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UCRL-51296

**MECHANICAL PROPERTIES OF GRANITE FROM THE
TAOURIRT TAN AFELLA MASSIF, ALGERIA**

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MS date: November 2, 1972

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Abstract

The mechanical properties of a granite from the French Hoggar test site in Algeria were measured to provide input for numerical codes seeking to predict rock response to a stress wave and to assist in formulating models on which these codes are based. The measured properties include pressure-volume behavior, failure envelope as a function of mean pressure, compressional and shear velocities as a function of pressure, and three-dimensional stress-strain measurements along various loading and unloading paths. This granite responds to stress in much the same way as other

granites that have been studied extensively. The failure envelope was determined to 30-kbar mean stress with no evidence of ductile behavior. Stress-strain experiments reveal the presence of long narrow cracks which close at stress levels below 0.5 kbar. The rock at atmospheric pressure was found to have a bulk modulus of 330 kbar and a shear modulus of 290 kbar. These yield an elastic compressional velocity of 5.24 km sec^{-1} , in good agreement with laboratory measurements on small samples and with field experiments within the massif over distances of several tens of meters.

Introduction

As part of an exchange program between the French Commissariat à l'Energie Atomique (CEA) and the United States Atomic Energy Commission, related to the peaceful use of nuclear explosives, we have received a suite of rock samples from a 765-m borehole in the Taourirt Tan Afella massif, on the Hoggar test site, in what was formerly French Algeria. The French have conducted several underground nuclear explosions in this massif. A summary of previous technical exchanges and a bibliography of the French reports describing the Hoggar

test site and experimental conditions is given by Stephens.¹

The Hoggar test site consists primarily of Taourirt Tan Afella (24° 03' N, 5° 02' E) and the surrounding plains.² The samples received (henceforth called Hoggar) were from a borehole drilled into the massif to within 40 m of the shot point, prior to the Monique explosion (117 kT). A cross-section of the massif through the borehole is shown in Fig. 1. We received samples from every 20 or 30 m between the surface and 750 m. Each sample is approximately 10 cm in

Fig. 1. Southwest-Northeast section through Borehole T.71.

Fig. 2. French CEA photograph of granite samples.

Table 1. Properties of the granite of Taourirt Tan Afella.³

Mineralogical analyses			
Quartz	35%	Chaye's index	64
Microcline	37%		
Plagioclase	25%		
Biotite	2.1%		
Muscovite	0.6%		
Chemical analyses			
SiO ₂	75.80%	K ₂ O	4.79%
Al ₂ O ₃	12.49%	TiO ₂	0.08%
Fe ₂ O ₃	1.30%	P ₂ O ₅	0.01%
MnO	0.04%	CO ₂	0.13%
MgO	0.03%	H ₂ O ⁺	0.48%
CaO	0.59%	H ₂ O ⁻	0.06%
Na ₂ O	3.80%		

length by 5 cm in diameter, although the size and core diameter vary slightly (Fig. 2). The samples were coherent, appeared relatively unaltered and showed little evidence of fracturing. Chemical and mineralogical analysis of the granite body are given in Table 1.

One of the primary goals of this exchange of rock samples is to compare numerical simulation techniques that seek to predict such explosion induced features as cavity dimensions, fracturing, ground

motion, and wave propagation. Since these calculational codes require mechanical properties as input, we have chosen to concentrate first on the rock samples closest to the explosion. The deepest sample (750 m) is from just outside the region in which the cavity was produced, and where peak stresses are of the order of tens of kilobars.

We have experimentally determined the pressure-volume loading behavior to 35 kbar, the failure envelope to 50 kbar mean pressure, and acoustic velocities to 10 kbar. In addition, the stress-strain relationships in quasi-static loading have been measured to 15 kbar to determine such parameters as the stress and path dependence of the shear modulus, and the properties on unloading from peak stresses below the failure envelope. The experimental techniques used have been described in detail elsewhere.⁴⁻⁸ The average density of the material studied is 2.61 g cm⁻³ and varied between 2.604 and 2.617. All stresses are referred to a cylindrical coordinate system with σ_1 , σ_2 and σ_3 the maximum, intermediate, and minimum principle stresses. Stress is taken as positive and strain as negative in compression.

Pressure-Volume Determinations

The pressure-volume relationship for Hoggar granite was determined on four different samples from 700 m. Two of these samples (1.15 cm diam X 2.54 cm cylinders) were compressed to 35 kbar in a quasi-hydrostatic piston cylinder apparatus. This apparatus uses tin as the pressure medium. The pressure-

volume relationship is determined from measurements of force and piston displacement. The results from the two 35-kbar quasi-hydrostatic runs are shown by the symbols O and Δ in Fig. 3. The remaining two samples (1.91 cm diam X 2.54 cm) were tested in a hydrostatic apparatus to 14 kbar. These samples

Fig. 3. Pressure-volume relationship for Hoggar granite, Climax Stock granodiorite, and Westerly granite. Pressure-volume relationships are shown for comparison.

were jacketed in 0.02-cm lead to prevent penetration of the pressure fluid into the rock. Strain was measured as a function of pressure by foil strain gages that are bonded to the lead jacket. The results for the hydrostatic tests are shown as $\square$ and ∇ in Fig. 3. For comparison, Fig. 3 also shows the pressure-volume relationships for Climax Stock granodiorite⁹ and Westerly granite.¹⁰

The results from all four runs appear to be in good agreement in the overlapping region. A curve is drawn through the experimental data up to 35 kbar. These data may be expressed as a power series,

$$V/V_0 = \sum_{i=0}^9 C_i P^i, \quad (1)$$

where C_i is a constant and P^i is pressure in kbar. The bulk modulus, K , can be expressed as a ratio of power series

$$K = \frac{\sum_{i=0}^9 C_i P^i}{\sum_{i=1}^9 i \cdot C_i \cdot P^{(i-1)}}. \quad (2)$$

Table 2 gives the values for C_i . Equation 2 gives a bulk modulus at $P = 0$ of 326 kbar.

Table 2. Polynomial coefficients in Eq. 2 and derived pressure-volume data.

i	C_i
0	1.000000000
1	$-3.06201539 \times 10^{-3}$
2	$1.59892659 \times 10^{-4}$
3	$-1.64618743 \times 10^{-5}$
4	$1.05764000 \times 10^{-6}$
5	$-3.22663929 \times 10^{-8}$
6	$1.45310915 \times 10^{-10}$
7	$1.86230791 \times 10^{-11}$
8	$-4.99569603 \times 10^{-13}$
9	$4.12613182 \times 10^{-15}$

P (kb)	V/V ₀	K (kb)
0	1.	326
0.5	0.9985	342
1	0.9971	357
5	0.9872	436
10	0.9765	487
15	0.9672	563
20	0.9594	675
25	0.9529	770
30	0.9468	795
35	0.9409	810

Determination of Shear Strength at High Pressure

The differential stress-strain behavior of this granite was determined in three types of tests: 1) uniaxial compression on cylinders 1.2 cm diam by 2.5 cm long under confining pressures ranging up to 22 kbar, 2) torsion of solid disks 0.25 cm diam by 0.7 cm long under pressures ranging up to 50 kbar, and 3) indirect tensile tests (Brazil) on right cylinders

1.9 cm diam by 3.0 cm long at 1 bar pressure. The compression tests were carried out in a fluid medium using jacketed samples. Pressures were determined from the resistance change of manganin wire coils and the axial loads imposed on the sample were measured within the pressure vessel with a force gage placed in mechanical series with the

test sample. Changes in sample length were determined from external piston displacements. Accuracies of measurement are estimated at 0.5 to 1.0% after calibration. General descriptions of the apparatus as well as discussions of general techniques used are described elsewhere.^{5,6} The torsion tests were carried out in a solid-pressure medium apparatus.¹¹ The mean pressures as well as the torques and twists applied to the sample disk were measured externally. Accuracies for these tests are believed to be about 5%. The indirect tensile tests were made in a standard testing machine having accuracies of <0.5%. All three test types were carried out at room temperature and at strain rates of 10^{-4} to 10^{-5} /sec.

UNIAXIAL COMPRESSION TESTS

Differential stress-axial strain curves at each pressure were calculated from the raw force-displacement data and the initial sample dimensions. Intercomparison of these curves over the range of pressures investigated along with visual observations on the deformed test samples then yielded an internally consistent pattern of behavior with pressure for the Hoggar granite.

In each case, the stress-strain curve showed a quasi-elastic portion followed by a narrow region of yielding (both in stress as well as in strain) which finally terminated in fracture. In most tests, with the exception of those at the highest pressures, the stress after fracture did not drop to zero but remained at about one-half the ultimate (fracture) value. The tensile fracture planes as well as

Table 3. Compression tests, Hoggar granodiorite.^a

σ_1	σ_1'	σ_3	σ_3'	τ	τ'	P_m	P_m'
ksi							
2087	0	0	0	1043	0	503	0
2162	0	0	0	1080	0	540	0
3680	2260	250	300	2720	580	2360	360
740	4100	510	530	3620	1765	2920	1720
10270	4520	1000	1080	4640	1720	4090	2230
9930	3490	1000	1040	4450	1230	3370	1860
15030	8760	2600	2080	6520	2240	6330	3640
14370	8210	2010	2130	6180	3040	6130	4150
16000	9110	3000	3110	6950	3000	7640	5110
17240	11230	3910	3100	7120	4040	7350	5940
19020	14620	3670	3840	7675	5380	8760	7430
17470	3430	3020	3150	7230	3120	7830	5270
10930	11470	4000	4200	7070	3620	9310	1050
21050	15050	5050	5210	8300	0	10080	5310
21170	12300	5100	5400	8040	3450	10440	7700
22610	6510	6060	6510	8780	0	11910	6510
25760	7300	7060	7300	9350	0	13295	7300
25400	7300	7060	7300	9200	0	13180	7300
33050	12350	12350	12350	10750	0	19520	12350
37110	15360	15360	15360	10880	0	22610	15360
42790	20260	20260	20260	11270	0	27770	20260
45330	21930	21930	21930	11700	0	29730	21930

^a σ_3 - confining pressure. All failures by brittle fracture. T. 71 test sample from 600 to 750 m.

the single or occasionally conjugate shear fractures in these samples did not puncture the thin-wall jacketing material. For the highest pressure tests, displacements on the fracture surfaces were sufficient to penetrate the jacket and allow the fluid pressure access to the rock with consequent drop in stress to zero. Total permanent strains before onset of fracture were about 1 to 2% with the tendency to increase somewhat with pressure. Behavior of all samples could thus be termed brittle.

The principal stresses at the point of fracture (σ_1, σ_3) as well as the stresses supported by the granite immediately after fracture (σ_1', σ_3') are summarized in Table 3. From this table it is apparent that σ_1 , or the shear stress $\tau, (\sigma_1 - \sigma_3)/2$, markedly increases with confining pressure σ_3 . Such behavior is to be expected if the

Failure mechanism responsible is dependent upon normal stress. Shear fracture and frictional sliding of adjacent surfaces are two such mechanisms. Figure 4 illustrates this increase in strength with pressure up to pressures of 22 kbar. Results on the same rock to 5 kbar¹² are also shown. Agreement between the two sets of data is considered very good at the lower pressures but only fair in the 2 to 4 kbar range. Discrepancies diminish at the highest comparable pressure and it appears the two curves might cross and diverge if higher pressure data were available. Also shown for comparison are data for two similar rocks—the Westerly granite to 20 kbar and the Climax Stock granodiorite to 8 kbar. The Westerly results are nearly parallel to that of the Hoggar to the highest pressures; the only significant difference is the 3 to 4 kbar offset in fracture strength at pressures above about 10 kbar. The Hardhat granodiorite apparently is stronger than both granites.

Results for both the Hoggar and Westerly granites are also shown as failure envelopes in shear stress-mean pressure space (Fig. 5). In addition, the strength of the Hoggar samples after fracture is shown for comparison. It is apparent that this granite retains considerable strength under pressure even though all cohesion is destroyed. Available data for the Hardhat and Westerly rocks also indicate comparable strengths after fracture.¹³

TORSION TESTS

The desire to determine the limiting shear strength as well as the pressures

at which the dominant mechanism of deformation became plastic flow in the component crystals (ductile behavior) prompted us to extend our measurements to the highest pressure possible. Compression testing becomes very difficult in fluids at pressures above about 25 kbar. Thus, we initiated a limited program of strength measurements in torsion in the pressure region 21 to 50 kbar in a solid pressure medium apparatus.

Results from the torsion tests in the form of torque-twist curves as well as the deformed samples had the same characteristics as the compression data discussed above. Values for the principal stresses at fracture, as calculated in the outer fibers of the deformed disk, are summarized in Table 4 for comparison with those for compression (Table 3). From these tables it appears the fracture strength is apparently still increasing to the highest pressures measured. Graphic comparison of both sets of results are

Table 4. Torsion tests, Hoggar granodiorite.^a

σ_1	σ_2	σ_3	τ	P_m
kb				
41.2	21.0	0.8	10.1	21.0
41.2	21.0	0.8	10.1	21.0
44.5	21.0	-2.5	11.8	21.0
56.2	29.0	1.8	13.6	29.0
56.6	29.0	1.4	13.8	29.0
63.2	35.0	6.8	14.1	35.0
61.4	35.0	8.6	13.2	35.0
79.5	50.0	20.5	14.8	50.0
80.6	50.0	19.4	15.3	50.0

^a All failure is by brittle fracture.
T. 71 test samples from 600 to 750 m

Fig. 4. Axial stress difference at failure as a function of confining pressure for Hoggar and Westerly granites and Climax Stock granodiorite.

Fig. 5. Shear stress (failure and post failure) as a function of mean pressure for Hoggar and Westerly granite.

Fig. 6. Comparison of failure as determined in compression and in torsion.

made in Fig. 6. Even though it has been demonstrated^{14,15} that the effect of the intermediate principal stress σ_2 (which is not identical in compression and torsion testing at similar pressures) causes shear strength-mean pressure failure envelopes for torsion to lie about 20% lower than for compression, the torsion envelope appears to be a smooth extension of that for compression. The solid pressure medium used in the torsion tests would be expected to increase the apparent strength somewhat. However, we regard the two sets of results to be in good agreement. Compressive shear strengths can then be expected to be about 13 to 14 kbar in the

Table 5. Brazil tests, Hoggar granodiorite.^a

σ_1	σ_2	σ_3	τ	P_m
bars				
228	0	-76	152	51
390	0	-130	260	87
261	0	-87	174	58
252	0	-84	168	56
225	0	-75	150	50
219	0	-73	146	49
225	0	-75	150	50
285	0	-95	190	63

^a All failure is by brittle fracture. T.71 test samples from 600-750 m.

50 to 60 kbar mean pressure range. In this region, the granite would still be brittle.

BRAZIL TESTS

The indirect tensile or "Brazil" test is useful in quickly and easily determining the position of the composite failure envelope at low positive as well as nega-

tive mean pressures where the influence of σ_2 on the envelope position is minimal. The tensile strengths so determined for samples of the Hoggar granodiorite are summarized in Table 5. Average values range from -85 to -90 bar. Results on other rocks indicate these tensile strengths can be expected to remain independent of confining pressure.¹⁵

Acoustic Velocity Determinations

Compressional and shear acoustic velocities have been determined to 10 kbar on granite from 720 m using the technique described previously.¹⁶ Briefly, the travel time of a 1-MHz wave through a 3-cm length of rock is measured as a function of confining pressure. The derived elastic bulk modulus is integrated as a function of pressure to compute the change in sample length and density with pressure. The observed travel-times are given in Figs. 7 and 8 and the computed velocities and derived moduli are given in Table 6.

Inspection of the data in Table 6 reveals that the initial bulk modulus is very close to the static determination of 326 kbar at atmospheric pressure. This is somewhat surprising as in most rocks, the acoustically derived moduli are considerably higher at low pressures¹⁷ owing to the presence of cracks and other imperfections which do not respond to the small stress pulse of the acoustic wave to the same degree as when a larger static pressure is applied. However, the data in Fig. 3 and the fit in Eq. 2 do not include low pressure increments below 1 kbar. Data taken with bonded strain gages be-

tween 1 and 200 bar indicate a bulk modulus of about 150 kbar. As will be shown later this value is influenced by the presence of cracks which close at low pressures. The velocities in Table 6 increase rather rapidly as cracks are closed and the derived bulk modulus quickly exceeds that derived from the static data (Eq. 2). The large velocity increase is primarily in the first 0.5 kbar, indicating that a majority of the cracks are closed by this pressure. This may be interpreted as meaning that the cracks have a high aspect ratio. Following Walsh¹⁸ the length of these cracks in the Hoggar granite is calculated to be approximately 10^3 greater than the width, a value similar to that observed for other granites.¹⁹ At 10 kbar the static modulus is still less than the acoustically derived modulus indicating that there are still a significant number of cracks which are not closed by 10 kbar pressure and thus the maximum/minimum ratio $< 10^2$. These cracks seem to be closed by about 20 kbar, if a linear extrapolation of the acoustically derived modulus is used.

The velocities determined at atmospheric pressure are in fairly good

Fig. 7. Compressional wave travel time as a function of pressure.

Fig. 8. Shear wave travel time as a function of pressure.

Table 6. Computed velocities and derived elastic moduli, Hoggar granite, T.71, 720 m.

Pressure (kb)	Density g cm^{-3}	Compr. velocity km sec^{-1}	Shear velocity km sec^{-1}	Bulk modulus (Mb)	Shear modulus (Mb)	Poisson's ratio	Young's modulus (Mb)
0.	2.610	5.18	3.00	0.3863	0.2351	0.247	0.5863
0.04	2.610	5.33	3.07	0.4139	0.2465	0.252	0.6170
0.10	2.611	5.54	3.19	0.4470	0.2659	0.252	0.6657
0.14	2.611	5.68	3.26	0.4701	0.2783	0.253	0.6972
0.20	2.611	5.88	3.37	0.5079	0.2969	0.255	0.7454
0.26	2.611	6.04	3.43	0.5441	0.3073	0.262	0.7759
0.30	2.612	6.15	3.46	0.5686	0.3132	0.267	0.7938
0.36	2.612	6.27	3.50	0.6009	0.3201	0.274	0.8154
0.40	2.612	6.33	3.52	0.6129	0.3245	0.275	0.8274
0.45	2.612	6.38	3.55	0.6252	0.3290	0.275	0.8397
0.50	2.613	6.41	3.57	0.6310	0.3327	0.276	0.8489
0.60	2.613	6.46	3.60	0.6382	0.3383	0.275	0.8626
0.80	2.614	6.50	3.64	0.6425	0.3456	0.272	0.8792
1.20	2.615	6.53	3.67	0.6465	0.3516	0.270	0.8930
2.00	2.619	6.56	3.70	0.6512	0.3579	0.268	0.9075
4.00	2.627	6.63	3.72	0.6585	0.3635	0.270	0.9232
6.00	2.635	6.65	3.73	0.6776	0.3665	0.271	0.9316
8.00	2.642	6.66	3.73	0.6823	0.3685	0.271	0.9369
10.00	2.650	6.68	3.73	0.6884	0.3694	0.272	0.9401

agreement with those given by Derlich²⁰ on other samples from the same massif. These are 5.50 km sec^{-1} for the compressional wave (V_P) and 2.40 km sec^{-1}

for the shear wave (V_S). Measurements in the field over longer paths give $V_P = 5.85 \text{ km sec}^{-1}$ and $V_S = 3.23 \text{ km sec}^{-1}$.²⁰

Three-Dimensional Stress-Strain Determinations

Measurements of the three-dimensional stress-strain relationship over a variety of loading paths in shear stress and mean stress space were carried out using cylindrical samples which were jacketed to prevent penetration of the pressure fluid into the pore space of the rock. For work at axial stresses above 5 kbar, the samples (2 cm diam $\times$ 3 cm) were loaded with the piston of a piston-cylinder pres-

sure vessel in which the confining pressure could be controlled independent of the advance of the piston.⁷ In this case the samples were jacketed with either 0.012-cm-thick copper or 0.025-cm-thick lead and the strain gages bonded to the jacket. For work at low axial stresses at confining pressures up to 4 kbar a fluid loading system⁸ was used and the samples (2.5 cm diam $\times$ 6 cm long) were jacketed

with a thin film of epoxy. We prefer this system at low axial stresses because it eliminates non-uniform loading of the sample resulting from either misalignment of the piston or a compliance mismatch between the sample and the piston. In both experiments we have corrected the strain gage outputs for the effects of pressure as outlined by Brace²¹ and Schock and Duba.²² The purpose of these experiments is two-fold: to determine the effective moduli of the rock on loading with large stresses, and to investigate inelastic effects.

UNIAXIAL STRESS

Several samples were loaded to failure in uniaxial stress at varying confining pressures. The measured axial and circumferential strains on loading to failure at atmospheric confining pressure are shown in Fig. 9. The initial decrease in axial strain is observed to be non-linear in contrast to the change in circumferential strain. This behavior in other granites has been attributed by Walsh²³ to the closing of long-narrow cracks which are oriented primarily in the direction normal to the maximum principal stress. Those cracks with major axes parallel to the maximum principal stress are not affected to the same degree, although they may tend to open slightly at low stress levels. However, these axially oriented cracks will become important at higher levels of axial stress. At stresses beyond those required to close the cracks oriented normal to the maximum principal stress, the effective moduli are thought to represent those of the intrinsic rock, unaffected by the presence of cracks.²³

Fig. 9. Axial and circumferential strain as a function of axial stress difference at atmospheric confining pressure.

Thus the axial stress-axial strain data in Fig. 9 indicate a Young's modulus of 400 kbar for the rock and its indigenous cracks. However, at axial stress differences of 600 bars, all of the cracks seem to be closed and Young's modulus of the intrinsic rock is determined to be 720 kbar.

As axial stress is increased above 1.6 kbar, circumferential strain is observed to increase in a nonlinear manner and continues to increase until failure. At the same time the axial strain exhibits almost complete linearity to failure. This behavior corresponds to an increase in the macroscopic volume of the rock (Fig. 10). This volume increase before failure (dilatancy) is well known in brittle crystalline rocks²⁴ and is thought to represent the effect of microfracturing²⁵ prior to ultimate failure. Because the predominant strain in this region is circumferential (Fig. 9), this microfracturing is probably the result of the

Fig. 10. Volume strain as a function of mean stress on uniaxial stress loading at atmospheric confining pressure. Data is taken from Fig. 9.

Fig. 11. Shear strain as a function of axial stress difference at atmospheric confining pressure. Data is from Fig. 9.

opening of cracks oriented parallel to the maximum principal stress.^{25,26} The shear strain with increasing axial stress difference, calculated from the data in Fig. 9, is given in Fig. 11. The initial shear modulus (one-half the slope in Fig. 11) is

found to be 190 kbar. However, after cracks are closed, the intrinsic shear modulus of the rock without cracks is 270 kbar. As dilatancy takes place the shear modulus then decreases and approaches zero as the rock fails.

In uniaxial stress experiments at high confining pressures, the confining pressure itself causes the cracks to close before an axial load is applied. Thus, the strains change more linearly with initial axial stress. The shear modulus, measured on initial loading at 1 kbar confining pressure (Fig. 12), is 320 kbar and decreases gradually as the rock approaches failure. At still higher pressure the initial shear modulus has changed very little and the data presented in Fig. 13 yield an initial shear modulus of 321 kbar for uniaxial stress loading at 6 kbar confining pressure. The rock in this experiment was not loaded to failure but to a high enough level so that dilatancy was observed (Fig. 14). In a separate

Fig. 12. Shear strain as a function of axial stress difference on uniaxial strain loading at 1 kbar confining pressure.

study⁷ it has been shown that dilatancy and microfracturing are associated with brittle fracture and that if macroscopic ductile flow is present, dilatant behavior is greatly diminished. This indicates that at mean pressures of 10 kbar (Fig. 14)

Fig. 13. Shear strain as a function of axial stress difference on uniaxial strain loading at 6 kbar confining pressure.

Fig. 14. Volume strain as a function of mean stress on uniaxial stress loading at 6 kbar confining pressure.

Fig. 15. Axial differential stress as a function of confining pressure for loading in uniaxial strain. The failure envelope from Fig. 4 is for comparison.

the deformation processes are still brittle, in agreement with the failure envelope data which indicated brittle fracture at mean pressures in excess of 30 kbar.

UNIAXIAL STRAIN

A number of experiments were carried out with loading under conditions of uniaxial strain. This is accomplished by varying the confining pressure to preclude radial strain as axial stress is increased. Uniaxial strain is the condition usually assumed to represent deformation by a plane shock wave. The shock wave produced by a nuclear explosion is of course not planar but may be considered to approximate these conditions at radii beyond several tens of meters.

Figure 15 compares the uniaxial strain loading path for Hoggar granite with the failure envelope. As has been found for other holocrystalline igneous rocks^{7,27} the uniaxial strain loading path appears to deviate away from the failure surface. This has implications in terms of the amount of rock which is fractured by a nuclear explosion. Recent evidence obtained by us on other rocks has shown, however, that the quasi-static uniaxial strain loading path may be influenced by microfracturing. Furthermore, on loading at high strain rates, the path may be considerably closer to the failure envelope.²⁸ Figure 16 shows the strains encountered during uniaxial strain loading. Both the axial stress and the mean stress are shown for comparison. The mean stress curve indicates that there is no evidence of dilatancy and that loading to the stress reached here is essentially along the same path as followed in the hydrostatic loading (Fig. 3). It is clear more research is needed on the effect of strain rate on loading and the processes leading to failure.

At the much higher strain rates characteristic of the conditions near a nuclear explosion, the mechanical properties of this granite can be expected to be somewhat different than those measured and discussed above. For example, we expect the shear strength-mean pressure failure envelope to be raised about 5% per decade increase in strain rate, based on data from other rocks.^{7,29} An increase in deformation rate is expected to enhance the already brittle behavior in the Hoggar granite.

The initial slope of the data in Figs. 15 and 16 yields shear modulus of about

290 kbar. This is higher than the value (190 kbar) found from initial uniaxial stress loading. Walsh and Brace³⁰ suggest that the progressive influence of increasing confining pressure inhibits slip on microcracks and that this is responsible for a higher value of the shear modulus. If we accept this value of the shear modulus as indicative of the intrinsic value for the rock, and if the initial bulk modulus is 330 kbar (Fig. 3), then Poisson's ratio is 0.16. The elastic wave velocity calculated from these moduli is 5.24 km sec^{-1} , in good agreement with measured values (Table 7).

The amount of rock not fractured on loading and which may be subsequently

Fig. 16. Axial stress (σ_1) and mean stress (P_m) as a function of volume strain for loading in uniaxial strain.

Table 7. Stress-strain relationships for Hoggar granite at atmospheric pressure derived from quasi-static measurements.

Bulk modulus	330 kb
Shear modulus	290 kb
Poisson's ratio	0.16
Compressional wave velocity	5.24 km sec ⁻¹

fractured on stress release is of considerable interest. We have investigated this possibility by considering the stress-time history. The SOC code³¹ indicates that a major portion of the release for a material with the properties of the Hoggar granite is carried out with the maximum/minimum principal stress ratio approximately equal to 2. We have therefore investigated several of these unloading paths from different points on the uniaxial strain loading curve, below the failure envelope. One of these is shown in Fig. 17. Comparison of the unloading stresses with the failure envelope in Fig. 4 shows that the material has unloaded to failure. Unloading from points at higher stress on the uniaxial strain loading curve also indicates intersection with the failure envelope. As unloading takes place (Fig. 17) the rock is observed to dilate before failure in the same way as for failure on loading (Fig. 18).

Fig. 17. Axial differential stress as a function of confining pressure on loading in uniaxial strain and unloading with $\sigma_1/\sigma_3 = 2.0$.

Fig. 18. Volume strain as a function of mean stress on uniaxial strain loading and unloading with $\sigma_1/\sigma_3 = 2.0$.

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