The effect on rock swelling due to the salinity difference between rock pore fluid and ambient fluid

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ABSTRACT
A consideration of swelling characteristics of shaley rock is essential for underground structures such as tunnels. The swelling characteristic known as time dependent deformation is mainly due to a mechanism of osmosis and diffusion between pore fluid in rock and ambient fluid. An extensive experimental program has been carried out to investigate the effect on rock swelling due to the salinity difference between rock pore fluid and ambient fluid having different salt concentrations. The test program includes free swell tests, semi-confined swell tests and null swell tests with measurements of salinity of rock pore fluid and calcite content on three rock formations including Georgian Bay, Queenston and Shaftesbury. It is observed that, for a given salinity difference between pore fluid of rock and the ambient fluid, a significant effect on swelling potentials exists both in vertical and horizontal directions during the free swell tests and semi-confined tests on Queenston, Georgian Bay and Shaftesbury shale samples.

RÉSUMÉ
Un examen du gonflement caractéristique de roche argilo-schisteuse est essentiel pour les ouvrages souterrains tels les tunnels. Le gonflement caractéristique qui représente une déformation en fonction du temps est principalement dû à un mécanisme d'osmose et de diffusion entre le fluide interstitiel dans la roche et le fluide ambiant. Un vaste programme expérimental a été réalisé pour étudier l'effet de la différence de salinité entre le fluide interstitiel et le fluide ambiant ayant différentes concentrations en sel sur le gonflement du roc. Le programme d’essais comportait des essais de gonflement, des essais de gonflement semi-confiné et des essais de gonflement nulle avec un suivi de la salinité du fluide interstitiel et du contenu en calcite sur trois formations rocheuses, y compris les schistes de la baie Georgienne, de Queenston et de Shaftesbury. Il a été constaté que, pour une différence de salinité donnée entre le fluide interstitiel et le fluide ambiant, un effet significatif existe sur le gonflement potentiel à la fois dans la direction verticale et horizontale et ce surtout lors des essais de gonflement et des essais de gonflement semi-confiné sur échantillons du schiste de Queenston, de la baie Georgienne et de Shaftesbury.

1 INTRODUCTION

It is known that the swelling rock would lead to many problems on the underground structures. In many tunnels around the world, time-dependent deformations (TDD) have been observed in the form of invert heave and/or lateral inward deflection especially on the springline of tunnels. In many cases, costly remedial and maintenance work had to be undertaken (Lo et al. 1978).

Time-dependent deformation exists in some sedimentary rocks of origin such as shale, anhydrites, marls and rock salts. However, the controlling mechanisms of the TDD behaviour for these rocks could be different. Lee and Lo (1993) reported that the major controlling mechanism of long term swelling is the interaction of clay minerals and pore water solution with ambient fluid. This interaction is explained by the processes of osmosis and diffusion. Lo and Lee’s study was performed using Queenston shale samples and different types of ambient fluids such as transformer oil, ethanol and salted water. The study revealed that the major controlling factor of the TDD is osmosis and diffusion process, and that the salinity difference from rock pore fluid to ambient fluid affected the swelling potential of Queenston shale.

In the study presented in this paper, three types of shale in Queenston, Georgian Bay and Shaftesbury formations were used to evaluate the effect of salinity difference between pore fluid of rock and ambient fluid. Queenston shale and Georgian Bay shale are commonly encountered rock formations in Southern Ontario, Canada. Queenston shale is a reddish brown mudstone exhibiting cross-anisotropic elastic deformation behaviours. Queenston shale also shows the highest rate and magnitude of TDD in horizontal directions among the shale units in Southern Ontario (Lo and Lee, 1990). Georgian Bay shale is a moderately soft, thin-medium bedded, medium grey rock that accompany with platy lamination (Guillet, 1977). The Shaftesbury shale underlies lowlands adjacent to the Peace, Hay and Chinchaga Rivers to the west of Alberta and extends eastward around the lower slopes of the Caribou Mountains Alberta. Shaftesbury shale is coarse to fine marine shale. It is the dark grey, fissile and non-calcareous shale (Hanna and Little, 1992).

The experimental study of swelling rock was performed on Queenston shale samples recovered in Niagara Tunnel, Ontario (recovered in 2010), Georgian Bay shale samples from the location of Billy Bishop Toronto City Airport Pedestrian Tunnel, Ontario (recovered in 2012) and from West Truck Sewer Tunnel in Mississauga, Ontario (recovered in 2010), and Shaftesbury shale samples from the site C hydroelectric project located near Peace River, approximately 6 km southwest of Fort St. John, British Columbia (recovered in 2011). The experimental program included: i) swell tests: free swell, semi-confined swell, and null-swell tests, ii) salinity measurements of rock pore fluid before and after swelling tests, and iii) calcite content tests on swelling test specimens.

In this paper, a brief explanation of the dominant swelling mechanism of the three shales submerged in various salt concentrations of ambient fluid are described. Results of testing, discussion and conclusions of the study on Queenston, Georgian Bay and Shaftesbury shale are provided in the follow sections.

2 SWELLING MECHANISIM

An extensive study was carried out to investigate the sources and mechanism of swelling behaviour of Queenston shale in the past (Lee, 1988; Lo and Lee 1990; and Lee and Lo 1993). It was reported that, during the swelling testing, any chemical reactions such as oxidation of sulphide to sulphate hydration of anhydrite to gypsum or the creation of new crystal structures during migration of moisture in shale was not occurred. It is explained that the swelling of shaley rock, as a consequence of dilution of pore water salt concentrations in rock, increase the space between the clay particles as osmosis and diffusion are the main sources for the dilution process (Lee and Lo, 1993; Hawlader et al. 2003). The process of osmosis is the spontaneous water movement through the shale into a rock pore fluid with a higher salt concentration. Diffusion is the net movement of a substance (e.g., an atom, ion or molecule) from a region of high concentration to a region of low concentration (Scheatzl and Thompson, 2015).

3 OBJECTIVE OF THE STUDY

The objective of this study was to study the effect of osmosis and diffusion processes in the controlled environment on the swelling potentials measured during swelling tests on Queenston shale, Georgian Bay shale and Shaftesbury shale. In particular, the objective was to verify the effect of salinity difference between rock pore fluid and ambient fluid on swelling potential on these shales while maintaining relative humidity of 100%(i.e., submerged condition) and constant temperature during the tests. The only variation was limited to the salinity differences between rock pore fluid and ambient fluid.

4 EXPERMENTAL PROGRAM

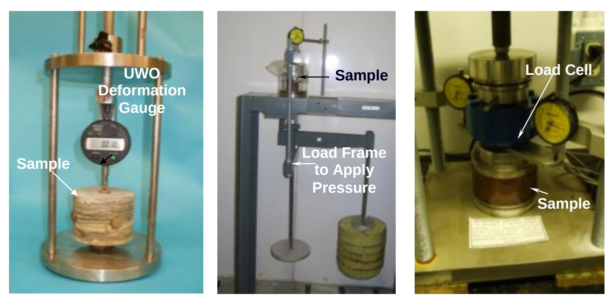
The experimental program for this study included thirty four (34) free swell tests (FST), five (5) semi-confined swell tests (SCST) and four (4) null swell tests (NST). In addition, seventy seven (80) water content tests and salinity tests, and thirty seven (38) calcite content tests were performed.

4.1 Preparation of Test Specimens

Shaley parts of the fresh rock cores were selected for swell tests. The initial water content and salinity of rock samples were firstly measured. For these two initial tests, adjacent rock pieces of each test specimen were selected, and denoted “Before Test”. After that, the fresh trimmed cylindrical specimens were prepared with a ratio of one diameter to one height.

For FSTs, specimens were placed in capped containers filled with ambient fluids having different salt concentrations. The minimum 8 litres of fluid was used to prevent a rapid change in salinity of ambient fluid. The electrical conductivity of ambient fluids was monitored during the tests whether there was a significant change in salinity during testing. Once the initial experiment was set up, the axial deformations were measured by UWO deformation gauge for 100 days (Lo et al. 1978). After the swelling test, each specimen was used for measurements of water, salinity and calcite content denoted “After Test”. Calcite content was only tested after the swell tests because that property is not affected by swell tests (Lo and Micic, 2010)

For SCSTs and NSTs, the ambient fluid was replaced with fresh water periodically. During the swell tests, the salinity of ambient water was recorded while the deformation in a direction (either vertical or horizontal) was measured during these two tests. The typical arrangements for three swell tests are presented in Figure 1.



(a) (b) (c)

Figure 1. Typical setup of swell tests: (a) FST, (b) SCST and (c) NST

4.2 Initial Properties of Rock Specimens

Queenston shale contains abundant quartz as non-clay mineral and illite and chlorite along with interlayered clays (Lee and Lo, 1990). Queenston shale used in this study is generally composed of dark reddish brown with distinct light green interbeds. Gypsum nodules are scattered within and around the core samples with variable size and frequency. For Queenston shale, thirteen (13) FSTs in ambient fluid having seven (7) different salt concentrations were carried out. Three (3) SCSTs were also performed in the submerged conditions and the ambient water was replaced several times depending on salinity variations in ambient fluid during the tests. The depths of FST specimens were between 3.6 m and 5.7 m from the lower point of the Niagara tunnel which are equivalent elevations of between 48.4 m to 51.1 m. The initial water contents of these specimens ranged from 1.6 % to 2.5 % (average - 2.0 %). The range of initial salinity of rock pore fluid of the specimens was from 211 g/L to 363 g/L (average - 271 g/L). Based on the predetermined water contents and salinities of rock pore fluid of the specimens, the seven different sodium chloride (NaCl) solutions were prepared as ambient fluids. The salt concentrations of ambient fluids at 0 g/L, 31.25 g/L, 62.5 g/L 125 g/L 187.5 g/L, 250 g/L and 300 g/L were used. In addition, depths of three SCST specimens ranged between 0.65 m and 5.8 m below the invert of the tunnel (corresponding elevations between 51 m and 56.15 m). The initial water contents were measured at 1.9 % and 2.4 %. The salinity of rock pore fluid of three SCST specimens was between 73 g/L and 221 g/L.

Georgian Bay shale used in this study is grey to dark grey and fine grained fissile shale interbedded with strong calcareous siltstone and limestone layers. In this study for Georgian Bay shale, fifteen (15) FSTs in six (6) different salt concentrations of ambient fluid were prepared. Two (2) SCSTs were also performed in the submerged conditions and the ambient water was replaced 4 to 5 times depending on salinity variations in ambient fluid during SCSTs. The depths of FST samples were between 21.3 m and 35.6 m below the ground surface for free swell tests. The equivalent elevations were between 40.9 m to 55.7 m. The initial water contents ranged from 2.2 % to 3.8 % (average - 3.1 %). The range of salinity of rock pore fluid of those specimens was from 95 g/L to 172 g/L (average - 134 g/L). Based on the water contents and salinities of rock pore fluid of the specimens before test, the ambient fluids were prepared with the salt concentrations of 0 g/L, 12.5 g/L, 25 g/L, 50 g/L 75 g/L, 100 g/L and 150 g/L. Depths of two SCST specimens ranged between 44 m and 47 m below the ground surface. The initial water contents were measured at 3.5 % and 4.0 %. The salinity of rock pore fluid of two SCST specimens was 160 g/L and 172 g/L.

Shaftesbury shale is also known as the swelling rock due to its containing of abundant swelling clay minerals (Hanna and Little, 1992). The Shaftesbury shale used is dark grey and very fissile shale with various sizes of ferrous nodules within samples. The sample appears to be poorly bonded and easily peeled out. Six (6) FSTs and four (4) NSTs in different salt concentrations of ambient fluid were prepared. The depths of test samples were between 29 m and 58 m below the ground surface. The initial water contents ranged from 4.7 % to 5.5 % (average - 4.6 %). The range of salinity of rock pore fluid of those specimens was from 24 g/L to 36 g/L (average - 30 g/L). On the basis of the predetermined water contents and salinities of rock pore fluid of the specimen, the ambient fluids with salinity ranging from 0 to 40 g/L were used in NSTs.

4.3 Methods of Testing

The methods of laboratory testing for time-dependent deformation of rocks (i.e., FST, SCST and NST) were developed by Lo et al. (1978). In FSTs, freshly trimmed rock specimens are permitted to deform unrestricted in all directions. A typical specimen for a FST is shown on Figure 1a. Their orthogonal dimensional changes of the specimen preserved under constant temperature and 100% humidity are measured with time. The “UWO deformation gauge” shown on Figure 1a is used to measure the dimensions of two horizontal (X and Y) and a vertical (axial) (Z) directions for 100 days.

In SCSTs, the strain changes of the rock sample in one direction are monitored by the dial gauge reading. A constant pressure is applied to the rock sample in the direction of measurement while deformations in perpendicular directions remained unrestricted. A typical setup for a SCST is shown on Figure 1b.

Test data from FST and SCST are analysed by plotting strain vs. logarithm (to the base of 10) of elapsed time (Lo et al, 1979, and Lo and Lee 1990). The slope of the curve between 10 and 100 days is represented by a straight line and is termed the “swelling potential (SP)” having a dimension of a percentage of swell strain per log cycle of time (%/log cycle). The swelling potential from FSTs gives an indication of tendency of the rock to expand upon stress relief, while the results of SCSTs characterize the effect of stress on swelling behaviour.

In NSTs, the critical pressure required to completely suppress swelling in a horizontal or vertical direction is measured. A typical setup is shown in Figure 1c. NST arrangement consists of the loading support frame, the load cell and loading cap assembly, digital deformation system and chamber where the specimens were submerged in different salt concentrated fluids. The measured stresses are plotted against the time to determine the swelling suppression pressure. The procedure and method of interpretation for the null swell tests have been discussed in Lo (1989) and Lo and Lee (1990).

5 RESULTS AND DISCUSION

5.1 Effect of Ambient Fluid Salinity on Swelling

<u>Queenston Shale</u>

The FST results including the vertical swelling potential (VSP) in z direction and horizontal swelling potentials (HSP) in x and y directions for Queenston shale specimens are presented in Table 1. From Table 1, it can be noticed that the swelling potential in vertical and horizontal directions decrease as the salinity difference decreases. Vertical swelling potentials ranged between 0.65 %/log cycle and 0.05 %/log cycle with salinity differences ranging from 0 g/L to 246 g/L. Horizontal swelling potentials ranged from 0.45 %/log cycle to 0.05 %/log cycle with the same range of salinity differences. Specimen Q-FST-01 swelled the most with a rate of 0.65 %/log cycle and 0.45 %/log cycle in the vertical and horizontal directions, respectively, with the salinity

Table 1 Summary of results of the swelling tests and salinity tests

Formation	Specimen ID	Depth	Water Content		Salinity of Rock Pore Fluid		Calcite Content (%)	Salinity			Swelling Potential (Strain) (% / log cycle)		
		(m)	Before*	After**	Before*	After**		Salinity of Ambient Fluid	Salinity Difference ***	Salinity Difference Ratio ****	HSPx	HSPy	VSP
			(%)		(g/L)		(%)	(g/L)	(g/L)		(%)	(%)	(%)
Queenston	Q-FST-01	5.21-5.27	2.1	2.1	246	23	6.9	0.1	246	1.0	0.40	0.45	0.65
	Q-FST-02	5.63-5.69	2.1	3.2	232	55	5.2	31.25	201	0.9	0.15	0.20	0.35
	Q-FST-03	5.22-5.28	2.5	2.7	211	61	6.8	31.25	180	0.9	0.10	0.10	0.35
	Q-FST-04	4.93-4.99	2.2	2.5	242	206	10.0	62.5	180	0.7	0.25	0.25	0.30
	Q-FST-05	4.51-4.57	2.0	2.4	284	202	6.0	62.5	221	0.8	0.25	0.25	0.45
	Q-FST-06	4.99-5.05	2.2	2.6	242	129	5.4	125	117	0.5	0.20	0.20	0.25
	Q-FST-07	4.65-4.71	2.0	2.6	247	85	6.8	125	122	0.5	0.20	0.20	0.35
	Q-FST-08	5.05-5.11	1.9	2.2	334	187	5.4	187.5	147	0.4	0.08	0.08	0.20
	Q-FST-09	4.71-4.77	2.0	2.4	247	170	7.0	187.5	60	0.2	0.11	0.11	0.15
	Q-FST-10	4.77-4.83	1.7	2.1	362	164	7.0	250	112	0.3	0.12	0.12	0.15
	Q-FST-11	4.45-4.51	2.0	2.3	243	283	6.0	250	-7	0.0	0.10	0.10	0.15
	Q-FST-12	3.61-3.67	1.9	2.8	328	231	3.8	300	28	0.1	0.15	0.20	-
	Q-FST-13	3.82-3.88	1.6	1.7	300	290	7.9	300	0	0.0	0.08	0.05	0.05
						SCST					Swelling Strain		
	Q-SCST-1	0.65-0.7	2.1	-	73	-	5.1	0	73	1.0	0.35		
	Q-SCST-2	1.3-1.35	1.9	-	173	-	-	0	173	1.0	0.40		
	Q-SCST-3	5.76-5.81	2.4	-	221	-	-	0	221	1.0	0.70		
Georgian Bay	GB-FST-01	29.45-29.51	2.2	4.5	153	46	4.1	0.1	153	1.0	0.22	0.22	0.75
	GB-FST-02	28.54-28.60	3.5	5.3	105	43	3.6	0.1	105	1.0	0.35	0.20	0.8
	GB-FST-03	35.44-35.50	3.2	4.7	147	33	3.9	12.5	134	0.9	0.30	0.30	0.65
	GB-FST-04	35.50-35.56	3.1	4.4	172	33	3.8	12.5	159	0.9	0.12	0.21	0.72
	GB-FST-05	35.18-35.24	3.2	4.7	166	71	2.9	25	141	0.8	0.20	0.20	0.63
	GB-FST-06	35.24-35.30	2.3	4.7	161	73	3.9	25	136	0.8	0.18	0.22	0.63
	GB-FST-07	32.36-32.42	2.6	4.9	164	108	3.6	25	139	0.8	0.25	0.25	0.65
	GB-FST-08	30.45-30.51	3.3	4.7	119	85	3.9	50	69	0.6	0.20	0.20	0.62
	GB-FST-09	30.52-30.57	3.6	5.8	109	9	3.6	50	59	0.5	0.10	0.10	0.64
	GB-FST-10	29.64-29.70	3.2	6.1	121	9	3.6	75	46	0.4	0.10	0.19	0.45
	GB-FST-11	29.53-29.59	2.3	4.7	158	120	4.6	75	83	0.5	0.08	0.08	0.35
	GB-FST-12	28.35-28.41	3.3	4.5	107	124	3.6	100	7	0.1	0.05	0.05	0.25
	GB-FST-13	28.20-28.26	3.0	6.2	122	37	3.2	100	22	0.2	0.05	0.05	0.3
	GB-FST-14	28.05-28.11	3.8	5.0	95	167	2.9	150	-55	-0.6	0.02	0.05	0.19
	GB-FST-15	27.99-28.05	3.3	4.5	105	202	2.2	150	-45	-0.4	0.02	0.02	0.11
						SCST					Swelling Strain		
	GB-SCST-1	46.45	3.5	4.3	160	32	4.1	0	160	1.0	0.60		
	GB-SCST-2	44.10	4.0	4.2	172	33	5.0	0	172	1.0	0.10		
Shaftesbury	S-FST-01	41.27-41.32	4.7	6.8	32	15	< 1.0	0	32	1.0	0.55	0.55	1.95
	S-FST-02	29.19-29.25	5.5	6.4	24	23	< 1.0	1	23	1.0	0.10	0.10	1.00
	S-FST-03	30.44-30.50	5.3	7.5	34	9	< 1.0	20	14	0.4	0.05	0.05	0.45
	S-FST-04	30.50-30.56	5.1	6.8	29	35	< 1.0	40	-11	-0.4	0.01	0.01	0.22
	S-FST-05	57.80-57.85	3.4	5.7	33	17	< 1.0	25	8	0.2	0.10	0.10	0.28
	S-FST-06	57.85-57.90	3.7	4.7	30	9	< 1.0	0	30	1.0	0.50	0.50	0.75
						NST					Supression Pressure (Mpa)		
	S-NST-1	29.13-29.19	4.7	5.2	32	40	< 1.0	40	-8	-0.3	1.1		
	S-NST-2	29.19-29.25	4.4	4.5	29	39	< 1.0	25	4	0.1	1.5		
	S-NST-3	30.44-30.50	4.7	4.9	22	28	< 1.0	15	7	0.3	1.2		
	S-NST-4	48.68-48.72	4.7	5.5	36	31	1.6	0	36	1.0	1.9		

* Water content and salinity tests were performed on rock pieces adjacent to the swell test specimens

** Water content, salinity and calcite content tests were conducted on free swell test specimens

*** Salinity Difference = Salinity of rock pore fluid - Salinity of ambient fluid

**** Salinity Difference Ratio = (Salinity of rock pore fluid-Salinity of ambient fluid) / Salinity of rock pore fluid difference of 246 g/L. On the other hand, specimen Q-FST-13 swelled the least with a rate of 0.05 %/log cycle in the vertical and horizontal directions, respectively, with the salinity difference of approximately 0 g/L. Vertical and horizontal swelling potentials are plotted against the salinity differences from rock pore fluid to ambient fluid in Figure 2.

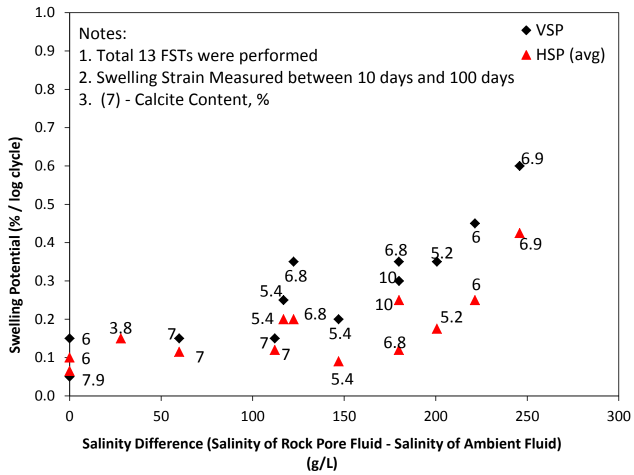


Figure 2. Swelling potential versus salinity difference from salinity of rock pore fluid to salinity of ambient fluid on Queenston shale

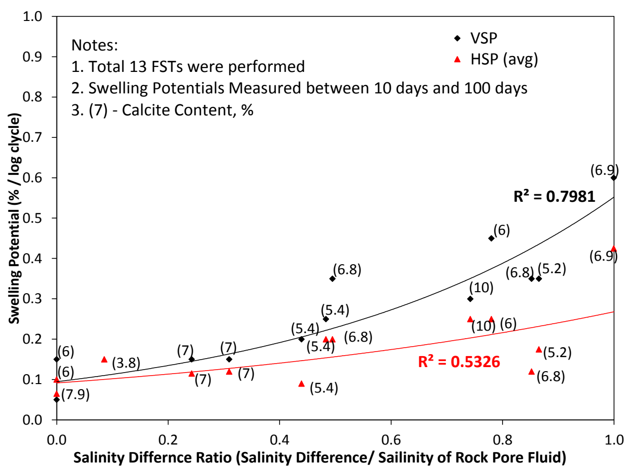


Figure 3. Swelling potential versus salinity difference ratio on Queenston shale

From Figure 2 it can be seen that the swelling potential was almost constant in both vertical and horizontal directions where the salinity difference is smaller than 120 g/L. Where salinity difference is between 120 g/L and 175 g/L, the vertical swelling potentials were measured between 0.2 %/log cycle and 0.35 %/log cycle, and the horizontal swelling potentials were measured between 0.08%/log cycle and 0.25 %/log cycle. Where the salinity difference is greater than 175 g/L the swelling potential increased rapidly.

Figure 3 shows the vertical and horizontal swelling potentials against salinity difference ratio. The ratio is defined as salinity difference normalized by salinity of rock pore fluid. The trend lines and R^2, the coefficients of determination, are presented in the figure. It is usually assumed that R^2 value higher than 0.8 indicates that the correlation is strong, less than 0.5 indicates a weak correlation, and between 0.5 and 0.8 indicates that correlation is moderate. The R^2 values for vertical swelling potential and the horizontal swelling potential against salinity difference ratio are 0.80 and 0.53, respectively. It is suggested that the vertical swelling potential has a strong correlation with salinity difference ratio. However, not a strong correlation was found between horizontal swelling potential and salinity difference ratio.

Georgian Bay Shale

Results of FSTs and SCSTs on Georgian Bay shale specimens are presented in Table 1. The table shows the measured and estimated swelling potentials. Vertical potentials for specimens, GB-FST5, GB-FST8, GB-FST9 and GB-FST-12 had to be estimated because these specimens broke in vertical direction before the completion of 100-day of testing. The estimation was assumed that no significant strain rate changes occurred from the time of breaking to the end of testing.

Based on the results presented in Table 1, the reduction of swelling potentials in the vertical direction can be found as the salinity difference decreases (i.e., the salinity of ambient fluid increases). The vertical swelling potentials of Georgian Bay shale specimens ranged from 0.85 %/log cycle to 0.25 %/log cycle while the horizontal swelling potentials ranged from 0.35 %/log cycle to 0.05 %/log cycle. The salinity differences varied from 159 g/L to -55 g/L. The negative value indicates that the salinity of ambient fluid is greater than the salinity of rock pore fluid. For specimens GB-FST1 and GB-FST2 submerged in the freshwater (approximately 0.1g/L of salt), the salinity differences from the rock pore fluid to ambient fluids were varied between 153 g/L and 105 g/L. The vertical swelling potentials of these two specimens were 0.85 %/log cycle and 0.78 %/log, and the horizontal swelling potentials were the same at 0.2 %/log cycle.

The swelling potential against the salinity difference between the rock pore fluid and the ambient fluid are presented in Figure 4. Swelling potentials from 0.25 % /log cycle to 0.3 %/log cycle were measured with salinity difference 20 g/L or less. With the salinity difference between 20 g/L and 125 g/L, the vertical and horizontal swelling potentials increased as the salinity difference increased. As the salinity difference is greater than 125 g/L, variations in the swelling potentials between 0.62 %/log cycle and 0.85 %/log cycle in the vertical direction were measured. Similar to the vertical swelling potential, the horizontal swelling potentials varied between 0.16 %/log cycle and 0.24 % /log cycle in this section.

Figure 5 presents the vertical and horizontal swelling potentials against the salinity difference ratio. R^2 values for the vertical and horizontal directions are approximately 0.83 and 0.74, respectively. It is suggested that there is a strong correlation between swelling potentials and salinity difference in vertical, but a moderate correlation in horizontal directions.

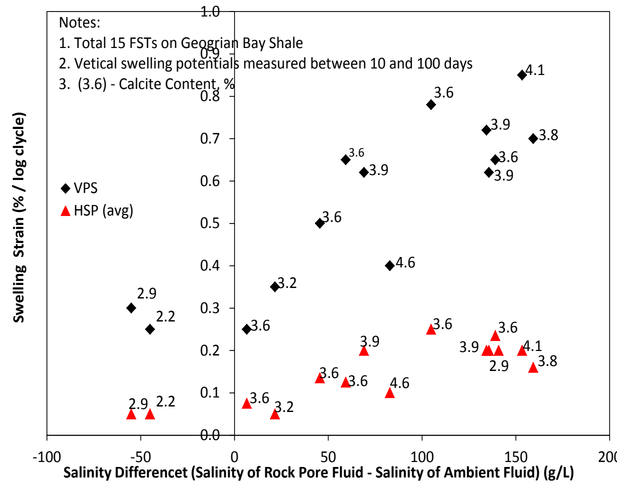


Figure 4. Swelling potential versus salinity difference from salinity of rock pore fluid to salinity of ambient fluid on Georgian Bay shale

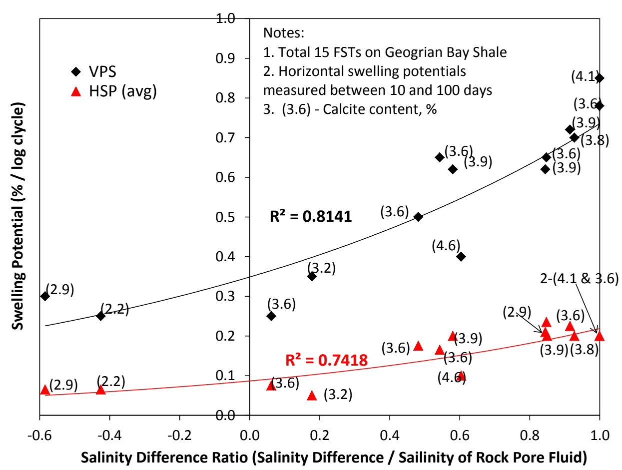


Figure 5. Swelling potential versus salinity difference ratio on Georgian Bay shale

Shaftesbury Shale

Figure 6 shows the changes in vertical swelling potentials in spite of the relatively small range of the salinity difference (i.e. within 40 g/L). As seen in Figure 6, the minimum vertical swelling potential was 0.22 % /log cycle with the salinity difference of -11 g/L. However, the horizontal swelling potential measured in this specimen was almost 0 %/log cycle.

The swelling potential then rapidly increased with the salinity differences greater than 30 g/L. The maximum vertical and horizontal swelling potentials were 1.95 %/log cycle and 0.55 %/log cycle, respectively, with the salinity difference of 32 g/L.

Figure 7 presents the swelling potentials against the salinity difference ratio. The R^2 values are 0.86 in the vertical direction and 0.74 in the horizontal directions. Although the number of tests was limited, a strong correlation between swelling potentials and salinity difference in the vertical and a moderate correlation in the horizontal directions were indicated.

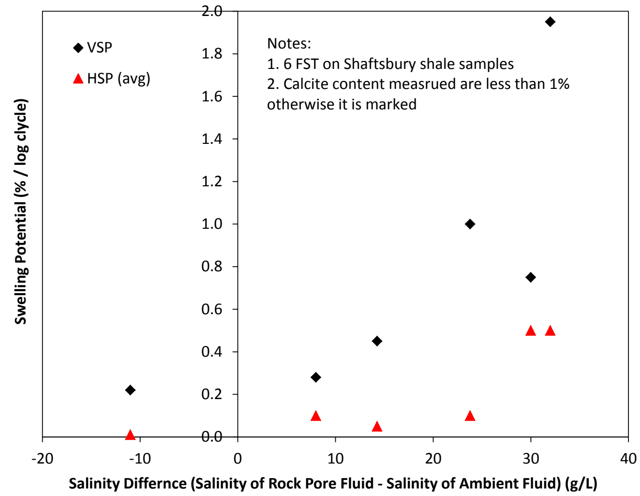


Figure 6. Swelling potential versus salinity difference from salinity of rock pore fluid to salinity of ambient fluid on Shaftesbury shale

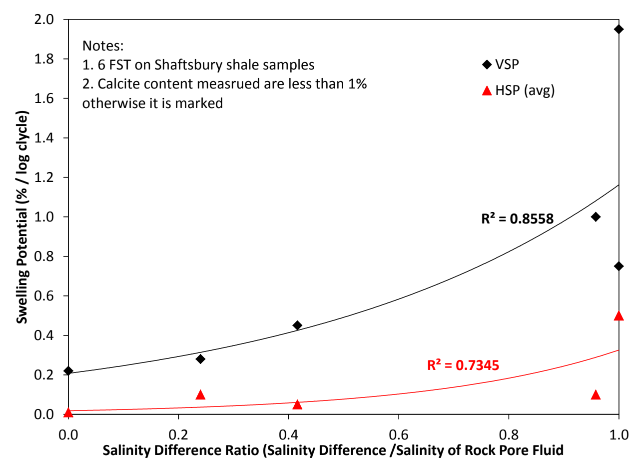


Figure 7. Swelling potential versus salinity difference from salinity of rock pore fluid to salinity of ambient fluid on Shaftesbury shale

5.2 Effect of Change in Ambient Fluid Salinity during Swelling

Queenston Shale

The vertical swelling strains measured in three SCSTs at different rock salinity on Queenston shale samples are plotted on Figure 8. The figure indicates that the ambient fluid was replaced with fresh water five times during the tests. As shown on the figure, the sudden increases of swelling strain were recorded on the sample Q-SCST-3 (i.e. with the highest pore water salinity of 221 g/L) after the 1st and 3rd water replacements. The smaller increases were recorded in the other two tested samples with significantly lower difference in salinity of rock pore and ambient fluids than that of Q-SCST-3. These results suggest that sudden increase in salinity difference between the rock pore fluid and ambient fluid can accelerate swelling on Queenston shale samples during the process of swelling.

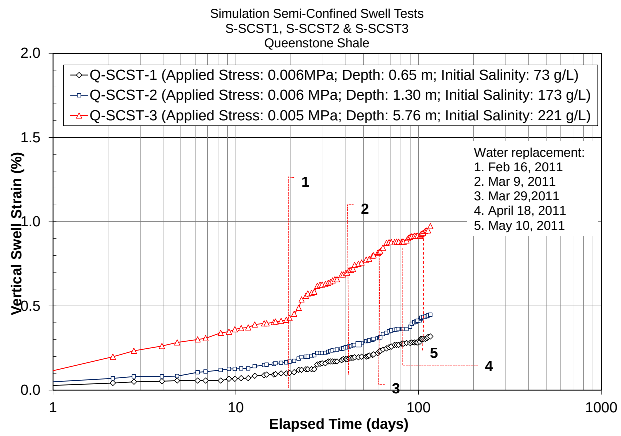


Figure 8. Result of SCSTs on Queenston shale with replacement of ambient fluid during tests

Georgian Bay Shale

In Figure 9, the vertical swelling strain and horizontal strain were plotted against logarithm elapsed time for two Georgian Bay shale samples. Figure 10 shows the electrical conductivity of ambient fluid measured and its corresponding salinity (i.e. dissolved salt concentration) in the ambient fluid. During these SCSTs, the ambient fluid replacements were made every 7 days until no significant changes in salinity of ambient fluid were measured. Five times of water replacements for GB-SCST-1 and four times replacements for GB-SCST-2 were conducted.

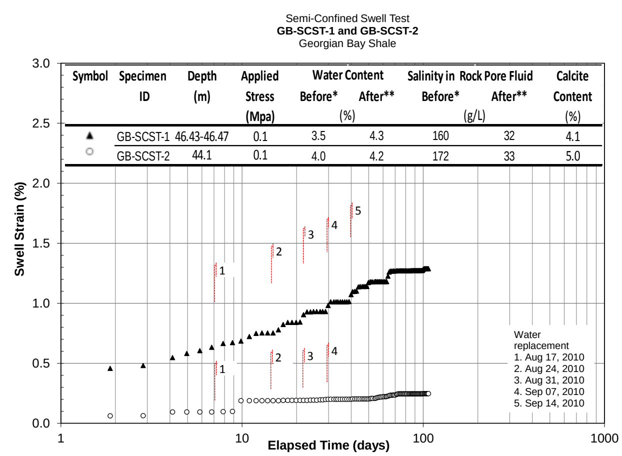


Figure 9. Result of SCSTs on Georgian Bay shale with replacement of ambient fluid during tests.

It can be seen in Figure 9, for GB-SCST-1, sudden increases of swelling strain after the 2nd to 5th water replacements were observed. On the other hand, such an increase was observed only after the 4th water replacements for GB-SCST-2. This behaviour can be explained by salinity differences in ambient fluid shown in Figure 9. For example, considering the measured electrical conductivity of ambient fluid for GB-SCST-1 and

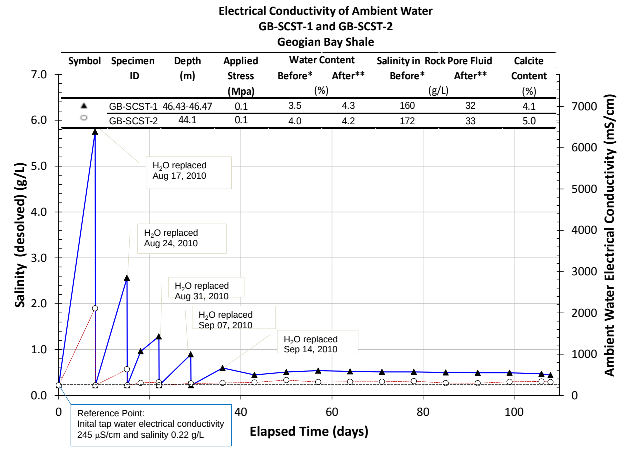


Figure 10. Salinity measurements of ambient fluid during SCSTs on Georgian Bay shale

GB-SCST-2, the differences in electrical conductivity after 7 days of tests were approximately 6145 µS/cm and 1865 µS/cm for GB-SCST-1 and GB-SCST-2, respectively. After 21 days of tests, electrical conductivity differences were then approximately 1185 µS/cm, and 74 µS/cm for GB-SCST-1 and GB-SCST-2, respectively. It is noted that GB-SCST-1 had more obvious changes in swelling strains after the replacement of ambient fluid. It is implied that the higher salinity difference between rock pore fluid and ambient fluid caused increase of swelling strain or acceleration of swelling on Georgian Bay shale specimens.

Both sets of results suggest that sudden increase in swelling may occur in tunnels if ingress of unexpected fresh water happens.

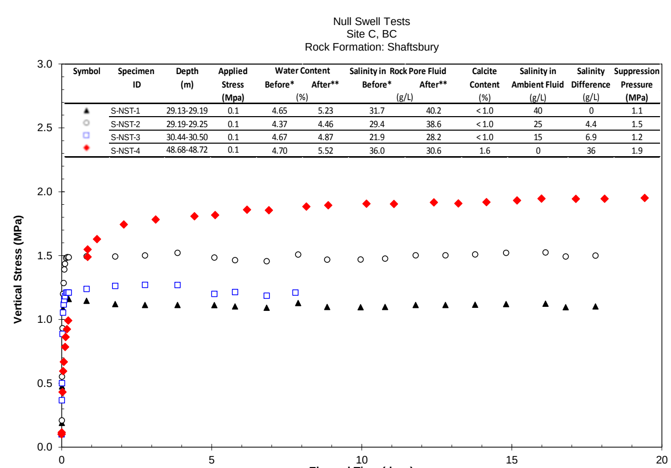


Figure 11. Results of NST with difference salt concentrated ambient fluid.

5.3 Effect of Ambient Fluid Salinity on Suppression Pressure

Shaftesbury Shale

Four NSTs were performed on Shaftesbury shale samples with different salt concentrations of ambient fluid (i.e. 40 g/L, 25 g/L 15 g/L and 0.1 g/L). The initial applied pressure was set at 0.1 MPa and the suppression pressures were measured until no significant change in pressure was reached.

The results of NSTs are shown in Figure 11. The measured suppression pressure was 1.9 MPa (i.e. maximum) on S-NST-4 with salinity of ambient fluid of 0.1 g/L while the suppression pressure of 1.1 MPa (i.e. minimum) was measured on S-NST-1 with salinity of ambient fluid of 40 g/L. Suppression pressures of 1.5 MPa and 1.2 MPa were then measured in between these two values on S-NST-2 with salinity of ambient fluid of 25 g/L and S-NST-3 with salinity of ambient fluid of 15 g/L.

6 CONCLUSIONS

From the results of the swell tests performed, the following conclusions may be made:

1) Results of free swell tests in ambient fluids with different salt concentration show that the vertical swelling potential has a strong correlation with an increase of the salinity difference between the rock pore fluid and ambient fluid for Queenston, Georgian Bay and Shaftesbury shale. The higher salinity difference causes the higher swelling potential in these formations of rock.
2) Based on results of semi-confined swell tests with replacement of ambient fluid by fresh water in a certain period of time during the 100 days of testing, the salinity difference between rock pore fluid and ambient fluid caused sudden increases of swelling strains. This indicates the salinity difference causes the increase or acceleration of swelling
3) Based on the results of null swell tests performed in different salt concentrated ambient fluid, salinity differences between rock pore fluid and ambient fluid significantly influenced on measured suppression pressure as well.

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