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Experimental research on water retention and gas permeability of compacted bentonite/sand mixtures

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Abstract

Highly compacted bentonite-based materials are often considered as buffer or sealing materials for deep high-level radioactive waste repositories. In situ, the initial state of bentonite-based materials is only partially saturated, which has a very high suction that will promote water absorption from the host rock. In addition, a gradient of water saturation will be formed between the external part and the central part of the compacted bentonite blocks. In this paper, water retention tests, under both constant-volume and free-swelling conditions, were performed to investigate the suction behavior of a compacted bentonite/sand mixture. In order to investigate the sealing ability of the partially saturated bentonite/sand mixture, gas permeability tests were also carried out under the in situ confining stress. It was found that the confining conditions have a limited effect on the water retention capacity of the compacted bentonite/sand mixture at lower levels of relative humidity (RH), while this influence is significant at higher RH levels. The results of gas permeability tests show that gas permeability is very sensitive to the water content and the confining pressure. When the sample (stable at RH=98%) was subjected to a in situ confining pressure (7–8 MPa), the gas permeability was very low (1.83×10^{-14} m/s) which indicates that gas tightness can be obtained even though the sample is not fully saturated.
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Keywords: Radioactive waste repositories; Bentonite/sand mixture; Water retention capacity; Gas permeability

1. Introduction

High-level radioactive waste (HLRW) repositories are usually constructed in bedrock (e.g., Callovo-Oxfordian argillite) several hundred meters below the ground surface. Such deep geological repositories are usually composed of a natural geological barrier (host rock), an engineered barrier made of a metallic canister, and bentonite-based materials. In this context, compacted bentonite-based materials are usually used to seal tunnels and galleries, or as buffer materials around the waste containers, the purpose of which is to create a "low permeable zone" around them (Alonso et al., 2006). To seal a repository gallery, the clay barrier (buffer) is usually formed by blocks of compacted bentonite-based materials arranged in vertical slices, which are put in place with initial construction gaps (Villar and Lloret, 2007). In addition, these gaps also exist between the host rock and the compacted bentonite blocks. The gaps account for 6.6% (FEBEX mock-up tests), 9% (French concept, according to Andra (the French radioactive waste management agency)), and 14% (SEALEX in situ tests) of the volume of the gallery (Martin et al., 2006; Andra, 2005a; Barnichon and Deleruyelle, 2009).

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The initial state of the compacted bentonite-based materials is usually partially saturated. Once placed in the galleries, they will be progressively hydrated due to the underground water infiltrating from the host rock. As indicated by some researchers, the amount of water that infiltrates into the bentonite-based materials depends largely on their swelling properties (Pierre, 2006; Siemens and Blatz, 2009; Cui et al., 2008; Ye et al., 2009a). The swelling properties of expansive materials, with the same initial conditions, clearly differ depending on the confinement conditions (constant-volume or free swelling) (Villar, 2007; Wang et al., 2012, 2013; Ye et al., 2009a; Cui et al., 2008; Tang et al., 2013), the confining stress applied to the materials (Mollins et al., 1996; Ng and Pang, 2000a, 2000b; Lloret and Villar, 2007; Hoffmann et al., 2007; Villar and Gómez-Espina, 2007; Cui et al., 2011), the chemical components of the water (Studds et al., 1998; Abdullah et al., 1999; Zhu et al., 2013; Wang et al., 2014), and/or the temperature (Ye et al., 2009b; Cui et al., 2011; Ye et al., 2013). In addition, the initial physical properties (e.g., dry density, water content, and clay-mineral content) and the initial state (e.g., loose or compacted) also have a great influence on the swelling properties of the materials (Komine and Ogata., 1994, 1999; Villar and Lloret, 2008; Siemens and Blatz, 2009; Tang and Cui, 2010; Agus et al., 2010).

In situ, the infiltration of water into the bentonite-based barrier is a very slow process. During this process, a gradient of water saturation will be presented between the external and the central parts of the clay barrier, as shown in Fig. 1. The external part of the barrier, that is hydrated first, will swell and will be confined in an extremely stiff host rock. As a consequence, it will compress the internal part not yet hydratedand apply a confining pressure. To assess the sealing ability of the barrier, especially for the central unsaturated part, it is essential to measure its permeability under in situ confining stress. In terms of the permeability of compacted bentonite-based materials, similar to their swelling properties, it also depends on the initial state (water content, porosity, and dry density) and the boundary conditions (confining stress, gas pressure, and temperature) (Villar et al., 2012; Vangpaisal and Bouazza, 2004; Cho et al., 1999; Sällfors and Öberg-Högsta, 2002; Lloret and Villar, 2007; Villar and Lloret, 2004; Didier et al., 2000).

In this study, firstly, the suction behaviors of four compacted bentonite/sand mixtures at both constant-volume and free-swelling conditions, were investigated. Then, the gas permeabilities of five partially saturated bentonite/sand mixtures, under in situ confining pressure, were measured to evaluate their sealing abilities.

2. Theoretical model

2.1. Equation of Kelvin–Laplace

The Kelvin–Laplace equation describes the relationship between the capillary pressure, P_{cap}, and the relative humidity, RH. The RH of the air above the meniscus in a capillary pore is given by Kelvin's equation (Thomson, 1871) and cited by Galvin (2005) as

$$ln(RH) = -\frac{\upsilon_m}{RT}\frac{2\gamma\ \cos\ \theta}{r} \qquad (1)$$

where υ_m is the molar volume, R is the universal gas constant, T is the temperature, γ is the surface tension, r is the radius of a droplet, and θ is the contact angle. Indeed, for a porous medium, it is assumed that this equation describes the relationship between the inside RH and the maximum radius of the pores which are filled with water under this RH. With the equation of

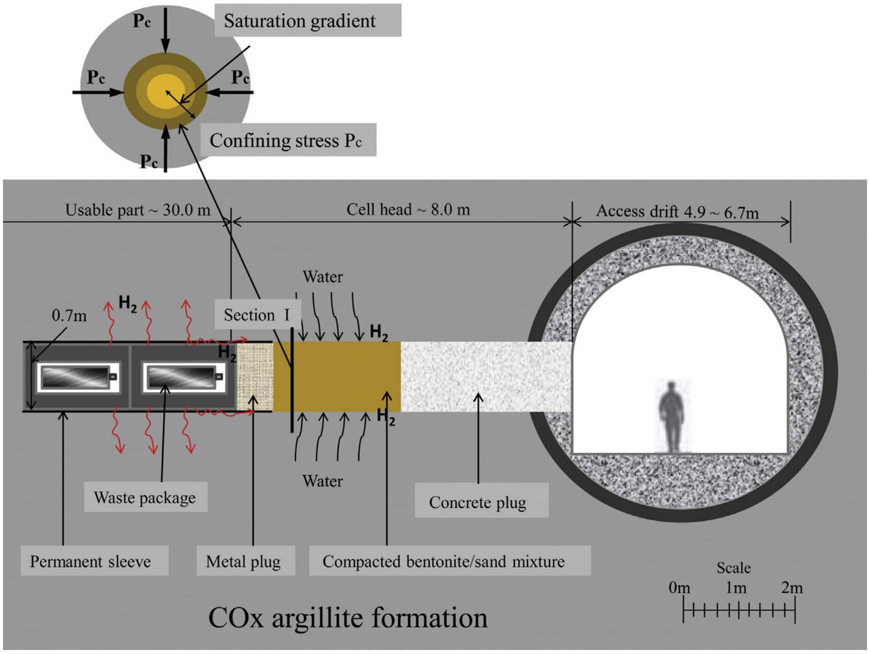

Fig. 1. Schematic diagram of the in situ saturation process: example of the access drift and storage gallery for type C waste, at a depth of -500m, after Andra (2005b).

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