Evaluation of the impact of pore fluid properties on the 1D Consolidation behaviour of clay based sealing material

Sumi Siddiqua
Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada
James A. Blatz
Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada

ABSTRACT
A series of 1D consolidation tests were performed on dense backfill (DBF) material with varying pore-fluid conditions and boundary constraints. Three types of fluid including distilled water (DW), NaCl and $CaCl_2$ solutions with salinity as high as 250 g/L were used as mixing fluid and reservoir fluid as specified in the experimental program. Confined and free swell were the two different types of boundary condition applied during initial saturation of the specimen. The two types of boundary condition were implemented to examine the effect of the boundary condition on initial saturation. The primary objective of these tests was to observe the influence of the pore fluid on the 1D consolidation behaviour of sealing materials proposed in the Canadian Repository sealing system. Also, the hydraulic and mechanical parameters of DBF material obtained from the consolidation tests are important for numerical modelling. The tests specimens were prepared in the in the Geotechnical Laboratory of the University of Manitoba from the dense backfill (DBF) material supplied by Atomic Energy of Canada Limited. All consolidation tests were carried out in the laboratory with specially designed oedometers suitable for dense backfill. Results of the test are discussed with reference to the hydro-mechanical behaviour and the potential influence on the materials appropriateness to be used as an engineered sealing material.

RÉSUMÉ
Une série d'essais de consolidation 1D a été réalisée sur du matériel de remblayage dense avec des conditions de fluide interstitiel variables et des contraintes aux limites variables. Trois types de fluide incluant l'eau distillée et des solutions de NaCl et de $CaCl_2$ avec la salinité aussi élevée que 250g/L ont été utilisés comme solvant et fluide de réservoir comme spécifié dans le programme expérimental. Confiné et dilatation libre étaient les deux différents types de conditions aux limites utilisés durant la saturation initiale du spécimen. Deux types de conditions aux limites ont été utilisés pour examiner l'effet des conditions aux limites sur la saturation initiale. L'objectif primaire de ces essais était d'observer l'influence du fluide interstitiel sur le comportement de la consolidation 1D des matériaux étanchéités proposés dans le système canadien de dépôt de matériau étanchéité. Aussi, les paramètres hydrauliques et mécaniques du matériel de remblayage dense obtenus à partir des essais de consolidation sont importants pour la modélisation numérique. Les échantillons étaient préparés dans le laboratoire géotechnique de l'université du Manitoba et ont été fournis par l'Énergie atomique du Canada limitée (EACL). Tous les essais de consolidation ont été effectués dans le laboratoire avec un oedomètre conçu spécialement pour du matériel de remblayage dense. Les résultats des essais sont discutés avec référence au comportement hydromécanique et l'influence potentiel sur la convenance des matériaux à être utilisé comme un matériau étanchéité.

1 INTRODUCTION

Multiple sealing system components are considered to be used in an emplacement room according to the design proposed in Ontario Power Generation's third case study for safe disposal of used nuclear fuel (Gierszewski *et al*. 2004). The design includes five different clay-based materials surrounding two containers aligned horizontally in the emplacement room. Various clay and aggregate mixtures will be used to provide the desired performance properties for the sealing and backfilling materials. A highly compacted 100 % bentonite (HCB) will be used to isolate the fuel containers from the geosphere. Bentonite clay that is mainly composed of smectite clay minerals is often preferred as a sealing and backfilling material due to its swelling potential and low permeability. Upon water uptake the sealing material close to the containers (HCB) will expand more than other less active sealing materials such as dense backfill (DBF). Eventually the less active sealing materials are expected to compress due to the swelling pressure imposed by the smectite rich materials. The interactive volume deformation processes of expanding and compression for each of the sealing system components are likely to continue until static equilibrium is attained.

Recognizing the potential issues related to system compliance, Chandler (2005) developed a numerical model based on the proposed in-room emplacement geometry to address the relative compliance of the in-room sealing system components on full saturation. In this regard, following the recommendation of Chandler (2005), to ensure the parameters of material properties used in compliance modelling are appropriate, a series of laboratory consolidation tests have been identified by Atomic Energy of Canada Limited (AECL).

There are ongoing research programs to evaluate the effect of high salinity on the hydraulic conductivity (k) and the swelling capacity of highly compacted bentonite based material (Karnland, 1998; Pusch 2001; Dixon *et al*. 2001; Villar 2005; Castellanos *et al*. 2008). Also, Dixon *et al*. 2002 presented hydraulic conductivity of DBF with maximum salinity of 60 g/L TDS (total dissolved solid). Therefore, this paper focuses on the hydro-mechanical behaviour of DBF material under the influences of various pore fluids. To examine the chemical impact on swelling, compression, stiffness and permeability of DBF a series of one dimensional oedometer tests were performed with distilled water (DW) and varied concentration of saline water (NaCl and $CaCl_2$). Also two different boundary conditions named as confined and free swell were studied during initial saturation of the specimen.

2 MATERIAL AND METHODS

2.1 Dense backfill material (DBF)

Dense backfill is one of the engineered barrier materials in the Canadian proposed repository system, described by Russell and Simmons (2003) and Maak and Simmons (2005). As summarized by Russell and Simmons (2003) dense backfill is currently defined as being composed of (5-6)% bentonite, 25% glacial clay and 70% crushed granite aggregate. It is compacted to a dry density of 2.12 Mg/m^3, with 10.6% water content to provide an initial saturation of approximately 80%. Specimens were provided to the University of Manitoba's Geotechnical Laboratory by Atomic Energy of Canada Limited.

2.2 DBF oedometer testing

Due to the large granite chips (size up to 35 mm) in the dense backfill, modified oedometer cells were constructed for this testing program. The cells were manufactured at the University of Manitoba using type 316 stainless steel to provide corrosion resistance for the use of concentrated salt solutions. The dimensions of the cells are 101mm in diameter and 101mm in height. Oedometer specimens were prepared by manually compacting the material inside the sample ring. Once the specimens were compacted to the target conditions, the sample ring was placed in the apparatus and the specified initial conditions were applied as defined by the testing matrix as shown in Table 1.

Table 1: Test schedule for 1D-Consolidation Tests of Dense Backfill (DBF)

Sample ID.	Mixing Fluid	Reservoir Fluid	Boundary Condition During Saturation
DBF1(06)	DW	DW	Initial Swelling
DBF2(06)	DW	DW	CV (confined)
DBF3(06)	100 g/L $CaCl_2$	100 g/L $CaCl_2$	Initial Swelling
DBF4(06)	100 g/L $CaCl_2$	100 g/L $CaCl_2$	CV (confined)
DBF5(06)	DW	DW	CS (confined)
DBF6(06)	100 g/L $CaCl_2$	100 g/L $CaCl_2$	CS (confined)
DBF1(08)	250 g/L $CaCl_2$	250 g/L $CaCl_2$	Initial Swelling
DBF2(08)	DW	250 g/L $CaCl_2$	Initial Swelling
DBF3(08)	250 g/L $CaCl_2$	250 g/L $CaCl_2$	CV (confined)
DBF4(08)	DW	250 g/L $CaCl_2$	CV (confined)
DBF5(08)	250 g/L NaCl	250 g/L NaCl	CV (confined)
DBF6(08)	DW	250 g/L NaCl	CV (confined)

Note: CV: Constant Volume; CS: Constant Vertical Stress; DW: Distilled Water

3 TEST RESULTS

3.1 Mechanical responses

3.1.1 Distilled water

The initial void ratio's were consistent for the three specimens prepared with distilled water yet the varying initial conditions resulted in varying void ratios under similar loading increments, as shown in Figure 1. The compression index varies considerably until a pressure of 1 MPa is reached. Later the slopes stabilize to a consistent value. The compression index ranges between 0.049 and 0.051, demonstrating a log linear behaviour of the material in the stress range between 1 and 4 MPa. The lack of linearity in the lower stress range could be attributed to particle realignment of the bentonite aggregate matrix; a secondary compression, *i.e.* creep. The swelling index varies between 0.005 and 0.007 over a wider stress range of 250 kPa to 4 MPa.

3.1.2 Saline solution

Similar to the distilled water specimens, the as prepared void ratios for the same concentration saline solution specimens are consistent (Figure 2). Void ratio values did not change depending on the type of mixing fluid, whether distilled water or saline water. The compression indices differ considerably until approximately 500 kPa, where the slopes approach similar values ranging between 0.039 and 0.042. At higher stress level values are consistent. It is important to note that the upper limit is smaller for saline solution than that of distilled water and these values are not governed by the type chemical (NaCl or $CaCl_2$) or the level of concentration.

The swelling indices for 100g/L $CaCl_2$ solution specimens are higher than 250g/L $CaCl_2$ and specimens with distilled water mixing liquid also show slightly higher swelling indices than those with saline solution.

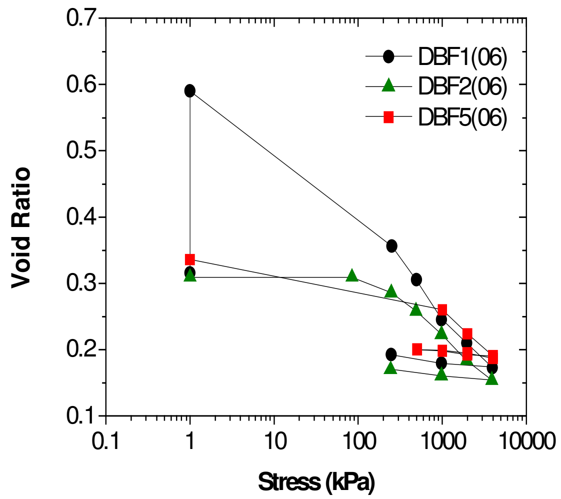

Figure 1. Void Ratio of distilled water consolidation specimens

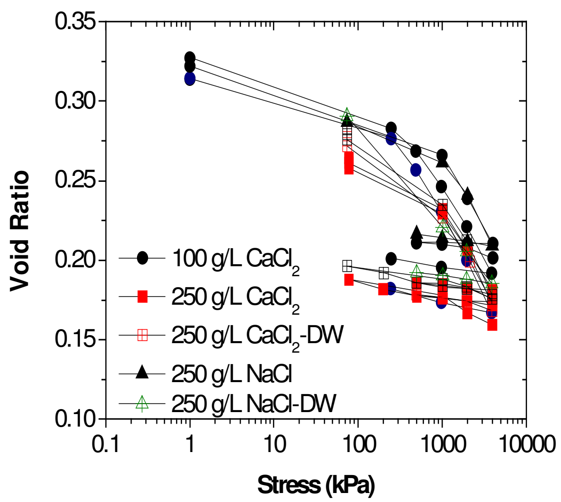

Figure 2. Void Ratio of saline water consolidation specimens

3.1.3 Salinity effect on Constrained Modulus

The 1-D constrained modulus (M) is computed for each load increment as follows (Bardet 1997):

$$1\text{D}-\text{Modulus}=\frac{1}{m_v}=\frac{\sigma'_{v1}-\sigma'_{v2}}{(e_1-e_2)/(1+e_1)} \qquad [1]$$

where m_v is the coefficient of volume compressibility, σ'_{v1} is initial effective stress for the increment, e_1 is the void ratio corresponding to σ'_{v1}; σ'_{v2} is final effective stress for the increment and e_2 is the void ratio corresponding to σ'_{v2}.

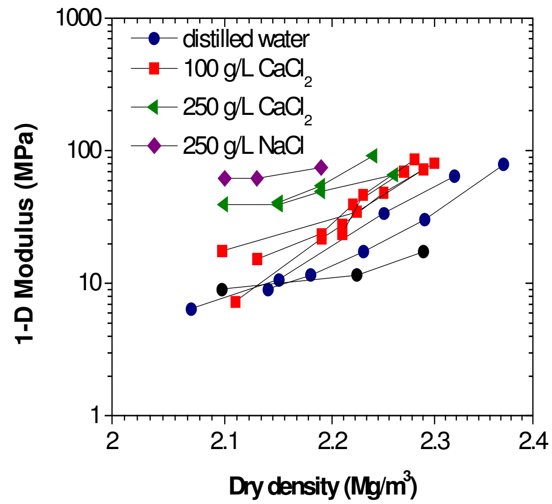

Figure 3. 1-D Modulus versus dry density for different pore fluid condition

In Figure 3, the variation of 1-D Modulus with dry density for distilled water and saline water specimens are presented. The value increases with an increase of salt concentration. The increase of stiffness with salinity is not only due to the solute effects but also void ratio changes undergone by the samples during the previous saturation path also play a significant role (Castellanos *et al.*, 2006).

3.1.4 Effect of salinity on vertical displacements

The vertical displacements experienced by the specimens soaked with distilled water and saline water for the applied stress of 4 MPa, are plotted against square root time (Figure 4). The distilled water specimens show a gradual increase of displacement with time and whereas the saline water specimens reach to the maximum displacement rapidly.

According to AECL reference design DBF is not required to developed a swelling pressure but rather act as a dense, stiff and stable filter material. Therefore the influence of pore water salinity on its swelling capacity was not studied.

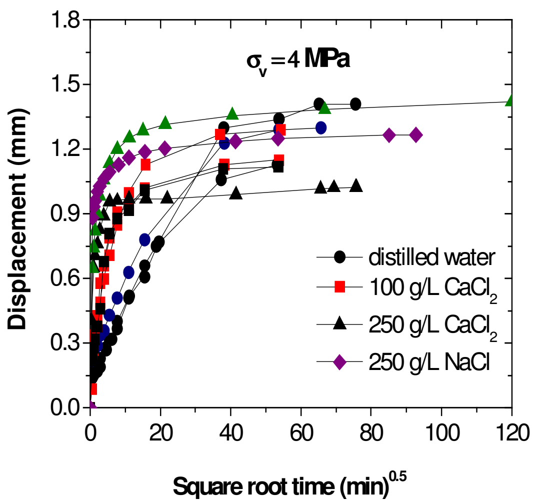

Figure 4. Time evolution of vertical displacements of specimens under different pore fluid condition

3.2 Hydraulic responses

Hydraulic conductivity (k) values were calculated for the loading and unloading increments of consolidation test by using the coefficient of consolidation (c_v) according to the following equation (Terzhagi 1943):

$$k = \frac{c_v \gamma_w}{1D - Modulus} \qquad [2]$$

Figure 5 presents hydraulic conductivity with respect to dry density for distilled water and various concentrations of $CaCl_2$ and NaCl solution. Although some points show an increase of permeability with increasing concentration but there is clear trend. Since DBF contains a higher percentage of non smectite clay minerals the hydraulic conductivity value is expected to be relatively insensitive to changes in pore fluid salinity.

3.3 Comparison based on boundary condition

3.3.1 Unconfined swell

To measure the swell potential of the specimen, a nominal load was applied and swell under that constant load was observed. The swell behaviour of the specimens tested was examined under a load of 1.27 kPa, the pressure applied by the top cap only. Specimens were allowed to swell under application of water to a maximum swell value (total vertical swell) of 20%. Comparing the void ratio vs. stress curves (*i.e.* Figure 6) for the unconfined swell specimens in distilled water and $CaCl_2$ solution suggest that the presence of calcium chloride notably reduces free-swell potential. Swell has a significant effect on time for total consolidation of subsequent loads, which is the length of time required for a consolidation step before application of the next step and is a function of the amount of swelling that has previously occurred.

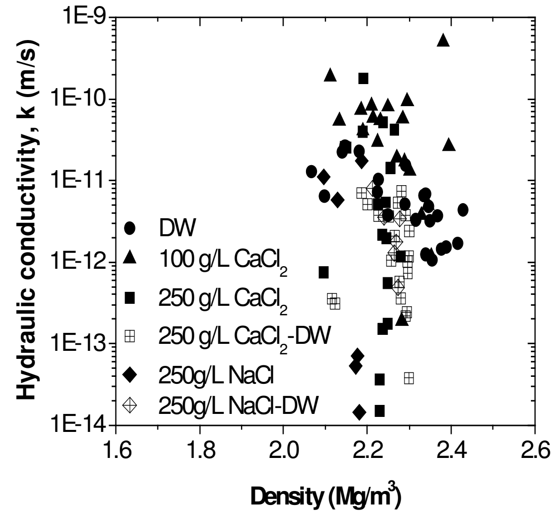

Figure 5. Hydraulic conductivity as a function of dry density and pore fluid condition

3.3.2 Constant Volume

Ensuring an initial constant volume condition requires that pressure be increased such that specimen volume is held constant until static equilibrium is reached. Essentially, this is identical to the unconfined swell case where the nominal static equilibrium pressure is 1.27 kPa. A final pressure of 84 kPa was required to maintain constant volume in the distilled water sample, whereas only 1.27 kPa prevents swelling of the saline solution specimen (Figure 7). This confirms the work by Dixon *et al.* (2002) that the swelling potential of bentonite is a function of salinity, where swelling potential decreases with increasing salt concentration.

3.3.3 Constant stress

In constant stress boundary condition specimens were instantaneously loaded to a pressure of 1 MPa. The unloading phase included additional unloading steps down to 500 kPa, following a peak pressure of 4 MPa. The time length of unloading steps was increased to enhance the monitoring of volume changes. A secondary loading phase was also implemented to investigate the reloading behaviour of the material.

As with the above two initial condition types the specimen compacted with the saline solution showed less compressibility than its distilled water counterpart as shown in Figure 8. This is readily evident in the first loading and unloading stage and less visible in the second loading stage. The compression index for the saline solution is 20% smaller than those for distilled water. The difference in swelling indices between the two is more difficult to interpret given the incompleteness of the swelling steps.

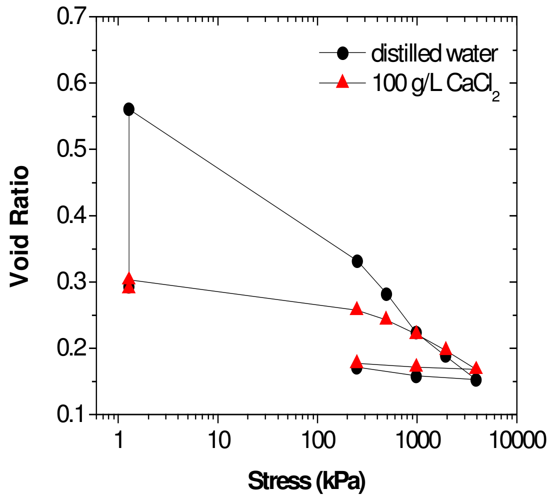

Figure 6. Void ratio comparison for specimen under unconfined swelling

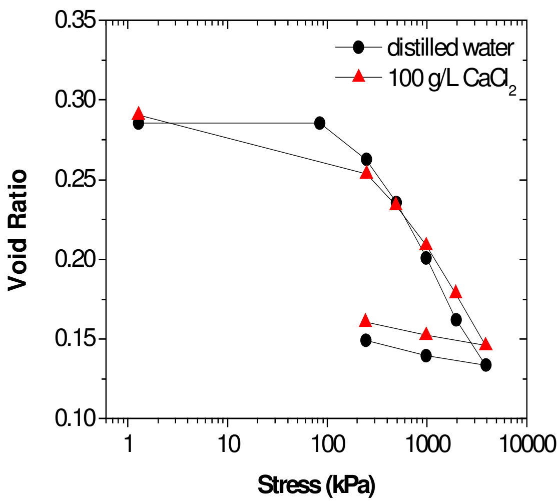

Figure 7. Void ratio comparison for specimen under constant volume

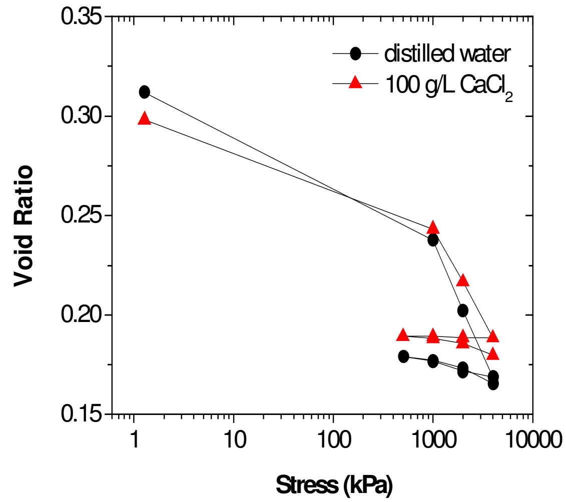

Figure 8. Void ratio comparison for specimen under constant stress

4 CONCLUSIONS

Experimental results were reported to understand the chemical influence on hydro-mechanical behaviour of dense backfill (DBF) material. A series of one dimensional consolidation tests were performed on DBF material compacted at 2.1 Mg/m^3. Compacted samples were tested with distilled water and different concentration of $CaCl_2$ and NaCl solutions.

As expected the swelling behaviour was not significant for DBF material due to low activity of the clay. Still results from free swell show the presence of calcium chloride reduces the swelling potential, likely due to the reduction in the double layer thickness. The compression and swelling indices show a reduction for specimens prepared or subjected to saline solution for the period of loading. Conversely material showed higher stiffness in saline water tests than distilled water. Since the material property is mainly governed by non swelling components of DBF and therefore the hydraulic conductivity values did not follow any specific trends. Still some points show higher values for saline water test in comparing to distilled water at the same density. Free swell and rigidly confined (constant volume or instantaneous loading) are the two different boundary conditions which were studied in the tests.

The results provide valuable set of experimental data for the performance study of DBF material and can be used for numerical modelling.

ACKNOWLEDGEMENTS

The authors acknowledge the work carried out by J.R. Baldwin and Ray Offman at the geotechnical laboratory of University of Manitoba.

REFERENCES

Bardet , J.P. 1997. *Experimental Soil Mechanics*. Prentice Hall Inc., Upper Saddle River. N.J.

Castellanos, E., Gens, A., Lloret, A. and Romero, E. 2006. Influence of water chemistry on the swelling capacity of high-density bentonite. *In Unsaturated Soils Proc. 4th Int'l Conf. of Unsaturated Soils.* April 02-06, Carefree, Ariz., A.S.C.E., Reston, Virginia.

Castellanos, E., Villar, M.V., Romero, E., Lloret, A. and Gens, A. 2008. Chemical impact on the hydro-mechanical behavior of high-density FEBEX bentonite. *Physics and Chemistry of the Earth*. 33:S516-S526.

Chandler, N.A. 2005. *Numerical modeling of the Stress and Displacement of Emplacement room Swelling Clay Materials.* Ontario Power Generation, Technical Memorandum, 6819(UF)-03782.02-T10, Toronto, Ontario.

Dixon, D.A., Chandler, N.A., and Thompson, P.M. 2001. The selection of sealing system components in AECL's 1994 Environmental Impact Statement, *Ontario Power Generation Supporting Technical Report*, 06819-REP-01200-10074-R00.

Dixon, D.A., Chandler, N.A., and Baumgartner, P. 2002. The influence of groundwater salinity and interfaces on the performance of potential backfilling materials. *In Trans. 6th International Workshop on Design and Construction of Final Repositories: Backfilling in Radiaoactive Waste Disposal*. ONDRAF/NIRAS, Brussels, Belgium, March 11-13.

Gierszewski, P., Jensen, M., Maak, P. and Vorauer, A. 2004. *Third case study-Site and design description.* Ontario Power Generation Nuclear Waste Management Diviosn Report 06819-REP-01200-10124-R00.

Karnland, O. 1998. Bentonite swelling pressure in strong NaCl solutions. *Posiva Oy Report*, POSIVA 98-01. Helsinki.

Maak, P. and Simmons, G.R. 2005. *Deep geologic repository concepts for isolation of used fuel in Canada. In Proc. Canadian Nuclear Society conff. Waste Management, Decommissioning and Environmental Restoration for Canada's Nuclear Activities*: Current Practices and Future Needs. May 8-11, Ottawa.

Pusch, R. 2001. Experimental study of the effect of high porewater salinity on the physical properties of a natural smectite clay. *SKB technical report* TR-01-07, Stockholm, 35 pp.

Russell, S.B. and G.R. Simmons. 2003. *Engineered barrier system for a deep geologic repository. Presented at the International High-Level Radioactive Waste Management Conference*. March 30-April 2, Las Vegas, NV.

Villar, M.V. 2005. MX-80 bentonite. Thermo-hydro-mechanical characterization performed at CIEMAT in the context of the prototype project. *Informes Técnicos Ciemat*, 1053, Madrid, 39 pp.