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From dilatancy to contraction: Stress-dependent failure mode progression in two porous sandstones subjected to true triaxial testing

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Porous sedimentary rocks such as sandstones are typical oil-bearing formations in which failure due to high stress concentration is likely to occur during wellbore drilling and subsequent operations. The objective of this research was to investigate the effect of σ_2 on strength, failure-plane angle, and failure mode under realistically simulated field conditions ($\sigma_1 \geq \sigma_2 \geq \sigma_3$). A series of true triaxial compression tests were conducted on two representative porous sandstones: Coconino (17.5% porosity, 99% quartz, with rounded and well-sorted 0.1 mm grains that are bonded by suturing and some quartz overgrowth), and Bentheim (24% porosity, 95% quartz, with sub-rounded 0.3 mm grains that are bonded exclusively by suturing).

Square cuboidal specimens (19 x 19 x 38mm) were subjected to independent loads in three principal directions, using the University of Wisconsin testing apparatus, creating a true triaxial state of stress ($\sigma_1 \geq \sigma_2 \geq \sigma_3$). In all tests, σ_3 and σ_2 were maintained constant at predetermined levels, while σ_1 was raised monotonically until failure occurred. The magnitude of σ_3 varied between 0 and 150 MPa, covering the range of brittle behavior, brittle-ductile transition, and the threshold to the ductile zone in the weaker Bentheim sandstone. It was found that in both rocks the compressive strength ($\sigma_{1,peak}$) for a given σ_3 increases as the preset σ_2 is raised between tests, and reaches a peak (15% over $\sigma_{1,peak}$ when σ_2 = σ_3 in the Coconino, and less than 10% in the Bentheim), beyond which it gradually drops, such that when $\sigma_2 \approx \sigma_{1,peak}$, the strength is approximately the same as when σ_2 = σ_3. This strengthening effect is considerably lower than that in previously tested crystalline rocks, such as Westerly granite and KTB amphibolite (more than 50%, *Haimson*, 2006). Plotting the test data in the τ_{oct} vs. σ_{oct} domain, where the two stress invariants τ_{oct}, the octahedral shear stress, and σ_{oct},the mean normal stress, are both taken at failure), Coconino shows a monotonically rising τ_{oct} with increasing σ_{oct}. In the Bentheim, on the other hand, the initially rising τ_{oct} forms a 'cap' at about σ_{oct} = 200 MPa, an indication of localized compaction, followed by a sharp decrease for larger magnitudes of σ_{oct}.

Failure characteristics in Coconino sandstone subjected to σ_3= $\sigma_2$evolve from a dilatant mode, expressed by a single shear band, or fault, dipping steeply from 80° at σ_3= 0 MPa, to 60° at σ_3= 100 MPa; to a diminishing dilatant mode, signaled by multiple parallel and conjugate shear bands (a characteristic of brittle-ductile transition) dipping at nearly 50°, at σ_3 = 120-150 MPa. At low preset σ_3, failure plane dip increases by as much as 15° as σ_2 is raised, but the increase gradually drops at higher σ_3. The role of $\sigma_2$in retarding the progression of the failure mode is noted, for example, at σ_3 = 100 MPa, where characteristics of brittle-ductile transition are gradually reversed as $\sigma_2$is raised. The more porous Bentheim sandstone is generally weaker. When subjected to σ_3= σ_2 between 0 to 60 MPa, its failure mode is dilatant, leading to a single fault dipping 80° at σ_3 = 0 MPa, to 50° at σ_3 = 60 MPa. For a constant σ_3, failure-plane angle rises with σ_2, but the increase is typically under 10°, somewhat less than in the Coconino. In the range of 60$<\sigma_3<$80 MPa, dilatancy disappears and failure takes the form of multiple parallel and conjugate shear bands, dipping at nearly 45°. At σ_3 = 80-120 MPa, the Bentheim undergoes contraction, evidenced by stress-strain behavior and induced by the emergence of localized shear-enhanced compaction bands (less than 45° dip), evolving into pure compaction bands at σ_3 = 150 MPa (dip approximately 0).