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Mechanical behaviour and transport properties of anhydrite - implications for caprock integrity during long-term storage of CO_2

S.J.T. Hangx (1,2), C.J. Spiers (1), C.J. Peach (1), A. ten Hove (1,2), and A.M.H. Pluymakers (1)

(1) High Pressure and Temperature Laboratory, Faculty of Geosciences, Utrecht University, P.O. Box 80021, 3508 TA Utrecht, the Netherlands, (2) Shell Global Solutions International, Kesslerpark 1, 2288 GS Rijswijk, the Netherlands

Geological storage of CO_2 in depleted oil and gas reservoirs offer one of the most easily and cheaply implemented options to reduce CO_2 emissions. To maintain storage integrity, mechanical damage of the caprock in the form of dilatation, fracturing, shear failure and associated permeability development should be prevented. Damage can be caused by deformation resulting from localised reservoir compaction or heave during fluid depletion or injection.
We investigated the mechanical strength and damage behavior of anhydrite-rich caprock, which seals many current and potential CO_2 storage sites around the world. To this end, we studied two types of stratigraphically equivalent, but texturally and compositionally different, anhydrite obtained from the basal unit of the Permian Zechstein evaporite sequence, which caps many potential CO_2 storage sites in the Netherlands. Main differences between the anhydrites were the grain size, grain shape and dolomite content. Our aim was to investigate the effect of rock texture and composition on the mechanical behaviour and damage characteristics of anhydrite, needed to assess the effect of lateral textural/compositional variations on lateral strength variations and susceptibility to mechanical damage.
Conventional triaxial compression experiments, dry and with fluids ($CaSO_4$ solution $\pm$ CO_2, P_p = 10-15 MPa), were performed under a range of conditions (T = 20-80°C, P_c = 1.5-50 MPa, strain rate $\sim 10^{-5}$ s^{-1}). Hydrofracturing experiments were performed under fixed axial load, increasing fluid pressure at a constant volumetric flow rate until failure occurred. The effect of stress on the permeability of deforming Zechstein anhydrite, going from mechanically stable, through dilatant conditions, into failure and the post-failure stage, was determined by combining the compression experiments (T = 20°C, P_c = 3.5-25 MPa, strain rate $\sim 10^{-6}$-10^{-7} s^{-1}), with transient pulse argon gas permeametry (P_p = 1-1.2 MPa). Our results were used to determine the failure envelopes for dry anhydrite and the effect of fluids upon them, while the permeability data was coupled with dilatancy envelopes, providing data on the effect of stress state on fault permeability.
For both anhydrites, we observed a transition from brittle to semi-brittle behaviour over the experimental range. Peak strength varied by 15-35% between the two anhydrites and could be described by a Mogi-type failure envelope. No influence of fluid on mechanical strength was observed, besides an effective pressure effect, implying that there was no chemical effect of $CaSO_4$ solution with or without high-pressure CO_2. Dynamic permeability measurements showed a change from "impermeable" ($<10^{-21}$ m^2) to permeable ($\geq 10^{-18}$-10^{-16} m^2) as a result of mechanical damage.
Combining our failure and dilatancy envelopes with simple analytical calculations based on the elastic flexure of a seal formation, and with calculations for Joule-Thomson cooling, show that for realistic conditions caprock integrity will not be compromised by mechanical damage and permeability development, even for a 15-35% reduction in strength due to lateral textural changes. However, more sophisticated geomechanical modelling of stress state evolution during caprock flexure and thermal cooling needs to be done to validate this statement.