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Technical Note

Direct Measurement of Volume Strain During Experimental Deformation of Porous Materials

M. P. OLSEN†
M. T. BRANDON†
R. B. GORDON†

INTRODUCTION

Volume strain data are often a necessary component for a program for experimental deformation of rocks and soils [1-4]. For example, Marone *et al.* [2] used a servo-controlled pressure intensifier coupled with an LVDT to record volume changes necessary to maintain a constant pore pressure within simulated fault gouge in a shearing apparatus. Their technique is both precise and reliable, but the equipment is relatively expensive. Volume strain can also be measured using radial strain gauges [5] mounted directly on the specimen, but this approach only measures local changes in the radial section of the deforming sample. The results become increasingly inaccurate if the specimen deforms by inhomogeneous barreling or localized fracture. For these reasons, we introduce here a new system for the measurement of changes in pore volume in porous materials.

DESCRIPTION OF THE NEW SYSTEM

The following features and requirements are common to any system that measures volume strain using displaced pore fluid: (1) the specimen must be fully flushed by the pore fluid prior to the experiment; (2) the pore fluid must communicate with all pore space in the specimen; (3) the specimen must be fully saturated; (4) the rate of deformation must be sufficiently slow to avoid any significant fluid pressure gradients; (5) the pore fluid in the specimen must have a connection to a reservoir of sufficient size to accommodate the changes in pore fluid volume.

Our system uses a vertical, steel stand-tube connected to the lower, drained end of a jacketed specimen (Fig. 1). One port of a differential-pressure transducer is connected to the base of the stand tube and the other to a constant reference pressure, either atmospheric pressure or a regulated pressure source. For our case, back pressure is supplied by a regulated cylinder of dry air to ensure that any gas in the system is dissolved in the pore fluid. A dilatometer (described below) is used to adjust

the fluid height in the stand tube and to replace volume loss due to compression of trapped air during application of the back pressure. The dilatometer is also used for calibration.

We used a Validyne DP-15 differential pressure transducer, which has two ports (" + " and " — ", where " — " refers to reference pressure port) separated by a flexible diaphragm. Flexure of the diaphragm due to a differential pressure between the ports results in a voltage output from the transducer. The data reported here were obtained using a transducer with a net pressure range of −86 to +86 kPa (±12.5 psi). The transducer voltage is fed into a Validyne CD-19A Carrier Demodulator and recorded on a PC-style computer using Labtech Notebook data-acquisition software. Standard high-pressure tubing, fittings and valves are used for the stand tube and associated plumbing. The inner diameter and length of the stand tube are selected to offer appropriate sensitivity and sufficient capacity for the total possible volume of displaced fluid. We used stainless steel tubing with a 2 mm i.d.

CALIBRATION OF THE SYSTEM

By isolating the specimen from the system, the dilatometer can be used to introduce a known volume of fluid into the stand tube. The dilatometer is a standard pressure generator (High Pressure Equipment Model 37-6-30) which has an internal piston diameter of
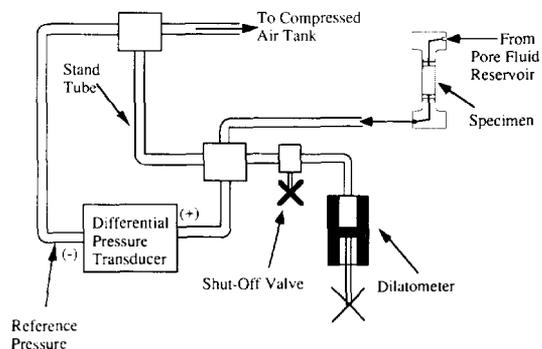

Fig. 1. Schematic diagram of stand-tube system for measuring pore-volume strain.

†Department of Geology and Geophysics, Yale University, P.O. Box 208109, New Haven, CT 06520-8109, U.S.A.
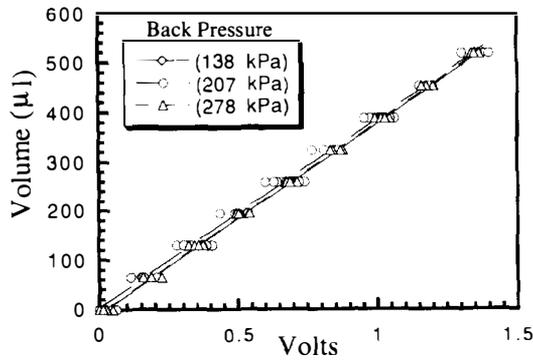
Fig. 2. Calibration data for stand tube. Data were measured using back pressures of 138, 207 and 276 kPa (20, 30 and 40 psi), in order to examine the pressure-sensitivity of the system. The system shows no significant sensitivity to back pressure is indicated.

9.52 mm that displaces 129 μl per full revolution of the handle. In our calibrations, fluid is added to and then removed from the stand tube by turning the dilatometer handle forward or backward by various increments, which allows us to calibrate the system and to test for hysteresis. These cycles were repeated for different back pressures to determine if the volume strain measurements are sensitive to the ambient back pressure.

A calibration curve is obtained by plotting the applied volume change as a function of transducer voltage (Fig. 2). The slope of the calibration line is 387 μl/V and is reproducible to within $\pm 1.5\%$ for a range of back pressures between 140 and 280 kPa (20–40 psi). Results indicate that this system is capable of resolving volume changes of ± 1 μl, equivalent to $\pm 0.004\%$ volume change for a typical specimen (51 mm long, 25 mm dia.). The calculated analytical precision at one standard error is ± 8 μl at midrange, or about $\pm 0.03\%$ volume strain.

Upon addition of fluid into the stand tube, there is a transient in the measured pore fluid volume (Fig. 3). This phenomenon shows exponential decay from an initial perturbation and is thus considered to reflect the dynamic response of the system. The following function of volume V (μl) and time t (sec).

$$V = A + B\, e^{-Ct}, \tag{1}$$

was fit to the data and yielded these values for the coefficients: $A = 2.69$ mV, $B = 41.21$ mV and $C =$
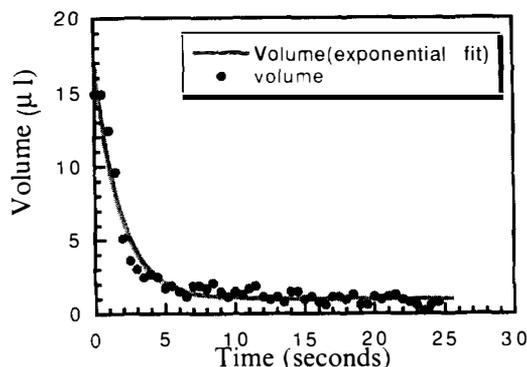

Fig. 3. Illustration of transient feature accompanying instantaneous addition of fluid to the stand tube. A voltage of 0.04 is equivalent to a volume of 17 μl, or 0.06% volume strain for a typical specimen. Ambient electronic noise is on the order of several millivolts.
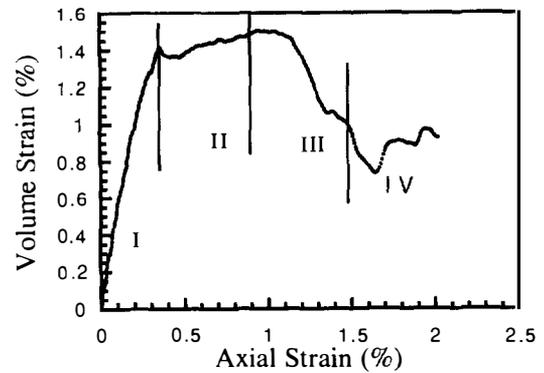

Fig. 4. Volume strain data for standard triaxial test (confining pressure = 45 MPa) on Massillon Sandstone. 0.1% axial strain corresponds to about 130 sec. The region defined by I corresponds to isotropic loading ($\sigma_1 = \sigma_3$). The small drop at the end of the isotropic loading phase is attributed to a slight drop in confining pressure at the load path transition. Region III is post-yield deformation. Peak strength is denoted by the boundary between regions III and IV.

0.54 sec^{-1}. The transient decays to 5% of its initial amplitude within approx. 5.5 sec. For our experiments, which are displacement controlled and which proceed at very slow rates, the second derivative of the volume strain with time is usually small enough that we can safely ignore this lag in system response. For experiments where pore-fluid flow and volume strain show rapid transient behavior, one would have to either calibrate this system response and deconvolve it from the measured signal (e.g. see [6, p. 88]) or use an alternate system.

PRACTICAL APPLICATIONS

The first step in a triaxial deformation experiment is to place a jacketed specimen on the lower base plug of the testing apparatus. The pressure vessel is filled with the confining medium and the specimen is kept under a small initial confining pressure (< 2 MPa) to maintain a seal between the specimen and the confining medium. The specimen is then flushed with pressurized fluid from the reservoir to obtain maximum saturation. End pieces and platens have centered pore-fluid drainage holes and are connected to high-pressure fittings which lead out of the pressure vessel. After passing through the specimen, the fluid exits the pressure vessel into the stand tube. Once the specimen is flushed, a valve is closed to isolate the reservoir and back pressure is then slowly increased. The dilatometer is adjusted to replace volume lost as air bubbles are compressed and total saturation is achieved. Output voltage from the transducer is monitored to ensure that fluid level never overflows the stand tube. When the desired back pressure is reached and the fluid height has been adjusted to an optimal starting point, a valve is closed to isolate the dilatometer. At this point the test is ready to be run.

This system is appropriate for use with a variety of porous materials, although our application is restricted to porous sandstone. Sample test data for Massillon Sandstone are shown in Fig. 4. Compactive volume strain is taken as positive. These data show some

post-failure ($> 1.1\%$ axial strain) fluctuations in volume strain which probably represent local fracture events since they coincide with surges in acoustic emission activity. The time scale over which these event occur are orders of magnitude greater than the typical relaxation time of the transients in the hydrodynamic response of the system.

In order to ensure that pore fluid may be freely displaced, the rate of deformation must be adjusted to take into account the geometric and fluid-flow properties of the material. Fischer and Paterson [7] give a useful approximation for determining maximum volume strain, $\dot{\varepsilon}_v$, given by the following inequality:

$$\dot{\varepsilon}_v < \frac{1}{100L^2\eta} \frac{k}{\beta_c}, \qquad (2)$$

where the variables are specimen length, L, dynamic viscosity of the pore fluid, η, bulk permeability, k, and storage capacity per unit volume β_c. Taking $\eta = 1.124\,\text{cP}$ for water, $L = 0.05\,\text{m}$, $k/\beta_c = \sim 10^{-4}\,\text{Pa}\,\text{m}^2$ for Massillon sandstone (measured experimentally), the maximum allowable strain rate is $0.36\,\text{s}^{-1}$, which is well above the $8 \times 10^{-6}\,\text{sec}^{-1}$ used in these experiments. Note that the permeability of Massillon sandstone is several orders of magnitude greater than that of the materials used by Fischer and Paterson [7]. A combination of high strain rate and low permeability will result in inhomogeneous pore pressures and unreliable volume strain results.

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