21. MECHANICAL PROPERTIES OF BASALT CORES FROM DEEP SEA DRILLING PROJECT HOLE 504B[1]

S. J. Bauer and J. Handin, Center for Tectonophysics, Texas A&M University[2]

ABSTRACT

From laboratory tests under simulated downhole conditions we tentatively conclude that the higher the triaxial-compressive strength, the lower the drilling rate of basalts from DSDP Hole 504B. Because strength is roughly proportional to Young's modulus of elasticity, which is related in turn to seismic-wave velocities, one may be able to estimate drilling rates from routine shipboard measurements. However, further research is needed to verify that P-wave velocity is a generally useful predictor of relative drilling rate.

INTRODUCTION

We were asked by the staff of the Deep Sea Drilling Project (DSDP) to reconnoiter the relation between triaxial-compressive strength and drilling rate for basalts from DSDP Hole 504B. Given the small supply of starting material, the availability of apparatus for unscheduled testing, and but little free time, we have roughly measured certain mechanical properties—static Young's modulus, ultimate compressive strength, and relative ductility—in both uniaxial and triaxial compression tests on oven-dried, 2 by 4 cm, copper-jacketed, cylindrical specimens at room temperature and a strain rate of $10^{-4}s^{-1}$. Where sufficient starting material (basalt) had been provided, we did duplicate experiments to assess reproducibility and found it to be good as compared with many dozens of tests on similar rocks in our laboratory. All specimens were cored parallel to the axis of the borehole. Too little material was available for an evaluation of the degree of anisotropy (if any).

Our apparatus is fully described by Friedman et al. (1980) and Bauer et al. (1981). The results on the DSDP basalts are consistent with those on a continental basalt reported in those papers.

In triaxial tests the maximum principal effective compressive stress ($\bar{\sigma}_1$) is axial, and the intermediate ($\bar{\sigma}_2$) and minimum ($\bar{\sigma}_3$) stresses are lateral and equal to the effective confining pressure (P_e), the difference between the external fluid confining pressure outside the jacket (P_c) and the internal hydrostatic pore pressure inside the porous specimen (P_p); that is $P_e = P_c - P_p = \bar{\sigma}_2 = \bar{\sigma}_3$, where all compressive stresses are counted positive. Since the pore pressure in our dry specimens is zero, the total and effective stresses are everywhere equal ($\sigma_i = \bar{\sigma}_i$).

Mechanical properties are read from the stress–strain curve at constant confining pressure, temperature and nominal axial strain rate. Differential stress ($\sigma_1 - \sigma_3$) is plotted against conventional axial strain (ϵ), change in length divided by original length.

The stress–strain curves of very brittle rocks like basalt at low temperature and effective confining pressure are typically S-shaped. At low levels of differential stress, the slope is relatively low, owing to the closure of cracks and other voids. At high stress levels the slope is also relatively low, owing to the opening of axial cracks and dilatancy precursory to microscopic failure (shear fracture). In between, from about 20% to 80% of ultimate strength, the slope is steepest and essentially linear. We define the static Young's modulus as the slope of this linear segment of the stress–strain curve, $E = (\sigma_1 - \sigma_3)/\epsilon$. The particular apparatus available for these tests is designed to measure the large permanent strains of ductile materials, not the very small strains in the elastic region. Changes in length are determined from external readings of loading-piston displacements, corrected for elastic distortions of the testing machine so that the accuracy in strain is of the order of $\pm 0.1\%$ of full scale. Nevertheless, our values for Young's modulus are consistent with those of similar rocks as reported in the standard literature (e.g., Birch, 1966, p. 160).

For very brittle rocks like basalt, the ultimate compressive strength is equivalent to the peak differential stress ($\sigma_1 - \sigma_3$) at macroscopic failure. Relative ductility is defined as the total axial strain achieved before failure. All our specimens broke along one or more shear fractures at strains of less than 2% and are regarded as relatively very brittle.

Since neither the virgin pore pressure nor the rate of invasion of seawater at the bottom of the drillhole are known, we cannot specify the effective confining pressure in the rock in contact with the drill bit. We have, therefore, elected to test the cores under extreme conditions of effective confining pressure in order to establish the probable upper and lower bounds on the mechanical properties. In uniaxial tests this pressure is zero. In triaxial tests on dry specimens it is equivalent to the head of seawater (approximately 10 MPa/km) particular to the depth of the borehole below sea level at any time during drilling.

Because heat transfer in the rock subjected to drilling is unknown, we have done all testing at room temperature (about 24°C). The seawater is doubtless colder and

[1] Anderson, R. N., Honnorez, J., Becker, K., et al., *Init. Repts. DSDP*, 83: Washington (U.S. Govt. Printing Office).
[2] Addresses: (Bauer) Sandia National Laboratory, Division 6313, Albuquerque, NM 87185; (Handin) Center for Tectonophysics, Texas A&M University, College Station, TX 77843.

the rock hotter, and frictional heating by drilling might raise the rock temperature somewhat. In any event, the mechanical properties of very brittle rocks like basalt vary but little within a range of $\pm 50°C$ (Handin, 1966, table 11-3).

The laboratory strain-rate of $10^{-4}s^{-1}$ is surely low relative to the local rates associated with drilling processes. However, the strength and ductility of very brittle rocks are relatively insensitive to rates within a range of 10 to $10^{-4}s^{-1}$ (Blanton, 1981; Logan and Handin, 1971).

EXPERIMENTAL RESULTS

Table 1 lists our data on Young's modulus (E in GPa), ultimate compressive strength ($\sigma_1 - \sigma_3$ in MPa), and strain at failure (ϵ in percent), together with the core depth interval (in meters below the seafloor), and total depth of the bottom of the hole below sea level (in kilometers). Confining pressures (P in MPa) are either zero (uniaxial test) or equivalent to the unit weight of seawater at the bottom of the hole, taken as 10 MPa/km (triaxial test). Also tabulated are approximate values of porosity (ϕ in percent), sonic velocity (c in km/s), and the drilling rate (m/hr.), taken from the shipboard logs and averaged over the core interval.

Young's Modulus

Young's modulus tends to increase with increasing confining pressure as expected because the rocks compact before they are loaded differentially. with only a single exception (Core 77), our values fall within the range of 40 to 112 GPa of those published on similar rocks (Birch, 1966, p. 160). The anomalously low moduli of Core 77 at both confining pressures are puzzling. Porosity is relatively high (5%), but not highest (6% for Core 8). Sonic velocity is relatively low (5.5 km/s), but not lower than that of Core 8 (also 5.5). Ultimate strengths (90 and 232 MPa) at both confining pressures are by far the lowest recorded, and drilling rate (4.58 m/hr.) is much the highest logged. Lacking petrofabric data, we do not speculate. The behavior of Core 77 does, nevertheless, follow the general tendency of drilling rate to increase with decreasing modulus (Fig. 1). Only those specimens from Core 130 tested under confining pressure are stiffer than we should have predicted from the slope of the modulus–drilling rate curves. These specimens are also the strongest of any, yet the associated sonic velocity is not the highest, nor is the drilling rate the lowest recorded. Again we do not speculate why.

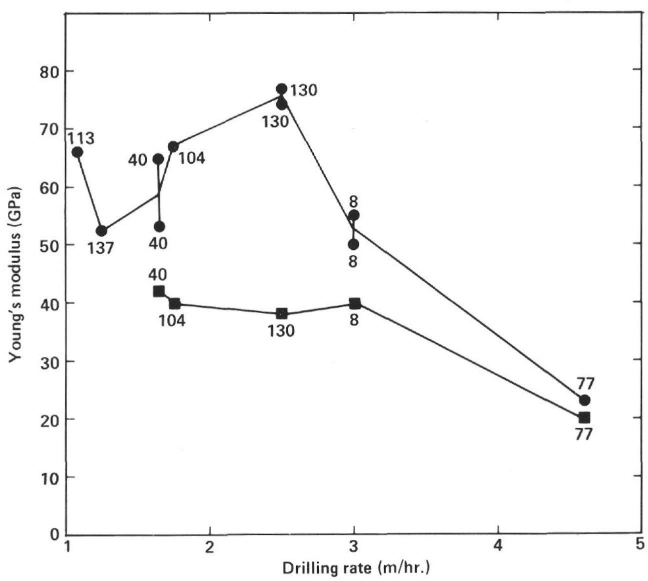

Figure 1. Drilling rate as a function of Young's modulus of elasticity (E) under effective confining pressures of zero (squares) or unit weight of seawater (circles). (DSDP core numbers are shown.)

Table 1. Experimental data.

Specimen number[a]	Core depth interval (m)	Core-Section (interval in cm)	Average depth (km)	P (MPa)	E (GPa)	$\sigma_1 - \sigma_3$ (MPa)	ϵ (%)	ϕ (%)	c (km/s)	Drilling rate (m/hr.)
8-1		8-1, 51–65		38	55	339	0.55			
8-2	316–326	8-4, 50–63	3.785	38	51	337	0.51	6	5.5	2.97
8-3		8-4, 50–63		0	40	168	0.20			
40-1		40-2, 55–70		0	42	217	0.69			
40-2	579–584	40-2, 55–70	4.045	40	53	377	1.31	3	6.0	1.64
40-3		40-2, 55–70		40	65	351	0.86			
77-1	888–898	77-1, 1–12	4.357	0	20	90	0.67	5	5.5	4.58
77-2		77-1, 1–12		44	23	232	1.43			
104-1	1116–1126	104-1, 77–84	4.585	0	40	254	0.79	2	6.5	1.75
104-2		104-1, 77–84		46	67	427	0.82			
113-1	1171–1176	113-1, 22–36	4.637	46	66	436	0.84	2	6.5	1.08
130-1		130-1, 2–12		47	74	459	0.79			
130-2	1279–1288	130-1, 138–148	4.748	47	77	510	0.87	1	6.4	2.50
130-3		130-1, 138–148		0	38	213	0.67			
137-1	1327–1332	137-1, 18–25	4.793	48	52	427	1.45	1	6.6	1.26

[a] Specimens are identified by two numbers. The first is the DSDP designation of the cored interval; the second is the number of our experiment on starting material from the same core.

Ultimate Compressive Strength

Our values are consistent with those published for a somewhat similar rock, the Cuerbio basalt (Friedman et al., 1979, table 3). Strength increases consistently with increasing confining pressure as predicted by the Coulomb–Mohr criterion (Handin, 1969).

At both confining pressures, drilling rates tend to increase with decreasing strength (Fig. 2), as they did with decreasing modulus (Fig. 1). Again those specimens from Core 130 that were broken under confining pressure appear to be anomalous, being too strong for the relatively high drilling rate. Specimens from Core 77 are much the weakest of any, and their moduli and associated drilling rate are consistently low. And again, without detailed knowledge of the composition and texture of these basalts, we do not try to explain these departures from the norm. Certainly, though, the strongest rocks tend to be associated with the lowest porosities and drilling rates and the highest moduli and sonic velocities.

Strain at Failure

Strain at failure rarely exceeds 1%, and all these basalts are regarded as relatively very brittle. This parameter increases, that is, the rocks become slightly more ductile, with increasing confining pressure, as expected, because fracture is inhibited by high normal stress. Similar behavior is reported for Cuerbio basalt (Bauer et al., 1981, table 1). The relation between strain at failure and drilling rate is inconclusive (Fig. 3). Specimen 137-1, (see Table 1), for example, has the lowest porosity, highest sonic velocity, and nearly lowest drilling rate, yet is the least brittle. On the other hand, the confined specimen from Core 77 is also among the least brittle, yet associated with by far the fastest drilling rate. Brittleness should probably favor drilling by enhancing chip formation and reducing the energy wasted on plastic deformation. However, until petrofabric data become available, we dare not say more.

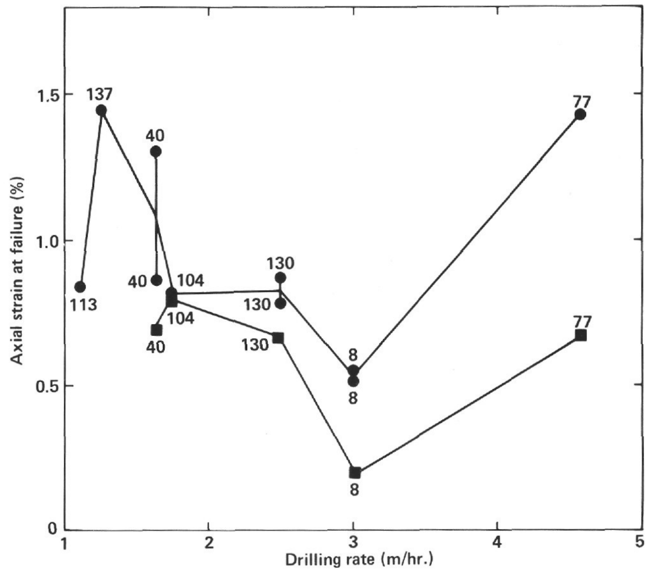

Figure 3. Drilling rate as a function of strain at failure, ϵ (relative brittleness) under effective confining pressures of zero (squares) or unit weight of seawater (circles). (DSDP core numbers are shown.)

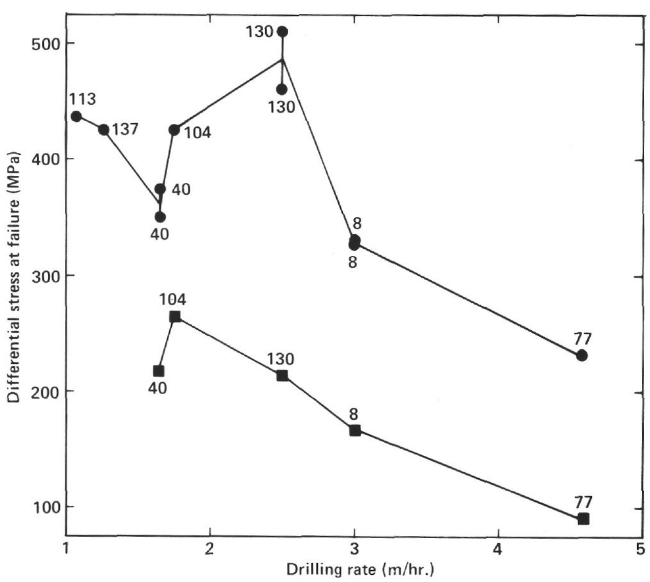

Figure 2. Drilling rate as a function of differential stress at failure (ultimate compressive strength) under effective confining pressures of zero (squares) or unit weight of seawater (circles). (DSDP core numbers are shown.)

DISCUSSION

With some notable exceptions, the drilling rates appear to correlate rather well with ultimate compressive strengths (Fig. 2). However, triaxial-compressive testing is relatively expensive, time-consuming, and hardly routine. The correlation with static Young's modulus is also pretty good (Fig. 1), which is not surprising since strength and modulus correlate well in turn (Fig. 4). Unfortunately, static elastic constants are not readily or routinely measured either. Correlation with dynamically determined moduli would be preferable because a large store of data is already available and sonic velocities are measured routinely. Let us calculate dynamic Young's modulus, using the sonic (compressional-wave) velocities from Table 1.

Since shipboard laboratory measurements are not done on long, thin bars in which stress-wave propagation is essentially one-dimensional, we cannot relate sound speed (c) to bulk density (ρ_b) and a single elastic modulus (E) as in the equation $c^2 = E/\rho_b$, where c is the so-called bar velocity. Instead we must apply the general equation for an isotropic, homogeneous medium (Obert and Duvall, 1976, p. 334) as follows.

$$c_p^2 = \frac{E(1-\nu)}{\rho_b\,(1+\nu)(1-2\nu)},$$

$$c_s^2 = \frac{G}{\rho_b}, \tag{1}$$

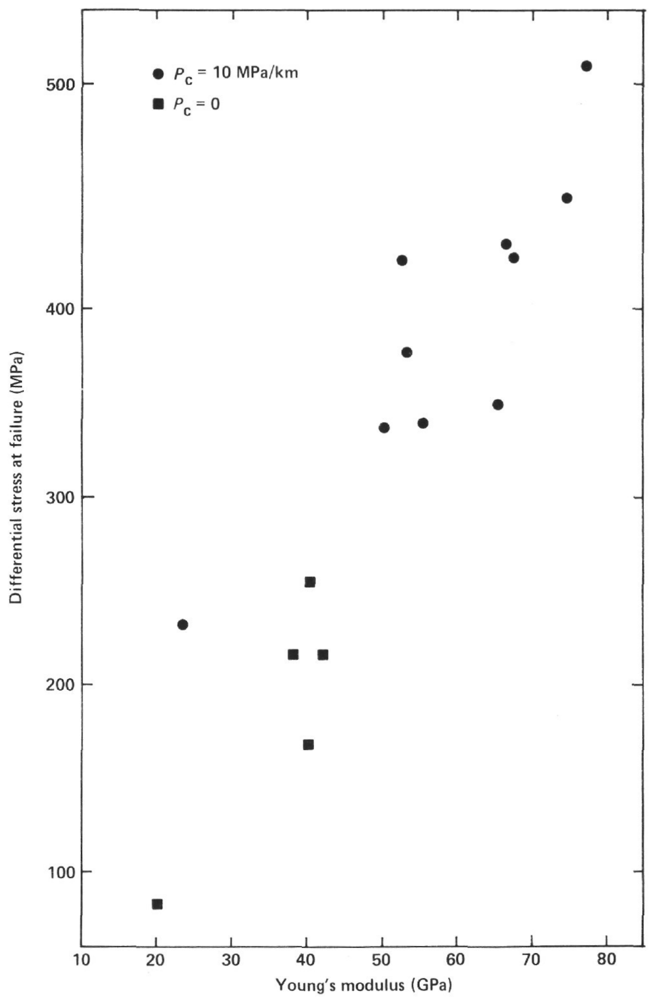

Figure 4. Differential stress at failure (ultimate compressive strength) as a function of Young's modulus of elasticity (E) under two different confining pressures.

where c_p = longitudinal (dilational or P-wave) velocity, c_s = transverse (shear or S-wave) velocity, G = modulus of rigidity, and ν = Poisson's ratio.

We calculate bulk density (ρ_b) from the grain density (ρ_g), which is very close to 3.0×10^3 kg/m^3 for all the basalt cores, and the fractional porosity (ϕ) from Table 1.

$$\rho_b = \rho_g - \phi(\rho_g - \rho_f), \quad (2)$$

where ρ_f = density of the fluid in the voids (sensibly zero if the rock is dry), and about 1×10^3 kg/m^3 in the water-saturated specimens tested in the shipboard laboratory.

Static values of Poisson's ratio for basalt are close to 0.25 (Birch, 1966, table 7-15), but are probably inappropriate for our calculations, and shear-wave data are lacking for our particular specimens. However, R. L. Carlson of Texas A&M's Geophysics Department has provided his unpublished compilation of nearly 200 determinations of γ from measurements of longitudinal and shear-wave velocities in basalts sampled by DSDP (pers. comm., June 1982). A good average value for water-saturated specimens under 40 MPa effective confining pressure is 0.3. Dynamic Young's modulus ranges from 20 to 100 GPa. Substituting ν = 0.3 and the values of ρ_b from equation (2) into equation (1) yields the following results (Table 2).

These dynamic Young's moduli fall within the range of Carlson's data. Let us compare them with the static moduli, first as also measured on unconfined specimens in uniaxial-compression tests (Table 2). The dynamic moduli exceed their static counterparts by factors of 1.6 to 3.3, or to 2.4, excluding Core 77. Differences in moduli result at least in part from the vastly different stress levels in the two types of tests, and the fact that P-wave velocities are higher in water-saturated, porous media do not entirely reflect the pertinent properties of the solid phase. Comparison of dynamic moduli with the static measurements on confined specimens in triaxial-compression tests reveals much closer agreement, the ratios ranging from 1.2 to 2.8, or 1.8 when Core 77 is omitted. The probable reason for this narrowing of the difference between the two sets of data is that by closing voids, confining pressure renders deformations more nearly perfectly elastic, like those associated with stress-waves of exceedingly small magnitude. Indeed, the dynamic moduli derived from P-wave velocities in thoroughly dry rock would probably coincide quite closely with the static moduli. In any event, relatively high sonic velocities and associated dynamic moduli do tend to correspond with slow drilling rates, probably owing to the fact that high moduli point to high strength, the parameter most affecting ease of drilling.

CONCLUSIONS

With a few notable exceptions that we cannot explain without more information about the starting material, we conclude that:

1. Drilling rates correlate rather well with both uniaxial and triaxial compressive strengths: rates decrease as strengths increase.
2. Compressive strengths increase systematically with both static and dynamic Young's moduli of elasticity.
3. Hence sonic (P-wave) velocity may be useful as a predictor of drilling rates, although more research is certainly needed to improve and then verify any such predictions.

REFERENCES

Bauer, S. J., Friedman, M., and Handin, J., 1981. Effects of water saturation on strength and ductility of three igneous rocks at effective pressures to 50 MPa and temperatures to partial melting. *Proc. 22nd U.S. Symp. Rock Mechanics*, pp. 73–78.

Birch, F., 1966. Compressibility; elastic constants. *In* Clark, S. P., Jr. (Ed.), *Handbook of Physical Constants—Revised Edition*. Geol. Soc. Am. Mem., 97:97–173.

Blanton, T. L., 1981. Effect of strain rates from 10^{-2} to 10 s^{-1} in triaxial-compression tests on three rocks: *Int. J. Rock Mech. Min. Sci.*, 18:47–62.

Friedman, M., Handin, J., Higgs, N. G., and Lantz, J. R., 1979. Strength and ductility of four dry igneous rocks at low pressures and temperatures to partial melting. *Proc. 20th U.S. Symp. Rock Mechanics*, pp. 35–50.

Handin, J., 1966. Strength and ductility. *In* Clark, S. P., Jr. (Ed.), *Handbook of Physical Constants-Revised Edition*. Geol. Soc. Am. Mem., 97:223–289.

________, 1969. On the Coulomb-Mohr failure criterion, *J. Geophys. Res.*, 74: 5343–5348.

Logan, J. M., and Handin, J., 1971. Triaxial-compression tests at intermediate strain rates. *Proc. 12th U.S. Symp. Rock Mechanics*, pp. 167–194.

Obert, L., and Duvall, W. I., 1967. *Rock Mechanics and the Design of Structures in Rock:* New York (J. Wiley & Sons).

Date of Initial Receipt: 18 May 1983
Date of Acceptance: 21 September 1983

Table 2. Comparisons of dynamic and static Young's moduli.

Core	Bulk density ($10^3 kg/m^3$)	Sonic velocity (m/s)	Unconfined modulus (GPa)[a]			Confined modulus (GPa)	
			Dynamic	Static	Dynamic/Static	Average static	Dynamic/Static
8	2.88	5500	65	40	1.6	53	1.2
40	2.94	6000	78	42	1.9	60	1.3
77	2.90	5500	65	20	3.3	23	2.8
104	2.96	6500	93	40	2.3	67	1.4
113	2.96	6500	93	—	—	66	1.4
130	2.98	6400	91	30	2.4	75	1.2
137	2.97	6600	96	—	—	52	1.8

[a] Data not available for specimens 113-1 and 137-1.