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Final Report: The objective of this project is to provide a fundamental understanding of microscale basis for the macroscopic deformation and transport properties of porous earth materials in relation to energy-related problems, using an integrated approach consisting of experimental rock mechanics testing, quantitative microscopy and statistical microgeometric characterization, and theoretical and numerical analyses. The overall goal of the research program is to enhance the fundamental understanding of failure and transport, and thereby strengthen the scientific basis for the application of laboratory results to various technological efforts of current societal concern and impact. We summarize below the key accomplishments of our project:

(1) In geomechanics the phenomenon of mechanical compaction is conventionally simulated using either the critical state or cap model, which have been incorporated into various numerical codes even though there have been limited constraints from a paucity of high-quality data. On the basis of our relatively complete data set on mechanical compaction in porous sandstone, a comprehensive analysis of our data in relation to constitutive modeling was presented by *Baud et al.* (2006), who mapped out the conditions under which some of the conventional models are valid and clarified the predictions on the inception of strain localization.

(2) A new experimental technique for mapping out the compactive yield envelope under undrained conditions was developed, and our data were summarized by *Tembe et al.* (2007). The technique allows one to characterize the initial yield envelope and its evolution with strain hardening, which typically require several conventional triaxial tests to acquire. Furthermore it circumvents variability from sample to sample.

(3) Digital image correlation is a technique that is widely used in experimental mechanics to map out the spatial distribution of strain, but seldom in geomaterials. *Louis et al.* (2007) developed a technique whereby X-ray radiographs of undeformed and deformed samples can be used to delineate the spatial distribution of relatively small inelastic strain and to characterize the influence of bedding on the development of strain localization (*Louis et al.*, 2007, 2009)).

(3) We have used the discrete element modeling for analyzing the complex micromechanics of brittle failure and compaction localization in clastic rocks. In particular we focus on the influence of grain-scale pore heterogeneity. The simulations of *Wang et al.* (2008) highlight how discrete compaction bands are promoted by grain-scale homogeneity. Compactive failure is accompanied by permeability reduction of up to several orders of magnitude, possibly with strong stress-induced anisotropy. *Zhu et al.* (2006) have formulated a probabilistic damage model that can realistically capture key attributes of the permeability evolution.

(4) Compaction bands are a compactant failure mode in porous rock, forming thin tabular structures normal to the maximum compressive stress with negligible shear offset. *Tembe et al.* (2008) investigated the conditions involved in the development of compaction

bands in sandstone, including the influence of composition and the geometric attributes of the bands across a range of length scales. Synthesis of field and laboratory data on band dimensions in five sandstones over four orders of magnitude revealed a quadratic scaling relation between the thickness and length of compaction bands. Using an anti-crack/anti-dislocation fracture mechanics model we obtained a scaling relation in which the stress level is inversely proportional to band thickness. Tembe et al. (2008) show that this relation provides a mechanical basis for interpreting discrepancies between laboratory and field data, with the implication that the critical strain energy release rate in the field is comparable to laboratory measurements.

(5) Micromechanics of brittle faulting and inelastic compaction in three carbonate rocks (Tavel, Indiana and Majella limestones) with initial porosities ranging from 10% to 30% was systematically investigated. Our observations underscore the importance of pore-emanated cracking in the development of brittle faulting, which implies that the brittle strength depends on only on the porosity but also the pore size. At higher pressures, our observations indicate that inelastic compaction involves pore collapse that initiates at the larger pores, and cataclasis dominates the deformation in the periphery of a collapsed pore. There represent some of the first systematic observations, which were presented in a paper submitted and another in preparation by *Vajdova et al.* (2010). To capture the cataclatic pore collpase processes, we developed a model treating the limestone as a dual porosity medium, with the total porosity partitioned between macroporosity and microporosity (*Zhu et al.*, 2010). The representative volume element is made up of a large pore which is surrounded by an effective medium containing the microporosity. Cataclastic yielding of this effective medium obeys the Mohr-Coulomb or Drucker-Prager criterion, with failure parameters dependent on porosity and pore size. The model predicts the onset of inelastic compaction at critical stresses that fall on caps in basic agreement with our laboratory data for limestones with porosities ranging from 3% to 30%.

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