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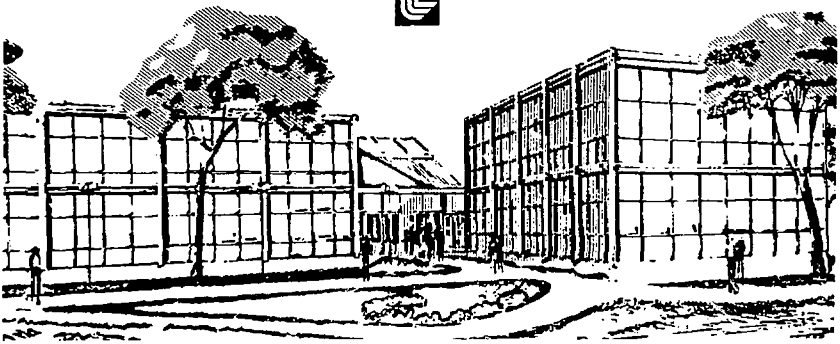

THE RESPONSE OF ROCKS TO LARGE STRESSES

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ABSTRACT

To predict the dimensions and characteristics of impact- and explosion-induced craters, one must know the equation of state of the rocks in which the crater is formed. Recent experimental data shed light upon inelastic processes that influence the stress/strain behavior of rocks. We examine these data with a view to developing models that could be used in predicting cratering phenomena. New data is presented on the volume behavior of two dissimilar rocks subjected to tensile sti ses.

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INTRODUCTION

When a body impacts or explodes in rock or soil, some of the energy is converted into heat and some into mechanical work on the surrounding material. The relative magnitude of heat and work as well as the form of the work itself (i.e., elastic, inelastic, fracture, compaction) are directly dependent on the mechanical response of the surrounding material to the stress conditions. Thus, knowledge of the nature of the relation between stress and mechanical response (strain) is needed to predict the effect of an impact or explosion. The crater form can be predicted if source parameters are known; the source energy and boundary conditions can be predicted if the crater form is known. Terhune and Stubbs (1970) have given an excellent description of the effect of material parameters (such as strength and compressibility) on crater dimensions. They have also compared calculations and observations of explosion-created craters. The purpose of this paper is to review recent experimental work on the response of rock to stress. We seek constitutive relations that can be incorporated into computer codes whose function is to predict the phenomenology of explosions or impacts. The underlying purpose of these experiments has been to increase understanding of the physical processes responsible for observed behavior, so that models developed can be applicable to a broad range of stress and strain conditions (i.e., so that they can be truly predictive, rather than simply fitted to experimental data).

To develop inelastic constitutive models, we must determine the stress and the strain tensor and the tensor that couples them (Schock, 1970) over the range of conditions encountered. Unlike those for elastic materials, the moduli (or stress/strain coupling coefficients) are not independent of stress state. The range of conditions in rock is commonly described by mean pressure (or the invariants of stress), shear stress (or the invariants of stress deviation), and strain rate. Constitutive relations may be considered in terms of stress and strain or, if strain-rate effects are considered, in terms of stress and strain rates. Experimental arrangements incorporating this range of conditions have become common. See, for example, the papers by Brace et al. (1966), Scholz (1968), Swanson and Brown (1971), Schock and Duba (1972), Schock et al. (1973), and Scholz and Kranz (1974). The answers to such questions as, "How complex must the models be to accurately describe the desired behavior?" and "What kinds of approximations must be used to make them usable in a time-limited computer code?" are of interest.

In the discussion that follows, brittle, ductile, and porous rocks will be discussed in order. Then, important effects such as fluid saturation and sample size will be considered. Within each classification, behavior in compression, tension, and at high strain rate will be considered. In almost all of the experimental work considered, there was a stress geometry such that the intermediate principal stress was equal to either the maximum or minimum principal stress. Other experimental conditions are difficult to achieve and will be given only brief mention. However, it should be noted that for point source explosions or impacts, shock waves and resultant stresses closely approximate this geometry over significant times and distances.

BRITTLE ROCKS

For our purposes, the failure of brittle rocks may be characterized by a through-going fracture that propagates at sonic or nearly sonic speeds. Inelastic behavior may be observed in the axial stress/strain relation, but total axial strain before failure is usually less than 1% (Griggs and Handin, 1960). Granite, limestone, and dolomite at low confining pressure, and quartz-cemented sandstones and metamorphic rocks exhibit this behavior. Failure stress in these materials is strongly dependent on and increases with confining pressure (Jaeger and Cook, 1969). It is not uncommon to observe changes of an order of magnitude with 0.1 GPa confining pressure. This is due primarily to the strong effect of pressure, which increases friction and thereby inhibits sliding on inter-granular crack surfaces.

One of the most striking characteristics of low-porosity, brittle rocks is that before they fail in compression, there is a pronounced nonlinear behavior in the axial-stress/radial-strain relation. This results from inelastic volume dilatancy (Brace et al., 1966), which characteristically precedes failure in these rocks (Scholz, 1968; Schock et al, 1973). This behavior has been ascribed to the opening and the propagation of cracks whose major axes are oriented parallel to the active principal stress. Such cracks open with a tensile stress in the region of the crack tip, even though all of the macroscopic stresses are compressive. Cracks with other orientations are compressed shut at much lower pressures.

Swanson and Brown (1971) determined that at constant strain rate, the curve that describes compressive failure in granite as a function of confining pressure is independent of loading path. A similar observation was made by Schock et al. (1973) for the onset of dilatant behavior as a function of confining pressure. If one considers the success of critical-strain-energy criteria for failure (Griffith, 1921; Sih and MacDonald, 1974), this uniqueness in behavior suggests a uniqueness in strain at a given mean pressure and shear stress. This hypothesis has been tested on several brittle rocks (Schock, 1976; Costantino and Schock, 1976) and has been found to be true for the stress conditions prescribed. This allows the construction of a constitutive relation that expresses dilatant strain in the form,

$$\varepsilon_d = \exp\left[\frac{dP}{x(\tau)} - A(\tau)\right] ,$$

where dP is an increment of mean pressure, τ is shear stress, and x and A are material constants. The production of dilatant volume thus appears to follow an exponential law. This form of constitutive relation is not only simple, but it expresses the rock behavior in terms of experimentally measurable and thermodynamically definable parameters. The relation has the additional advantage of being able to predict failure shear stress accurately (Schock, 1976). The physical meaning of the exponential form is not yet clear.

After loading in compression due to an impact or an explosion, one or more of the principal stresses in the rock medium may become tensile during unloading. Brittle rocks typically fail in tension at stress levels an order of magnitude or more below those in compression, again presumably because of the lack of friction on grain boundary cracks when the active stress is tensile. Thus, significantly larger volumes of rock may be affected by inelastic phenomena resulting from tensile stresses than compressive stresses. Investigation of this stress regime has been carried out by Brace (1964), who monitored the axial strain and, more recently, in our laboratory (Schock and Louis, 1974), where both axial and radial strain were monitored. These latter results on Westerly granite were obtained on "dog-bone-shaped" samples in the apparatus described by Schock and Duba (1972).

The experimental stress paths are shown in Figure 1. The circles represent failure points and collectively describe failure in tension as a function of confining pressure. The two points on the ordinate are extension data (all principal stresses are compressive), for which the minimum principal stress was atmospheric pressure. The coincident strain data are shown in Figure 2 in terms of mean pressure and volume strain. Significantly, the amount of dilatant behavior is a function of the ratio of tensile to compressive stress in the particular test. Apparently, oriented cracks that will not open until they propagate through the specimen when no stress is tensile, are pulled open by the tensile stress when the compressive stress is lowest. The rock also becomes substantially weaker in these instances, perhaps because of the presence of open cracks. The dilatant behavior as a function of the tensile-stress/compressive-stress ratio (as shown in Figure 2) would seem to lend itself to a simple relation useful in a constitutive equation. More work is required to define the exact form of this relation.

Failure in brittle rocks is a strong function of strain rate (Green and Perkins, 1968; Logan and Handin, 1970; and Green et al., 1972). Increases of failure stress of about 5% per order-of-magnitude increase in strain rate generally are observed. This is a significant amount, which, when considered over 8 to 10 orders of magnitude of strain rate, must be accounted for in calculations of the effect of dynamic impulses on rocks. In addition, there is evidence in the combined results of static and shock-wave experiments that the onset of dilatant behavior is suppressed (occurs at higher stress) and that the dilatant strain is reduced as the strain rate increases (Schock and Heard, 1974). This evidence, together with the observation of Scholz (1968) that microfracturing becomes localized only near the failure stress, suggests that brittle failure at very high strain rates ($>10^4$/s) may be a much more disruptive process involving more of the rock volume than commonly observed visually in the laboratory at low strain rates. At low strain rates, microfractures have time to terminate and relieve local stress concentrations. For example, some brittle rocks are observed to strain for periods of greater than two weeks at constant stress below their fracture strengths (Kranz and Scholz, 1976). Laboratory specimens failed at strain rates of $\sim10^{-4}$/s commonly show one or two through-going fractures. On the other hand, there is evidence of "pulverized" rock at the edges of nuclear-explosion-induced cavities (Borg, 1972), where extremely high strain rates (perhaps $>10^5$/s) were achieved.

DUCTILE ROCKS

With increased confining pressure, many of the mineral constituents in rock undergo a transition from brittle to ductile behavior (Handin et al., 1967). In addition, some rocks contain minerals that are ductile at normal pressures. The resulting behavior is distinguished from brittle failure in that the rock does not achieve a maximum shear stress at a fixed strain. Many ductile rocks exhibit work-hardening; stress and strain continue to increase in a highly nonlinear manner, with the result that a unique failure surface does not exist.

Since dilatancy is related to the opening of microcracks, it is expected to be an inherent property of brittle rocks and to be absent in ductile materials, where flow and creep reduce stress concentrations at crack tips. Experimental confirmation of this has been found in several graywacke sandstones that exhibit brittle fracture at low confining pressures and flow at high confining pressures (Schock et al., 1973). At high confining pressure, argillaceous and carbonate cements flow, allowing for rearrangement of the brittle quartz and feldspar grains and suppressing the dilatancy characterized by microfracturing.

A diminishing of dilatant behavior also is seen in these rocks when they are subjected to tensile stresses. Graywacke sandstone loaded in a similar manner to the granite in Figures 1 and 2, exhibits little or no tendency to dilate (Figure 3). Since at these low confining pressures, the rock fails by brittle fracture, the explanation for this behavior must lie in the nature of the cracks themselves. In order for tensile stress of the order of megapascals (tens of bars) to open cracks in granite, aspect ratios must be very small ($<10^{-5}$) (Walsh, 1965). Thus, the average aspect ratio of the cracks present in this sandstone is large enough so that they do not open before the material fails.

The effect of an increasing strain rate is (1) to raise the stress level for a given amount of strain (higher deformation modulus) and (2) to raise the pressure at which rocks go from brittle to ductile behavior (Handin et al., 1967; Schock et al., 1973). This decrease is ductility with increasing strain rate amplifies the importance of brittle deformation phenomena in explosive and impact events in rock. Even though there are rocks that behave in a ductile manner at the highest strain rates, most common rock types, if ductile at atmospheric confining pressure, show a ductile/brittle transition with increasing confining pressure (Handin et al., 1967).

POROSITY

Early observation (Schock et al., 1973; Schock and Heard, 1974) indicated that granites and graywacke sandstones did not fail when compressed quasi-statically in uniaxial strain (constant radial strain) to simulate plane-wave shock-loading conditions. On the other hand, loading to failure did take place in very porous, brittle rocks, such as tuff, subjected to the same conditions (Heard et al., 1971). Furthermore, there appeared to be little or no dilatancy prior to failure when these tuffs were loaded at constant confining pressure. This suggests that at least in some rocks, catastrophic pore collapse rather than a through-going fracture was the dominant failure mode. This idea is supported in part by a curvature of the failure envelope concave to the shear stress axis. The subsequent work of Duba et al. (1974a) on a sandstone with 26% gas-filled porosity verified these conclusions by demonstrating that the failure envelope was effectively depressed by pore collapse from that for the matrix material without pores.

Another significant observation is that the compressibility of a material in the pore-collapse region is a function of the shear stress (Schock et al., 1971; Schock et al., 1973; Shipman et al., 1974; and Schock et al., 1976). The volume strain in the pore collapse region, unlike that in the dilatant region previously discussed, is stress path dependent. This shear-enhanced compaction is not incorporated in most constitutive relations derived to treat inelastic pore collapse (Herrmann, 1969; Carroll and Holt, 1972a; Carroll and Holt, 1972b; and Bhatt et al., 1975). Instead, only properties under the hydrostatic or presumed hydrostatic conditions of most experiments are treated.

One of the more successful forms of constitutive relations is

$$P = 2/3\tau \ (\ell n \ 1/\eta),$$

where τ is yield stress $(\sigma_1 - \sigma_3)$ η porosity, and P pressure in the yield region. This form results from a consideration of the ideally plastic deformation of a hollow sphere. τ can be made to vary with porosity. For rocks, Bhatt et al. (1975) considered τ in terms of a Mohr-Coulomb material.

To date, two methods have been used to treat shear-enhanced pore collapse specifically. Shipman et al. (1974) fitted data on porous uranium metal. Data on other porous metals (Johnson et al., 1974; Kuhn and Downey, 1971) and on some porous rocks and soils (Nelson et al., 1971) can be fitted with models using movable failure surfaces and computing strain through "associated" flow rules. These models are complex and require a large number of tests to define an equally large number of parameters.

FLUID SATURATION

When water is allowed into the pore space in a dry rock, it can introduce large departures from the response to stress. The collapse of pore space in water-saturated rocks is controlled, not only by the strength of the pore wall, but by the compressibility of the water. The pressure on the pore fluid controls failure by dictating the effective stress, i.e., the difference between applied stress and pore pressure (Terzaghi, 194?). When rocks remain completely saturated to failure, the failure stress is observed to decrease with increasing fluid pore pressure (Heard, 1960). During dilatant behavior, brittle rock will behave almost as if it were dry, if the total volume of water is fixed so that the rock becomes unsaturated. As the microcracks open, the resulting volume increase is such that the pore pressure drops until the rock becomes undersaturated (Duba et al., 1974b). If that pore space is connected so as to allow the fluid pressure to increase, strength will decrease. This is the mechanism of the suggested dilatancy model of earthquake generation (Scholz et al., 1973). The brittle/ductile transition is also controlled by the effective stress (Heard, 1960).

Wherever movement of fluid is possible, strong strain-rate effects on behavior are expected (Martin, 1972). The movement of fluid through pore space is a strong function of its viscosity. Since viscosity is the relation between stress and strain rate, it follows that the pressure in the fluid is a function of time, at a given strain.

Water may also introduce complications through its behavior as a thermodynamic fluid during shock loading (Stephens, 1969). Consider a saturated rock that has been adiabatically shocked such that the temperature is above 100°C. On isentropic unloading, the pressure will drop faster than the temperature, and water may convert to steam with a volume increase and a release of energy associated with the latent heat of vaporization. This energy will be added to that from the impact or explosion to enhance crater formation.

SUMMARY

These observations lead to the development of simplified constitutive models that can be used to predict the response of rock to impact loading by identifying the important parameters that determine that response. The importance of shear stress and mean pressure in defining regions of behavior has been demonstrated. It has been shown experimentally that dilatancy is related to failure in low-porosity, brittle rocks. The onset of dilatant behavior can be defined in terms of mean stress and shear stress, and, once begun, it can be described by a simple constitutive relation involving these two system variables. For rocks that exhibit flow instead of fracture, little or no dilatancy is observed.

Compaction of pore space can be an important process in rock behavior in terms of enhanced compression and decreased failure shear strength, both of which absorb energy that might otherwise by used in the cratering process. In addition, compaction is influenced by shear stress. These observations may be summarized in a schematic diagram (Figure 4). Here, the axes are the two system variables, shear stress and confining pressure (function of mean stress). The failure envelope, which defines the limit of shear stress in terms of mean stress for low-porosity material, the dilatant and compaction region boundaries, and pore collapse and ductile failure envelopes, are all defined in terms of the system variables. In Figure 4, all of these boundaries are shown in a general, not a rigorous sense. That is, they are movable in both coordinates and may not even exist for a given rock type (e.g. compaction in low-porosity rock). Within a given region,a third system variable may be used to define a constitutive relation, such as has been shown for dilatant and compacting material.

Some qualifications not shown in Figure 4 must be considered. The influence of water has been mentioned, but it has not been quantified to allow treatment in this sense. More studies are needed. The effect of strain rate likewise is not shown. Cyclical loading affects strength (Peng et al., 1974), dilatant behavior (Scholz and Kranz, 1974), as well as compaction (Schock et al., 1976). The effect of the intermediate principal stress may also be important (Handin et al., 1967; Mogi, 1972), the symmetry of the cratering process at early times notwithstanding. More studies to define and describe this effect are called for. Finally, sample size can be a serious problem, in terms of critical phenomena excluded by the limited size of laboratory samples. Pratt et al. (1976) show that failure shear stress can be a strong function of sample size.

Despite these limitations, the observations represented schematically in Figure 4 provide insight into the processes taking place, and they suggest ways in which these processes may be modeled. Through a study of the mathematical form of the model, we may achive a better understanding of the physical processes that control the behavior.

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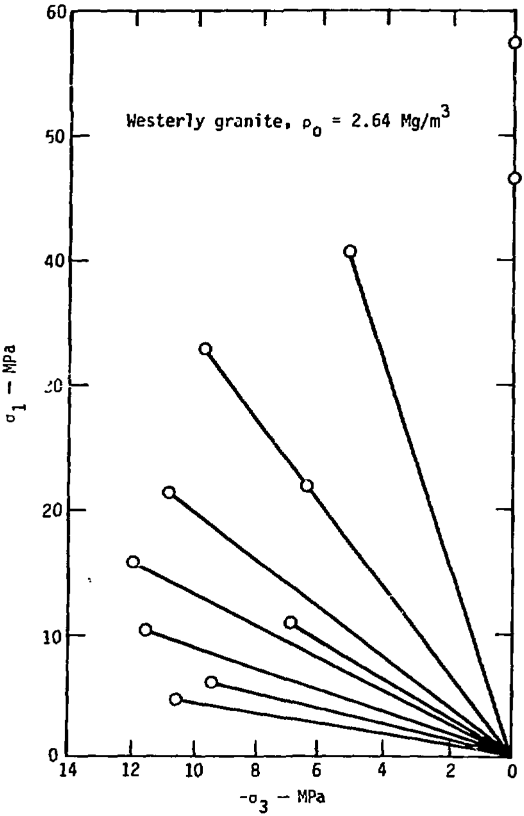
FIGURE CAPTIONS

Fig. 1 Stress paths to failure (circles) for a number of samples of Westerly granite (initial density 2.64 Mg/m^3) in terms of the tensile stress (σ_3) and the maximum compressive stress (σ_1). The intermediate principal stress (σ_2) was in all cases equal to σ_1.

Fig. 2 Behavior of Westerly granite during the loadings shown in Figure 1 in terms of mean pressure $(2\sigma_1 + \sigma_3)/3$ and sample volume strains.

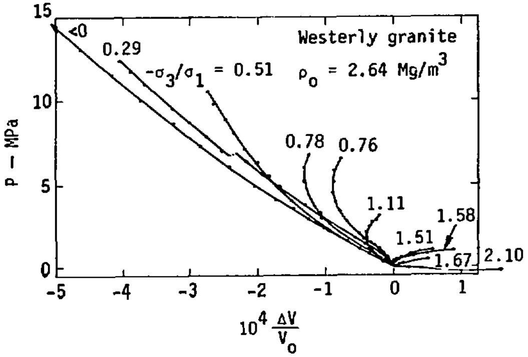
Fig. 3 Behavior of Lance sandstone during loading with one principal stress tensile, in terms of mean pressure and volume strain.

Fig. 4 Schematic representation of boundaries in shear-stress/confining-pressure space for noncyclically loaded rock. Axial strains shown for ductile failure are values of permanent strain. After Schock _et al_. (1973).



Westerly granite, ρ_0 = 2.64 Mg/m^3
σ_1 — MPa
$-\sigma_3$ — MPa
60
50
40
30
20
10
0
14
12
10
8
6
4
2
0

Figure 1.



Westerly granite
ρ_o = 2.64 Mg/m^3
<0
0.29
$-\sigma_3/\sigma_1$ = 0.51
0.78
0.76
1.11
1.58
1.51
1.67
2.10
15
10
5
0
p — MPa
-5
-4
-3
-2
-1
0
1
$10^4 \frac{\Delta V}{V_o}$

Figure 2.

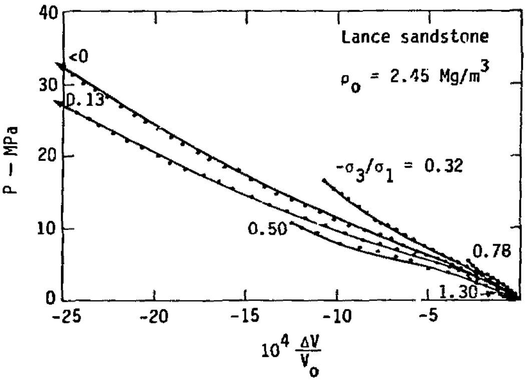
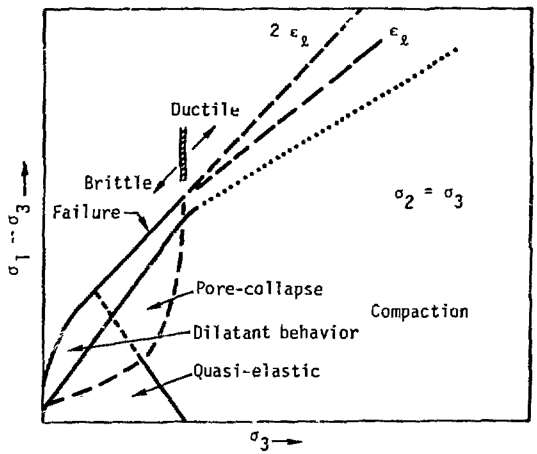

Lance sandstone
ρo = 2.45 Mg/m3
-σ3/σ1 = 0.32
<0
0.13
0.50
0.78
1.30
P — MPa
10^4 ΔV/Vo
40
30
20
10
0
-25
-20
-15
-10
-5

Figure 3.



2 ϵ_ℓ
ϵ_ℓ
Ductile
Brittle
Failure
$\sigma_2 = \sigma_3$
$\sigma_1 - \sigma_3$
Pore-collapse
Compaction
Dilatant behavior
Quasi-elastic
σ_3

Figure 4.