Influence of soil structure heterogeneities on the behaviour of backfill materials based on mixtures of bentonite and crushed rock

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Abstract

In situ compaction of a mixture of bentonite and crushed rock or sand has been proposed for backfill or buffer materials for the concept of nuclear waste disposal in many countries. At present a mixture of 30% bentonite and 70% crushed rock is used for backfilling tunnels in two full-scale tests in the Swedish underground laboratory Aspö HRL. In advance of those tests, mixtures of 0–50% bentonite and different ballast materials have been investigated in the laboratory regarding hydraulic conductivity, swelling pressure and other geotechnical properties. By comparing the results from different tests and also comparing them with expected properties, assuming that the bentonite is evenly and homogeneously distributed with a constant clay density in the ballast structure, a substantial influence of the soil structure has been exposed.

Inhomogeneous distribution of the clay matrix means that there are clusters of clay with higher density than the average clay density and also that there are pockets with very low or no clay. These clusters and pockets are believed to be of the same size as the grain size of the ballast material or up to 20 mm for the backfill used in ÅHRL. Laboratory results show that these inhomogeneities may result in several changes in properties. The differences increase with increasing heterogeneity.

The following conclusions regarding the influence of heterogeneities on the soil structure and the backfill properties were drawn:

- The influence of the soil structure on the hydro-mechanical properties of backfill materials is very strong
- Heterogeneities in grain size and bentonite distribution in centimeter scale in a backfill cannot be avoided with present mixing techniques
- In general, the heterogeneities increase with decreasing clay content at identical mixing procedure
- The influence is strong on swelling pressure and hydraulic conductivity
- Swelling pressure and hydraulic conductivity increase with increasing heterogeneities

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1. Introduction

Backfilling of tunnels and shafts in underground nuclear waste storage facilities is included in the basic concepts of most deep repositories. In the Swedish main concept with vertical deposition holes placed in...
the floor of parallel tunnels (KBS3-V), the function of
the backfill in the tunnels is vital for proper function-
ing of the repository. Before closure of the repository,
all connecting tunnels, shafts and rooms used for
transportation, etc. must be backfilled. The latter parts
stand for about half of the excavated rock volumes in
a KBS3-V repository and are thus also important for
the concept with horizontal placement of canisters in
deposition tunnels (KBS3-H).

The backfill is proposed to consist of a mixture of
ballast material (sand or crushed rock) and bentonite.
The production includes a procedure of mixing the
ballast and the bentonite and also adding water during
the mixing, since the backfill must have good com-
paction properties. The quality of the product
achieved after mixing depends much on the mixing
procedure and on the distribution of the grain size of
the ballast material and the granular size of the
bentonite. It is difficult to achieve a homogeneous
material considering the scale of a few centimeters.
Separation during transport and handling may also
contribute to heterogeneities in the backfill in a larger
scale.

The most important properties for the required
hydro-mechanical function of the backfill are the
hydraulic conductivity, the swelling properties and
the compressibility. Heterogeneities in the structure
of the backfill after compaction in the tunnels seem to
have a large influence on both the swelling properties
and the hydraulic conductivity but probably not very
much on the compressibility. Both laboratory tests and
theoretical considerations reveal these effects.

2. Backfill material

Mixtures of 0–30% bentonite and 100–70% bal-
last material are at present considered for backfill
material in the Swedish basic repository concept and
also tested in two large-scale engineering tests in
Åspö Hard Rock Laboratory. In one of the tests
(Backfill and Plug Test) the bentonite material con-
sists of natural sodium bentonite from Volclay MX-80
crushed to a granular size between 0.06 and 0.6 mm
(see Fig. 1) (Johannesson et al., 1999). In the other
test (Prototype Repository) the bentonite originates
from Milos in Greece (Silver and Baryte Ores Min-
ing). The bentonite has been converted from Ca-
to Na-bentonite by soda treatment and was ground and
dried by LKAB in Luleå. It was grind to a fine powder
with 90–95% of the dry particles smaller than 0.074
mm.

The ballast material is either crushed TBM-muck
(rest product from the TBM drilling of the test tunnel)
or a mixture of crushed rock (from drill and blast
evacuation) and commercially purchased fine grained
crushed granite (19%) and powder (7%). The latter is
used in the Backfill and Plug Test and the crushed

Fig. 1. Granule size distribution of MX-80 as bulk material and grain size distribution of dispersed MX-80 (Johannesson et al., 1999).
TBM muck is used in the Prototype Repository. The final grain size distribution of the ballast is composed to be moraine like (“Fuller curve” for optimal compaction properties) and similar for the two tests (see Fig. 2) (Gunnarsson et al., 2001).

Other ballast materials and bentonite types have also been used in some laboratory tests with up to 50% bentonite in the mixture.

3. Soil structure

The perfect homogeneous soil structure of these mixtures fulfils the following criteria:

(1) Homogeneous distribution of the ballast grains in the structure so that larger voids between large particles are filled with medium particles and the medium voids between these particles are filled with small grains and so on to a homogeneous mass without large voids.

(2) Homogeneous distribution of the bentonite in the voids between the ballast grains so that the clay
matrix has the same dry density in all voids and a density that thus can be calculated (clay dry density).

In a perfectly homogeneous soil the ideal clay void ratio $e_c$ can be calculated according to Eq. (1).

$$e_c = e \cdot \left(1 + \frac{\rho_{cs}}{\rho_{bs}} \cdot \frac{1 - K}{K}\right)$$  \hspace{1cm} (1)

where $e_c =$ ideal clay void ratio (total volume pores divided by volume clay solids); $e =$ void ratio of backfill (total volume pores divided by total volume solids); $K =$ clay content (clay dry weight divided by total dry weight); $\rho_{bs} =$ density of ballast solids; $\rho_{cs} =$ density of clay solids.

For the real soil structure, however, none of those criteria is fulfilled. The magnitude of the deviation depends mostly on the mixing procedure and equipment and the clay content. Field mixing in the scale for large tests with rebuilt concrete mixers yields more inhomogeneous backfill than laboratory mixing in high-speed mixers like Eirich mixers.

The inhomogeneities in the real structure can thus be caused by not fulfilling one of the two criteria or most likely both. Criterion 1 is probably more critical for the compaction properties and thus mainly affecting the compressibility, while at the same average dry density the hydraulic conductivity and swelling properties are mostly affected by criterion 2 since they are almost entirely depending on the clay properties.

The soil structure of an inhomogeneous backfill of such mixtures will thus contain small parts with no clay in the “ballast voids” and parts with clay. The density of the clay in the ballast voids may also vary, since the clay in the well-filled pores will be more...
compacted and thus have a higher density than poorly filled pores.

The inhomogeneities are also enhanced with decreasing percentage clay since the number and volume of the unfilled parts increase.

The real structure is complicated with many types of variations in the structure. Fig. 3 shows a picture of a 30:70 bentonite/crushed rock backfill after mixing. Fig. 4 shows an outline of the structure after compaction but before wetting and Fig. 5 shows the structure after wetting. Three different types of bentonite fillings before wetting are shown and exemplified with numbers:

- Well-filled pores (numbers 1–3)
- Partly filled pores (numbers 4–6)
- Unfilled pores (numbers 7 and 8)

After wetting the bentonite in the pores is assumed to be homogenized and not to have affected the ballast structure. The result of the saturation is illustrated with three different pore types:

- Pores with high bentonite density
- Pores with low bentonite density
- Empty pores

The real structure may be both more and less homogeneous than the outline in Figs. 4 and 5 but it is obvious from these figures that the properties must differ from the properties of a structure with evenly distributed bentonite with the same density in all pores. Fig. 5 agrees well with a digitalized micrograph of a thin section of the backfill (see Fig. 8.3 in Pusch et al., 1999).

4. Influence on swelling pressure

The swelling pressure of a perfectly mixed backfill, with evenly distributed bentonite in all pores in
the ballast structure, can be calculated from the measured swelling pressure of pure bentonite considering the ideal clay void ratio $e_c$. This swelling pressure is the same as the swelling pressure of the clay matrix $e_c$ if one assumes that all voids are filled with clay (corresponding to the effective stress theory but clay pressure instead of water pressure). However, the measured swelling pressure $\sigma_m$ differs from $\sigma_c$ if all pores are not filled. The average void ratio of the pores filled with clay, here named the effective clay void ratio $e_e$, may be derived from the clay void ratio that corresponds to the swelling pressure $\sigma_m$ of pure clay. By comparing $e_e$ and $e_c$ the degree of clay filling $D_e$ (volume of filled pores divided by total pore volume) may be derived. $D_e$ is calculated from

<table>
<thead>
<tr>
<th>Bentonite content/salt content</th>
<th>Void ratio $e$</th>
<th>Ideal clay void ratio $e_c$</th>
<th>Measured pressure $\sigma_m$ (kPa)</th>
<th>$\sigma_m/\sigma_c$</th>
<th>Effective clay void ratio $e_e$ (from $\sigma_m$)</th>
<th>$D_e = e_e/e_c$</th>
<th>Source $\sigma_m$</th>
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<td>1.02</td>
<td>1.01</td>
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<td>0.76</td>
<td>3600</td>
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<td>21</td>
<td>4*</td>
<td>5.3</td>
<td>2.5</td>
<td>0.71</td>
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</tbody>
</table>

* Extrapolated from measurements.

The swelling pressure of MX-80 bentonite as a function of void ratio with saline and nonsaline water added. Compiled from Börgesson et al. (1995) and Karnland et al. (2000).
the ideal clay void ratio \(e_c\) and the effective clay void ratio \(e_e\) according to Eq. (2)

\[
D_c = \frac{e_c}{e_e}
\]  

(2)

where \(D_c\) = degree of clay filling in the pores; \(e_c\) = ideal clay void ratio assuming all voids are filled with clay with the same void ratio; \(e_e\) = effective clay void ratio considering only the voids that are filled with clay (assumed having the same void ratio).

A number of measurements of swelling pressure have been made. The results of such measurements on backfill with different water added are shown in Table 1. Both measured swelling pressure \(\sigma_m\) and the swelling pressure \(\sigma_c\) taken from the swelling pressure at the ideal clay void ratio \(e_c\) are shown. The effective void ratio \(e_e\) and the degree of clay filling \(D_c\) are also shown. The swelling pressure of the clay matrix is taken from the measurements shown in Fig. 6 when both salt water and salt-free water are added (compiled from Börjesson et al., 1995 and Karmland et al., 2000).

The results show that the expected swelling pressure (assuming completely homogeneous clay matrix that fills up the entire pores) is lower for all materials except for some of the 50:50 mixtures. The mixtures of 10% and 30% bentonite have a much higher measured swelling pressure than expected, which means that the homogeneity is poor, since the clay density of the filled pores must be much higher and thus yield a much higher swelling pressure. The degree of clay filling \(D_c\) is thus low (0.3–0.7) and, since the void ratio decrease is an about linear function of the decreasing degree of clay filling while the increase in swelling pressure as a function of the decrease in void ratio is logarithmic, the resulting swelling pressure is much higher if the homogeneity is poor. However, the 50% clay mixture has a rather small difference between expected and measured swelling pressure, which shows that the homogeneity is much better, probably due to the high bentonite content, which makes the ballast structure separate and allows for the bentonite to fill all the space between the grains. The degree of clay filling is thus also close to 1.0.

Water with salt content 1.2% has been added to some of the tests. The difference between expected and measured results is about a factor 6 for these mixtures and the degree of clay filling 0.7, which is about the same as for the salt free mixtures. In Fig. 7 the swelling pressure relation \((\sigma_m/\sigma_c)\) is plotted as a function of the degree of clay filling, and in Fig. 8 the degree of clay filling is plotted as a function of the bentonite content.

5. Influence on hydraulic conductivity

It is obvious from the layout of the soil structure in Fig. 5 that also the water transport in the backfill must be affected by the heterogeneities. If water is trans-
ported from left to right in the soil in Fig. 5, one can find some preferential paths that the water will seek. Fig. 9 shows two such paths. In these 10–15-mm-long paths only 2–3 mm are closed by clay gel. If in a sample tested in laboratory there are a few such paths that may be even less hindered by clay, they may dominate the flow and yield a much higher hydraulic conductivity than the corresponding structure that has clay evenly distributed in all pores.

Several laboratory determinations of the hydraulic conductivity of backfill materials have been performed and a similar study can be done as was done concerning the swelling pressure. The expected hydraulic conductivity $k_e$ is calculated according to Eqs. (3) and (4).

$$k_e = k_c n_b$$  \hspace{1cm} (3)

$$n_b = \frac{e_b}{1 + e_b}$$  \hspace{1cm} (4)

where $k_e =$ expected hydraulic conductivity; $k_c =$ hydraulic conductivity of the clay in the pores assuming homogeneous density; $n_b =$ ballast porosity; $e_b =$ ballast void ratio (Eq. (5)).

$$e_b = (e_c + 1) \cdot \frac{K}{1 - K} \cdot \frac{\rho_{bs}}{\rho_{cs}}$$  \hspace{1cm} (5)

where $e_c =$ ideal clay void ratio; $K =$ clay content (clay dry weight divided by total dry weight); $\rho_{bs} =$ density of ballast solids; $\rho_{cs} =$ density of clay solids.

Table 2 shows the results of measured hydraulic conductivity and the expected results calculated according to Eq. (3).

$k_c$ is taken from measurements on pure MX80 bentonite compiled in Fig. 10 for 0% and 1.2% salt content in the added water (from Börgesson et al., 1995 and Karnland et al., 2000).

The results show that the measured hydraulic conductivity is higher or much higher than expected for all backfills.

These tests, which are done in the same way with the same mixing and testing technique, show that for salt-free water there is a change in behav-
our at about 30% bentonite content for the tested backfill materials. At that bentonite content the blocking of water pathways with bentonite seems large enough to make the system work as predicted, while this is not the case for lower bentonite contents. The influence of salt is (except for a general increase in hydraulic conductivity) that the difference between measured and predicted conductivity is larger and occurs also for 30% bentonite content. The lower swelling potential of the bentonite when salt is added seems to reduce the blocking possibility and allows for the passages shown in Fig. 9.

Fig. 11 shows the influence of the bentonite content on the increased hydraulic conductivity, that is \( k_m/k_e \) as a function of the bentonite content. The general trend is that lower clay content and higher salt content yield larger increase except for the com-

<table>
<thead>
<tr>
<th>Bentonite content/salt content</th>
<th>Void ratio ( e )</th>
<th>Ideal clay void ratio ( e_c )</th>
<th>Measured hydraulic conductivity ( k_m ) (m/s)</th>
<th>Ballast porosity ( n_b )</th>
<th>Expected hydraulic conductivity ( k_e ) (m/s) from ( e_c )</th>
<th>( k_m/k_e )</th>
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<td>30%/0%</td>
<td>0.49</td>
<td>1.70</td>
<td>( 3 \times 10^{-12} )</td>
<td>0.54</td>
<td>( 1.5 \times 10^{-12} )</td>
<td>2.0</td>
<td>Johannesson et al. (1999)</td>
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<td>( 6.7 \times 10^{-12} )</td>
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<td>( 7 \times 10^{-13} )</td>
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<td>( 2 \times 10^{-9} )</td>
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<td>( 8.4 \times 10^{-10} )</td>
<td>18</td>
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</table>

\( ^a \) Extrapolated from measurements.

Fig. 10. Hydraulic conductivity of MX-80 bentonite as a function of void ratio with saline and nonsaline water added. Compiled from Börgresson et al. (1995) and Karnland et al. (2000).
combination of 10% bentonite content and 1.2% salt, but
the expected hydraulic conductivity was for this case
taken from an extrapolated value of hydraulic con-
ductivity, which may be incorrect.

6. Conclusions

The influence of heterogeneities in the soil struc-
ture of backfill materials made of mixtures of crushed
rock and bentonite powder on the hydromechanical
properties is very strong. At poor mixing or low
bentonite content, the bentonite will be unevenly
distributed in the pores between the ballast particles.
With the present mixing technique and the materials
used for the tests referred to in this article, it seems
the limit where the backfill will be inhomogeneous is
between 30% and 50% bentonite content. 30:70 and
low salt content seems though to be a good combi-
nation since the measured swelling pressure is higher
and the measured hydraulic conductivity only slightly
higher than the theoretical values for an ideally
homogeneous material.

The result of such heterogeneities is that the
swelling pressure of the backfill is higher than would
have been the case if the bentonite had been evenly
distributed, since the pores with bentonite of high
density dominate the swelling pressure behaviour.
Evaluation of the degree of bentonite filling in the
pores $D_{c}$ shows that it varies, as expected, very much
with bentonite content. $D_{c}$ $\sim$ 0.4 for backfill with
10% bentonite, $D_{c}$ $\sim$ 0.7 for backfill with 30%
bentonite and $D_{c}$ $\sim$ 1.0 for backfill with 50% ben-
tonite.

The hydraulic conductivity is increased by these
heterogeneities since pathways for water transport are
formed. Bentonite content, mixing technique and salt
content in added water seem to influence these devia-
tions from expected behaviour.

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