DEVELOPMENT OF SHEAR BANDING IN SANDSTONE

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Summary Closed-loop, servo-controlled compression tests were conducted to investigate the development of shear banding in Berea sandstone. The experiments were performed with a Vardoulakis-Goldscheider type plane-strain apparatus, designed to allow the shear band to develop in an unrestricted manner. Dilatancy and friction were evaluated at three confining pressures, and several tests were halted in the strain-softening regime. Thin section microscopy and digital image analysis provided direct observations of the shear band. Porosity increase within the shear band was 4-8 grain diameters wide and associated with intragranular microcracks; increased porosity did not extend beyond the tip of the shear band.

PLANE-STRAIN EXPERIMENTS

From laboratory compression tests on geomaterials, it is observed that a uniform deformation pattern changes and further deformation is localized in a narrow region called a shear band. This localized feature is typically observed in earth materials such as dense sand and overconslidated clay, as a zone of high shear strain relative to the surrounding material. In dense sands, shear banding is associated with motion of individual particles and may be described by equilibrium bifurcation theory [1]. In brittle earth materials such as sandstone, shear banding may be related to intragranular microcracks, phenomenon that has been inferred from other experiments [2,3,4]. A few studies have shown the complexity between porosity and mean stress in the localization process [3,4]. Understanding the mechanisms involved in the development of a shear band in sandstone is of primary interest in this research.

Constitutive behavior

Plane-strain compression [5] experiments were performed and data from three tests (5, 10, 20 MPa confinement) are shown in Figures 1 and 2. The dilatancy angle ψ, where $\sin\psi=-\Delta\varepsilon_p/\Delta\gamma_p$ and $\Delta\varepsilon_p$=incremental plastic volume strain and $\Delta\gamma_p$=incremental plastic shear strain, was calculated from the onset of plastic deformation to near peak stress (Fig. 1). Dilatancy showed strong pressure dependence. The degree of compactive behavior at the onset of plastic deformation, observed as a negative dilatancy angle, was larger for tests with higher confining pressure. The dilatant response of each specimen seemed to approach a limiting value; higher confinement resulted in a smaller value of peak dilatancy.

Using the stress parameters $s=(\sigma_1+\sigma_3)/2$ and $t=(\sigma_1-\sigma_3)/2$, the linear Mohr-Coulomb yield condition can be written as $t=s\cdot\sin\phi+c\cdot\cos\phi$ and the friction angle ϕ can be estimated from $\sin\phi=t/s[1/(1-Q/s)]$. The parameter Q is the intercept at t=0; for Berea sandstone, Q=-9.25 MPa. The linear yield function showed sensitivity to pressure (Fig. 2), while a nonlinear yield function could reasonably represent the response. Note that the sandstone displayed non-normality.

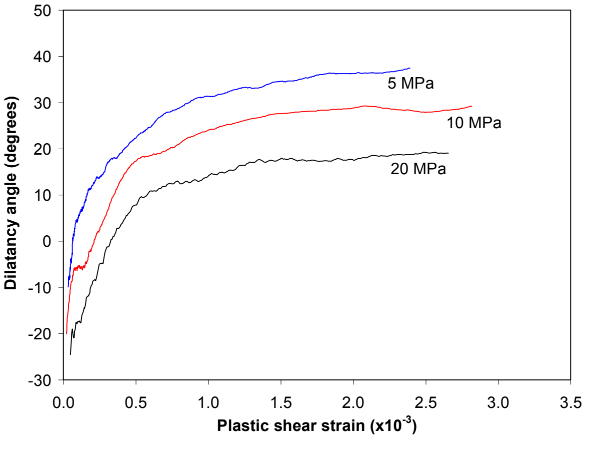

Figure 1. Dilatancy of Berea sandstone.

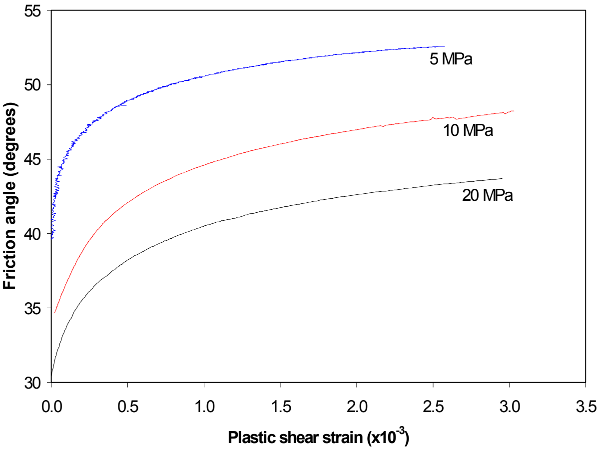

Figure 2. Friction of Berea sandstone.

Post-failure observations

Thin sections for optical microscopy were prepared from specimens where deformation localized and softening occurred, but the shear band was not fully developed; the specimens remained intact and the shear band was well preserved. Care was taken in handling the specimens by potting them in hydrostone to facilitate cutting the specimens in half; then the blocks were quenched in low viscosity, blue epoxy to increase the visibility of porosity and to preserve the structure of the material during slide preparation. The thin-sections were examined under reflected and transmitted light at magnifications ranging from 4x to 52x. Photographs were taken with a digital camera mounted on the microscope.

The shear band seemed to initiate at a stress concentration, either the corner of the specimen (Fig. 3) or, when present, an imperfection (a 3-mm diameter hole) introduced in the specimen. From displacement measurements and acoustic emission locations, it was concluded that the shear band initiated around peak stress and then propagated in the softening regime until the test was stopped. All the specimens showed similar deformation mechanisms along the shear band, although only one experiment at 5 MPa confinement will be presented.

Progressive failure

Microcracking among individual grains was the dominant failure mechanism. For example, areas with high microcrack densities were outlined in black (Figs. 3a,b,c). The intensity of grain cracking within the shear band was greatest near the corner of the specimen and decreased as the surface was traced towards the center of the specimen. Areas of high crack density also appeared to have the greatest amount of grain size reduction and there seemed to be a larger amount of pore space (Figs. 3a,b). The shear band also propagated through regions where grain fracturing was not observed; in these locations the shear band transected grain contacts. Although the path of the shear band was not completely straight, the overall orientation was about 76° from the minor principal stress direction.

A numerical code was written to provide an efficient means for analyzing the relative porosity of epoxy-impregnated thin-sections. The code was set up to receive a digital image (*.bmp). The colors of most concern were blue, the color of the epoxy filling the pore spaces, and white, the color of individual grains which compose the matrix of the sandstone. The bitmap image used three parameters, R, B, and G, to define the color of each pixel, with a value between 0 and 255. The intensity of the R channel consistently defined the boundary of grain and pore space and was the channel used to differentiate blue pore space from the white grains composing the matrix.

The areas of increased porosity, 4-8 grain diameters wide, did not extend beyond the tip, which was determined by the last observable intragranular microcrack. An absence of notable porosity change in the immediate vicinity of the tip suggested that a porosity increase was not detected prior to microcracking. The porosity change that corresponded to the shear band was observed in areas with high densities of intragranular microcracks. Therefore, it seemed that the localized porosity increase was related to the evolution of microcracks after the initial inception of the shear band.

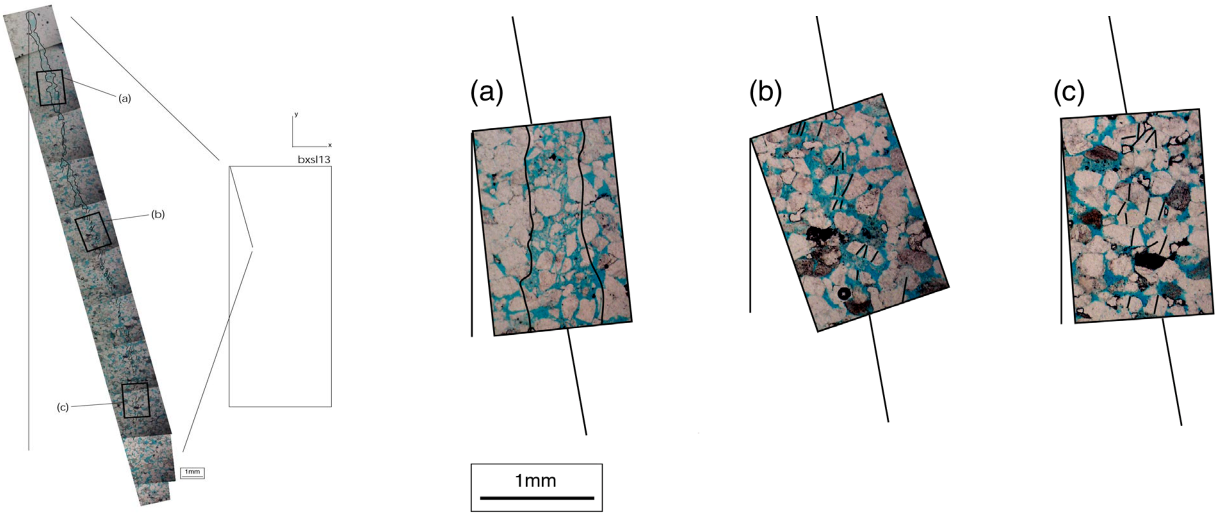

Figure 3. Shear band in Berea sandstone at 5 MPa confinement.

CONCLUDING REMARKS

A suite of plane-strain compression tests were performed on Berea sandstone with the University of Minnesota Plane-Strain Apparatus, which allowed shear banding to develop and propagate in an unrestricted manner. Thin-section microscopy was performed on deformed specimens and the shear band showed a progression of deformation from the inception point, where the deformation was characterized by a high density of intragranular microcracks with broken grains, to the tip, where the intragranular microcracks were significantly less dense and separated by intact grains.

References

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