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The experimental study of bentonite swelling into fissures

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ABSTRACT: The geological disposal of radioactive waste, based on a multi-barrier concept wherein the first barrier consists of the metal waste container and the final barrier the host rock, is widely considered the only viable solution to this issue. The bentonite-based seal around the canister forms one of the barriers. The unique swelling and sealing capabilities of bentonite play a major role in repository safety concepts in that they allow the bentonite barrier to withstand serious mechanical damage without its function being compromised.

This paper presents experimental research focusing on the dynamics and mechanics of the sealing of cracks and joints using bentonite-based materials. Physical models were used to simulate the contact point of bentonite-based sealants with cracks in the rock mass. The models examined the ability of the tested material to fill the crack thus preventing the creation of a preferential water pathway. The results show that in most cases total bentonite advance (for the same material) into fissures is, primarily, linearly dependent on fissure width. The absolute value of advance could be related to the overall swelling ability of the material characterized by its swell index or swelling pressure.

KEYWORDS: disposal/storage radioactive waste, bentonite buffer, geomechanics, erosion, fissures.

The geological disposal of radioactive waste, based on a multi-barrier concept wherein the first barrier consists of the metal waste container and the final barrier the host rock, is widely considered the only viable solution to this issue. The bentonite-based seal around the canister with radioactive waste forms one of the barriers and it features significantly in most deep geological repository concepts since it will prevent free water movement to and from the canister and thus prevent the spread of radionuclides to the biosphere following the eventual deterioration of the canister.

The unique swelling, self-healing and sealing capabilities of bentonite play a major role in repository safety concepts in that they allow the bentonite barrier to withstand serious mechanical damage without its function being compromised. The rock surrounding the bentonite barrier might well contain fractures varying in size from micro-fractures in the excavation damaged zone (EDZ) to relatively large (several mm and more wide) fractures in the case of a catastrophic event which causes damage to the repository. One of the functions of the bentonite barrier is to seal such cracks and joints effectively, but not causing big mass losses into these cracks. Therefore, it is essential that the dynamics and mechanics of the sealing of cracks and joints by bentonite-based materials are thoroughly investigated. Here the bentonite/water/host rock relationship was studied in great detail with investigation work focusing on aspects such as bentonite host rock interaction (Gens *et al.*, 2002), bentonite water interaction (Arcos *et al.*, 2003) and bentonite erosion (Birgersson *et al.*, 2009; Push, 1983). Bentonite

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migration into fissures has been touched upon in a number of research projects (Birgersson *et al.*, 2009) and has been studied implicitly as part of several larger experiments. However, the only experimental work focusing specifically on this issue to date is that conducted by Tanai & Matsumoto (2008) for Kunigel V1.

The aim of this research is therefore to study how bentonite is able to fill voids of different sizes in the context of which a series of small experiments was designed and performed. The aim of these experiments was to determine to what extent bentonite is able to reach into linear fissures and the speed at which the process occurs.

EXPERIMENTAL WORK

Physical models were used to simulate the contact point of bentonite-based sealants with cracks in the rock mass. The models examined the ability of the tested material to fill the crack, thus preventing the creation of a preferential water pathway. The models simulated the contact zone of a bentonite-based material and a crack (discontinuity) in the rock mass upon contact with water which allowed the examination of the limits and dynamics of the processes underway.

Material

RMN bentonite, i.e. Ca-Mg bentonite from the Rokle deposit in the Czech Republic, was used for research purposes. The bentonite was mixed with quartz sand in some of the test series.

The Rokle deposit – bentonitized tuff and tuffites – forms part of the Tertiary north-Bohemian basin, the underlying bed of which is made up of pre-volcanic sediments and whose capping consists of a multi-layer formation of lava bodies (based on basalt) and pyroclastic rocks; all covered by Quaternary sediments. Rokle bentonite is calcium-magnesium-based and is mined by the Keramost, a. s. company (Chvátal, 1995). The percentages of individual minerals/chemicals contained in the raw bentonite used in the experiments are in Table 1.

Methodology

In order to investigate the swelling of bentonite into fissures a relatively simple experiment was designed. The aim was to mimic the linear contact of highly-compacted bentonite with a straight fissure.

The models consisted of highly compacted cubes (50 mm × 50 mm × 40 mm; ρ_d = 1600 kg/m^3) of bentonite-based material enclosed with concrete and featuring a mantissa which simulated the fissure (Fig. 2). The whole of the model was covered with a sheet of Perspex and submerged in water (Fig. 3). The artificial fissure was therefore filled with tap water from the outset and swelling took place primarily on the face of the cube exposed to it. As the water infiltrated more and more into the bentonite cube, swelling progressed and more material expanded into the fissure (Fig. 4). At the

TABLE 1. Composition of RMN bentonite (Křížová *et al.*, 2006)

Mineral	Montmorillonite	Illite	Kaolinite	Quartz	Calcite
Weight %	64	10	5	19	2

Mineral	$-H_2O$	$+H_2O$	SiO_2	TiO_2	Al_2O_3	Fe_2O_3
Weight %	7.55	4.58	46.73	3.14	11.48	10.02
Mineral	FeO	MnO	CaO	MgO	K_2O	Na_2O
Weight %	0.21	0.16	4.54	2.33	0.81	0.58
Mineral	S	CO_2	P_2O_5	C		Total
Weight %	0.04	2.5	0.52	4.89		100.08

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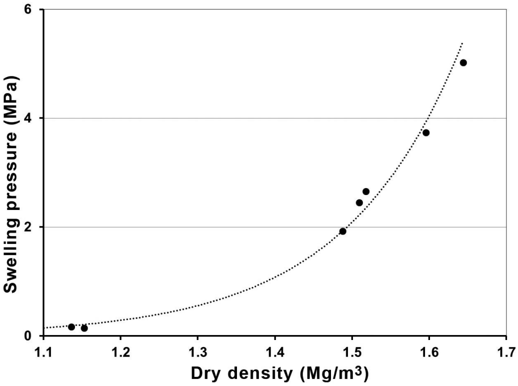

FIG. 1. Swelling pressure–dry density relationship for RMN bentonite.

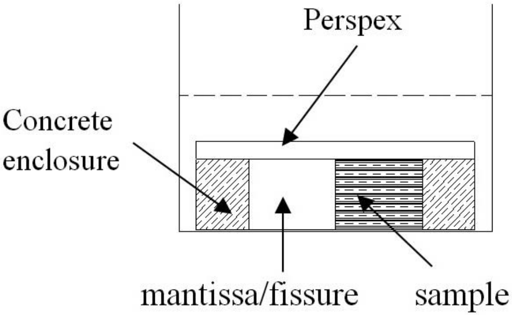

FIG. 2. Scheme of the physical model.

end of the process, the fissure was either partially or completely filled with bentonite depending on the material making up the cube.

The models were equipped with an easily exchangeable mantissa in order to simulate artificial fissures of various sizes (5, 10 and 16 mm). In this way the influence of void width was examined.

RESULTS

Several tests were performed on RMN bentonite (Fig. 5) and a bentonite/sand mixture. The advance of the bentonite was observed through the Perspex glass plate and recorded on daily basis. This allowed the study of the speed of the advance of the bentonite into the void and allowed the team to evaluate in detail the dynamics of the process.

The results show that in most cases total bentonite advance (for the same material) into fissures is, primarily, linearly dependent on fissure width (Fig. 6). The absolute value of advance could be related to the overall swelling ability of the material characterized by swell index or swelling pressure.

A SUMMARY OF THE THEORY

It is supposed that there must be equilibrium at the location at which bentonite enters the gap simulating the fracture (Fig. 7).

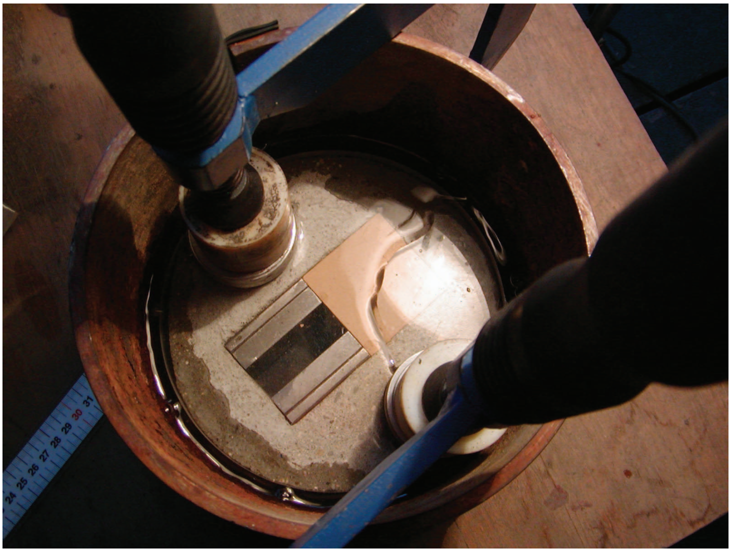

FIG. 3. Assembled physical model.

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FIG. 4. The advance of bentonite into a fissure.

A force acts at the entrance to the gap which is the result of swelling pressure pushing the bentonite into the fissure. This force (per metre of gap) is equal to:

$$F_{\mathrm{sw}} = \sigma_{\mathrm{sw,\ max}}\, d$$

where d is the aperture of the gap, and $\sigma_{\mathrm{sw,\ max}}$ represents the swelling pressure of the material outside the gap.

This force must be in equilibrium with friction τ on both sides of the gap. Friction depends on the stress σ and the friction coefficient φ.

$$\tau = \sigma.\tan(\varphi)$$

The total force (per metre of gap) arising from friction can be calculated as:

$$F_{\mathrm{fr}} = 2\int_0^l \tau dx$$

where l is the distance the material penetrated into the gap.

The principal source of stress inside the gap consists of the swelling pressure of the material therefore

$$F_{\mathrm{fr}} = 2\int_0^l \tau dx = 2\int_0^l \sigma_{\mathrm{sw}}(\rho_d).tg(\varphi)dx$$

Swelling pressure at full saturation is a function of dry density ρ_d. For most bentonite-based materials it can be approximated using an exponential function (Fig. 8: Šástka & Vašíček, 2012; Wanga *et al.*, 2012)

$$\sigma_{\mathrm{sw}}(\rho_d) = a.e^{b.\rho d}$$

where a and b represent material constants.

For the sake of simplicity the linear decrease of dry density in the gap can be assumed to be

$$\rho_d(x) = \frac{x}{l}.(\rho_{d,\ \max} - \rho_{d,\ \min}) + \rho_{d,\ \min}$$

$$\frac{d\rho d}{dx} = \frac{\rho_{d,\ \max} - \rho_{d,\ \min}}{l}$$

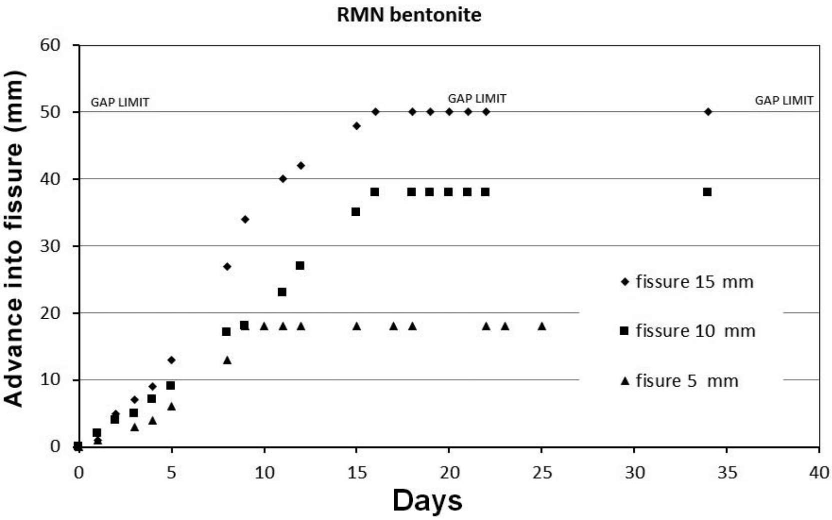

FIG. 5. Results for RMN bentonite.

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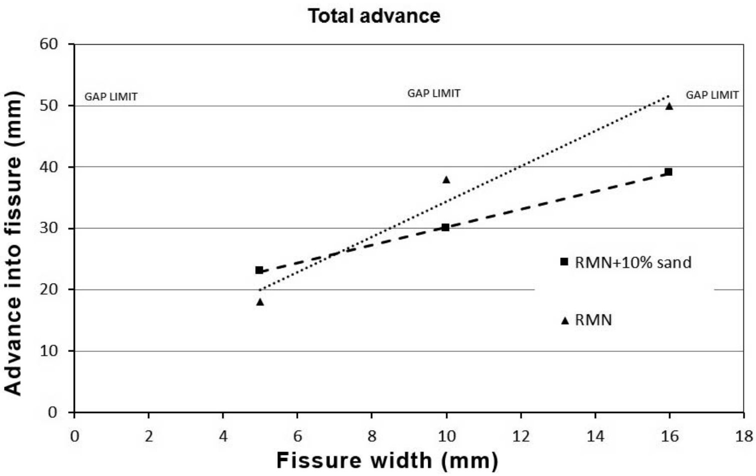

FIG. 6. Results for RMN bentonite and RMN+sand mixture.

Using the substitution

$$
\begin{aligned}
F_{\mathrm{fr}} &= 2\int_0^l \sigma_{\mathrm{sw}}(\rho_d).tg(\varphi)dx \\
&= 2\int_{\rho_{d,\ \mathrm{min}}}^{\rho_{d,\ \mathrm{max}}} a.e^{b.\rho_d}.tg(\varphi).\frac{l}{\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}}}d\rho_d \\
&= \frac{2}{b}tg(\varphi).\frac{l}{\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}}}.\left[a.e^{b.\rho_d}\right]_{\rho_{d,\ \mathrm{min}}}^{\rho_{d,\ \mathrm{max}}} \\
&= \frac{2}{b}tg(\varphi).\frac{l}{\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}}}.\left[\sigma_{\mathrm{sw,\ max}}-\sigma_{\mathrm{sw,\ min}}\right]
\end{aligned}
$$

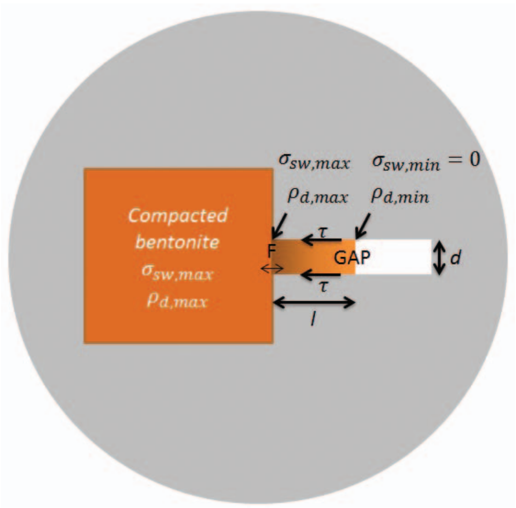

FIG. 7. Scheme

There is no swelling at the free face at the end of the gap. Therefore

$$\sigma_{\mathrm{sw,\ min}} = 0$$

$$F_{\mathrm{fr}} = \frac{2}{b}tg(\varphi).\frac{1}{\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}}}.\sigma_{\mathrm{sw,\ max}}$$

Note: $\rho_{d,\ \mathrm{min}}$ can be easily determined by the swell index because it represents dry density under free swelling conditions.

At this point it is possible to fully assemble the equilibrium equation:

$$F_{\mathrm{sw}} = F_{\mathrm{fr}}$$

$$\sigma_{\mathrm{sw,\ max}} = \frac{2}{b}tg(\varphi).\frac{1}{\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}}}.\sigma_{\mathrm{sw,\ max}}$$

From which it can be seen that the distance (material penetration into the fracture) has a linear dependence on fracture aperture d for the same material.

$$l = \frac{d.b(\rho_{d,\ \mathrm{max}}-\rho_{d,\ \mathrm{min}})}{2.tg(\varphi)}$$

CONCLUSION

Both the simplified analytical solution and the experimental results clearly indicate a linear dependence on the aperture of the fracture for the

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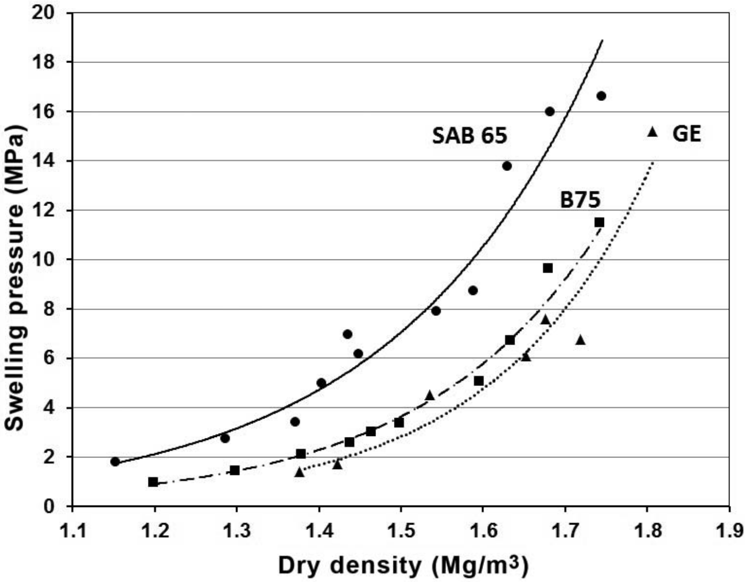

FIG. 8. Example of the swelling pressure–dry density relationship for various materials (Šťástka & Vašíček, 2012).

same material. Overall performance depends on the total swelling ability of the material given by its swelling pressure–dry density curve and the friction angle.

The next step of the research is to gather data for more bentonites and bentonite-based materials. This will allow the full verification of the derived dependency and checking of whether other parameters need to be included in the theoretical solution. A knowledge of how much bentonite fills the crack and the distance of penetration is important for the performance assessment of a repository. Unfilled cracks could create preferential pathways for water flow; moreover, low-density bentonite could be prone to water erosion.

The linear dependency indicates that long narrow fractures could pose more risk than wider fractures since, most probably, they will not be completely filled. From this point of view the character of the EDZ is of significance and is therefore of importance for both the buffer around the canister and the backfill of the access tunnels and shafts. The most significant risk concerns the access tunnels. Depending on the excavation technique employed, longitudinal fractures could be created within the EDZ (or fractures could be created as the result of a major seismic event etc.). Such fractures are less likely to be filled than fractures around the buffer since it is expected that the backfill will swell significantly less than the buffer (Arcos *et al.*, 2003). This is potentially very dangerous since it could lead to the creation of long pathways for the transport of water (potentially to the surface).

The above impacts repository performance not only with regard to water but it also impacts the way in which gas could propagate within the repository. The linear dependency factor means that in certain scenarios narrow fractures would not be sufficiently filled (since the bentonite would not advance far enough). A gradual decrease in bentonite density means that gas could take the opportunity to escape from the repository in this way since lower density means less "resistance" to gas flow. Together, unfilled or poorly filled sections of fractures along the access tunnels could potentially create undesired "collectors" for water and gas flow. Therefore, a knowledge of fracture filling and sealing is essential for the assessment of repository performance.

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