Dynamic Tensile Strength of Lunar Rock Types

STEPHEN N. COHN AND THOMAS J. AHERN
Sennological Laboratory, California Institute of Technology, Pasadena, California 91125

The dynamic tensile strengths of four rocks have been determined. A flat plate impact experiment is used to generate 1-μs-duration tensile stress pulses in rock samples by superposing rarefaction waves to induce fracture. A gabbroic anorthosite and a basalt were selected because they constitute the two major rock types as occur on the lunar highlands and mare, respectively. Although these have dynamic tensile strengths which lie within the ranges 150-174 MPa and 157-176 MPa, whereas Arakanian metarhyolite and Wescott granite exhibit dynamic tensile strengths of 67-88 MPa and 95-116 MPa, respectively, the effect of climatic weathering and other factors, which may affect propagation of the present results to the moon, have not been explicitly studied. The reported tensile strengths are based on a series of experiments on each rock where determination of incipient spallation is made by terminal microscopic examination. These data are generally consistent with previous determinations of at least one of the rocks. For basalt, we have cautiously deemedly altered (hydroxyaltered) but physically coherent rock. The tensile failure data do not bear a simple relation to compressive results and imply that any modeling involving rock fracture consider the tensile strength of igneous rocks under impulse loads distinct from the values for static tensile strength. Generally, the dynamic tensile strengths of numerous igneous rocks range from ≈50 to 100 MPa, with the more basic, and even amphibolite-bearing samples, yielding the higher values.

INTRODUCTION

Central to impact and explosive cratering processes, underground explosive excavation and fragmentation, and planetary accretion via large body interactions is the dynamic fracture behavior of rock. Experimental high velocity impact craters (micromillimeter to decimeter range radius) produced in pristine rock and glass show that a major portion of the mass fractured by impact is in the form of plates spalled concentrically about the crater [Höcker, 1969; Fedder, 1971]. Excavation processes and consequently the final ejecta distribution and partitioning of energy strongly depend upon the brittle tensile failure characteristics of the rock, probably more so than compression failure mechanisms. Laboratory experiments and numerical modeling show that crater evolution and ultimate shape are sensitive to the failure behavior of rocks [Quaide and Oberbeck, 1968; O'Keeffe and Ahern, 1976; Melosh, 1977].

Developing predictive capabilities in the field of explosive cratering has required examination of the dynamic fracture and fragmentation of rock [Shockey et al., 1975; Curran et al., 1977], and the possibility of its use in recoring of coal and oil shales, which requires prior rubblization, has attracted attention to its behavior under dynamic loads as well [Muir et al., 1977]. Furthermore, Merkle and Mische [1977] propose that the dynamic strength and deformation behavior of rocks composed of metamorphic surfaces may have been important in controlling accretion of planetesimals in the early stages of planetary formation.

Most studies of the strength of rock have been in the quasi-static regime of hydraulic or mechanical press experiments with strain rates as low as 10^-6 per second ranging up to 3 x 10^6 per second obtainable with Hopkinson-bar apparatuses. The tensional fracture strength of rocks exhibits very little dependence on strain rate at rates below 10^6 per second but increases dramatically at the highest strain rates produced by shock waves in explosion, impact, and the highest strain rate Hopkinson-bar experiments [Rinehart, 1965; Stevens, 1974; Kumar, 1968; Grady and Holleman, 1977]. Quasi-static tests, such as employing the Brazilian geometry, demonstrate a stronger dependence on specimen size and geometry than strain rate [e.g., Price and Koli, 1967]. Care must be exercised in comparing fracture strength values over the range of strain rates, since the low strain rate experiments all maintain uniaxial stress states, in the test material, while the shock wave techniques produce uniaxial strain. Nevertheless, Kuma's examination of temperature effects upon the compressive fracture strength of rock suggests that a thermal activation process dominates at low strain rates, but inertial and frictional shearing controlled failure appears to dominate failure processes at strain rates between 10^3 and 10^6 per second [Kumah, 1976]. Grady and Lippin [1980] have examined a series of tensile failure modes and point out several previous models and a wide class of data suggesting that tensile fracture strength is proportional to the cube root of strain rate. However, sufficient data on the behavior of various brittle materials, under high rate loading, are lacking. In this study we have selected two basic igneous rocks, a basalt and a gabbroic anorthosite, because these are the same rock types as occur on the lunar mare and highlands, for determination of dynamic tensile fracture strength. Two other rocks, Arakanian metarhyolite and Wescott granite, were also tested for comparison with previous studies and different techniques. At a strain rate between 10^6 and 10^8 per second the rock samples are subjected to 1-μs-duration tensile stress pulses in a flat plate impact experiment. The stress level is varied to determine the stress which produces fracture initiation and growth. This is detected by microscopic examination for incipient spall cracks in polished thin sections made from the recovered samples. While such an approach does not determine the strain rate dependence, the conditions of fracture are appropriate for cratering and other dynamic tensile fracture processes.

EXPERIMENTAL DESIGN

A dynamic tensile stress pulse is produced by superposing along the midlength of the study sample, two co-rotating planar rarefaction waves, each originating from a free surface reflection of a compressive wave [Shockey et al., 1975; Curran et al., 1973]. Protected recovery of the tree-flying rock target,
after the initial impact, allows it to be sectioned and microscopically examined.

The experimental system (Figure 1) utilizes a 40-mm bore powder gun fitted, for these experiments, with a compressed gas breach firing system which provides velocity control in the desired range of 30 to 90 m/s. This produces tensile stresses between 27 and 243 MPa (0.27 to 2.43 kbar). The 7-g projectile, machined from polycarbonate, fits in the barrel without O-rings or other seals to twist motion. Rearing in the barrel during evacuation to 100 μm Hg, it is retained by a strand of fine magnet wire which breaks when the stored charge of compressed air is dumped through the breach.

The impact plate is mounted on the front of the projectile. Polymethylmethacrylate (PMMA) sheet stock is used for the impact plate material in these experiments, since it has a low shock impedance (Barber and Holsenbach, 1970). The impact plate is press fitted into the projectile so that it is supported circumferentially, making its rear face a free surface.

Tension is produced in the rock target by superposing two converging, 310° rarefaction waves in a tensile strain configuration (Figure 2). The initial impact between the impact plate and the rock target produces compressional shock waves propagating away from the plane of contact into each medium, putting both into uniaxial compression. The wave trav-
eling into the impact plate reflects off the fire rear surface as a relief wave and propagates back to the contact plane, reducing the stress to zero. The geometry, in each experiment, is chosen so that the impact plate relief wave reaches the contact plane, reducing the stress to zero at the same time that the forward propagating wave in the target re- defines from the target’s free surface as a relief wave; this corre- sponds to the fifth case depicted in Figure 2. The two surface- reflection waves propagating in from the surfaces of the target drop the stress to zero, but each wave is accelerating material away from the plane of potential tensile failure so that when they meet, they superpose to produce tensile, shown in the seventh state, 1.59 µs after impact. The figure de- picts two cases. If no fracture occurs, then the two waves propagate to the sample’s surface, bringing the whole target into tension; this is shown by the dashed lines. The two waves each reflect from the free surfaces as compressive waves and propagate to the midplane, tripping the stress to zero in their path, and superept in the middle to produce compression, begin- ning a new cycle. This cycle repeats until the energy is dissipated. The midplane of the target is held in tension for at least ~1 µs between states 7 and 11. This interval is controlled only by the velocities of propagation and the thickness of the target and impact plate; it can be increased by using proportionally thicker elements.

In the case where fracture does occur, the free surface created by the fractures radiates a compression wave which drops the stress on the target to zero as it propagates away from the fracture surface. This is depicted in Figure 2 by ignoring the dotted lines and hatching. If fracture is induced in the target, the period of tension is reduced to the time interval between initial stress and the development of the fracture so that in practice, while unfractured samples experience ~1-µs intervals in tension, samples which do fracture are held in ten- sion for shorter periods of time.

The rock target is machined to approximately 20-mm diameter and 6-mm thickness with parallel faces, one slightly bev- elled to aid identification in this section. The target is then fin- ished on a surface grinder and hand-lapped to within 1 µm of flatness across the face. Using a bristle wax working compound, it is suspended in a loose-fitting annulus so that its impact sur- face projects forward slightly. The mounting annulus and tar- get are then fastened to the recovery vessel by three spring- loaded alignment screws. The impact surface of the target is oriented normal to the axis of the barrel by reflecting an axial laser beam back down the barrel. The impact platen on the projectile is also carefully fitted normal to the axis of the pro- jectiles to insure planar impact.

The target assembly is positioned in front of an aperture in the recovery vessel, as shown in Figure 1. This permits the rock sample to fly freely into the recovery vessel after snapping its wax supports upon impact but prevents the larger-diameter projectile from following. The target, or target pieces if fragmentation occurs, collect in a cloth sack which acts as it flies free of its support. The sack and enclosed rock target are decanted and cushioned by loosely stuffed rags and foam rubber in the recovery chamber.

During the experiment, only the impact velocity of the pro- jectile is recorded, from which the dynamic stress may be cal- culated, as described below. The velocity of the projectiles

<table>
<thead>
<tr>
<th>TABLE 1. Properties of Rocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock</td>
</tr>
<tr>
<td>------------------------------</td>
</tr>
<tr>
<td>Arkansas schist</td>
</tr>
<tr>
<td>Wastler granite</td>
</tr>
<tr>
<td>Beaver Bay gabbro anortosite</td>
</tr>
<tr>
<td>Rainbow breccia</td>
</tr>
</tbody>
</table>

*Grady and Hollenback [1979].  †This study.

The modal fractions, from X-ray analysis, are approximate.
prior to impact is determined by the sequential interruption of three laser beams, one at the muzzle and two which traverse the barrel (Figure 1), during the final 46 cm of projectile travel. Each beam is monitored by a photodiode detector that triggers a time interval counter which is lashed when the next beam is interrupted. The counters provide an accuracy of ±10 μs, and beam spacing is measured to ±0.3 mm, resulting in an overall precision of ±0.5% for average interval velocities (Ahrens et al., 1972). However, over the velocity range of 10 to 90 m/s the projectile is still accelerating as it approaches the muzzle of the barrel so that increases of 20% were not uncommon between the first and second average interval velocities.

We relied instead on the velocity of the projectile as it leaves the barrel, which was measured by recording, on a dual-trace oscilloscope, the signal from the third laser detector with a calibrated 10-KHz time signal on the second trace. The velocity is then determined from the length of the projectile and the time interval that the laser beam is blocked. Measuring the interval time from the photographic record of the oscilloscope trace is the principal limit on accuracy. The overall accuracy varied from ±1% to ±2% depending how close the actual velocity is to the predicted velocity and hence whether the signal occupies most of the oscilloscope sweep.

To maintain a state of uniaxial strain in the target samples during the tensile pulse, the sample must have a sufficiently large diameter that relief waves from the edges do not propagate into the region of interest. As the tensile strain ends, at each point, after the shock wave has traversed at most twice the thickness of the sample beyond that point, the minimum diameter to assure strictly uniaxial strain in the center of the target is 4 times the thickness. In this experiment the target must be smaller than the projectile to allow recovery so that in practice, a ratio of 3 to 1 is employed. Consequently, relief waves from the initial compressional phase will reach the center of the target during the tensile phase, shifting the dynamic stress state somewhat by increasing the tension acting on planes normal to the impact plane and increasing the axial stress level approximately 15%, but the greatest principal stress will still act normal to the impact plane. Our calculations of stress levels assume uniaxial strain, ignoring this effect.

Induced tensile split fractures are expected to lie normal to the axis of greatest principal tension and will therefore be parallel to the impact face. In this experiment the strain rate and length of time at tension are held essentially fixed while the stress level is varied by varying the impact velocity; thus it is the stress level at which crack growth is initiated, under dynamic loading, that is determined.

**Dynamic Stress Level**

The intensity of the tensile stress created by combining the two relief waves in the target is a function only of the densities and wave velocities of the target and impact plate, and of the impact velocity. We have assumed that the relief waves travel at the same velocity as the compression waves and that attenuation of the stress waves is low so that the magnitude of the

---

**Fig. 2** (a) Reflected light photomicrograph of overlap of two adjacent induced cracks in Arkansas novaculite in a sample which showed 11 2- to 4-mm cracks running entirely across both cross sections. (b-d) Westerly granite samples strained at increasing levels to demonstrate fracturing, indicating that the dynamic tensile strength is exceeded (Figures 3) and 5); and the widening and fracturing on multiple planes and fragmentation that develops at higher stresses (Figure 4).

The impact plane is parallel to the long dimension in each image.
tensile stress developed equals the compressional stress in the first phase of compression.

The level of compressional stress is governed by the familiar equation:

\[ \sigma = \frac{\Delta \rho / \rho_0}{\rho_0} \cdot \frac{\rho_0}{\rho_0} = K \sigma \]

which relates the stress level, in the target, to known quantities.

The impact plate material, PMMA, has been extensively studied by Barker and Hollenbach [1970]. Its density is 1.18 g/cm³, and, in the low-temperature regime relevant to this study, it has a shock wave speed of 2.8 km/s. The speed of rarefaction waves exceeds that of the compressional waves by no more than 5%, at these stress levels, and this difference is ignored.

As only the impact velocity is measured during the experiment, the actual shock wave velocities in the target and impact plate, for each experiment, are unknown. However, the measured variation of shock wave velocity with stress level is small to PMMA over the range of interest. While rock materials show substantial increases in longitudinal velocity under uniaxial stress conditions between stresses of zero and 50 MPa [Ticho, 1973], it is shown below that these variations are not important to the determination of stress levels. For the rock samples it is assumed that the shock wave velocity is equal to the ultrasonic longitudinal velocity measured in this study.

We also assume that the elastic moduli and consequently the propagation velocity do not change significantly as the rock goes from compression to extension. Failure of this assumption would imply that the tensile stress produced is different from the compressional stress which is determined by (2). The shape of the stress wave as it propagates through the target is also unknown; however, in Grady and Hollenbach's experi-
TABLE 2. Record of Shots for Each Rock

<table>
<thead>
<tr>
<th>Impact Velocity, m/s</th>
<th>Stress, MPa</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.9</td>
<td>40</td>
<td>0.3-mm crosshatched grid of cracks presumed induced by thin sectioning. Since cracks are also seen in mounting material.</td>
</tr>
<tr>
<td>21.0</td>
<td>57</td>
<td>0.3-mm crosshatched grid of cracks presumed induced by thin sectioning. Since cracks are also seen in mounting material.</td>
</tr>
<tr>
<td>21.6</td>
<td>58</td>
<td>No cracks</td>
</tr>
<tr>
<td>24.7</td>
<td>67</td>
<td>No cracks</td>
</tr>
<tr>
<td>28.3</td>
<td>76</td>
<td>0.3-mm crosshatched grid of cracks also in mounting material.</td>
</tr>
<tr>
<td>32.7</td>
<td>88</td>
<td>11.20- to 4.0-mm-long cracks</td>
</tr>
<tr>
<td>34.7</td>
<td>105</td>
<td>2.20- to 4.0-mm-long cracks</td>
</tr>
<tr>
<td>38.4</td>
<td>103</td>
<td>3 chains, perpendicular to impact plane, of 0.5-mm cracks trending ~43° to impact plane</td>
</tr>
<tr>
<td>86.9</td>
<td>235</td>
<td>Fragmented</td>
</tr>
</tbody>
</table>

Wectrosite Granite

29.2                 | 76          | No cracks |
36.4                 | 95          | No cracks |
39.2                 | 102         | 18.25- to 4.0-mm-long cracks |
44.8                 | 136         | Coalesced cracks across entire section |
46.2                 | 120         | Coalesced cracks across entire section |
52.1                 | 135         | Coalesced cracks across entire section |
57.2                 | 146         | Coalesced cracks across entire section and macroscopic fractures/brittle fractures |
101.5                | 264         | Fragmented |

Gabbroic Anorthosite

38.5                 | 97          | No cracks |
38.5                 | 108         | No cracks |
39.8                 | 111         | No cracks |
42.0                 | 118         | 3-mm cracks normal to impact plane |
50.6                 | 142         | 2-mm-long chains of cracks normal to impact plane |
51.6                 | 144         | No cracks |
52.1                 | 146         | 12-mm crack parallel to impact plane |
54.8                 | 153         | 2-mm cracks at multiple impact sites |
62.0                 | 174         | Coalesced cracks across entire section |
73.3                 | 205         | Coalesced cracks across entire section |
73.8                 | 207         | Coalesced cracks across entire section |

Rudite Basalt

21.5                 | 60          | No cracks |
22.7                 | 63          | No cracks |
34.6                 | 97          | No cracks |
37.6                 | 105         | No cracks |
41.0                 | 115         | No cracks |
42.7                 | 119         | No cracks |
44.1                 | 120         | No cracks |
45.8                 | 128         | No cracks |
56.0                 | 157         | No cracks |
63.8                 | 179         | 10-2- to 4-mm cracks across entire section |
70.0                 | 195         | Spall along midplane, half with free surface in one plane, impact half in four pieces |

ments, where a record of free surface velocity rather than sample recovery is obtained, rise times corresponding to strain rates of 10^5-10^6 per second are observed for rarefaction waves [Grady and Hollenbach, 1977, 1979].

While the shock wave velocities of the rocks studied are not measured, the effect of these uncertainties in $K$, the proportionality factor relating impact velocity and induced stress in (1), is small. This is due to the low shock impedance, $I$, (product of density and wave velocity) of PMMA compared to the rocks studied. From (2) we have

$$\Delta \eta = c \Delta K = K \Delta c$$

which relates fractional change in shock wave velocity to resulting fractional change in the value determined for stress. Substituting the values for PMMA and selected rocks (Table 1) into (3) yields

$$\Delta \eta = \frac{\Delta c}{c} < 0.2$$

which shows that a 10% variation in the elastic wave velocity produces less than 2% change in the value of stress determined. Thus the difference between the shock wave velocity, in a particular experiment, and the ultrasonic velocity used to calculate stress may be neglected. The values of $K$ relating stress in megapascals to projectile velocity in meters per second range between 2.6 and 2.8, shown in Table 1 for the selected rocks.

LITHOLOGIES OF ROCKS

Four competent, low-porosity rocks were selected for dynamic tensile fracturing in this study. A range of textures is explored. The most finely textured material is a 10-μm-grained quartzite (novaculite). The remaining three rocks have igneous origins with grain sizes ranging from 0.1 mm to 1.5 mm. All samples of each lithology were made from the same piece of source rock at the same orientation. No effort has been made to examine variations in behavior due to orientation, since Shockey et al. [1975] concluded in their study of Arkansas novaculite, which shows a strong preferred flaw orientation, that dynamic strength properties are independent of orientation. One sample of each material was selected for thin sectioning to establish a baseline crack distribution for comparison to the cracks produced by the impact experiments. None of these control sections showed flaws greater than 0.5 mm in length, nor were any preferred orientations of the larger flaws observed which might confuse identification of induced spall cracks in a target when examined microscopically after recovery. In addition to the control samples, for each rock several tests were made at low stress levels which failed to produce spall cracks, and so the above statements apply to these sections as well, confirming the general absence of flaws which we identify as spall cracks, in unstrained samples. The distinguishing properties of each of the four rocks are given below and in Table 1.

Novaculite, from Hot Springs, Arkansas, is a microcrystalline (10-μm grain size), homogeneous quartzite composed of uniform-sized, randomly oriented quartz grains cemented with silica. This material is transparent to a thickness of about 0.2 mm, permitting extensive microscopic examination. Its dynamic tensile strength and fragmentation properties have been studied by Shockey et al., [1973, 1974], who also report an intrinsic, oriented system of flaws up to 1-mm diameter (sample diameter of 3.3 mm). The type is a microcrystalline material, which is known to produce spall cracks in a target when examined microscopically after recovery. In addition to the control samples, for each rock several tests were made at low stress levels which failed to produce spall cracks, and so the above statements apply to these sections as well, confirming the general absence of flaws which we identify as spall cracks, in unstrained samples. The distinguishing properties of each of the four rocks are given below and in Table 1.
Westley granite, quarried in Westach, Rhode Island, is a widely studied, medium grained (0.1-0.5 mm) granite primarily of feldspar and quartz. The crack density and geometry in Westley granite are reported by Hudley [1975]. She observed no cracks greater than 0.3 mm, with a scanning electron microscope, in unrestressed samples.

Rashton basalt, quarried near Golden, Colorado [Minette et al., 1977], is a homogenous, fine-grained (0.2-1.5 mm) unweathered porphyritic basalt which shows no porosity of 0.5-5 mm cracks when examined microscopically (sample courtesy of H. Speidel).

Rashton basalt and the Beaver Bay gabbroic anorthosite were chosen mainly because these are nominally the same rock types as are present on the lunar mare and highlands, respectively. Thus the behavior of the basalt and gabbroic anorthosite is expected to be representative of the pristine lunar crust under impact cratering processes. The other rocks were chosen for comparison to previous studies, some using different techniques to determine the same properties.

### ANALYSIS AND RESULTS

Targets are removed from the recovery vessel in the cast in which they are sealed after lying free of the mounting annulus. In general, they are intact and competent, exhibiting no visible failures at the surface, except for very highly stressed samples, which may spall into two equal pieces along their midplane or fragment. Some Arkansas novaculite samples, because of the transparency of this rock, displayed obvious internal crack surfaces. The sample disks are cut diametrically. The two halves are moulded with 45° faceted faces together and impregnated with epoxy. The cut surface is polished and mounted on a slide, and this section is cut and polished resulting in two separate parallel sections viewing the internal fracture of the sample.

Cracks 0.1-4 mm are easily delineated and photographed (Figures 3 and 4) using reflected light microscopy. In transmitted light, the high contrast between adjacent grains, particularly in the igneous rocks, enables easy identification of grain boundaries but obscures the crack traces which often follow along them. Since the cracks are generally not open, Figure 3d as an exception, the accentuation due to polishing process is necessary to see them at all.

Distinguishing possibly preexisting cracks from induced cracks is problematical, since the samples cannot be examined prior to testing. Consequently, it is assumed that every crack observed in this section was produced by the imposed experiment. This is in general untrue, since Arkansas novaculite and Westley granite have documented natural flaws with maximum diameters less than 1 mm [Shockley et al., 1974; Hudley, 1976] and the Rashton basalt and gabbroic anorthosite presumably also have natural populations of flaws. Nevertheless, for the determination of target recovered from low-around spots and those never stressed show that the population of 0.5-mm and larger cracks is low, since most were observed in the thin sections. In addition, induced cracks are expected to be parallel to the impact surface, so many of those observed were found; naturally occurring cracks would not be expected to show such a preference.

The number, location, and orientation of cracks are recorded for each recovered target. Figures 3 and 4 show some examples of the observed cracks in each of the rocks studied. In each photomicrograph the impact face is parallel to the long dimension so that the observed cracks are normal to the maximum principal tension, as expected. Crack initiation and growth begin, for each rock, over a range of stress levels presumably reflecting statistical variations in the distribution of flaws from sample to sample. This effect is demonstrated in Table 2. Stress levels at or slightly above the level which produces no cracks is shown.

### TABLE 3. Dynamic Tensile Strength and Crack Lengths

<table>
<thead>
<tr>
<th>Rock</th>
<th>Dynamic Tensile Strength, MPa</th>
<th>Stress Distribution (Full Length)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1.5-2.4 mm</td>
</tr>
<tr>
<td>Arkansas novaculite</td>
<td>67-88</td>
<td>88</td>
</tr>
<tr>
<td>Water granite</td>
<td>95-116</td>
<td>102</td>
</tr>
<tr>
<td>Gabbroic anorthosite</td>
<td>153-174</td>
<td>153</td>
</tr>
<tr>
<td>Rashton basalt</td>
<td>157-179</td>
<td>179</td>
</tr>
</tbody>
</table>

The dynamic tensile strength, as defined in the text, is shown for each rock along with the stress level and distribution of cracks, by size, for the sample tested at the lowest stress level producing dynamic tensile failure.

### TABLE 4. Comparison of Dynamic Tensile Strength by Various Authors

<table>
<thead>
<tr>
<th>Method</th>
<th>Dynamic Tensile Strength, MPa</th>
<th>Author</th>
</tr>
</thead>
<tbody>
<tr>
<td>Free surface velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pullback signal</td>
<td>73-68</td>
<td>Stress [1978]</td>
</tr>
<tr>
<td>Free surface velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pullback signal</td>
<td>34-62</td>
<td>Shockey et al. [1979]</td>
</tr>
<tr>
<td>Terminal examination</td>
<td>67-88</td>
<td>this study</td>
</tr>
<tr>
<td>Rashton granite</td>
<td>12-17</td>
<td>Stress [1979]</td>
</tr>
<tr>
<td>Free surface velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pullback signal</td>
<td>45</td>
<td>Grady and Hollenbeck [1979]</td>
</tr>
<tr>
<td>Terminal examination</td>
<td>95-116</td>
<td>this study</td>
</tr>
<tr>
<td>Basalt (Various)</td>
<td>118</td>
<td>Stress [1979]</td>
</tr>
<tr>
<td>Free surface velocity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pullback signal</td>
<td>130</td>
<td>Grady and Hollenbeck [1979]</td>
</tr>
<tr>
<td>Terminal examination</td>
<td>157-179</td>
<td>this study</td>
</tr>
</tbody>
</table>

The terminal examination method is described herein. Tensile strength may also be determined by measuring the drop in velocity of the target's free surface due to the arrival of the compression wave generated by the expanding tensile crack. The technique is described by Grady and Hollenbeck [1979].
dunes crack growth cause several fractures to form. Adjacent fractures tend to terminate with slight overlap of their respective crack tips as in Figure 3a and 4b.

We define the dynamic tensile strength to be the tensile stress which produces a chain of nearly coplanar cracks traversing the whole cross section of the target; however, this stress is less than the stress which produces strength failure, since the cracks need not coalesce. Figures 3a-3c and 4a-4d show the transition from chain to block close to the dynamic tensile strength of the particular rock. The fractures are essentially confined to one surface intersecting any traverse to the rock. This concept of strength failure overlap. Applying the above definition of dynamic tensile strength yields a range of values for stress as shown in Table 2. At low stress there is no transition from single crack to multiple cracks producing a series of tensile cracks at the midplane of the target. At the high end is the minimum stress which repeatedly produces cracks across the entire cross section. Consequently, we prefer to view the dynamic tensile strength of each of these rocks as a range of stress levels, as shown in Table 3, rather than a single value with associated error bars.

The two "lunar" rock types exhibit the highest dynamic tensile strength of the rocks tested. Gabbreic anorthosite killed over the range 152-174 MPa, and Rahnite basalts at 172-179 MPa. Western granite also demonstrated exceptional strength at 95-116 MPa, and Aralesian novaculite, with a dynamic tensile strength range of 67-88 MPa, showed itself stronger under dynamic loads than most other sedimentary rocks (Grady and Hollebahn, 1979). In calculations where a simple dynamic fracture strength criterion is sufficient, these values are more appropriate to describe rock behavior under shock loading than are static fracture strengths, which have often been applied but which are considerably lower.

While this analysis provides no direct observations of the fracture process, the results obtained correlate closely with the crack growth velocity in the sample. Table 3 displays the distribution of cracks, tabulated according to full observed length, for the lowest stress shot, for each rock, which produced a continuous line of small cracks at the midplane of the sample. The longest crack traces observed, in each rock, are slightly greater than 4 mm long. If we assume a bilinear crack tip growth, then the maximum crack tip propagation is approximately 2 mm, and if this occurs during the first tensile cycle, which lasts 1-2 s, it implies an average crack velocity close to one-third the longitudinal wave velocity, which has been observed by Shockly et al. (1973).

discussion

The values for dynamic tensile strength determined by the techniques described and the determination method of this study and Shockly et al. (1973), and by Steven et al. (1974) and Grady and Hollebahn (1979), using the drop in free surface velocity due to the compression waves radiating from the induced spall crack, do not agree well, as shown in Table 4. Besides disagreement in values determined by the two different techniques, which can be attributed to experimental differences, there also exist disagreements between values determined by separate studies using the same methods. Table 4 shows that these disagreements are not systematic.

It is perhaps tempting to ascribe these differences to sample variability, but more likely the inconsistency is due to the inadequate description of rock brittle failure by the single-parameter dynamic tensile strength. Nevertheless, where a simple failure criterion is desired and its imprecision is tolerable, the presently determined dynamic tensile strength provides a useful description of the dynamic failure of rock. Table 4 shows that with the exception of a single experiment on one sample, the dynamic tensile strength of nongranular rocks ranges from 100 to 180 MPa, with the more basaltic rocks producing the higher values. We believe the greater tensile strength of basaltic rocks, which includes Grady and Hollebahn's data (1979) Deumer basalt which contains significant quantities of amphiboles, is an unexpected but significant result. The dynamic tensile strengths of igneous rocks are much higher than ever determined under quasi-static tensile conditions. The static strength of granite, for example, measured by Rheinheits (1965), is 6.8 MPa, while the dynamic values in Table 4 range between 43 and 127 MPa.

It is clear that igneous rocks, and the lunar rock types in particular, are highly resistant to short-pulse tensile stress in the range 100-150 MPa, much greater than the values assessed in previous crater modeling studies (O'Keefe and Ahrens, 1976). The present high static values of the dynamic tensile strength should be used in future efforts to model heat accretion and fragmentation processes relating to the formation of solar system objects, and for impact and explosive cratering and excavation studies.

Acknowledgments. We would like to thank Raymond Jelinek for his comments on this manuscript, Jonna Virginia for her assistance with petrographic analysis, and Donna Grady and Vernon Sporlir for supplying rock samples. This work was supported under NASA grant NGL 105-002-139. Contribution 3309, Division of Geological and Planetary Sciences, California Institute of Technology, Pasadena, California 91125.

REFERENCES


CORN AND AHRENS: STRENGTH OF LUNAR ROCK TYPE


(Received October 4, 1973; revised July 6, 1980; accepted September 19, 1980.)