Laboratory II: Mechanical Properties of Rocks

(Due: October 21, 2005)

Using the Paterson gas-medium apparatus, you will measure axial load, axial displacement, and determine the Young's modulus, yield strength of an intact rock core specimen.

1. Experiment Description

Initial Sample

A sample of Carrara Marble has been prepared for a triaxial compression test. The sample is a right-cylinder, 10 mm in diameter and 20 mm long. Porosity is estimated to be ~ 0.1%.

Measurement

Using the load cell in the Paterson gas-medium apparatus, apply a constant displacement rate on the sample and see how the load changes. We will record axial load (kN), LVDT (Linear Variable Displacement Transducer) position (mm), confining pressure (MPa) and temperature (ºC) at a certain time intervals. The axial load increases with increasing strain rates and we will apply three different strain rates to the sample. The summary data file will be posted on the MIT Server later and will include the sample dimensions and the deformation conditions.

Calculation

Axial stress

During the deformation experiment, we measure axial load rather than axial stress (also called compressional stress, differential stress or true stress). It is therefore necessary to convert internal loads to stress. Axial stress is equal to the axial load F divided by the cross-section area of the sample (A),

$$\sigma = \frac{F}{A} \tag{1}$$

The data file measured load in kN. Stress should be converted to MPa. The variation of the cross-section during deformation must be taken into account (especially for large strains). We assume the volume of sample is constant throughout the deformation, AL = constant (where L is the length of the sample).

Axial strain

Displacement for triaxial displacement test will be measured using a LVDT located outside the pressure vessel. The LVDT measure not only the displacement of the sample due to an applied load but also the displacement of the deformation column.

$$\Delta L_{measured} = \Delta L_{sample} + \Delta L_{column} \tag{2}$$

In order to calculate the axial strain of the sample, you must subtract out the deformation of the column. The contribution of the column to the measured displacement can be calculated by knowing the applied compressive load F and the stiffness of the deformation column C_{column}.

$$\Delta L_{column} = F / C_{column} \tag{3}$$

The stiffness of the deformation column has already been calculated for you and is 61.5 kN mm^{-1}. As the length of the sample varies with time from an initial value L_0 to a final value $L(t)$, we obtain the instantaneous value of the total strain (natural strain or compressional strain) at time t by integration.

$$\varepsilon_{sample} = \int_{L_0}^{L(t)} \frac{dL}{L} = \ln\left(\frac{L(t)}{L_0}\right) \approx \frac{\Delta L}{L_0} \tag{4}$$

Where the sign + and − respectively correspond to extension and compression. To be simple, we use the positive value in the compressional test. The approximation is correct at small strains only.

Power law equation

The strain-rate $\dot{\varepsilon}$ is determined as the slope of the creep curve ε(t). The power-law equation describes quite well the dislocation creep behavior of a considerable number of materials in the stress range that corresponds to laboratory experimental conditions.

$$\dot{\varepsilon} = \dot{\varepsilon}_0 \, \sigma^n \, \exp\left(-\frac{Q}{RT}\right) \tag{5}$$

Where $\dot{\varepsilon}_0$ is a pre-exponential factor perhaps containing chemical fugacity, σ is the differential stress, $n = \partial \ln \dot{\varepsilon} / \partial \ln \sigma$ is the stress exponent, $Q = -R \partial \ln \dot{\varepsilon} / \partial (1/T)$ is the activation energy for creep, and RT is the standard Boltzmann term.

Note that the $\log \dot{\varepsilon}$ - logσ plot is seldom linear over a wide range of applied stresses, and the power-law equation does not hold at all stresses.

2. Exercises

There are two text files named carrara marble_rheology.txt and solnhofen limestone.txt, using the solnhofen limestone.txt, do the exercise 1-3; then use the carrara marble_rheology.txt to do the exercise 4. (one ref. on Carrara Marble: S.J. Covey-Crump, Evolution of mechanical state in Carrara marble during deformation at 400 to 700° C, JGR, 103(B12),p29,781-29,794 (1998))

1. An experiment begins when the compressive stress begins to increase. Note this value of stress, and correct the stress and displacements measured at this point in the spreadsheet to zero. Calculate the compressional stress σ_{true} using equation 1. As discussed above, the

measured displacement is the sum of the displacement of the sample and the displacement of the deformed column (equation 2). Compute the displacement of the sample using equation (2) and (3) and plot the compressional stress versus the displacement of the sample on the same plot as compressional stress versus measured displacement. Compare the two plots.

2. Convert the calculated displacement of the sample to strain using equation (2) through (4), and plot compressional stress versus axial strain for the sample. The plot of compressional stress versus axial strain yields the best description of the deformation behavior of the specimen. Determine point where the deformation becomes nonlinear, this is the yield strength of the rock, and also the peak stress o

3. Calculate the Young's modulus E from the slope of the straight line portion of the compressional stress vs. axial strain curve (equation 6). What is the yield strength and peak-stress of this sample.

$$E = \frac{\Delta\sigma}{\Delta\varepsilon_{axial}} \qquad\qquad (6)$$

4. Calculate the compressional stresses at the three different strain rates and fit the $\log\dot{\varepsilon}$ - $\log\sigma$ plot with a straight line. Calculate the stress exponent n in equation (5).

3. Discussion

1. Compare the values of Young's modulus, yield strength of Carrara Marble with other calcite rocks (Table 1). Explain.

2. For the plot of axial stress versus axial strain of different materials, one would expect different mechanical behavior (figure 1). Which kind of behavior do you observe in this experiment? And which factors will affect its behavior (e.g. strain rate, temperature and grain size) and how?

3. How do you expect the relationship between the $\log\dot{\varepsilon}$ and $\log\sigma$ will change at different stresses?

4. Effective pressure, confining pressure minus pore pressure, can play a large role in the strength of rocks. What effect do you think increasing the confining pressure would have on Young's modulus, yield stress?

5. For the plot of axial stress vs. axial strain for solnhofen limestone, do you observe a nonlinear stress-strain relationship at low stress level? Explain.

**** Note: to be simple, we use the same initial sample length of 20 mm at all temperatures.

Table I. Mechanical properties of calcite rocks at room temperature and 30 MPa effective pressure

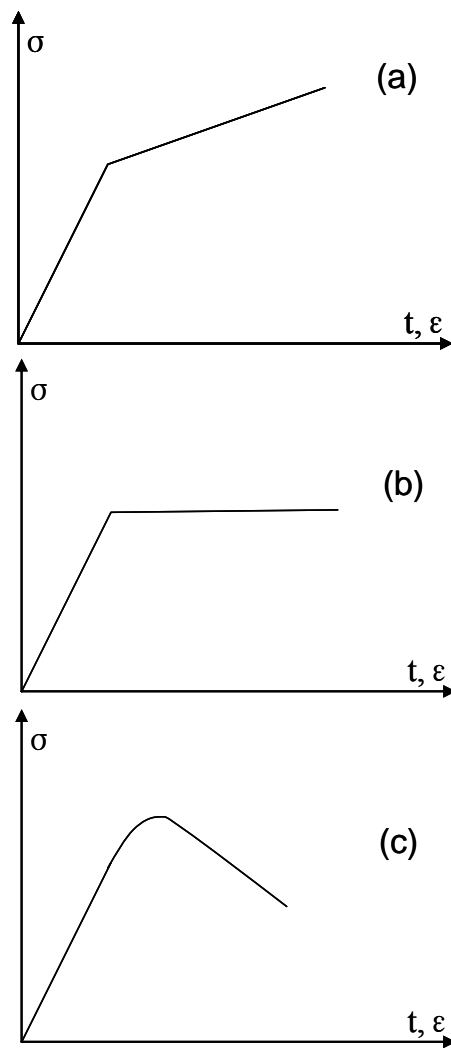| Rock	E (GPa) Young's modulus	σ_Y(MPa) Yield strength	Grain size (mm)
Solnhofen limestone	29.8	245	0.006
Saillion marble	~90	180	0.030
Wombeyan marble	~70	76	0.846
Carrara Marble	~76	60	0.230

Figure1. stress-strain curves ($\dot{\varepsilon} = cons\tan t$) for material with various properties: (a) work-hardening, (b) no work-hardening, steady-state creep, (c) work-softening, accelerating creep rate.