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Crack healing in rocksalt via diffusion in adsorbed aqueous films: Microphysical modelling versus experiments

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A B S T R A C T

Microcracks within the excavation damaged or disturbed zone (EDZ) in a salt-based radioactive waste repository (or an energy storage facility) can heal/seal by mechanical closure driven by compaction creep, by surface-energy-driven processes like diffusive mass transfer, and by recrystallization. It follows that permeability evolution in the excavation damaged zone around a backfilled or plugged cavity will in the short term be dominated by mechanical closure of the cracks, while in the longer term diffusive mass transfer effects are expected to become more important. This paper describes a contribution to assessing the integrity of radioactive waste repositories sited in rocksalt formations by developing a microphysical model for single crack healing in rocksalt. More specifically, single crack healing models for cracks containing a thin adsorbed water film are developed. These microphysical models are compared with single crack healing experiments, which conclusively demonstrate diffusion controlled healing. Calibration of unknown model parameters, related to crack surface diffusivity, against the experimental data enable crack healing rates under repository conditions to be estimated. The results show that after the stress re-equilibration that follows repository sealing, crack disconnection can be expected on a timescale of a few years at laboratory humidity levels. However, much longer times are needed under very dry conditions where adsorbed aqueous films are very thin.

1. Introduction

Despite the disaster caused at the Fukushima nuclear plant by the tsunami that struck the Tohoku region of Japan on 11 March 2011, the rapidly growing need to reduce anthropogenic emissions of CO_2 to the atmosphere is presently driving renewed interest in nuclear energy and therefore in geological disposal or storage of radioactive waste. Against this background, rocksalt is still very much on the agenda as a suitable host rock for radioactive waste repositories (see Fig. 1), because of its low permeability and its potential for fracture healing due to its ductile rheological properties (Langer, 1993, 1999; Silberschmidt and Silberschmidt, 2000; Arson et al., 2012). After the construction of a mined repository in a rocksalt formation, the salt surrounding the openings will be mechanically, hydraulically and geochemically altered (Cai and Kaiser, 2005), forming a narrow zone of damaged, permeable rocksalt known as the excavation damaged or disturbed zone (EDZ) (Tsang et al., 2005). Following disposal of the radioactive waste, the repository rooms, boreholes, drifts and shafts will be backfilled with crushed salt removed during construction. The backfill will, on the one hand, support the converging walls of the excavated cavities, limiting or ultimately reversing the mechanical damage occurring in the walls. On the other hand, it will serve as a ductile, compacting fill that will help to isolate the disposed wastes from the biosphere.

As well as understanding the behaviour of the backfill, it is important that the extent, the transport properties and the evolution of the EDZ surrounding the various mined openings can be predicted. These are determined by the creep behaviour of the salt and backfill material and by the initiation, growth and healing of cracks and fractures in the EDZ, on the macro and micro-scale, that accompany stress redistribution during convergence of the mined openings (Tsang et al., 2005; Zhu and Bruhns, 2008). In the last 30 years, much research has been done on the mechanical behaviour of rocksalt and of backfill as well as on damage development (Senseny et al., 1992; Peach and Spiers, 1996; Hunsche and Hampel, 1999; Lux et al., 2000; Silberschmidt and Silberschmidt, 2000; Schulze et al., 2001; Hou, 2003; Cinar et al., 2006; Alkan et al., 2007; Liang et al., 2007; Günther and Salzer, 2007; Lux, 2009). This has shown that when the deviatoric stress in the converging walls of a cavity or borehole reaches a sufficiently high value compared to the mean stress, i.e. passes through the so-called dilatancy boundary in stress space (Hunsche, 1998), microcracks develop, mainly along grain boundaries but also within grains,

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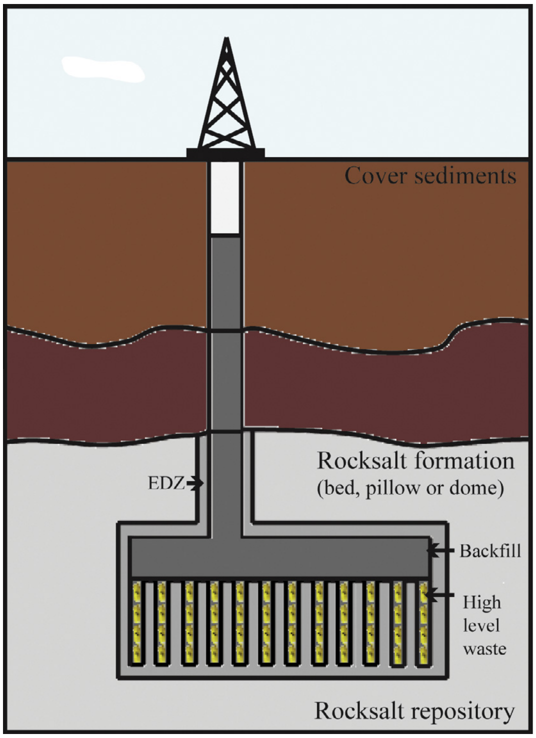

Fig. 1. Schematic drawing of a sealed radioactive waste repository in rocksalt, where the various cavities and boreholes are surrounded by an excavation damaged zone (EDZ).

increasing porosity and permeability. Much less has been done on crack healing effects in salt (exceptions include the work of Chan et al. (2001), Schulze (2007) and Miao et al. (1995), on backfill healing), though crack healing experiments have been executed upon a number of other geological materials (Calcite: Hickman and Evans, 1987; Quartz: Smith and Evans, 1984; Brantley et al., 1990) as well as ceramics (Kim et al., 2007; Song et al., 2008), semiconductors (Yasutake et al., 1986) and metals (Ralph et al., 1994; Gao et al., 2001; Zhang et al., 2003, 2004). Generic modelling studies of crack healing processes have also been conducted both at the single crack scale (Nichols, 1976; Smith and Evans, 1984) and at the continuum scale (Yu et al., 1995; Huang et al., 2002; Greenwood, 2004).

Since crack healing in salt will play a key role in determining the evolution of permeability in the EDZ in rocksalt repositories, particularly in the long term, a better understanding of the processes involved is needed. Crack healing/sealing and permeability reduction in the EDZ can occur by three different physical mechanisms (Fig. 2). In the first place, there is purely mechanical closure of cracks due to compaction of the bulk rock by elastic deformation, plastic flow or flow by pressure solution (e.g. Chen et al., 1996; Kim and Lee, 2001; Chan et al., 1998, 2001), occurring in a regime of increasing mean normal stress (Fig. 2A). The second mechanism is that of diffusive or "chemical" crack healing driven by surface energy reduction. This mechanism involves the necking down of cracks to form tubes and eventually isolated, sub-spherical fluid inclusions (Smith and Evans, 1984; Urai et al., 1986; Hickman and Evans, 1987; Brantley et al., 1990; Schutjens and Spiers, 1999; Cinar et al., 2006; Lux and Eberth, 2007). In this case, transport of material occurs by diffusion through thin water films adsorbed to the solid surface or filling the cracks completely (Fig. 2B). The process not only reduces crack permeability but also restores strength, as illustrated in the recent work by Salzer et al. (2007) on cohesion developed by mass transfer at interfaces between polycrystalline salt blocks. The last mechanism, crack healing by recrystallization, is a process whereby grain boundary migration of fluid-filled grain boundaries overgrows the crack, leaving sub-spherical fluid inclusions behind (Urai et al., 1986; Peach et al., 2001; Ter Heege et al., 2005a,b) (Fig. 2C). Mechanical

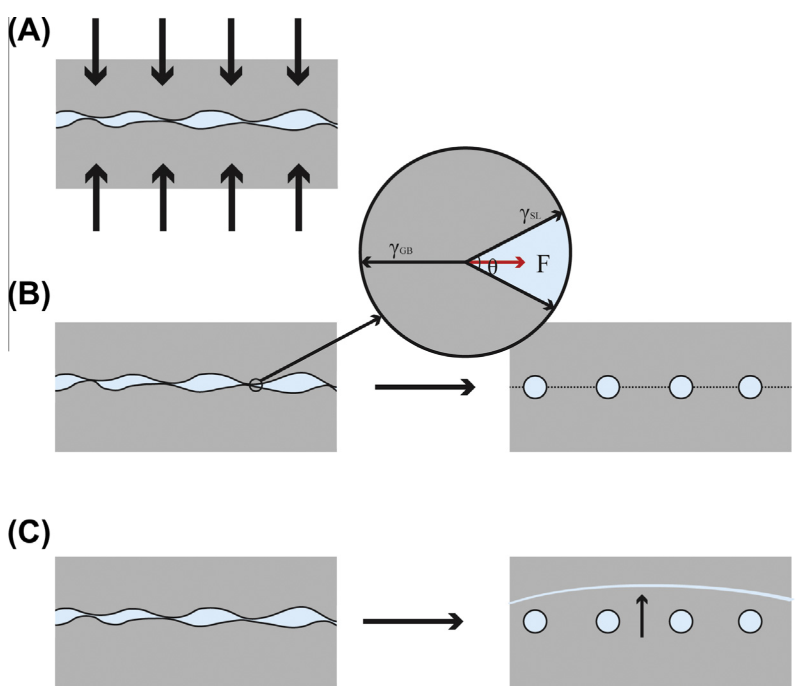

Fig. 2. Physical mechanisms by which crack healing/sealing and permeability reduction can occur in the EDZ in rocksalt. (A) Mechanical closure of cracks in association with compaction of the bulk rock by elastic deformation or plastic flow. (B) Necking down (occlusion) of cracks and pores to form arrays of disconnected tubular and spherical inclusions, by means of surface-energy-driven, diffusive mass transport facilitated by adsorbed water films or free pore brine. (C) Crack and pore occlusion through fluid-assisted grain boundary migration (recrystallization).