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Parametric studies on confinement of radionuclides in the excavated damaged zone due to bentonite type and temperature change

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ABSTRACT

A parametric study is presented in this paper in order to examine the potential of the extruding bentonite into a fracture in the EDZ to confine radionuclides. Radionuclide migration of cesium and neptunium were studied at elevated temperatures and for a sodium- and calcium-type bentonite. Parameter values were obtained based on empirical studies for hydraulic conductivity, molecular diffusion, and sorption. Results indicate extrusion speed is affected by temperature changes. Elevated temperatures also affect radionuclide migration. For Cs, migration is enhanced due to decreasing sorption, while Np migration is inhibited due to increasing sorption. The potential to confine radionuclides is favorable, and the choice of bentonite does not seem to affect radionuclide confinement in the extruding region.

1. Introduction

Management of high level radioactive waste (HLW) will involve geologic disposal. The repository conceptual designs incorporate multiple barriers to radionuclide release, both engineered and natural, to provide isolation of waste from the biosphere in the long term (IAEA, 2003). A waste package consisting of a stable matrix such as borosilicate glass or uranium oxide, and a surrounding buffer material, comprise two engineered components in the repository (cf. SKB, 1999; JNC, 2000; Posiva Oy, 2006).

The buffer material will limit water infiltration to the waste package, delaying corrosion of the waste package and radionuclide release (cf. SKB, 1999; JNC, 2000; Posiva Oy, 2006). For the water-saturated repository concept, compacted bentonite is utilized as the buffer material. Montmorillonite is the primary mineral in bentonite. Important physical properties include low permeability, low hydraulic conductivity, and high sorption capacity (Pusch, 1981; Nakano et al., 1986; Low, 1992; Cho et al., 1999). Bentonite will also swell beyond its initial volume when in contact with water (cf. Lambé and Whitman, 1969; Madsen and Müller-Vonmoos, 1989; Low, 1992; Laird, 2006). This will cause bentonite to extrude into any intersecting rock fractures (Pusch, 1981; Nakano et al., 1986). Bentonite provides both mechanical functions, to fix waste canisters and enhance structural support, and hydraulic functions, limiting the infiltration of water in the EBS, delaying corrosion, and inhibiting radionuclide migration (Pusch, 1981; Bucher and Müller-Vonmoos, 1989). Bentonite is classified based on the exchangeable cation in the montmorillonite molecule; i.e., sodium-type or calcium-type. The exchangeable cation can affect the properties of the bentonite.

A repository constructed in crystalline rock will contain many fractures due to natural conditions or construction activities. These fractures will form pathways for release in which radionuclides will migrate to the far-field by: (i) dissolution from the waste matrix, (ii) diffusion through the buffer material, and (iii) advective and dispersive transport through the fracture (Harada et al., 1980; Ochs et al., 2001, 2003).

The purpose of this study is to examine the performance of the bentonite extrusion region in the fracture from the perspective of radionuclide confinement. This study is twofold; we investigate radionuclide confinement in the extrusion region based on: (i) possible temperature variations in the region and (ii) utilization of different bentonite types. We consider changes to the intrinsic properties of bentonite due to possible temperature variations and bentonite type. A parametric study was developed for this purpose. The confinement potential of the extrusion region is then examined by modeling the transport of cesium and neptunium in a water-saturated fracture.

2. Background

2.1. Experimental and external modeling studies

Numerous studies of bentonite exist in the literature (cf. Pusch, 1981; Boisson, 1989; Börgesson, 1990); here, the main studies relevant to the current work are summarized. The experiments by Kanno and Wakamatsu (1991) and Kanno and Matsumoto (1997) determined that bentonite extruded into a fracture at a rate that was proportional to the square root of time. A Japanese

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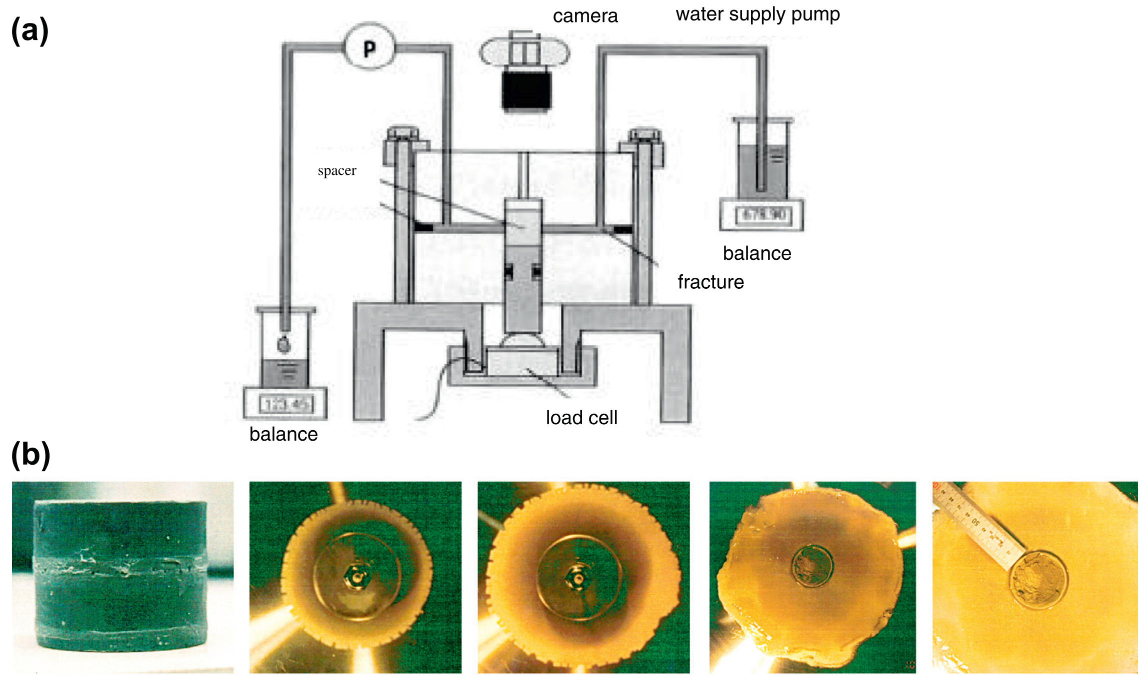

Fig. 1. The bentonite extrusion model applied in this study is based on prior experimental study. The experimental apparatus is shown in the top figure (a). When a specimen of confined bentonite was placed in contact with water, the specimen expanded into a horizontal, water filled gap. Photographs were taken by a camera that was mounted above the experimental apparatus and shown in the bottom figure (b). The initial bentonite specimen is shown by the leftmost photograph. Subsequent photographs to the right show the specimen in various stages of extrusion with time. The studies showed that the bentonite specimen extruded at a rate proportional to the square root of time.

sodium–bentonite (Ishikawa et al., 1989) was used in this experiment with dimensions of 50 mm in diameter and 50 mm in height. Extrusion into a simulated fracture was observed when bentonite was contacted with water. The experimental apparatus is shown in Fig. 1a. Photographs of the experiment are shown in Fig. 1b. An empirical relationship for the location of the extruding edge[1] was obtained as (Kanno and Wakamatsu, 1991; Kanno and Matsumoto, 1997)

$$R(t) = A\sqrt{t} + R(0) \quad 0 \leqslant t \leqslant 100\ \text{h}, \tag{1}$$

where A is an empirical constant. Results also indicated that friction effects are negligible for an aperture greater than 1 mm.

A mathematical model was then developed by Kanno et al. (2001) to describe bentonite extrusion in a water-saturated rock fracture. The model was based on the diffusion of solid particles driven by swelling pressure differences. A formula was developed for a diffusion coefficient of solid particles in terms of the solid-phase volume fraction, the aperture, and the viscosity of the solid phase. The model was established based on the theory of clay particle diffusion by Nakano et al. (1986). Results were obtained by this model for the spatial distribution of solid material. Kanno et al. (2001) also confirmed that friction will affect extrusion at apertures below 1 mm. The material property values used for the estimation of the solid diffusivity were obtained in limited ranges of the solid-phase volume fraction (Kanno et al., 2001).

2.2. Mathematical modeling study

A mathematical model was developed in order to examine any potential effects of the extrusion phenomenon on radionuclide transport. This modeling study was motivated by the previously discussed studies. A coupled model was established by Borrelli and Ahn (2008a, 2008b) for bentonite extrusion and radionuclide migration through a water-saturated, planar fracture. An overview of the fundamental principles governing the model system is provided.

A diffusion-type governing equation was developed to describe the void ratio[2] distribution in the fracture. This model is based on the principle that the driving force governing extrusion is based on the observation of bulk water flow in the system due to swelling pressure and soil consolidation theory (Terzaghi, 1931). The location of extruding edge in the fracture was modeled by evaluating the net mass flow rate of water in the system. The study by Kanno et al. (2001) did not include a mathematical model for the location of the extruding edge. Friction effects of the fracture wall was neglected.

The bentonite extrusion model system was coupled to an advection–diffusion transport model (Harada et al., 1980). The advection term is different than the standard transport model due to the moving solid phase. This transport equation included spatial and temporal dependencies of parameters due to bentonite extrusion. Finite element solutions were obtained for the radionuclide concentration in the aqueous phase.

An idealized case study was then developed in order to determine the effects of bentonite extrusion on the confinement of radionuclides in the fracture. The major conclusion from this study indicated that the extrusion region exhibited the potential to contain radionuclides and enhance performance of the engineered barrier.

3. Conceptual model

It is important that descriptions of the major physical processes are clear for this study. First, we describe general considerations in

[1] The extruding edge is defined as the interface between the extruding bentonite and water.

[2] The void ratio is defined as the ratio of void volume to solid volume; in this model, the void volume is filled completely by water.