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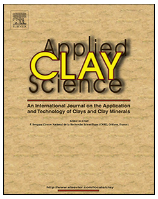

Research paper

Salinity effects on the erosion behaviour of MX-80 bentonite: A modelling approach

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A R T I C L E I N F O

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A B S T R A C T

The erosion behaviour of bentonites is influenced by the ions concentration to which they are exposed, which could lead to link the erodibility of bentonite to salinity. However, changes in salinity produce further changes in bentonite hydration and swelling that are not always considered. The aim of this work is to apply a numerical model to inspect the influence of salinity in the erosion behaviour of MX-80 bentonite, analysing the effect of swelling on erosion. To this end, a coupled hydro-chemo-mechanical and erosion model, which considers the expansive behaviour of bentonite as a function of salinity, and a hydro-mechanical model with a salinity-dependent erodibility coefficient are used to simulate pinhole erosion laboratory tests with saline waters. The results of the simulations illustrate that the influence of ion species concentration in the erosion behaviour of bentonites does not need a change in erodibility to be reproduced. On the contrary, they show that hydro-chemo-mechanical effects, and especially the changes that salinity induces in the swelling behaviour of bentonite, play a key role in erosion. Taking them into account leads to a more consistent formulation approach that can explain the observed behaviour, and, for that reason, such an approach is strongly recommended to analyse bentonite erosion processes.

1. Introduction

Bentonite is considered a main component of engineered barriers in deep geological repository concepts for spent nuclear fuel, because of properties such as high swelling potential, retention capacity and low hydraulic conductivity (Pusch, 1992; Yong, 1999). For this reason, bentonite is included in several repository concepts, like KBS-3, developed for Sweden and Finland (Posiva, 2013; SKB, 2011). In those concepts, there is a concern about the possibility of bentonite barriers being eroded by groundwater flowing through intersecting fractures in the host rock (Neretnieks et al., 2009; Reid et al., 2015). In addition, the salinity of groundwaters at repository depth will vary along time in the surroundings of bentonite barriers (Hellä et al., 2014).

The behaviour of bentonites subject to erosion processes is modified when exposed to waters of different salinities, as the amount of eroded mass changes with salinity (Baik et al., 2007; Raudkivi and Tan, 1984; Schatz et al., 2013). For this reason, it could be thought that bentonite erodibility is affected by salinity conditions, and that lead to, when modelling bentonite erosion, using a bentonite erodibility coefficient that is a function of ions concentration (as for instance in Raudkivi, 1998). On the other hand, it is well known that salinity conditions can modify bentonite response regarding swelling capacity, swelling velocity and hydraulic conductivity (Alawaji, 1999; He et al., 2016; Petrov and Rowe, 1997; Sun et al., 2015; Warkentin and Schofield, 1962). These effects would also modify bentonite behaviour with respect to erosion.

To study experimentally the changes in the erosion behaviour of MX-80 bentonite under different ions concentrations, Sane et al. (2013) performed a series of laboratory pinhole tests. In those tests, sodium and calcium chloride aqueous solutions with concentrations up to 70 g/L were circulated through the bentonite samples, and the mass eroded from the samples along time was measured. As in the aforementioned works, the results obtained were substantially different for the different ions concentrations tested.

The objective of this paper is to inspect the influence of salinity in the erosion behaviour of MX-80 bentonite by modelling these pinhole tests. To this end, two approaches will be used: a hydro-mechanical formulation with an erodibility coefficient variable with salinity (as done in the past by, for instance, Raudkivi, 1998), and a hydro-chemo-mechanical formulation with a constant erodibility coefficient. The novelty of the latter approach is to take into account the expansive behaviour of bentonite as a function of salinity, which will affect how it is eroded. The aim of the inspection is to assess the feasibility of these two modelling concepts.

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Table 1
Properties of Volclay MX-80 bentonite (after Kumpulainen and Kiviranta, 2010 and Kiviranta and Kumpulainen, 2011).

Chemical composition (weight %)	
SiO_2	64.32
Al_2O_3	19.00
Fe_2O_3	3.30
MgO	2.56
Na_2O	2.03
CaO	1.66
CO_3	0.99
K_2O	0.62
FeO	0.48
S (other than SO_4)	0.18
TiO_2	0.15
Organic C	0.15
SO_4	0.08
Mineralogical composition (weight %). Phases present as traces not included	
Smectite	79.1
Muscovite	7.5
Quartz	4.4
Calcite	3.1
Tridymite	1.9
Plagioclase	1.7
Gypsum	1.3
Magnetite	1.1
Other properties	
CEC (eq/kg)	0.89
$Na^+/K^+/Ca^{2+}/Mg^{2+}$ (eq/kg)	0.61/0.02/0.19/0.07
Liquid limit	510
Plasticity index	460

In addition to describing the studied material and the adopted model, the following sections will analyse and model the experimental results of the pinhole erosion tests, and discuss the scope of the two modelling approaches proposed.

2. Materials and methods: description and results of erosion tests

The samples used in the laboratory tests were made of Volclay MX-80 bentonite, which was characterized by Kumpulainen and Kiviranta (2010). Its main properties are summarized in Table 1. This material is a natural bentonite from Wyoming with a high smectite content (nearly an 80%) and sodium as the main exchangeable cation (it constitutes approximately a 70% of the cation exchange capacity, *CEC*). As other sodium bentonites, MX-80 is highly plastic and expansive when exposed to low salinity water, but its swelling properties can be affected by salinity. For this reason, Navarro et al. (2017) studied the free swelling behaviour of a very similar MX-80 bentonite when exposed to saline solutions (sample Be-Wy-BT007-1-Sa-R, Kiviranta and Kumpulainen, 2011).

The laboratory tests were carried out by B + Tech Oy (Finland). The data obtained in the tests with low salinity water were presented and modelled by Navarro et al. (2016), while the rest of analysed test results were published by Posiva (Sane et al., 2013). All the tests used cylindrical samples with a diameter of 100 mm. The initial bulk density and water ratio of the samples were 2.03 g/cm^3 and 17% respectively. Two different sample lengths were used: 100 mm and 400 mm. All samples were produced with a central longitudinal pinhole processed during compaction (for more details, visit Sane et al., 2013, and Navarro et al., 2016). Two different pinhole diameters were used: 6 and 12 mm. The two different pinhole diameters and lengths produce comparable results, according to Sane et al. (2013).

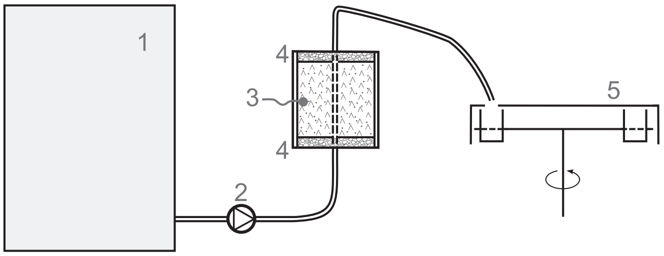

Fig. 1. Pinhole test layout. 1. Water solution container, 2. pumping system, 3. bentonite sample, 4. sintered filters, 5. rotating effluent collection system. Modified from Navarro et al. (2016).

Table 2
Composition of the solutions used in the tests. TDS: total dissolved solids.

Solution	TDS (g/L)	NaCl concentration (g/L)	$CaCl_2$ concentration (g/L)
Brackish-saline water	10	6.47	3.53
Saline water	35	16.75	18.25
Highly saline water	70	26.58	43.42

An aqueous solution was circulated through the sample at a constant flow rate of 0.1 L/min, and the effluent was collected at various times along the test with the help of an automated rotating system (Fig. 1). The solids concentration of the effluent was analysed to determine the mass eroded from the bentonite sample. Several tests were conducted, circulating an aqueous solution of a different concentration in each test. In addition to a low salinity water (with a solids content of about 30 mg/L), a 10 g/L, a 35 g/L and a 70 g/L solutions were used. Only two cations (sodium and calcium) and one anion (chloride) were present in these solutions, whose compositions are shown in Table 2. The 10 g/L solution is a brackish-saline groundwater simulant water for Olkiluoto, site for the Onkalo deep geological repository of spent nuclear fuel in Finland, at repository depth during the operational phase (Hellä et al., 2014). The 35 g/L solution represents the maximum expected salinity for the groundwater at repository depth (Hellä et al., 2014), and corresponds to a saline water with a Ca^{2+}/Na^+ mass ratio of 1:1. The 70 g/L solution represents the maximum allowed salinity for the groundwater in the vicinity of the repository (Hellä et al., 2014), and corresponds to a highly saline water with a Ca^{2+}/Na^+ mass ratio of 3:2.

The matrix of analysed cases is shown in Table 3 for the results previously analysed by Navarro et al. (2016) (low salinity solution) and Table 4 for the rest of cases (note that only tests performed with Volclay MX-80 and with given erosion rate values along the test in Sane et al., 2013 have been used), indicating the parameters of their geometry and the salinity of the circulated solution. The cumulated eroded mass along time for all the tests, grouped for the different salinities, is shown in Fig. 2. The mass loss is normalized by meter length of the sample to allow comparison between tests of different sample lengths. The tests in Table 4 were run for 70–75 h. Two of the tests in Table 3 were run for longer times, but only their evolution up to 100 h is shown to make comparison easier (the full series can be found in Navarro et al., 2016). As stated by Sane et al. (2013), the results obtained do not substantially depend on the sample length (see test S2a in Fig. 2a) or on the initial hole diameter (see test 20 in Fig. 2c). However, the erosion results

Table 3
Matrix of test cases with low salinity solution (from Navarro et al., 2016).

Case	Cell length (mm)	Initial hole diameter (mm)
S1a	100	6
S1b	100	6
S1c	100	6
S2a	400	6
S3a	100	12