Journal of Contaminant Hydrology 170 (2014) 10–27

Contents lists available at ScienceDirect

Journal of Contaminant Hydrology

journal homepage: www.elsevier.com/locate/jconhyd

Effect of gas pressure on the sealing efficiency of compacted bentonite–sand plugs

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ARTICLE INFO

Article history:
Received 17 January 2014
Received in revised form 22 August 2014
Accepted 17 September 2014
Available online 28 September 2014

Keywords:
Sealing efficiency
Swelling
Bentonite–sand
Gas breakthrough pressure
Gas migration pathways

ABSTRACT

This research relates to the assessment of the sealing ability of bentonite/sand plugs when swollen in presence of both water and gas pressures, in the context of deep underground radioactive waste storage. Compacted bentonite/sand plugs are placed inside a constant volume cell, and subjected to swelling in presence of both water and gas: swelling kinetics and effective swelling pressure P_{swell} are identified. Secondly, the gas breakthrough (GB) characteristics of swollen plugs are assessed to determine their ability for gas migration, which has to be minimal for sealing radioactive waste repositories.

We show that gas pressure P_g does not affect significantly P_{swell} until a threshold $P_g > 2$ MPa. When swelling occurs inside a tube with a smooth (turned) inner surface, continuous GB occurs when P_g is equivalent to the effective P_{swell} (obtained without gas pressure, at 7.32 MPa ± 0.11). When the plug swells inside a grooved tube, continuous GB does not occur up to $P_g \geq 10.5$ MPa: smooth interfaces are a preferential gas migration pathway rather than grooved interfaces, and rather than water-saturated bentonite–sand plugs. With smooth tubes, in presence of $P_g \geq 2$ MPa, although P_{swell} is not affected, gas passes through the sample at significantly lower values than P_{swell}, due to partial sample saturation. It is concluded that GB pressure is a more accurate indicator of partial sample saturation than swelling pressure P_{swell} alone.

1. Introduction

1.1. Industrial and scientific context

For all industrialized countries possessing a significant nuclear energy program, an important issue is the management of high-level and long-lived radioactive waste. A promising option is to resort to long-term repository in deep geological formations, such as within claystones (Cariou et al., 2012, 2013; Davy et al., 2009; Stenhouse et al., 1996) or granite (Birgersson et al., 2008). Repository design includes an engineered barrier around the waste containers, which aims to create a low permeability zone around them (Alonso, 2006; Komine, 2004).

In this context, bentonite–sand mixtures have been chosen by several countries as a buffer and backfill material aimed at separating radioactive waste from the surrounding host rock (Wersin, 2003; Xie et al., 2006; Zheng et al., 2011). In particular, in the French repository concept, partially water-saturated bentonite/sand plugs are compacted and assembled to form a whole buffer structure (Fig. 1), which aims to seal the disposal pits by progressive bentonite swelling, owing to underground water seepage (Davy et al., 2009; Horseman et al., 1999; Liu et al., 2012; Ochs et al., 2003; Villar and Lloret, 2006). While bentonite provides good swelling capacity and low permeability (when it is fully or near fully water-saturated), sand is used to improve the thermal conductivity of the non-saturated buffer and its mechanical stability (Arnedo et al., 2008).

In situ, the main channels for underground water seepage are at the interface between the wall of the disposal pit and the

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http://dx.doi.org/10.1016/j.jconhyd.2014.09.006
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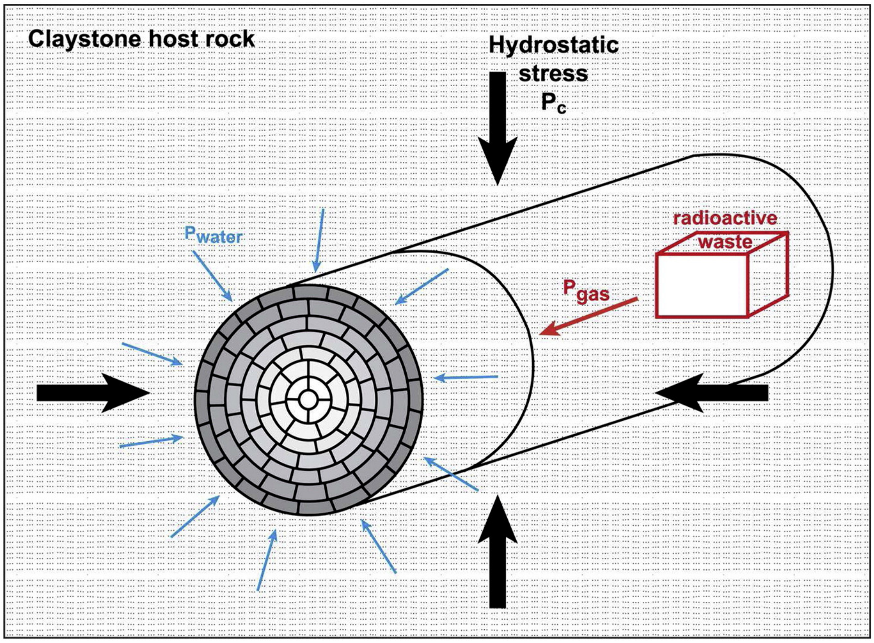

Fig. 1. Industrial context: Schematic diagram of the bentonite/sand seal of an underground radioactive waste storage tunnel, in presence of both underground water and gas (generated by corrosion). The seal also comprises structural concrete and reworked claystone—Example of the French design for type C waste (high-level and long-lived), after (ANDRA, 2005).

buffer structure, so that, when the peripheral buffer plugs are sufficiently saturated (and swollen), water is able to move through to the buffer core and progressively saturate the whole structure. As a consequence, a heterogeneous swelling of bentonite is expected over time (Villar et al., 2005), so that sealing will be progressive (Fig. 1). Meanwhile, gas generation (mainly of hydrogen) is expected within the repository tunnels, due to humid corrosion, degradation of organic matter or water radiolysis (Birgersson et al., 2008). Preferential gas pathways are bound to form and propagate through any partially water-saturated medium, and in particular through the core of the bentonite/sand seal. A competition is inferred between the sealing provided by swollen bentonite, and gas attempts to migrate through the buffer to the surrounding host rock, and potentially through to the environment at large, simultaneously carrying out radionuclides (Popp, 2009).

It is this potential failure scenario that Andra (the French National Radioactive Waste Management Agency) has charged us to investigate and quantify: what is the swelling ability of bentonite/sand plugs placed in presence of both water and gas? for partially swollen bentonite/sand plugs, what is the gas pressure corresponding to gas passage (or breakthrough)?

In this contribution, an original laboratory experiment has been devised, which provides unidimensional investigation of these questions: it is a simplified reproduction, at the laboratory scale, of the swelling and sealing behavior of bentonite/sand plugs along the radial axis of the buffer structure (Fig. 1). The set-up allows swelling of bentonite/sand plugs at constant volume, in presence of both water and gas, by using a composite tube placed in a hydrostatic cell (to avoid fluid leakages), see Fig. 4 and Section 2. Assessment of the sealing ability of partially saturated plugs is performed with the same set-up.

Our study provides input data to 3D numerical simulations at the scale of the repository tunnel (Fall et al., 2014). For experimental validation at the structure scale, the PGZ *in situ* experiment is currently undertaken, in parallel to our laboratory investigations (Harrington et al., 2012).

1.2. Aims and scopes

When in presence of an extensive supply of water, the swelling of bentonite/sand plugs is well described in terms of kinetics and amplitude (Bosgiraud, 2004; Davy et al., 2009; Gatabin, 2005; Lee et al., 2012). Several influential factors are accounted for, e.g. boundary conditions, dry density or void ratio (Sellin and Leupin, 2013; Sun et al., 2009; Villar and Lloret, 2008; Wang et al., 2011). Under given initial conditions (compaction state, water content, etc.), a general observation is that full bentonite saturation is reached when effective swelling pressure P_{swell} reaches an asymptote (Tripathy et al., 2004). However, no such knowledge exists whenever bentonite/sand plugs are let to swell under constant volume, in contact with both a water-saturated plug and gas, as is the case *in situ* for the buffer core. The first aim (and originality) of this contribution is to provide quantitative experimental data for such a swelling case. This will help determine whether the effective swelling pressure P_{swell} alone is an adequate indicator of full water-saturation: by how much does P_{swell} display lower values whenever the plug is partially water-saturated?

To this date, gas migration through fully water-saturated compacted clay plugs has also been extensively investigated (Amann-Hildenbrand et al., 2012; Davy et al., 2009; Gallé, 2000; Hildenbrand et al., 2002; Horseman et al., 1999; Liu et al., 2012; Marschall et al., 2005; Pusch and Forsberg, 1983; Thomas et al., 1968), as follows.