

SEP 8 1966

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by

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Reprinted from

A STUDY OF SERPENTINITE
National Academy of Sciences--National Research Council
Publication 1188

3391 8 112

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Laboratory Measurements

Triaxial compression tests have been made on cylindrical specimens 0.5 in. in diameter and 1.0 in. long, cut from each of the three Mayaguez serpentinite cores provided (from depths of 49 m, 180 m, and 270 m). The specimens were jacketed in thin, annealed, copper tubes and shortened at a rate of about one per cent per minute. They were tested in the received condition. The theory and technique of triaxial compression testing, the apparatus, and the nomenclature of rock deformation are all fully discussed in the references cited.

Tests were conducted at confining pressures of 0.75, 1.25, and 1.75 kilobars and at temperatures of 25°C, 100°C, and 200°C. The highest pressure and temperature are about what one would expect below 10,000 ft. of sea water and 20,000 ft. of low porosity silicate rock. In some instances two tests under identical conditions are available to evaluate reproducibility. The mean deviation of the derived stress-strain curves is only a few per cent, and this suggests that the rock is statistically homogeneous.

Table 1 lists the experiment number, the core sample designation (in meters), the load orientation (T and 1 cylinders are cut parallel and normal to the cores, respectively), the confining pressure and temperature, the ultimate strength (maximum ordinate of the stress-strain curve), the total recorded strain (per cent longitudinal shortening), and the angle between the shear fracture (or fault) and the longitudinal axis of the specimen (direction of maximum principal compressive stress). Stress and strain measurements have a sensitivity of 0.1 per cent and an accuracy of 0.5 per cent. The temperature is known and held within $\pm 2^\circ\text{C}$. The tabulated fracture angle represents the average trend and is meaningful only to $\pm 2^\circ$.

Results

Without detailed information about the mineralogy and fabric of the rocks both before and after deformation, any interpretation of these results must be regarded as tentative and will certainly be incomplete. However, the following facts are obvious from inspection of Table 1 and the representative stress-strain curves (Fig. 1):

1. At room temperature the rocks are brittle at all pressures. After a small, essentially elastic strain of the order of 1 per cent, sudden failure occurs

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TABLE 1

Summary of Triaxial Compression Tests on Mayaguez Serpentine

Exp. No.	Load ¹	Confining Pressure (kilobars)	Temp. (°C)	Total Strain (per cent)	Ultimate Strength (kilobars)	Fracture Angle ² (deg.)
49-Meter Core						
1621	T	0.75	25	1.5	3.12	22
1622	T	0.75	25	1.3	3.15	22
1640	T	1.25	25	1.7	3.38	26
1571	1	1.25	25	1.7	3.58	26
1649	1	1.25	25	1.6	3.40	30
1550	T	1.75	25	1.0	3.64	30
1657	T	1.75	25	1.3	3.45	27
1626	T	1.75	100	1.9	2.63	31
1654	T	1.75	200	2.0	2.46 ³	23
1596	T	1.75	200	7.3	1.55	24
180-Meter Core						
1539	T	0.75	25	2.4	4.50	21
1542	T	0.75	25	1.2	4.35	25
1546	T	1.25	25	1.5	6.15	27
1547	T	1.25	25	1.1	5.98	27
1570	1	1.25	25	1.2	5.30	33
1648	1	1.25	25	1.1	5.11	27
1553	T	1.75	25	1.1	6.72	35
1655	T	1.75	100	0.8	4.65	26
1653	T	1.75	200	1.0	4.60 ³	35
1595	T	1.75	200	6.1	2.76	22
270-Meter Core						
1536	T	0.75	25	1.3	4.45	24
1537	T	0.75	25	1.8	4.14	24-30
1543	T	1.25	25	1.7	5.10	22
1624	T	1.25	25	1.3	4.92	33
1569	1	1.25	25	1.8	3.30	32
1646	1	1.25	25	1.2	3.38	28
1656	T	1.75	25	0.8	5.90	30
1642	T	1.75	100	1.0	3.69	35
1652	T	1.75	200	6.6	3.54 ³	30
1594	T	1.75	200	5.2	2.33	32

¹T and 1 cylinders are compressed parallel and normal to the core axis, respectively.

²The shear fracture or fault angle is measured from the longitudinal axis of the specimen (direction of maximum principal compressive stress).

³Specimen open (hollow piston); volatiles can escape.

by shear fracturing with loss of cohesion and release of stored strain energy. The shear fracture angle tends to increase with confining pressure and lies between 20° and 35° for all three samples.

2. At room temperature the ultimate compressive strength increases nearly linearly with confining pressure (Fig. 2). The effect is least in the 49-meter sample, which is also the weakest of the three.

3. At room temperature and the same confining pressure (1.25 kilobars), the strengths of T cylinders of 180- and 270-meter samples exceed those of 1 cylinders. The reverse is true of the 49-meter sample. None of the differences is large, however, and the rocks are nearly statistically isotropic.

4. At constant pressure (1.75 kilobars), heating effects a decrease in strength and an increase in apparent ductility. However, failure, signaled by the peak in the stress-strain curve, is due to localized faulting without total loss of cohesion. There is no macroscopic evidence of uniform flow.

5. Although specimens are always jacketed to deny access of the confining kerosene, tests can be done with either a solid or a hollow piston so that the specimen is either completely isolated or open to the atmosphere. In the latter arrangement, the pressure of any interstitial fluid can remain sensibly zero, provided that permeability is sufficient to allow its escape from the system. The effective confining pressure—the difference between the total and pore pressures—then remains equal to the external hydrostatic confining pressure on the jacket. However, volatiles cannot escape from an isolated specimen. Heating isolated specimens from 25°C to 200°C reduces strength nearly linearly by as much as 60 per cent (Fig. 2). The only other high-temperature tests on a serpentinite were made by D. T. Griggs (personal communication, March 1963), who also observed a drastic reduction in strength, some 50 per cent, by heating from 25°C to 300°C at 5 kilobars confining pressure. Note, however, that the strengths of open specimens at 200°C are only about 35 per cent below room temperature values (Fig. 2).

Conclusions

Temperatures of the order of 100°C to 200°C do not much influence the strength and ductility of most silicate rocks. What special mechanism might be involved that would be consistent with the experimental results? The effect may be associated with pervasion of the serpentinite by a fluid phase released during a hydrous-anhydrous transformation. The interstitial pressure in an isolated specimen could then rise at least to the value of the vapor pressure at test temperature. The effective confining pressure, and hence the strength of the aggregate, would be much reduced even if the properties of the solid phases were little affected. We have measured the gas evolved from the 49-meter sample by heating to 200°C at atmospheric pressure—1.4 and 0.01 weight per cent of water and CO_2 , respectively—probably enough to fill the small amount of void space in this rock. H. C. Heard (personal communication, January 1963) has recently observed a ten-fold strength reduction in gypsum as it passes through the transition to anhydrite plus water. The principle seems well established.

Our preliminary measurements under test conditions reveal that the vapor pressure probably does not exceed 1 bar and so cannot lower the effective confining

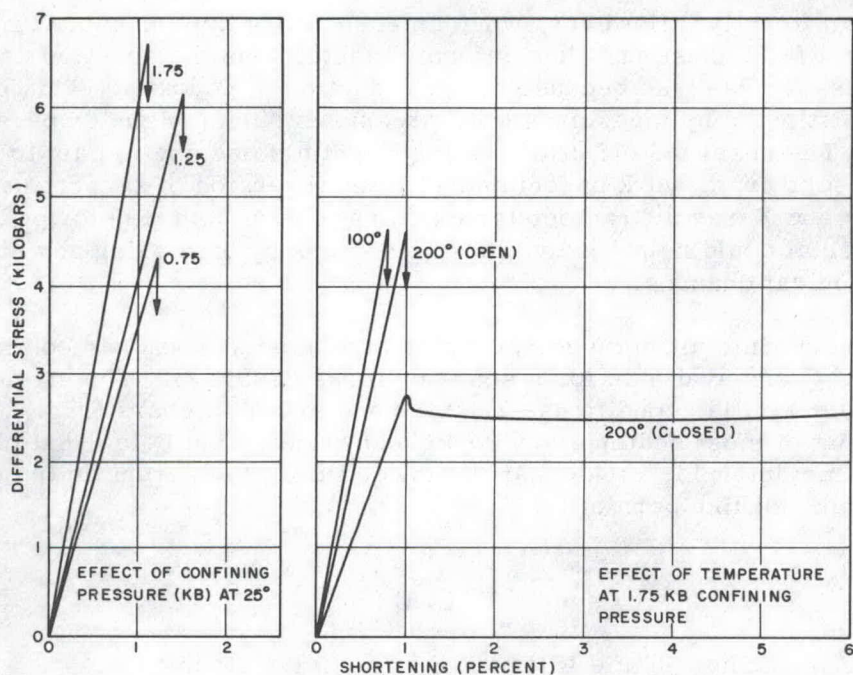


Figure 1. Stress-strain curves for T cylinders of the 180-meter sample compressed at different confining pressures and temperatures. These are representative of all samples. The curves are essentially linear (elastic) to the point of rupture. The slopes (Young's modulus) increase with pressure and decrease upon heating.

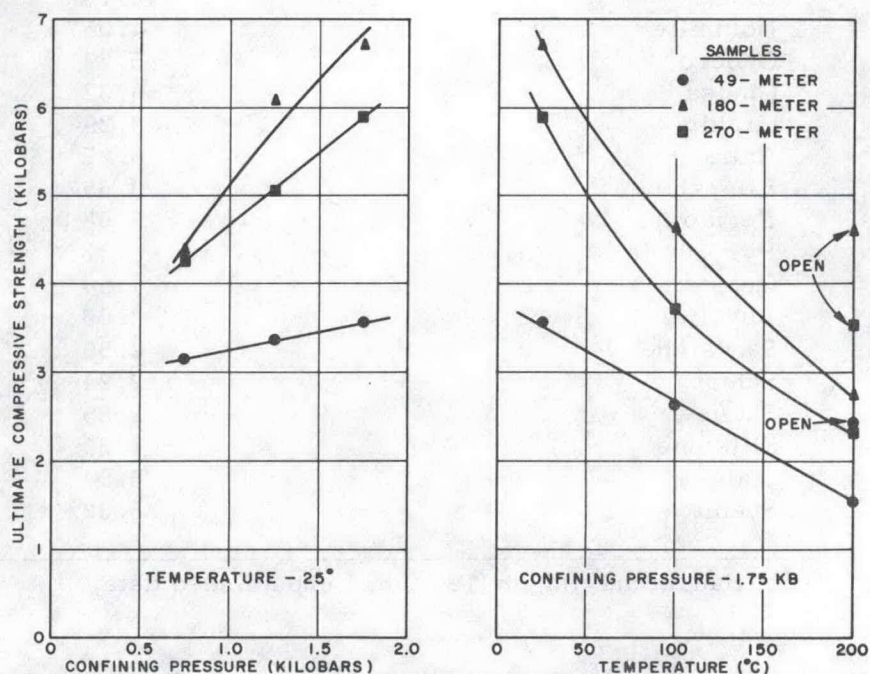


Figure 2. Ultimate compressive strengths of T cylinders of the three samples as functions of confining pressure and temperature.

pressure significantly. However, when an essentially impermeable aggregate is saturated by a fluid phase and then deformed faster than the reaction can reverse, the pore pressure can rise because of the reduction of porosity. This possibility could be investigated by measuring pore pressures during high-temperature experiments. The observed effect of heating might also be due in part to modifications of the solid framework associated with the inversion of serpentine minerals. Microscopic and X-ray diffractometer examinations of both undeformed and deformed material could help resolve these questions by disclosing any structural and mineralogical changes.

The short-time ultimate compressive strengths at 1 kilobar confining pressure and 150°C are available for a score of rocks (Table 2). The strength of serpentinite under similar conditions—2.1 kilobars to 3.6 kilobars (Fig. 2)—is comparable to that of most sedimentary rocks and granite, but below that of most other igneous and metamorphic rocks. At the lower limit, the serpentinite behaves much like shale, and not like peridotite.

TABLE 2
Short-Time Ultimate Compressive Strengths
of Some Dry Rocks (Kilobars)
at 1 Kilobar Confining Pressure and 150°C*

Amphibolite	6.54
Anhydrite	3.35
Diabase	5.10
Diorite	6.13
Dolomite	4.05
Gabbro	5.29
Gneiss	6.32
Granite	3.29
Halite	0.27
Limestone	3.65
Peridotite	5.08
Pyroxenite	5.31
Quartzite	7.50
Rhyolite	8.00
Sandstone	2.50
Schist	2.24
Shale	2.05
Siltstone	1.35
Slate	5.04
Syenite	5.32

* From Handin and Hager (1958) and unpublished data.

At low temperatures the serpentinite could most probably support an uncased borehole to any depth now contemplated. Let us suppose that the lithostatic pressure below 20,000 ft. of superincumbent rock and 10,000 ft. of sea water is roughly

1.75 kilobars, and that the hydrostatic pressure at the base of the 30,000-foot column of sea water in the hole is about 1 kilobar. Since a stress concentration of at least 2 must exist even at smooth walls, the minimum stress difference will be of the order of 1.5 kilobars. This is less than half the ultimate strength at 25°C. However, the strengths of isolated specimens at 200°C are approaching this anticipated minimum stress difference so that collapse of a deep hole under realistic conditions seems to be a serious possibility. In our opinion, a better understanding of the effects of heating and good estimates of the probable working temperatures are essential.

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