Investigation of the mechanical behaviour of light and dense backfill material subjected to various pore fluid conditions

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ABSTRACT
This paper summarizes triaxial and 1D-consolidation oedometer tests performed on light and dense backfill under a series of pore fluid chemistry. The pore fluids are distilled water, NaCl and $CaCl_2$ solutions with a maximum total dissolved solids (TDS) of 250 g/L. Results of the tests are analyzed to evaluate the mechanical behaviour of the materials. The influence of pore fluid chemistry on the stress-strain behaviour is studied. Both triaxial and oedometer tests results are compared between two materials. Results are also presented for the specific volume with respect to mean effective stress for distilled water and saline solution tests condition. The light backfill which is composed of 50% sand and 50% bentonite clay by weight shows a noticeable sensitivity to the pore fluid chemistry on its mechanical properties. While dense backfill which is composed of 5% bentonite, 25% glacial lake clay and 70% crushed granite aggregate are not sensitive to the chemistry of the pore fluid.

RÉSUMÉ
Ce document résume les essais oedométriques triaxial et 1D-consolidation effectuée sur le remblai léger et dense, sous une série de la chimie des fluides des pores. Les fluides interstitiels sont l'eau distillée, de NaCl et CaCl2 solutions avec un maximum total des solides dissous (TDS) de 250 g / L. Les résultats des tests sont analysés pour évaluer le comportement mécanique des matériaux. L'influence de la chimie des fluides des pores sur le comportement de déformation des essais oedométriques et le comportement contrainte-déformation des essais triaxiaux sont étudiés. Les deux essais triaxiaux et oedométriques résultats sont comparés entre les deux matériaux. Les résultats sont également présentés pour le volume spécifique à l'égard de la contrainte effective moyenne pour l'eau distillée et de solution saline tests de condition. Le remblai léger qui se compose de 50% de sable et d'argile bentonite 50% en poids montre une sensibilité notable à la chimie du fluide interstitiel sur ses propriétés mécaniques. Bien que le remblayage dense qui se compose de 5% de bentonite, argile 25% du lac glaciaire et 70% agrégats de granit concassé ne sont pas sensibles à la chimie du fluide interstitiel.

1 INTRODUCTION

Light backfill and dense backfill, two different sealing system components of the proposed Canadian deep geological repositories are examined in this study. Light backfill material is composed of 50% silica sand and 50% of Na-bentonite. Dense backfill is composed of 75% crushed granite 25% glacial lake clay and 5% Avonlea bentonite (by dry weight) (Russell and Simmons 2003).

1D consolidation and triaxial tests were performed on saturated light and dense backfill specimen. Series of tests were performed with various pore fluid conditions to examine the impact of pore fluid chemistry on the mechanical performance of the materials. These tests also allow identifying the sensitivity of the material subjected to chemical species present in the pore fluid.

Tests were carried out with synthetic chemical solutions prepared in the laboratory for experimental control purposes. Given the predominant cation species in the actual groundwater the two main salts were selected for the tests, which include solutions of sodium chloride (NaCl) and calcium chloride ($CaCl_2$). Tests also considered variable concentrations to cover the anticipated range of salinity that has been observed in the crystalline rock of the Canadian Shield and the sedimentary rock in southern Ontario. TDS can be as high as >200 g/L in the groundwater at potential repository locations; hence, a maximum salinity of 250g/L was considered for both NaCl and $CaCl_2$. Tests with higher TDS will allow studying the materials behaviour under extreme salinity that the sealing materials could face at the repository condition. The overall testing pore fluids for light and dense backfill included distilled water, 50g/L, 100g/L and 250g/L of NaCl solutions; and 100g/L and 250g/L of $CaCl_2$ solutions.

2 LABORATORY TESTS

2.1 1D-consolidation tests in oedometer

Standard 50 mm diameter by 19 mm tall light backfill specimens were prepared for 1D-consolidation tests following the compaction method described in Siddiqua et al. (2011). Oedometer tests for light backfill were conducted using conventional dead-weight type oedometer in general accordance with ASTM D2435

(1996). Large custom-built oedometer cells were used for 101mm by 101 mm dense backfill specimens. Larger size specimen was prepared for dense backfill to accommodate the larger rock chips present in the material.

2.2 Triaxial tests

Specimen preparation is described in Siddiqua et al. (2011). Triaxial specimens were subjected to consolidated drained tests (CID) or consolidated undrained tests with pore water pressure measurement (CIŪ) in general accordance with ASTM D4767 (2004). Following compaction specimens were installed in the triaxial cell and immediately subjected to their target mean effective stress levels. The saturation and consolidation procedure of triaxial specimens are documented in Siddiqua et al. (2011). After achieving the target degree of saturation, specimens were sheared at a constant strain of 0.0021 mm/min. During the shearing phase, measurements of axial load, axial strain, cell pressure and back pressure were recorded. Drainage of the specimen was prevented in CIŪ tests with measurement of pore water pressure taken near the base of the triaxial cell. A separate set of specimens were tested under drained conditions, where drainage valve was kept open and the change in volume was measured using burettes connected to the drainage lines.

3 RESULTS AND DISCUSSION

3.1 Stress-strain behaviour

Figure 1 and 2 displays the light and dense backfill triaxial tests as deviator stress vs. axial strain with two different pore fluids: distilled water and 250 g/L $CaCl_2$ solution.

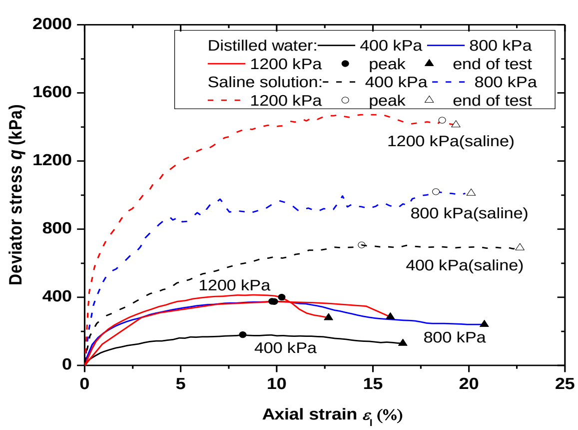

Figure 1: Typical stress-strain curves from CID triaxial tests on light backfill

Two types of tests for light backfill (Figure 1) shows the peak is higher for specimens saturated with saline pore fluid. Generally less strain-softening is observed for the specimens saturated with saline solution.

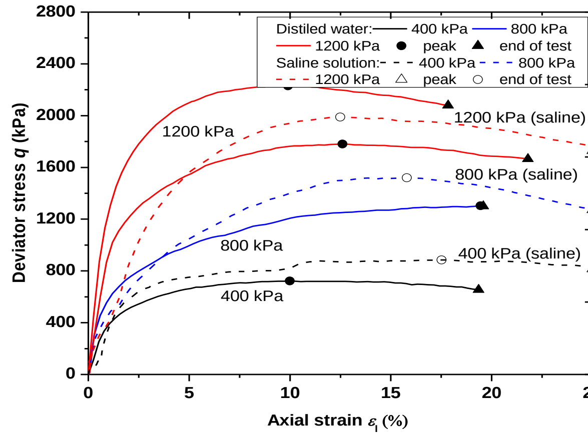

Figure 2: Typical Stress-strain curves from CID triaxial tests on dense backfill

On the other hand distilled water and saline solution saturated dense backfill specimens exhibited similar stress-strain behaviour with similar peak strength as shown in Figure 2. The strain-strain relationship generally displayed ductile behaviour. Some exceptions are noted in CID tests where material showed some strain softening at higher effective stress.

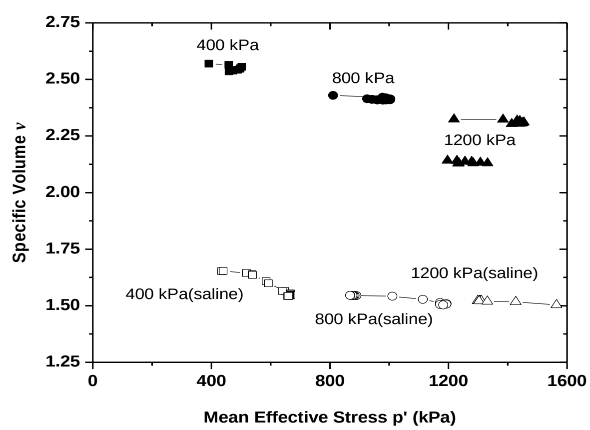

Figure 3: Specific volume and mean effective stress for light backfill specimens saturated with distilled water and saline solution

3.2 Specific volume- effective stress

Pore fluid also has an effect on the specific volume (or dry density) at the end of the saturation phase for light backfill. Specific volume versus mean effective stress for the CID tests on light backfill is plotted in Figure 3. The light backfill specimens saturated with saline pore fluid have significantly lower specific volumes than the specimens prepared and saturated with distilled water.

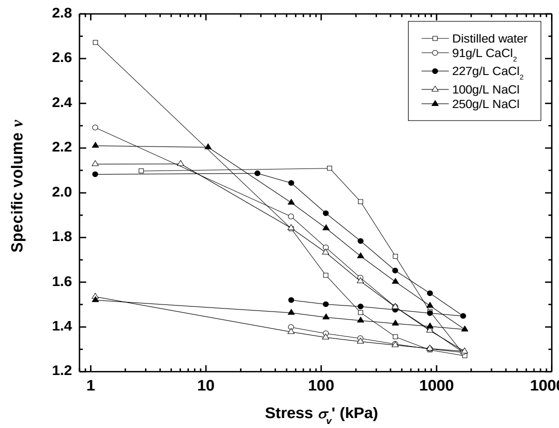

Figure 4: 1D-condolidation of light backfill in oedometer: specific volume *v* and vertical effective stress σ'$_v$ (log scale)

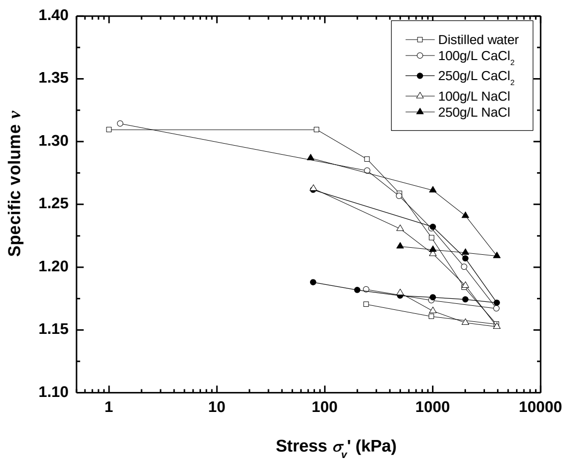

Figure 5: 1D-condolidation of dense backfill in oedometer: specific volume v and vertical effective stress σ'v (log scale)

This reduction in specific volume indicates that the specimens saturated with saline solution had a less open micro-structure after isotropic consolidation and during shearing. Therefore, the expansion of elastic region and the reduction in specific volumes for these specimens can be a result of osmotically induced consolidation (Barbour and Yang 1993). The cations within the saline pore fluid will result in a reduction of the diffusive double layer thickness resulting in a more stable structure (Barbour and Yang 1993). Triaxial tests were performed with single type of saline solution therefore it will be too early to bring such conclusion. Therefore triaxial tests on light backfill with a wider range of TDS would be useful to further this observation.

To investigate further results of oedometer tests are plotted with a logarithmic stress axis and the response in compression and unloading is described for light and dense backfill in Figure 4 & 5 respectively. The smectite rich sealing material, light backfill, with distilled water shows strong hysteresis between loading and unloading stages. Whereas the light backfill material tested with saline pore fluid does not show any hysteresis and the unloading curve from such tests are generally linear.

The dense backfill with lower amounts of smectitic minerals shows the typical consolidation response of non swelling clay with minor swelling at the unloading stage.

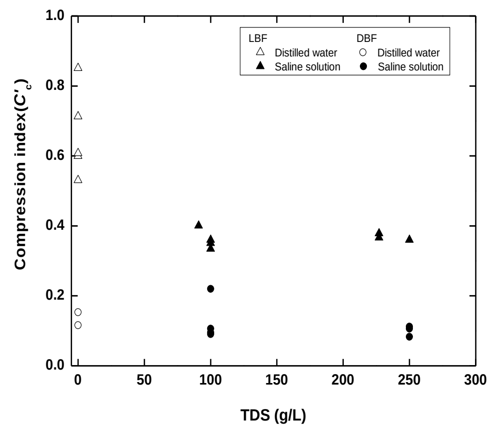

Figure 6: The effect of pore fluid chemistry on the Compression Index C_c

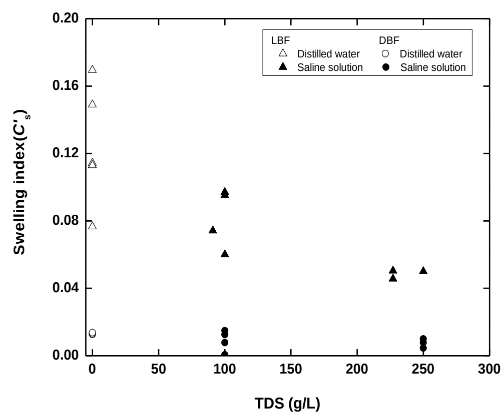

Figure 7: The effect of pore fluid chemistry on the Swelling Index C_s

3.3 Compression and swelling indices

Results of oedometer tests are plotted with a logarithmic stress axis and the response in compression and unloading is described using a compression index Cc and a swelling index Cs. The compression and swelling indices for light backfill and dense backfill are shown in (Figure 6 and 7) with respect to TDS of the pore fluid. Two different observations for the materials are established. First, compression and swelling indices of light backfill decrease noticeably with an increase in pore fluid salinity. A decrease in the compression indices indicates a reduction of material compressibility and an increase of the stiffness, while a decrease in the swelling indices indicates a reduction of swelling capacity of the material.

Second, compression and swelling indices for dense backfill are not sensitive to the pore fluid chemistry. The data from Figure 5 shows a slight increase in stiffness with an increase of pore fluid concentration and the swelling indices are not sensitive to the type and amount of salt.

3.4 Strength envelopes

Peak and critical state strength envelopes were defined from the test data. Peak strengths observed in Figure 1 & 2 and the corresponding mean effective stress, were used to define the peak strength envelopes. Critical state is defined as a state where there is no change in deviator stress, excess pore water pressure and volume with continued shear straining. Critical state strength was taken from near the end of test portions of the stress-strain curves, where little change in deviator stress and porewater pressure were observed with continued shearing. Strength parameters include the critical state strength envelope (M, slope of the critical state line (CSL) in p',q-space) and the corresponding friction angle at critical state (ϕ'_{cs}). Table 1 provides a summary of strength parameters for light and dense backfill prepared with fresh and saline water as the pore fluid.

Table 1: Summary of strength parameters for light and dense backfill

		Peak State (*p*-*q* space)		**Critical State**	
Material	**Pore fluid**	M_{peak}	**Friction Angle** ϕ'_{peak} (°)	M_{cs}	**Friction Angle** ϕ'_{cs} (°)
LBF	Distilled water	0.40	11	0.37	10
LBF	227 g/L $CaCl_2$	0.96	24	0.90	22
DBF	Distilled water	1.1	28	1.1	28
DBF	250 g/L $CaCl_2$	1.1	28	1.1	28

4 SUMMARY

The results of the triaxial and oedometer testing program have provided information regarding the mechanical behaviour of saturated light backfill (LBF) and dense backfill (DBF) materials for a range of pore fluid salinities.

The testing of light backfill revealed brittle, strain-softening behaviour. The strength of light backfill is strongly influenced by pore fluid salinity, increasing from M = 0.40 with fresh water as the pore fluid to M = 0.96 with a pore fluid salinity of 227 g/L $CaCl_2$. Similarly, the yield locus expanded when saline pore fluid was used. Light backfill was observed to be stiffer and less compressible with increased pore fluid salinity.

In contrast, the testing of dense backfill indicated the mechanical behaviour of this material is not strongly dependent on pore fluid chemistry. This can be accounted for by the high aggregate content of the dense backfill with its behaviour controlled by aggregate-aggregate interaction rather than the clay component. The strength of this material was characterized by an M value of 1.1 under both fresh water and saline (250 g/L $CaCl_2$) pore fluid conditions. Only slight to insignificant changes in stiffness, yielding, and compressibility were observed with increased pore fluid salinity.

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