Kuusela-Lahtinen, Auli; Sinnathamby, Gowthaman; Mendez, João; Sołowski, Wojciech T.; Gallipoli, Domenico; Pintado, Xavier; Korkiala-Tanttu, Leena K.

Estimation of water retention behaviour of MX-80 bentonite partially saturated with saline solution

Published in:
3rd European Conference on Unsaturated Soils – E-UNSAT 2016

DOI:
10.1051/e3sconf/20160911006

Published: 12/09/2016

Please cite the original version:
Estimation of water retention behaviour of MX-80 bentonite partially saturated with saline solution

Abstract. The water retention behaviour of partially saturated MX-80 bentonite with pure water is relatively well investigated. However, in practical cases, the water contains a number of chemical compounds which affects the bentonite behaviour. In particular, bentonite is used in buffer applications of geological repositories for spent nuclear fuel, where the concentration of total dissolved solids in groundwater is expected to increase significantly with time. This paper investigates water retention behaviour of MX-80 type bentonite partially saturated with deionised water as well as 1M NaCl solution. In the experiments the specific volume of bentonite has been kept approximately constant.

1 Introduction

A wide range of bentonite and other swelling clay materials have been studied extensively, partially because of their potential for creating nearly impermeable self-healing barriers. Those barriers are useful for isolating toxic waste material, such as nuclear waste. Due to the very long service life of such barriers, the understanding of the barrier material must be very thorough. Likewise, the accuracy of the barrier material characterisation must be exceptional.

The present study describes the water retention behaviour of MX-80 bentonite partially saturated with: (1) deionised water and (2) 1 molar solution of NaCl. The paper adds to significant existing body of knowledge on MX-80 bentonite water retention behaviour e.g. [1-8].

Establishing the water retention curve is essential for determination of its behaviour upon wetting and drying. Water retention must be known not only for deionised water, but also for wide range of saline solutions. This study uses mainly filter paper technique to estimate the matric and total suctions of partially saturated bentonite. Filter paper data has been compared to the psychrometer measurements for selected bentonite samples.

2 Materials and Methods

2.1 Material

MX-80 bentonite has been formed as a result of hydrothermal alteration of volcanic ash during the Cretaceous period. No characterisation of the material has been performed in this study. Based on [1], MX80 bentonite is composed mainly of montmorillonite (65–82%), quartz (4–12%), feldspars (5–8%), and smaller quantities of cristobalite, calcite and pyrite. The liquid limit and plastic limits of the MX-80 bentonite are 350%-570% and 70%, respectively. The density of the bentonite grains in the study was taken as 2.82 Mg/m³ [1].

Figure 1. MX-80 bentonite from Wyoming, USA: a) raw bentonite powder, b) hydrated with 1M NaCl solution (target saturation after compaction 40%), and c) hydrated with deionized water (target saturation after compaction 40%).

Cretaceous period. No characterisation of the material has been performed in this study. Based on [1], MX80 bentonite is composed mainly of montmorillonite (65–82%), quartz (4–12%), feldspars (5–8%), and smaller quantities of cristobalite, calcite and pyrite. The liquid limit and plastic limits of the MX-80 bentonite are 350%-570% and 70%, respectively. The density of the bentonite grains in the study was taken as 2.82 Mg/m³ [1].

The MX-80 bentonite utilised in the study was supplied in a powder form with the original gravimetric...
water content being around 11-12%. Deionised water and 1 M NaCl water solution were used for hydrating the samples to the target saturation levels.

### 2.2 Methods

In order to prepare the cylindrical samples (50mm diameter, 20mm height), the oven dried (105 ºC) MX-80 bentonite powder was mixed with water (pure or saline, as required). The amount of water has been chosen such that the desired target degree of saturations and specific volume should be reached after pressing the samples to the correct height.

Upon mixing, the saline water yielded a fairly uniform mixture of MX-80 with small lumps, while the deionized water produced larger lumps (Fig. 1). The mixture was then placed in an air-tight plastic bag and sealed. The lumps were crushed manually inside the sealed plastic bag to ensure a uniform distribution of moisture within the mixture. Once the mix was uniform, it was left in the sealed bag for two weeks to equilibrate at room temperature.

The pressing procedure has been the same for all the samples. Following the equalisation period of at least two weeks, carefully weighted amount of bentonite powder at water content correct for the targeted degree of saturation has been put into the steel mould. The mould was coated with a very thin layer of PTFE lubricant. The top and the bottom of the sample were isolated from the piston and background by thin plastic sheets (so almost no moisture could escape the bentonite during pressing).

Then the samples have been uniaxially pressed at a loading rate of around 1mm/min till reaching the desired height of 20 mm (Fig. 2 a,b). Due to noticeable relaxation of the samples after the initial pressing (around 0.6 mm), they were pressed multiple-times. The target dry density of all the samples was 1.6 g/cm³. See Figure 3 for typical stress-displacement curves.

Samples have been measured multiple times in order to estimate their volume. Knowing the sample volume, water content and wet weight, dry densities were computed (Fig. 4). However, despite using high accuracy press and significant care, some variation of dry density (as indicated in Fig. 4) was unfortunately impossible to avoid. However, the achieved uniformity of dry density is similar to that of previous studies [1]. The dry-density variation seems to be correlated with the sample degree of saturation, as well as with the salinity of pore fluid. To achieve more uniform dry density distribution of samples, instead of following the same preparation procedure for all the samples, the procedure perhaps should be modified for drier and wetter samples. The drier samples should be pressed to lower height and the wetter samples to higher height.

In a conventional filter paper test, a single soil specimen is cut into two halves and the ‘contact filter paper’ for matric suction measurements is placed in between. However, since the bentonite samples were almost impossible to cut into two pieces, as an alternative, both halves were pressed separately (the target height of each was 20 mm) to produce quite identical samples. Pressed samples were then sealed in air-tight plastic bags and left for moisture equalisation for at least one night before commencing the filter paper test.
Soil suction measurement with filter paper technique is well established method of estimation of suction. The major advantage of this technique is the ability to measure both total and matric suction quite reliably without expensive equipment.

The filter paper technique measures suction indirectly by relating the water absorbed by the filter paper with suction by means of a calibration curve for the particular filter paper used. The total suction is measured with a filter paper not being in contact with the sample; hence the paper is wetted via the water vapour. The contact filter paper measures matric suction.

The Whatman® Grade 42 type filter paper was used in the present study. The filter paper was cut to fit the diameter of the bentonite samples. The experimental procedure was very similar to these in [9,10].

In the filter paper test, a contact filter paper, sandwiched between the upper and lower halves of the soil sample, measures the matric suction. The contact filter paper is enclosed by two high-permeable protective filter papers to avoid any contamination. The non-contact filter paper, placed on top of the soil specimen measures the total suction (Fig. 5).

Once the contact-filter paper was in position, an electrical tape was used to tape both halves of the samples together to enforce firm contact between the filter papers and the samples. The filter paper assembly was then immediately enclosed in an air-tight transparent plastic jar and the lid was taped with the electrical tape to prevent any possible exchange of humidity with the environment. The jars in the present study were oriented upside-down (Fig. 4d) (lid on the floor). This orientation facilitates the emplacement and removal of the bentonite sample and the non-contact filter paper without much disturbance in shorter period of time compared to the orientation proposed in [9].

The jar was then stored inside an air-tight plastic container (Fig. 2e). The plastic container was subsequently placed in a constant temperature water-bath (+25°C ±0.2°C) for equilibration over a period of two weeks (Fig. 2f). The equilibration period was longer than often recommended 1 week (e.g. [9]) to make sure the equilibrium is fully reached.

Once the equilibration time is over, the assembly was removed from the water bath and the gravimetric water content of the filter papers were determined with a high precision scale of 0.0001g accuracy (Fig. 2g). Insertion of a piece of thermal insulation material between the metal plate of the balance and the aluminium tin containing the wet filter paper helped to minimise the waiting time for a stable reading. Corresponding suction values were obtained from the calibration curves (see section 2.2.3).

To determine the matric suction of the MX-80 specimens, calibration curves for Whatman 42 filter paper by Hahmlin [11] (eq. 1), Leong et al. [12] (eqs. 2 & 3) alongside the standard ASTM [10] (eqs 4 & 5) as well as using calibration using van Genuchten [13] curve (eq. 6, 14) were tested in the present study:

\[
\log \Psi = 8.022 - 3.683 \log w_f 
\] (1)

\[
\log \Psi = 2.909 - 0.0229 w_f, w_f \geq 47
\] (2)

\[
\log \Psi = 4.945 - 0.0673 w_f, w_f < 47
\] (3)

\[
\log \Psi = 5.327 - 0.0779 w_f, w_f \leq 45.3
\] (4)

\[
\log \Psi = 2.412 - 0.0135 w_f, w_f > 45.3
\] (5)

\[
\Psi = 0.051 \left( 248/w_f \right)^{6.615} - 1 \right]^{0.473}
\] (6)
where Ψ is soil suction (kPa) and \( w_f \) is filter paper water content (%). Unfortunately, there is relative lack of calibration data in high suction ranges typical for bentonite (corresponding to suctions above 10 MPa), as shown in Figure 6. In the calculations, ultimately the ASTM calibration has been used.

Filter paper, when initially wetted by a saline solution and subsequently dried, will change its mass due to the salt residual from absorbed water. To take that effect into account, we note that in each dm\(^3\) of 1M saline solution there is 58.44 g of NaCl and that the density of such solution at 25 °C is approximately 1042.54 g/dm\(^3\). Hence, for 1M solution of NaCl, the salt mass remaining in the filter paper after evaporation of water is equal to the evaporated water mass multiplied by \( 58.44 / (1042.54 - 58.44) \). The filter paper water content was than calculated as the quotient of the evaporated water mass and the clean dry filter paper mass, which is, in turn, the difference of the weighted dry filter paper mass and the mass of salt remaining on the filter paper:

\[
wf = \frac{\text{water mass}}{\text{dry filter paper mass} - \text{salt mass}} \quad (7)
\]

### 3 Results and discussions

In the experimental program 36 samples partially saturated with pure water and 33 samples partially saturated with 1 molar solution of NaCl were tested. The degree of saturation of samples varied from approximately 10% to above 95%.

The results for bentonite saturated with pure water are shown in Figure 7. Figure 8 shows that those suctions are within the range of the typical published values, e.g. [1, 3, 5-6] and are further confirmed by psychrometer readouts (Table 1). The water retention curve for bentonite partially saturated with 1 molar NaCl (Fig. 9) is
somewhat different to that of deionised water. Matric
suctions for pure and salty water are shown in Figure 10. It
is quite clear that most significant difference in the
water retention behaviour for pure and salty water is at
higher saturations. The likely reason is that saturating
the bentonite with the salty solution leads to creation of
different microstructure and pore sizes in the material.
That, in turn, leads to quite different water retention
characteristic. However, some part of the differences may
be attributed to the variation in dry densities of the
samples saturated with pure water and salty solution.

As a first check of the filter paper technique accuracy, the
obtained suctions have been compared against values
from psychrometer tests. Suctions obtained with the filter
paper technique seem to match the psychrometer results
reasonably well (see Table 1), with the biggest difference
at very high suction where filter paper measurements are
known to be less reliable.

Furthermore, it is expected that, on average, the
difference between total and matric suction in case of
samples saturated with deionised water should be low (as
the osmotic suction component should be zero assuming
no salt is present in the natural bentonite; very small
amounts of salt may be present though [20]). That is
indeed confirmed – the average difference between the
matric and total suction measurements (for all the
samples partially saturated with water) is just 0.083 MPa.
However, the standard error of that mean value is
significant and equal to 1 MPa. In case the error in for
each value is computed in % of the total suction, the
standard error of the mean is approximately 2%.
Similarly, for salty solution the average difference
between matric and total suction is 3.95 MPa. That value
matches the estimated value of osmotic component of
suction (4.6 MPa [14]) somewhat poorer than in the case
of deionised water. The standard error of the difference
between total and matric suction is also higher
(approximately 2.05 MPa). Hence the obtained mean
value of 3.95 MPa is within reasonable statistical error.
Finally, omitting the correction for salt residue in the dry
filter paper decreases the average value of the osmotic
suction to 3.67 MPa (standard error remains the same).
All the measurements were made for three samples with
the same target degree of saturation. Those samples have
some unavoidable variation in dry density (see Fig. 4).
That variation, unfortunately, affect the suction values in
the samples. Nonetheless, having sets of three samples
for each degree of saturation, it is possible to compute the
average value and standard deviation of each set
(Fig. 11), even though such error estimates based only on
three data-points should be treated with caution.

Averaging the average standard error for each three
samples set gives approximately 1.5 MPa (matric suction,
water), 1.4 MPa (total suction, water), or approximately
3% and 2.7% of the suction value, respectively. Those
values for matric (2.9 MPa, 4.6%) and total suction (2.7
MPa and 3.7%) in samples partially saturated with 1M
NaCl solution are again higher. It is unclear why, despite
following exactly same procedure for samples saturated
with pure water and salty solution, the inaccuracies are
larger for salty solution.

The standard error of the degree of saturation value is
very small for most of the samples. The averaged values
for all the samples are 0.0023 (0.47%) and 0.0039
(0.73%) for samples partially saturated with pure water
and saline solution, respectively. The errors are so small
that they could not be shown in Figure 11.

In general, the obtained water retention characteristic of
bentonite fit reasonably well into the known body of data.
However, there are some interesting features that attract
attention.

In particular, there is somewhat significant variance
between the matric and total suction values close to
saturation seen in samples partially saturated with each

---

**Table 1. Comparison of filter paper and psychrometer results.**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sr [%]</th>
<th>Suction [MPa]</th>
<th>Difference [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>51_w_20_3</td>
<td>20.3</td>
<td>98.7</td>
<td>120.3</td>
</tr>
<tr>
<td>11_w_40_5</td>
<td>34.8</td>
<td>78.0</td>
<td>85.1</td>
</tr>
<tr>
<td>35_w_80_4</td>
<td>68.8</td>
<td>35.2</td>
<td>39.9</td>
</tr>
<tr>
<td>45_w_100_3</td>
<td>90.5</td>
<td>20.2</td>
<td>20.7</td>
</tr>
</tbody>
</table>

---

**Figure 11. Standard errors (computed based on 3 samples for
each average value) for matric and total suctions.**
liquid (in case of salty solution, beyond the expected value of osmotic suction) which are difficult to explain (Figs 7 & 9).

Furthermore, there are clear differences in matric suction in the region of high saturations between samples saturated with pure and saline liquid (Fig. 10). Those differences may be due to differences in microstructure caused by saline solution, as well as some variation of dry density. Should they be confirmed in further studies, they may be one reason of the altered bentonite behaviour when saturated with salty solutions.

4 Conclusions & future work

The paper provides further data on water retention behaviour of MX-80 bentonite. The aim of the study was to obtain high quality consistent set of water retention data for bentonite. Here only the results from the first part of the testing program is shown – the investigation of the effects of various saline solutions will be continued in summer 2016. Presented data will also be further confirmed by psychrometer measurements of total suction. Subsequent microstructural investigations are also planned.

The planned testing program will offer further insights on how salinity affect the water retention behaviour of bentonite, as well as perhaps provide some further link between changes in microstructure, salinity of wetting liquid and water retention behaviour. These results, in turn, will allow for more accurate prediction of long term behaviour of bentonite barriers. Providing such predictions is the final goal of this research program.

Acknowledgements

The authors would like to gratefully acknowledge that the presented research has been funded by K YT2018 Finnish Research Programme on Nuclear Waste Management via THEBES project.

References