Swelling of Highly Compacted Bentonite-Sand Mixtures Used as Sealing Materials in Radioactive Waste Disposal

Simona Saba, Anh-Minh Tang, Yu-Jun Cui, and Jean-Dominique Barnichon

Abstract. In the radioactive waste disposal concepts, highly pre-compacted bentonite-sand mixtures are considered as appropriate sealing materials to fill the galleries. Compacted elements of bentonite-sand mixtures are placed adjacent to each others, forming a plug that should limit the transfer of radionuclide. The bentonite has proven to have the capability of retaining radionuclides and the capability of swelling when getting in contact with water and then closing all the voids in the system especially the radial technological void being the gap between the bentonite-sand elements and the host rock. Indeed, when the bentonite-sand elements is emplaced in the gallery, they are first in an unsaturated state and they will start being saturated by the host-rock pore water. They will then start swelling, forming a gel that will close the gap. In this work, such hydration process is experimentally analysed on a small scale. The swelling is analysed by time-lapse photography, its kinetic is also studied by image processing. We can see that the swelling of this material is fast and large, and we can distinguish different states of the material during swelling, starting from the dry centre to the outer boundary. On the other

---

Simona Saba
Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay Aux Roses, France
Ecole des Ponts ParisTech, Laboratoire Navier, Marne-La-Vallée, France
e-mail: `simona.saba@enpc.fr`

Anh-Minh Tang
Ecole des Ponts ParisTech, Laboratoire Navier, Marne-la-Vallée, France
e-mail: `anhminh.tang@enpc.fr`

Yu-Jun Cui
Ecole des Ponts ParisTech, Laboratoire Navier, Marne-la-Vallée, France
e-mail: `cui@cermes.enpc.fr`

Jean-Dominique Barnichon
Institut de Radioprotection et de Sûreté Nucléaire (IRSN), Fontenay Aux Roses, France
e-mail: `jean-dominique.barnichon@irsn.fr`

hand, the presence and behaviour of sand grains in the gel formation is evidenced by images as well. The sand grains are found to be covered by bentonite particles and being carried with the bentonite swelling.

Keywords: radioactive waste disposal, bentonite-sand mixture, swelling, digital image analysis.

1 Introduction

In the high-level radioactive waste repository concepts, pre-compacted elements of bentonite-sand mixture could be used as sealing material thanks to its low permeability, high swelling and high radionuclide retardation capacities (Pusch, 1979; Yong et al., 1986). When emplaced in the gallery, such bentonite-based seals are first in an unsaturated state. Once the repository is closed and local groundwater conditions are re-established, water in the host rock formation will flow towards the repository and start saturating the seals from their extremity. When absorbing water, bentonite swells and forms a gel which should fill the radial technological void as the gap between the seal and the host rock. After filling all the technological voids, the gel will be consolidates between the host rock and the swelling core.

In this study, the radial swelling and gel formation are investigated. Small compacted bentonite-sand disks were immerged in distilled water and time-lapse photography coupled with digital image analysis was performed to study their swelling kinetics for different dry densities. Swelling was defined as the variation of the disk surface with time. The growth of the total surface and the reduction of the dry central surface were monitored. The movement of sand grains was also investigated. It was found that the sand grains were firstly pushed radially by the swelling of the bentonite aggregates until the surrounding material becomes too loose to support them: the grains finally dropped down by gravity.

2 Materials and Methods

2.1 Materials

The soil studied is a mixture of MX-80 bentonite (Gelclay WH2) and quartz sand with a bentonite content of 70% in dry mass. The bentonite has a montmorillonite content of 92%; it has an average specific gravity of 2.76, a liquid limit of 520%, and a plastic limit of 42%. The grain size distribution curve determined by sedimentation shows that 84% grains are smaller than 2 μm (clay fraction).

2.2 Methods

The prepared disks have been compacted statically using a mechanical press, they have a diameter of 35 mm and a thickness of 10 mm. Several disks were prepared by compaction at different dry densities. They were then placed between two transparent Plexiglas plates to avoid the axial swelling of the disk when the whole frame was immerged in distilled water. A computer controlled camera was fixed on a special holder above the container at a defined height and was able to take photos automatically at a given time interval. Artificial lighting was used and the system was covered with a black fabric to isolate it from external lights in order to avoid the changing in lights between day and night (see fig. 1).

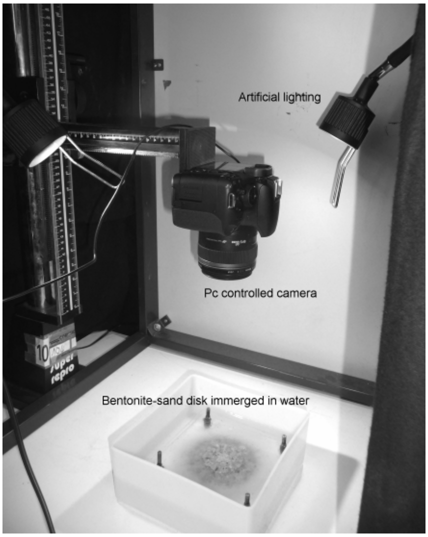

Fig. 1. The experimental system: A computer controlled camera is fixed above a bentonite-sand sample immerged in distilled water to follow its swelling with time.

Photos were then analysed using an image processing program (*Fiji of ImageJ*) to help estimate surface and tracking object movements. For the estimation of surface, an automatic method can be used: photos were first treated (contrast enhancing, illumination, background removal), then a threshold value was applied to isolate the surface of interest. This is a delicate action especially as the interface gel/water is not sharp since the bentonite gel is transparent. Therefore, for the estimation of the surface evolution with time, a manual selection of the surface was used. Finally, to avoid confusion in units, photos are calibrated with the original object units (in mm).

3 Results and Discussion

3.1 General Observation

The swelling of bentonite-sand disks was studied using time lapse photography coupled with digital image analysis. The swelling of the disk is due to the swelling of bentonite present in the mixture.

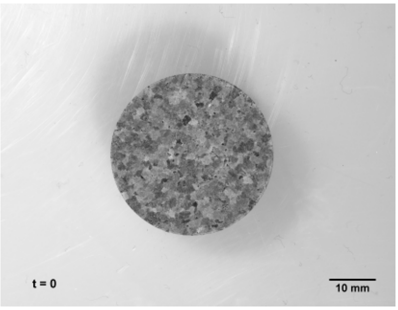

Fig. 2. Initial state of a bentonite-sand disk with a dry density of 1.97 Mg/m^3.

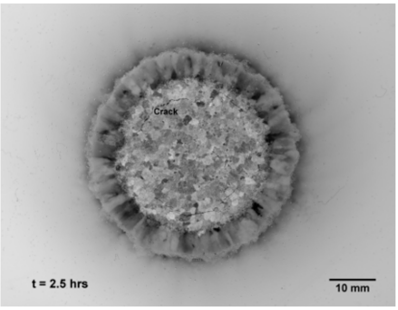

Fig. 3. Same disk after 2.5 hours (swelling = 60%).

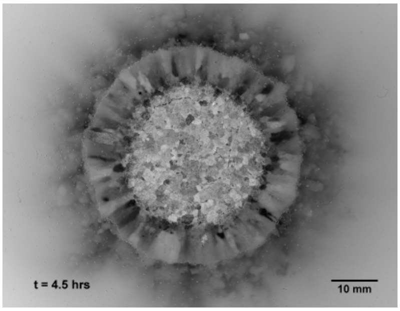

Fig. 4. Same disk after 4.5 hours (swelling = 70%).

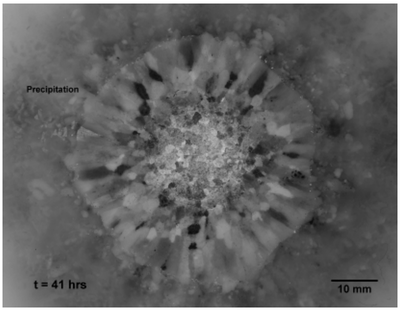

Fig. 5. Same disk after 41 hours (swelling = 125%).

Figs. 2, 3, 4 and 5 show a bentonite-sand disk compacted to a dry density of 1.97 Mg/m^3 at different times during swelling starting from its initial state (Fig. 2). In Fig. 3, it is noted that there are some cracks in the dry centre during the first hours of swelling, and they are closing with time (see Fig. 4) to disappear at the end. This is explained by the rearrangement of the aggregates. The last three figures show three different states of the material in the disk viewed from its upper face: an external ring of loose gel, a ring of saturated material not turned into gel yet and a dry centre. In fact, water was absorbed by the disk starting from its boundary; the bentonite aggregates on the boundary started swelling first as they have enough free space to produce a gel. Actually, knowing the microstructure of the bentonite aggregates we understand the way they swell when in contact with water (Mitchell, 1993). As water continued infiltrating to the disk, internal bentonite aggregates did not have enough space to swell freely and then did not turn into a gel, while in the dry centre water still did not arrive. With time, the gel on the extremity became very loose due to the exfoliation of the bentonite aggregates and their precipitation to form a bentonite suspension (see Fig. 5). This phenomenon of water over-saturation of aggregates was also evidenced by Montes (2002). It is explained by the existence of a certain amount of water causing the exfoliation of aggregates into small particles (Ye et al. 2009). Consequently, the internal bentonite started swelling freely following the same mechanism. As an overall result, the gel surface became larger and the dry surface became smaller due to water infiltration.

3.2 Swelling Kinetics

Experimental results on the swelling of bentonite-sand disks are obtained after digital image analysis (i.e. a two-dimensional analysis). In Fig. 6, three curves are illustrated: one for the variation of the external total surface of the disk, one for the variation of the dry central surface and the difference between the two curves that represents the surface of the gel ring.

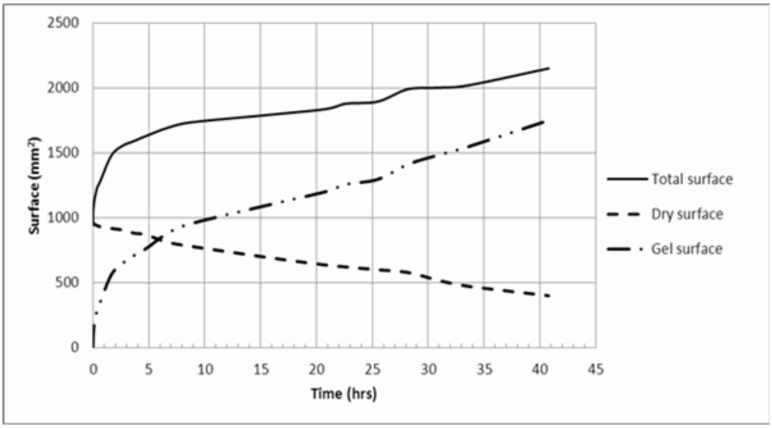

Fig. 6. Variation of the total surface, dry surface and gel surface with time for a bentonite-sand disk having a density of 1.97 Mg/m^3.

The shape of the total surface curve shows a rapid swelling for the first three hours, after that it becomes slightly slower and exhibits a constant rate. The test was stopped after 2 days when the swelling reached 300%. The variation of the dry surface is almost linear, which makes the shape of the gel surface curve similar to that of total surface but with a sharper slope. The gel surface curve is moving towards the total surface curve, which indicates that at a certain time the curves will superimpose and this corresponds to the state where the disk becomes saturated and the maximum swelling is reached.

3.3 Presence of Sand Grains

Fig. 7 shows the trajectory of a sand grain during the disk swelling; the grain apparently disappears after six and a half hours (Fig. 8). In fact, when the disk was in contact with water and the bentonite aggregates started to swell radially, the sand grains were covered by swelled bentonite and were pushed outwards by the pressure from the radial swelling. When the swelled bentonite around the sand grain exfoliated and became loose (similar to a bentonite suspension), the sand grains fell down.

From another point of view, the proportion of sand in the compacted disk is about 30% in dry mass. When the swelled bentonite formed an external ring containing transported sand grains, the volume fraction of sand grains became lower. The concentration in sand grains was lower on the outer boundary of the disk and is mainly located at the bottom.

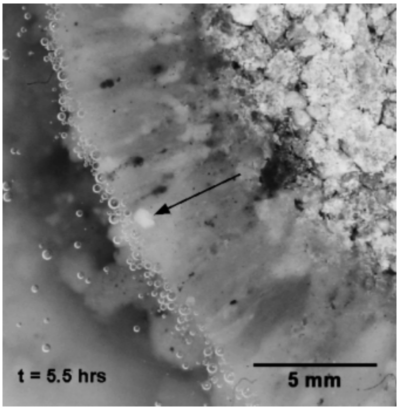

Fig. 7. A sand grain pushed radially in the gel formation.

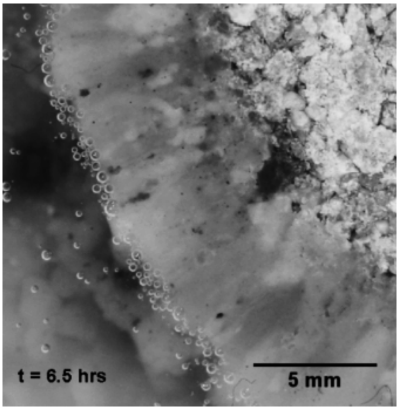

Fig. 8. Precipitation of the sand grain (not visible anymore).

4 Conclusion

The swelling of a compacted bentonite-sand disk is experimentally studied using time-lapse photography coupled with digital image processing. The main advantage of this method is the rapidity for obtaining qualitative and quantitative results. However, it was difficult to analyse the images automatically due to lack of contrast.

Thanks to the observations of the photos it was possible to identify different states of the material during swelling: the dry centre, the gel extremity and a saturated un-swelled surface in between.

The image analysis allows drawing swelling kinetic curves and tracking the trajectory of a sand grain during swelling. It was found that the swelling started rapidly and then became slower. The sand grains were found to be covered with swelled bentonite and pushed outward until they dropped down and precipitated under gravity when the swelled bentonite became very loose similar to a bentonite suspension.

References

Mitchell, J.K.: Fundamentals of soil behaviour. John Wiley and Sons, Inc., New York (1993) ISBN: 0-471-85640-1

Montes-Hernandez, G.: Etude expérimentale de la sorption d'eau et du gonflement des argiles par microscopie électronique à balayage environnementale (ESEM) et analyse digitale d'images. PhD thesis, Louis Pasteur University, Strasbourg I, France (2002)

Pusch, R.: Highly compacted sodium bentonite for isolating rock-deposited radioactive waste products. Nucl. Technol. 45(2), 153–157 (1979)

Ye, W.M., Cui, Y.J., Qian, L.X., Chen, B.: An experimental study of the water transfer through compacted GMZ bentonite. Engineering Geology 108, 169–176 (2009)

Yong, R.N., Boonsinsuk, P., Wong, G.: Formulation of backfill material for a nuclear fuel waste disposal vault. Canadian Geotechnical Journal 23(2), 216–228 (1986)