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Reactive transport modelling of cement-groundwater-rock interaction at the Grimsel Test Site

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A B S T R A C T

An in situ experiment at the Grimsel Test Site (Switzerland) to study water-cement-rock interaction in fractured granite was modelled. It consisted of a hardened cement source in a borehole intersecting a water conducting fracture. Grimsel groundwater was injected into this borehole. Two other boreholes at about 0.56 m and 1.12 m from the emplacement borehole were used to monitor the evolution of water composition for 5 years. The modelling approach was based on a 1D radial model for the emplacement borehole and a small volume of rock (fault gouge) around it, and a 2D model for the rest of the domain. The results of the 1D model were used as input for the 2D model. Both models showed dissolution of the fault gouge minerals. Results from the 1D model showed dissolution of portlandite in the cement with an increase in porosity. The 2D model showed a reduction in porosity in the fault gouge due to mineral precipitation. Near the emplacement borehole ettringite precipitated. At the centre of the plume there was precipitation of C-A-S-H and hydrotalcite. At the edge of the hyperalkaline plume calcite, hydrotalcite and illite precipitated.

1. Introduction

Ordinary Portland Cement (OPC) is frequently used for radioactive waste storage as a part of the engineered barrier system or as structural support in the host rock. The cement pore water is hyperalkaline (pH > 13) and can react chemically with the host rock of the repository. Several studies have investigated the interaction between the cement, the hyperalkaline plume and the host rock (Read et al., 2001; Savage et al., 2002; Gaucher et al., 2004; Hoch et al., 2004; Sánchez et al., 2006; Mäder et al., 2006; Pfingsten et al., 2006; De Windt et al., 2008; Soler and Mäder, 2010; Savage et al., 2011; Soler, 2013; Kosakowski and Berner, 2013; Moyce et al., 2014; Soler, 2016; Martin et al., 2016). In general, they found a reduction in porosity due to precipitation of secondary minerals. Our study was part of the LCS Project (Long-Term Cement Studies), with the objective of studying the water-cement-rock interaction and their effect on water flow and solute transport properties. To do so, an in situ experiment was started in 2009 at the Grimsel Test Site underground rock laboratory (Switzerland, www.grimsel.com). First, a tracer experiment was performed to characterize the initial flow and transport properties of the rock (granite) around the test site. Afterwards, the in situ experiment was performed. A hardened cement source was installed in a borehole intersecting a water conducting fracture. Then, Grimsel groundwater was circulated or injected into this borehole and the evolution of water composition in the fracture was monitored for 5 years. A preliminary reactive transport model corresponding to the formation of a high-pH plume and its interaction with the rock was reported by Saaltink and Soler (2016). The conceptual model considered a 1D radial model for the emplacement borehole and a small volume of surrounding rock (fault gouge), and a 2D model for the rest of the domain. The results of the 1D model were used as input for the 2D model. The objective of our study is to develop a qualitative and partially quantitative understanding of the geochemical processes that took place during the experiment. To do so, we followed the same conceptual model as Saaltink and Soler (2016), with a relatively simple flow model, which was based on an initially homogeneous fracture. The results of the numerical model

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were compared with the available experimental data. We used the monitoring data of flow rates and solution composition at the emplacement, observation and extraction boreholes, the data from post-mortem analysis of the cement made by the Swiss Federal Laboratories for Materials Science and Technology (EMPA) and the mineralogical analysis from samples next to the emplacement borehole made by the British Geological Survey (BGS).

2. In situ experiment

The experiment took place at the Grimsel underground rock laboratory (Switzerland). Pre-hardened Ordinary Portland Cement hollow cylindrical segments were emplaced in a borehole (emplacement borehole) intersecting a water-conducting fracture. Starting from the centre, the borehole contained an inner dummy (inert cylinder) followed by the cement and a water-filled gap. Two other boreholes (called observation and extraction boreholes) were placed at 0.56 and 1.12 m away from the emplacement borehole. There were no cement pieces in the observation and extraction boreholes. These boreholes were instrumented with multiple packer systems to capture the effluent from a specific fracture. A skin of low permeability was assumed to surround the boreholes (Fig. 1). Grimsel groundwater was circulated and injected in the emplacement borehole. Water was extracted at the observation and extraction boreholes and the chemical compositions of the different solutions were monitored. After the injection was started in the emplacement borehole, elevated pH and solute concentrations reflecting interaction with the cement were observed in the observation and extraction boreholes.

3. Numerical model

3.1. Modelling approach

Our conceptual model considered only a simple homogenous fracture of 5 mm thickness, taking into account the reactions that could have occurred during the interaction between the cement, Grimsel groundwater and the fault gouge filling the fracture. The simulations were carried out using the Retraso-CodeBright software package (Saaltink et al., 2004). The modelling approach considered two different models (1D radial and 2D). First, a detailed 1D radial model simulated the emplacement borehole (hardened cement paste) together with the surrounding skin (Fig. 1b). Then, the results of this model (solute concentrations at the outer boundary of the skin of the emplacement borehole) were used as input for the 2D model that simulated the fracture plane at the scale of all three boreholes (emplacement, observation and extraction). The conceptual model assumed that during the initial test period without injection of water in the borehole the permeability in the skin was low enough to avoid flow of water in that zone. It also assumed that when water was injected, the flow in the skin was only affected by this injection (radial flow) and was not affected by the extraction in the other boreholes.

3.2. Geometry and mesh

The geometry of the 1D radial model reflected the hardened cement paste, the existing gap between cement and rock and the skin with total length (radius) of 80 mm (Fig. 1b). In the model, a thicker and thinner cement zone (from 35 to 41 mm) was finally

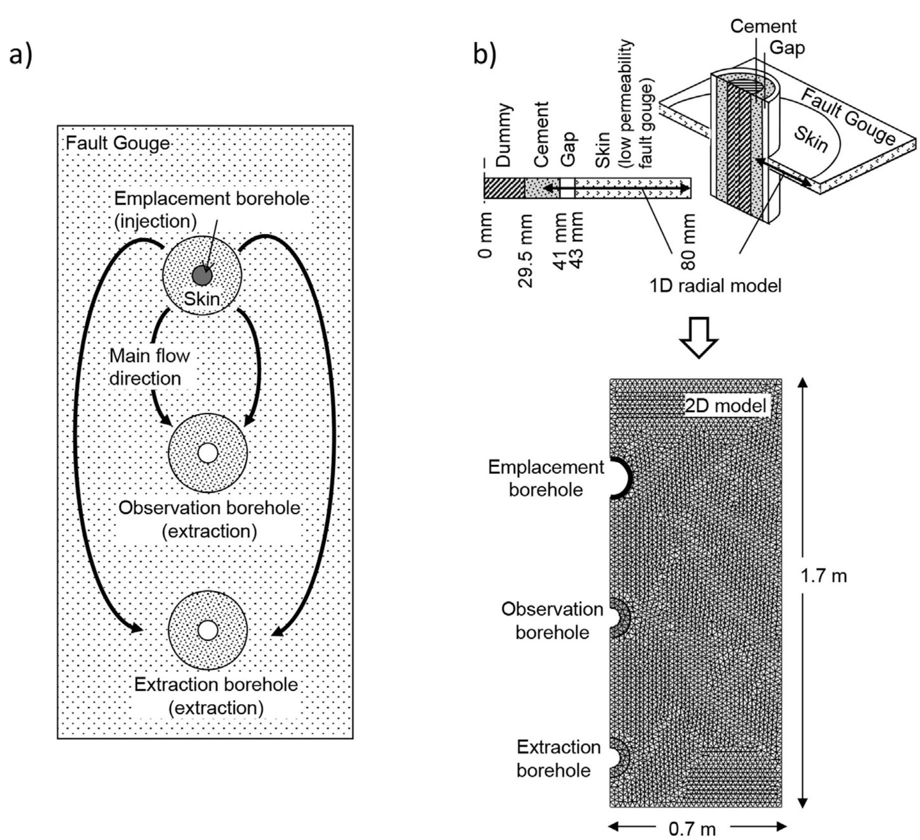

Fig. 1. Conceptual model a) Plan view of the fracture plane with the three boreholes; lines indicate the main direction of flow b) Geometry of the 1D and 2D models.