater diameters for laboratory experiments performed on planar targets, and still found a discrepancy. For example, experimenters using "semi-infinite" cubic basalt targets (10) found average crater diameters to be 4.4 cm, while Eq. 1 gave 2.2 cm for the same initial conditions. Exp. No. 376 (large cylinder) from Fujiwara et al. (1) had a $D_c = 5.4$ cm, while scaling predicted a diameter of only 3.5 cm. Additional comparisons between scaling relations and results from small target laboratory cratering are necessary to assess the mismatch.

We also used our 2D numerical code to examine the effects of impacts into curved surfaces. In general, code-predicted crater diameters for the impact experiments plotted in Figure 1 were larger than that derived from scaling theory, but still somewhat smaller than the actual data. Further, in the Fujiwara et al. (1) study, experiments 376 and 386 (strong mortar targets) were performed under nearly the same conditions, except that No. 386 was an impact into a sphere, and No. 376 an impact into the planar surface of a cylinder. The crater measured on the sphere was 35% larger than that formed on the cylinder. Figure 2 shows our 2D hydrocode simulation of these experiments. We find good agreement with the experimental results: the impact crater formed on the cylinder was smaller than that created on the spherical surface.

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Figure 1: The crater diameters resulting from high-speed laboratory impact experiments into spherical, strong cement mortar targets (1, 6) are shown as a function of collisional specific energy. Also shown are the diameters predicted from crater scaling laws (5) under the same initial conditions. Scaling seems to underestimate crater sizes typically by about a factor of 2.

Figure 2: Pressure and damage contours (left/right) resulting from high speed 2D impact simulations using spherical (left) and cylindrical (right; large radius, impact into the planar end) strong cement mortar targets. Crater diameters ($D_c$) are approximated by the intersection of the edge of the damage contour and the surface. The same collisional energy ($E = 5.3 \times 10^6$ erg) was delivered to both the spherical and cylindrical targets, yet $D_c$ was ~40% larger for the spherical case, which agrees with experiment results (1).