Journal of Rock Mechanics and Geotechnical Engineering 6 (2014) 126–132

Contents lists available at ScienceDirect

Journal of Rock Mechanics and Geotechnical Engineering

journal homepage: www.rockgeotech.org

Microstructure and anisotropic swelling behaviour of compacted bentonite/sand mixture

Simona Saba [a,b], Jean-Dominique Barnichon [a], Yu-Jun Cui [a,*], Anh Minh Tang [a], Pierre Delage [a]

[a] Ecole des Ponts ParisTech, Laboratoire Navier, Marne La Vallée, France
[b] Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay-aux-Roses, France

ARTICLE INFO

Article history:
Received 2 January 2014
Received in revised form
15 January 2014
Accepted 22 January 2014
Available online 3 February 2014

Keywords:
Bentonite/sand mixture
Nuclear waste disposal
Anisotropy
Swelling pressure
Microstructure
Microfocus X-ray computed tomography (μCT)

ABSTRACT

Pre-compacted elements (disks, torus) of bentonite/sand mixture are candidate materials for sealing plugs of radioactive waste disposal. Choice of this material is mainly based on its swelling capacity allowing all gaps in the system to be sealed, and on its low permeability. When emplaced in the gallery, these elements will start to absorb water from the host rock and swell. Thereby, a swelling pressure will develop in the radial direction against the host rock and in the axial direction against the support structure. In this work, the swelling pressure of a small scale compacted disk of bentonite and sand was experimentally studied in both radial and axial directions. Different swelling kinetics were identified for different dry densities and along different directions. As a rule, the swelling pressure starts increasing quickly, reaches a peak value, decreases a little and finally stabilises. For some dry densities, higher peaks were observed in the radial direction than in the axial direction. The presence of peaks is related to the microstructure change and to the collapse of macro-pores. In parallel to the mechanical tests, microstructure investigation at the sample scale was conducted using microfocus X-ray computed tomography (μCT). Image observation showed a denser structure in the centre and a looser one in the border, which was also confirmed by image analysis. This structure heterogeneity in the radial direction and the occurrence of macro-pores close to the radial boundary of the sample can explain the large peaks observed in the radial swelling pressure evolution. Another interesting result is the higher anisotropy found at lower bentonite dry densities, which was also analysed by means of μCT observation of a sample at low bentonite dry density after the end of test. It was found that the macro-pores, especially those between sand grains, were not filled by swelled bentonite, which preserved the anisotropic microstructure caused by uniaxial compression due to the absence of microstructure collapse.

1. Introduction

In the concept of deep radioactive waste disposal in clayey host rocks, sealing materials are used to limit water fluxes around the excavated galleries in the post-closure phase. Compacted bentonite/sand mixtures are often considered as possible sealing materials due to their low permeability, good radionuclides retention capacity and swelling ability (Pusch, 1982; Yong et al., 1986). A possible configuration used in sealing plugs consists in a series of pre-compacted bentonite/sand disks inserted between two concrete confining components. Once the disposal galleries are closed, plugs will be progressively infiltrated by the host rock pore water. They will swell and seal the so-called technological voids of the system (Wang et al., 2013), i.e. the voids remaining between blocks and at the interfaces with the rock after placement. Afterwards, swelling pressure will progressively develop both radially along the host rock and axially along the adjacent bentonite/sand disks and then on the mechanical confining components. In the design of sealing plugs, the swelling pressure is a key parameter to be controlled. Indeed, it must be high enough to ensure good sealing performance and at the same time it must be lower than the in situ minor stress in the host rock and the yield stress supported by the confinement elements.

Generally, a unique swelling pressure considered as isotropic is taken into account in the design of sealing plugs and/or engineered barriers and in the assessment of their swelling behaviours. Accordingly, laboratory measurements are concentrated on only

* Corresponding author. Tel.: +33 164153550.
E-mail address: yujun.cui@enpc.fr (Y.-J. Cui).
Peer review under responsibility of Institute of Rock and Soil Mechanics, Chinese Academy of Sciences.

Production and hosting by Elsevier

1674-7755 © 2014 Institute of Rock and Soil Mechanics, Chinese Academy of Sciences. Production and hosting by Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.jrmge.2014.01.006

one swelling pressure, usually the axial one. A number of studies on the swelling properties of compacted bentonite-based materials were reported (Pusch, 1982; Komine and Ogata, 1994, 2003, 2004; Delage et al., 1998; Agus and Schanz, 2005; Komine et al., 2009; Wang et al., 2012). The swelling pressure can be determined in the laboratory by different methods: constant volume, swell-load, zero swell and adjusted constant volume methods (Tang et al., 2011). As mentioned above, the swelling pressure was measured in most cases in the axial direction. Some authors also tried to measure the radial swelling pressure, e.g. Börgesson et al. (1996), Cho et al. (2000) and Lee et al. (2012). Lee et al. (2012) measured both the radial and axial swelling pressures in a constant volume cell with pressure sensors mounted in the two directions. They found a difference between the radial and axial swelling pressures, i.e. the larger difference was observed at higher dry densities. This was explained by the anisotropic microstructure of compacted bentonite.

In order to better understand the macroscopic response of the compacted bentonite/sand mixture, especially in terms of swelling pressure, an investigation of the microstructure is needed. Various observations of the microstructure of compacted bentonites and sand/bentonite mixture have been carried out using mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM) (Villar and Lloret, 2001; Cui et al., 2002; Montes-Hernandez, 2002; Lloret et al., 2003; Delage et al., 2006). These techniques require a cautious preliminary dehydration of the samples, most often by freeze-drying. They provide local observations on a small part of millimetric samples. For a larger scale, microfocus X-ray computed tomography (μCT) is needed. This technique allows a high-resolution non-destructive three-dimensional (3D) observation without any sample pre-treatment. Moreover, further 3D information on the whole sample (including grain size distribution as well as pores distribution and inter-connectivity) can be obtained. μCT has been previously applied to monitor hydro-chemo-mechanical processes (Comina et al., 2008), to detect dessication cracks (Gebrenegus et al., 2006; Mukunoki et al., 2006), and to investigate the microstructure of compacted bentonite-based materials (Kozaki et al., 2001; Van Geet et al., 2005; Kawaragi et al., 2009).

In this study, the swelling pressure of a small scale compacted disk of bentonite and sand was studied in both radial and axial directions. Different swelling kinetics were identified for different dry densities and along different directions. In parallel to the mechanical tests, microstructure investigation at the sample scale was conducted using μCT.

2. Material and methods

2.1. Material

The material studied is a compacted mixture of Wyoming MX-80 bentonite (commercial name Gelclay WH2) and quartz sand (commercial name TH1000) with a proportion (in weight) of sand of 30%. The mixture was provided in boxes. Actually, examination of the sand proportion (S) in the samples tested showed that the real proportion varies from 32% to 40%. The initial water content (w) of the mixture was 10.2% corresponding to a suction of 73.3 MPa (measured using a chilled mirror dew point tensiometer). Note that this mixture is the same as that used in the in situ experiments (SEALEX) carried out in the Tournemire underground laboratory (Barnichon et al., 2012) by IRSN (Institut de Radioprotection et de Sûreté Nucléaire, the French expert national organisation in nuclear safety).

The grain size distribution of the bentonite powder obtained by dry sieving is presented in Fig. 1 together with that of pure

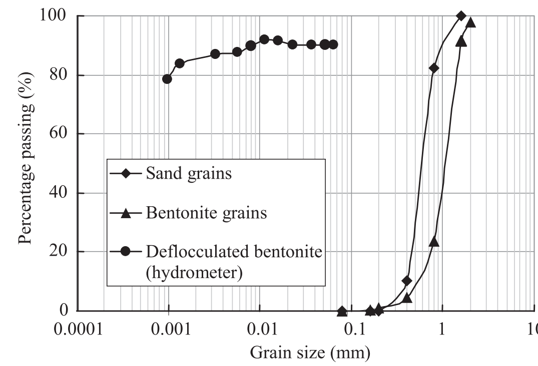

Fig. 1. Grain size distribution curves of bentonite, sand and deflocculated bentonite.

bentonite obtained using the conventional hydrometer method. The grain size distribution of the sand is also shown in Fig. 1. The curves show that materials are well sorted with a mean grain diameter D_{50} of 1.2 mm and 0.6 mm for bentonite and sand, respectively. The unit mass of bentonite particles was measured and found equal to 2.77 Mg/m^3, in agreement with the literature data (Madsen, 1998; Karnland et al., 2006). The unit mass of sand is 2.65 Mg/m^3. The main clay mineral of the MX-80 bentonite is montmorillonite (92%), other minerals being quartz, alumina, and hematite (Tang et al., 2008).

2.2. Anisotropic swelling pressure experimental setup

The experimental setup is presented in Fig. 2. The compacted sample is placed between two porous stones and filter papers. On top, a piston is fixed with a screw to prevent any axial displacement upon swelling. During the test, the sample is saturated from the bottom with synthetic water having the same chemical composition as the pore water from the Bure underground research laboratory (Andra, see details in Table 1). A total pressure sensor is mounted on the cell inner wall to measure the radial swelling pressure. A force transducer is mounted axially in order to measure the axial force generated by the soil swelling. All data are recorded by a data logger.

A series of tests have been performed using two cells, with samples being compacted either inside (In-cell) or outside (Out-cell) the cell. Tests with different dry densities (ρ_d) ranging from

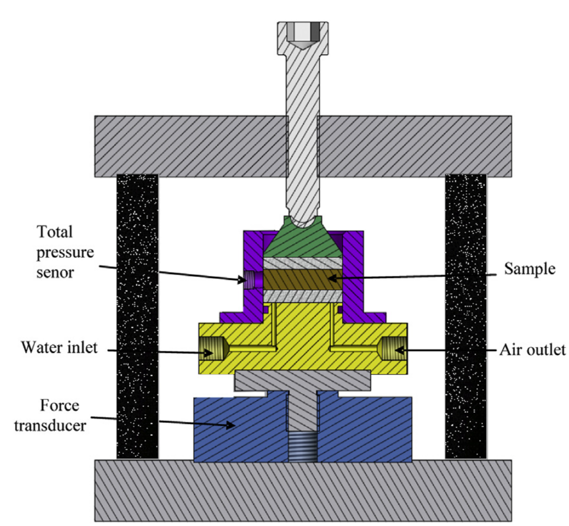

Fig. 2. Layout of the constant volume cell for the swelling pressure tests.