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Title: Micromechanics of Failure in Brittle Geomaterials
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Accomplishment:

This project is collaborative with Dr. Joanne T. Fredrich of Sandia National Laboratories. The overall objective is to provide a fundamental understanding of brittle failure processes in porous and compact geomaterials, which is central to several energy-related programs at the U. S. Department of Energy (e.g., oil and gas exploration/production, reservoir engineering, drilling technology, geothermal energy recovery, nuclear waste isolation, and environmental remediation). Although major advances have been made over the past two decades, our understanding is rudimentary and the effects of key parameters such as grain boundary structure and cementation, damage state, and load path on the deformation and failure mode of brittle geomaterials are still largely unknown.

The research methodology emphasizes the integration of experimental rock mechanical testing, quantitative microscopy, and detailed analysis using fracture mechanics, continuum plasticity theory, and numerical methods. Significant progress has been made in elucidating the micromechanics of brittle failure in compact crystalline rocks, as well as high-porosity siliciclastic and carbonate rocks. Substantial effort has also been expended towards applying a new quantitative three-dimensional imaging technique to geomaterials and for developing enhanced image analysis capabilities.

Technique for imaging the 3-D pore structure of geomaterials

Ability to determine both the initial pore structure and its evolution with stress is essential for elucidating the micromechanics of brittle failure, as well as the effects of microstructural damage on other rock properties of practical importance such as permeability and elastic moduli. Conventional imaging technologies, such as optical light microscopy and scanning electron microscopy, offer only a two-dimensional view. We developed a new technique for imaging the pore space of geomaterials in three-dimensions using laser scanning confocal microscopy [*Fredrich, Menédez and Wong, 1995*]. The essential feature is that both illumination and detection are confined to a single location on the specimen at any one time. In-plane resolution is greatly enhanced, and resolution to 200 nm can be achieved. Using this technique, one can non-destructively "slice" sequential series of thin optical sections from which three-dimensional reconstruction of the pore space can be directly created using commercially available image analysis software. The data provide important insight into the 3-dimensional complexity of the pore geometry as related to brittle failure and fluid transport processes.

Mechanics of compressive failure in sandstone

We conducted a comprehensive study of the inelastic and failure behavior of 6 sandstones (Adamswiller, Berea, Boise, Darley Dale, Kayenta and Rothbach) with porosities ranging from 15% to 35%. Most experiments were conducted in triaxial compression on samples saturated with distilled water. A broad range of effective pressures were selected so that the transition in failure mode from brittle faulting to cataclastic flow could be observed. To investigate the effect of loading path, some triaxial extension tests were also conducted.

The mechanical data for saturated sandstone deformed in triaxial compression were presented and analyzed by *Wong, David and Zhu* [1997]. Under relatively low effective pressures, samples fail by brittle faulting with dilatancy and strain softening. Under relatively high effective pressures, samples fail by cataclastic flow with shear-enhanced compaction and strain hardening. The initial yielding is identified with the onset of shear-enhanced compaction. We have obtained one of the most complete data sets for the compactive yield stress in sandstone. Our new data validate several key concepts currently assumed in continuum models of compaction. First, the compactive yield stresses map out an approximately elliptical envelope in stress space, in agreement with the critical state and cap models. Second, the normality condition of plasticity theory can be adopted to associate a flow-rule with the compactive yield envelope. The data provide additional insight into microstructural controls on compaction behavior. The compactive yield envelopes expand with decreasing porosity ϕ and grain size R. The critical stress for the onset of grain crushing and the brittle-ductile transition both scale as $(\phi R)^{-3/2}$, and geologic data on tectonic faulting in siliciclastic formations (of different porosity and grain size) are consistent with this model. While our data are in reasonable agreement with current continuum models for compactive failure, they also underscore the inadequacy of certain theoretical models for the development of dilatancy and shear localization.

Effect of water on compressive failure of sandstone

It has generally been recognized that the presence of interstitial fluid can lower the compressive strength through chemical processes such as stress corrosion and the Rehbinder effect. Published data indicate that the extent by which strength is reduced in the presence of water is highly variable in sandstone. To investigate this question, hydrostatic and triaxial compression tests were performed on sandstone under nominally dry and saturated conditions at room temperature. Significant differences were observed in the strain hardening behavior of nominally dry and water-saturated samples deformed at the same effective pressure and strain rate. *Zhu and Wong* [1997] observed that water-weakening effects in both the brittle faulting and cataclastic flow regimes are particularly pronounced in sandstones with about >10% feldspar. Unlike previous studies which focused on comparison of the compressive strength, our measurements include volumetric strain, porosity change and acoustic emission and such an integrated approach provides additional insight into the coupling between water-rock interaction and mechanical deformation. The data allow us to formulate a theoretical model to consistently interpret the dilatant and compactive failure behaviors due to presence of water and initial damage in a fracture mechanics framework [*Baud, Zhu and Wong*, 2000]. A review of our research on mechanical compaction was also presented [*Wong and Baud*, 2000].

Micromechanics of compressive failure: observation and model

Quantitative microstructural study and theoretical modeling elucidate the micromechanics of failure. *Menéndez, Zhu and Wong* [1996] characterized the evolution of damage in Berea sandstone using both optical and scanning electron microscopy. In the brittle faulting regime, shear localization did not develop until the post-failure stage after the peak stress had been attained. The microcrack density data show that very little intragranular cracking occurred before the peak stress was attained, even though appreciable acoustic emission activity was observed. The inference is that dilatancy and acoustic emission activity in the prefailure stage are due primarily to intergranular cracking, probably related to the shear rupture of lithified and cemented grain Contacts. Near the peak stress, intragranular cracking initiates from grain contacts, and this type of Hertzian fracture first develops in isolated clusters, and their subsequent coalescence results in shear localization in the post-failure stage. The very high density of intragranular microcracking and pronounced stress-induced anisotropy in the post-failure samples are a consequence of shear localization and compactive processes operative inside the shear band. In contrast, Hertzian fracture was a primary cause for shear-enhanced compaction and strain hardening throughout the cataclastic flow regime. Grain crushing and pore collapse seem to be most intense in weakly cemented regions.

Motivated by the microstructural observations, *Wong and Wu* [1995] investigated the effect of cementation on the micromechanics of compressive failure using the finite element technique. The development of stress-induced cracking is governed by the fracture mechanics at grain contacts. The Hertzian model for grain contact assumes two spheres in elastic contact, and theoretical solutions for the stress fields are available when either only normal load is applied or when tangential load causes full slip conditions. However, the contact grains may be under normal and tangential loadings simultaneously and the contacts may undergo partial slip. *Shah and Wong* [1997] formulated a superposition technique by which the stress fields and fracture mechanics parameters for this more realistic scenario can be evaluated. Preliminary theoretical results for a model of uniform spheres obtained by *Shah and Wang* [1996] are in qualitative agreement with experimental observations.

We also investigated the micromechanics of failure and spatial evolution of damage in the Darley Dale sandstone of intermediate porosity (~13%). Our observations indicate significant differences with the micromechanical behavior of a weakly cemented porous sandstone, and the microstructural observations underscore the variability of micromechanics of failure [*Wu, Baud and Wong*, 2000].

The Brittle-Ductile Transition in Porous Carbonate Rocks

We have completed a study on the mechanics of the brittle-ductile transition in the Solnhofen limestone. For the first time, a fairly complete set of data on porosity change and failure mode in this limestone with porosity of ~3% have been acquired. Our mechanical data show that the failure modes are associated with complex interplay of dilatancy, pore collapse and crystal plasticity processes, and several micromechanical models have successfully been employed to consistently interpret the phenomena [*Baud, Schubnel and Wong*, 2000]. This study has established the framework for future study on the failure and porosity change in porous carbonate rocks in general.

Publications:

Baud, P., A. Schubnel, and T.-f. Wong, Dilatancy, compaction and failure mode in Solnhofen limestone, , *J. Geophys. Res.*, **105**, 19289-19303, 2000.

Baud, P., W. Zhu, and T.-f. Wong, Failure mode and weakening effect of water on sandstone, *J. Geophys. Res.*, **105**, 16371-16390, 2000.

Fredrich, J. T., B. Menéndez and T.-f. Wong, Imaging the pore structure of geomaterials, *Science,* 268, 276-279, *1995.*

Menéndez, B., W. Zhu and T.-f. Wong, Micromechanics of brittle faulting and cataclastic flow in Berea sandstone, *J. Struct. Geol.,* 18, 1-16, 1996.

Shah, K. R., and T.-f. Wong, Fracturing at contact surfaces subjected to normal and tangential loads, *Int. J. Rock Mech. Min. Sci.* 34, 727-739, 1997.

Shah, K. R., and T.-f. Wong, Grain fracturing and comminution in porous materials, in *Rock Mechanics: Tools and Techniques, Proc. 2nd NARM Symp.,* ed. M. Aubertin, F. Hassani, and H. Mitri, A. A. Balkema, Rotterdam, 859-866, 1996.

Wong, T.-f. and L. Wu, Tensile stress concentration and compressive failure in cemented granular material, *Geophys. Res. Let.,* 22, 1649-1652, *1995.*

Wong, T.-f., and P. Baud, Mechanical compaction of porous sandstone, *Revue de l'Institut Français du Pétrole*, **54**, 715-727, 1999.

Wong, T.-f., C. David, and W. Zhu, The transition from brittle faulting to cataclastic flow in porous sandstones: Mechanical deformation, *J. Geophys. Res.,* 102, 3009-3025, 1997.

Wu, X. Y., P. Baud, and T.-f. Wong, Micromechanics of compressive failure and spatial evolution of anisotropic damage in Darley Dale sandstone, *Int. J. Rock Mech. Min. Sci.*, **37**, 143-160, 2000.

Zhu, W. and T.-f. Wong, Shear-enhanced compaction in sandstone under nominally dry and water-saturated conditions, *Int. J. Rock Mech. Min. Sci.* **34,** *3/4, paper no. 364,* 1997.