A number of unsolved Lunar problems are related to the strength of lunar rocks. The nonhydrostatic shape of the moon, the existence of mascons, and the remarkably deep moonquakes indicate that the lunar interior has a high strength and low fluidity.

Anderson and Hanks (1) discussed that the nonequilibrium shape of the moon and the persistence of mascons can be explained by assuming viscosities of $2 \times 10^{24}$ to $5 \times 10^{25}$ poise for a shell of 200 km thick on the basis of Shimazu's calculation (2). These estimates of the viscosities are substantially higher than the earth's upper mantle viscosity, $10^{21}$ poise, but appear comparable with a theoretical estimate of the viscosity distribution of the present lunar interior (3). However, the most recent lunar thermal history calculation shows that the temperature of the upper 500 km of the moon had been much higher than previously supposed. Toksöz et al. (4) calculate the temperature at a depth of 200 km as higher than $1200^\circ$K ($T/T_m = 0.75$) during the first one billion years after the formation of mascons. The viscosities relevant to the isostatic adjustment of the mascons are those corresponding to the temperature of $T/T_m \leq 0.75$ and a stress level of $10^2$ bars. According to Weertman's estimate, which is partly based on experimental data from terrestrial rocks, the viscosity at such conditions is on the order of $10^{20}$ poise. This is orders of magnitude lower than that required for the long persistence of the mascons. Since evidence for an early hot moon is overwhelming (e.g., 5, 6), we would like to investigate the possibility that the discrepancy of the viscosity estimate is due to an oversimplification of the mechanical properties of lunar materials.

Tittmann and Housley (7) demonstrated that the internal friction of a terrestrial basalt decreased dramatically when the sample was outgassed under conditions of high vacuum and thermal cycling. The similar effect of volatiles on the internal friction was also observed for lunar rocks (8, 9). These studies suggest that the mechanical properties of rocks are significantly affected by the existence of volatiles, water in particular, in grain boundaries and crack tips. The effect of moisture on crack growth has also been discussed in the ceramics and rock mechanics literature (10, 11). These studies show that the rate of crack growth increases approximately linearly with increasing partial pressure of water.

Since lunar conditions are characterized by high vacuum and consequently the absence of water, lunar materials may have very different mechanical properties from terrestrial rocks. We believe that understanding of the effect of volatiles on the mechanical properties of rocks is a key to the solution of many unsolved lunar problems.

Two nearly identical right circular cylinders (1.78 cm diameter by 4.12 cm length) of hypabyssal basalt (Boulder, Colorado) were tested to failure under nearly identical uniaxial stress. The only difference in the two tests was the atmosphere surrounding them. Both samples were outgassed for 40 hours in a vacuum chamber at approximately $10^{-6}$ torr and at a temperature of $200^\circ$K.
This temperature was chosen as a compromise between the desire to achieve maximum outgassing and the fear of introducing a significant number of thermal cracks. After the outgassing of Sample A, a partial pressure of water of approximately 10 mb was introduced into the vacuum chamber. The sample was stored in this environment for several days before the load was applied. Sample B remained under vacuum. All further tests were performed at room temperature.

The samples were loaded under uniaxial compression and the axial displacement and force recorded as a function of time. Up to 1.9 kb the stress was increased at $1.8 \times 10^{-4}$ kb/sec. The samples were then cycled between 1.9 and 1.75 kb at three stress rates in the following order: $4.7 \times 10^{-5}$ kb/sec, $1.4 \times 10^{-4}$ kb/sec, $4.2 \times 10^{-4}$ kb/sec. The stress was again increased at $1.8 \times 10^{-4}$ kb/sec to 2.3 kb and cycled in the same manner between 2.15 and 2.3 kb. Two more sets of cycling (at the highest stress rate only) were obtained between 2.4 and 2.5 kb, and 2.5 and 2.6 kb. The stress increase was continued at $1.8 \times 10^{-4}$ kb/sec until the samples failed.

The behavior of the rocks can be separated into three distinct stages. In the first stage, from zero to 0.4 kb, the stress-strain relationship is controlled by crack closure. Between 0.4 and 2.2 kb is the elastic stage. In this stage there is no (measurable) hysteresis during cycling. The wet and dry samples behave the same. The third stage is above 2.2 kb and is characterized by the formation of new cracks.

It is in stages I and III where the presence or absence of volatiles significantly influences the behavior of rocks. As can be seen in Figure 1, the effective Young's modulus of the wet sample (Sample A) is significantly lower than that of Sample B. We interpret this to be due to the influence of volatiles in high stress areas during crack closure. In the elastic range the Young's modulus is the same for the wet and dry samples. Above 2.2 kb new cracks begin to open and are influenced by the volatiles. Figure 2 illustrates the difference in behavior between Samples A and B in this stage. The wet sample shows a much larger hysteresis upon repeated cycling than does the dry sample. In the case of the dry sample, coincident with stage III there is also an increase in the pressure in the vacuum chamber. Each time the uniaxial stress is increased in this stage, the gas pressure in the chamber increases. New previously inaccessible gas is released from the rock. The final strength of the dry rock was 2.9 kb, as compared to 2.7 kb for the wet rock.

Based on these results, we conclude that volatiles (or their absence) may play a major role in earth-based experimentation and its applicability to lunar processes. The moisture content in the test chamber was varied by approximately six orders of magnitude for the two samples, yet only slight differences in both behavior at high stresses and the ultimate strength were observed. Studies on the influence of moisture on crack growth in single crystals suggest that the dryer sample should exhibit much less anelastic strain than the wet sample at similar stresses. The fact that the dry sample continued to outgas during deformation suggests that 1) it was not thoroughly dried during the bakeout cycle, 2) the observed behavior represents that of a sample at moisture conditions significantly greater than $10^{-6}$ torr, and 3) the ultimate effect of volatiles upon physical properties must be determined.
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Mizutani, H. et al.

with either artificial samples created under high vacuum or well outgassed lunar samples.

References

Fig. 1. Young's modulus versus axial stress for dry - and wet - samples. Horizontal bars represent axial stress range over which the Young's moduli were calculated. Note the difference of the Young's moduli for Samples A and B in stage I.

Fig. 2. Stress strain curves for wet and dry samples during stage III. Note large hysteresis for wet sample.