Swelling Potential of Queenston Shale in Lubricant Fluids

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ABSTRACT
The effect of lubricant fluids used in the drilling process for microtunnels, such as polymers solution and bentonite slurry, on the swelling behaviour of Quuenston Shale from Southern Ontario was investigated. Lubricant fluids and fresh water were used as ambient fluids in a series of free swell tests performed on Queenston shales from Niagara and Milton regions. The tests results revealed a significant difference in the swelling behaviour of the Queenston Shales in these fluids. The polymers solution caused a significant suppression of the swelling of both Queenston shales, while the bentonite slurry caused moderate suppression of the swelling of Niagara Queenston shale, and a slight increase of the swelling of Milton Queenston shale, compared to water. This finding may have a significant impact on evaluating the swelling associated with the drilling process and in the design of underground structures in Queenston Shale.

RÉSUMÉ
L'effet des fluides lubrifiants sur le comportement du gonflement de schiste localisé au Sud de l'Ontario a été étudié. Deux fluides lubrifiants, une solution de polymères et un coulis de bentonite, ainsi que de l'eau fraîche ont été utilisés pour une série d'essais de gonflement en laboratoire. Les essais ont été effectués sur des échantillons de schiste de Queenston des régions de Niagara et de Milton. Les résultats des essais ont révélé une différence significative dans le comportement de gonflement du schiste de Queenston pour chacun des fluides par rapport au gonflement dans l'eau. La solution de polymères a provoqué une diminution marquée du gonflement pour les deux schistes de Queenston. Pour le coulis de bentonite, la diminution du gonflement du schiste de Queenston provenant de Niagara est moindre, tandis que le gonflement du schiste de Queenston provenant de Milton a augmenté. Cette constatation peut s'avérer essentielle dans l'évaluation du gonflement associée au processus de forage et dans la conception de structures souterraines dans le schiste de Queenston.

1 INTRODUCTION

Queenston shale, among other sedimentary rocks in Southern Ontario, exhibits swelling deformations upon time when an excavation in the rock mass takes place. Part of the swelling deformation takes place during the excavation process. However, additional swelling deformation may occur after the excavation and this swelling component is termed as time-dependent deformation. The time-dependent deformation of some rocks can be significant in both magnitude and the effect on the built structure. In Southern Ontario, the distresses in the buried structures in swelling rocks were recognized in the early years of the past century, where the Canadian engineers recorded an inward movement of the wheel pit walls in Niagara falls in 1903 (Morison, 1957), and the movements had been continued for 70 years (Lee and Lo, 1976). In Thorold tunnel, which was constructed in shaly limestone, severe cracks were reported in one of the walls of the tunnel just after one year of construction (Bowen et al 1976). The swelling phenomena can cause significant damage to the built structures, such as invert heave, roof spalling, and lateral inward deformation in several tunnels (Lo and Yuen, 1981). In Europe, the distresses in some of the tunnels constructed in sedimentary rocks were in a similar manner, and even more severe as some invert heaves in the rate of hundreds of millimeters per year were reported, (Einstein and Bischoff, 1975).

Extensive investigation of the swelling phenomena of swelling sedimentary rocks in Southern Ontario, including Queenston shale, was initiated by Lo and co-workers in 1975-1978. During that period, a test method known as the free swell test, and a measuring apparatus, known as the modified free swell test apparatus, were developed to measure the time-dependent deformation of rocks. Lo et al. (1978) studied the time-dependent deformation of Queenston and other shales of Southern Ontario, and underscored the anisotropy in the swelling behaviour of these shales with respect to the rock bedding. Lee and Lo (1993) investigated the swelling mechanism of Queenston shale of Southern Ontario, and concluded that three conditions have to be met in order for the swelling to occur: a) the relief of in-situ stress, b) the accessibility to water, and c) salinity gradient between the pores of the shale and the ambient water. Hefny et al. (1996) extended the investigation of the long-term swelling behaviour of Queenston shale, and concluded that the swelling may last for more than ten years. Hawlader et al. (2003) investigated the influence of the applied stress on the long-term swelling behaviour of Queenston shale, and developed a constitutive model that accounts for these effects. Al-Maamori et al. (2014) compiled the geo-mechanical properties of rocks, including Queenston shale, in Southern Ontario and the neighbouring regions. They commented that the compiled swelling properties were derived from tests performed on rocks submerged in water, and the behaviour of rocks in fluids other than water, such as lubricant fluids utilized in micro-tunnelling process needs to be investigated.

Installing a pipeline using micro-tunnelling process may last for several weeks before the cement grout can replace the lubricant fluid. During this period, where lubricant fluids fill the tunnel aperture, a significant amount of the swelling deformation of the Queenston shale may occur. The objective of this research is to investigate the influence of the lubricant fluids that are utilized in the micro-tunnelling process, such as polymers solution and bentonite slurry on the swelling behaviour of Queenston shale from Southern Ontario. By knowing the swelling behaviour of the Queenston shale in lubricant fluids, the swelling deformation associated to micro-tunnelling process can be evaluated. The swelling parameters derived from swell tests in lubricant fluids can be used to calculate the expected swelling stresses on the micro-tunnelling machine and on the installed pipeline. Therefore, the design of underground structures in these shales can be more reliable.

In this paper, the behaviour of Queenston shales from Milton and Niagara regions in Southern Ontario, in polymers solution and bentonite slurry, in addition to water was investigated. A series of free swell tests was performed using polymers solution, bentonite slurry, and water as ambient fluids during the test period. The swelling potential as the rate of swelling strain that occurs during a log cycle of time in the vertical and horizontal directions, with respect to the rock bedding was measured according to Lo et al. (1978). The results of the swelling tests were used to derive the swelling potential of both Queenston shales in the different fluids. The tests results revealed that using the lubricant fluids can cause a significant difference in the resulted swelling potentials of the Queenston shales, compared to that resulted from water.

2 METHODOLOGY

The free swell test was utilized to perform a series of tests on Queenston shale from Milton and Niagara in Southern Ontario. The test procedure and the test apparatus were both developed in the University of Western Ontario by Lo et al. (1975-1978). As described by Lo and Hefny (1999), the free swell test apparatus consists of a base pedestal, supporting frame, a digital dial gauge with accuracy to the nearest 0.001 mm, and calibration pins. The digital deformation gauge and the base pedestal have both sharp tips that can hold the specimen in the centre of the v-hole during each swelling strain measurement. The height of the dial gauge can be adjusted through the screw in the supporting frame to accommodate for more than one size of the specimens, as indicated in Figure 1. Before each measurement, the gauge is calibrated against a standard calibration bar that has v-holes in its top and bottom. The recovered Queenston shale samples were immediately wrapped with electrical tape and saran wrap to prevent moisture loss. The samples were placed inside PVC pipes and were secured with rubber caps at the ends and a mechanical clamp to protect samples during handling and transporting to the lab. The free swell tests' specimens were cut in the lab to heights equal to their diameters (63 mm-Milton Queenston shale and 60 mm-Niagara Queenston shale), as they were cored from the boreholes. In this way, the same apparatus was used to measure the swelling deformation of the specimen in the vertical direction as well as in two orthogonal horizontal directions, with respect to the rock bedding, without adjusting the height of the digital gauge for the subsequent reading. The specimen's cutting was performed using a diamond saw and the requirements in the (ASTM 2008) for preparing cylindrical rock specimens were followed. Immediately after that, the specimens were marked at the centre of their top and bottom surfaces, and also at the centre of each opposite sides in the orthogonal horizontal directions. At the centre of each face of the specimen, a strain point was mounted using super bounder glue. The strain points were specially fabricated from brass with one side flat/or has the same curvature of the specimens.

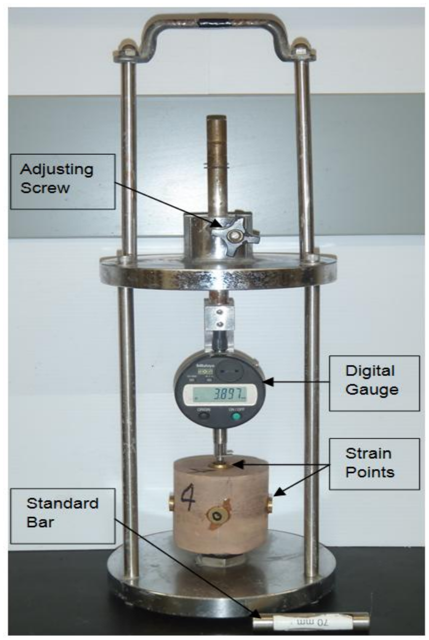

Figure 1. Free swell test apparatus and specimen

According to the test procedure presented in Lo et al. (1978), before placing the specimen in the ambient fluid, the initial readings were taken for each Queenston shale specimen in three orthogonal directions, after calibrating the apparatus. The free swell tests started when specimens were kept fully submerged in the lubricant fluids and in fresh water inside plastic containers. In these containers, specimens were seated on a wire mesh to ensure full exposure to the ambient fluid. During the test period, Queenston shale specimens were allowed to expand freely in all directions without any restraint. The water used in this research was tap water, and it was used to prepare the lubricant fluids. The free swell tests were performed in a temperature controlled room in 10±1 degree Celsius (C°). The swelling deformations of the specimens in the three orthogonal directions were measured every day for hundred days. For each ambient

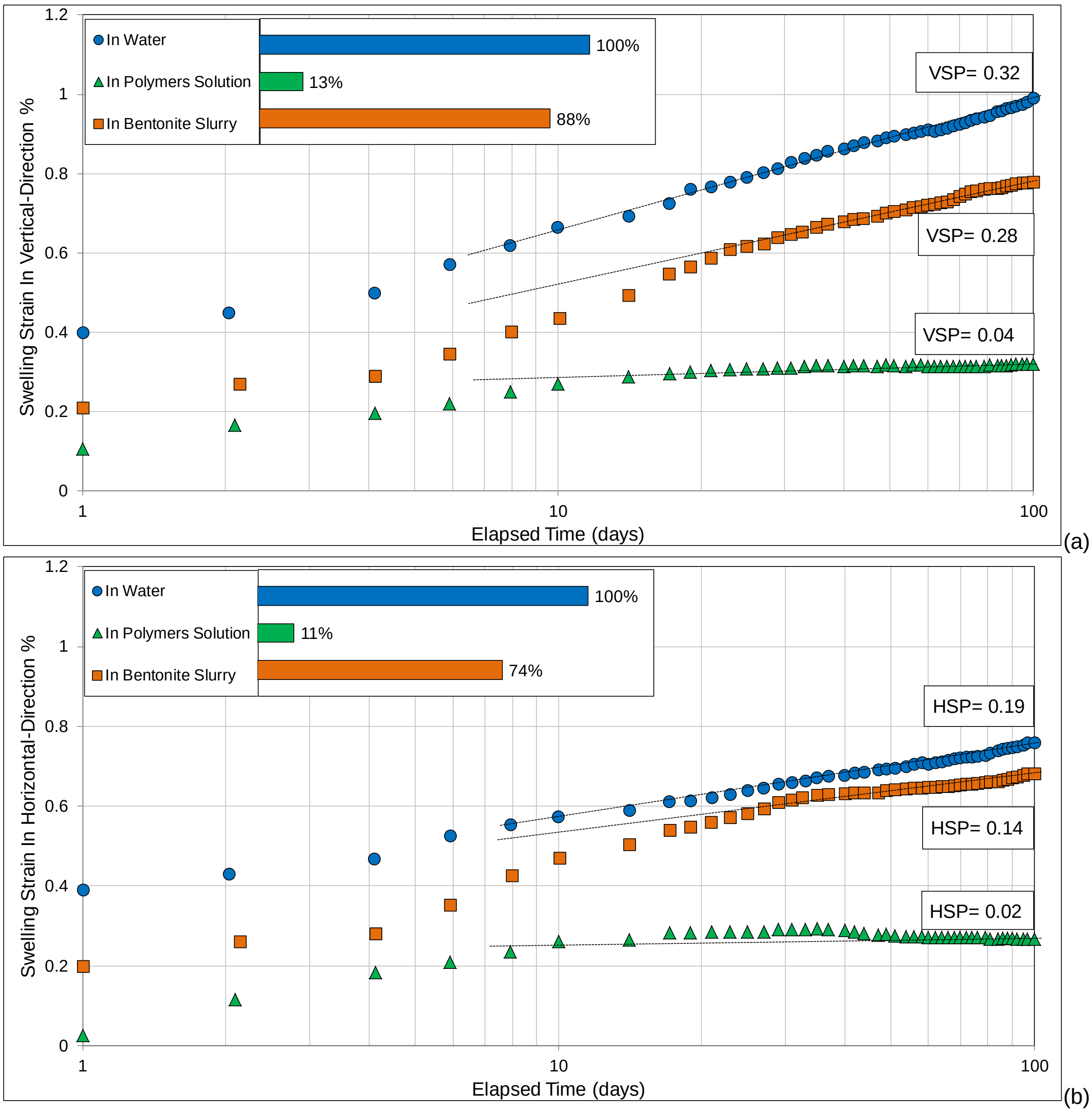

Figure 2. Typical results of the free swell tests performed on Niagara Qeenston shale from depth ≈125 m-137 m below natural ground level: a) Vertical strains, b) Horizontal strains

Table 1. Average swelling potential of Niagara Queenston shale

Ambient fluid	HSP (rate of strain%/log cycle of time)	VSP (rate of strain%/log cycle of time)	Moisture Content (%)	Pore Water salinity before test (g/L)	Pore Water salinity after test (g/L)	Decrease in pore salinity (%)	Calcite content (%)
Water [6]	0.120 - 0.260 (0.190)	0.300 - 0.600 (0.450)	1.1 – 1.41 (1.34)	314.8 - 423.9	109.5 - 120.5	65 - 73	7.6 - 9.5
0.8% Polymers solution [6]	0.001 - 0.060 (0.031)	0.020 - 0.080 (0.060)	1.07 – 1.41 (1.18)	375.9 - 435.7	277.9 - 323.6	22 - 26	7.4 - 8.0
8% Bentonite slurry [6]	0.140 - 0.190 (0.163)	0.200 - 0.400 (0.300)	1.034 – 1.27 (1.13)	362.7 - 434.5	180.2 - 208.1	50 - 52	7.9 - 8.3

Note: value in [ ] represents number of performed tests, value in ( ) represents the average swelling potential.

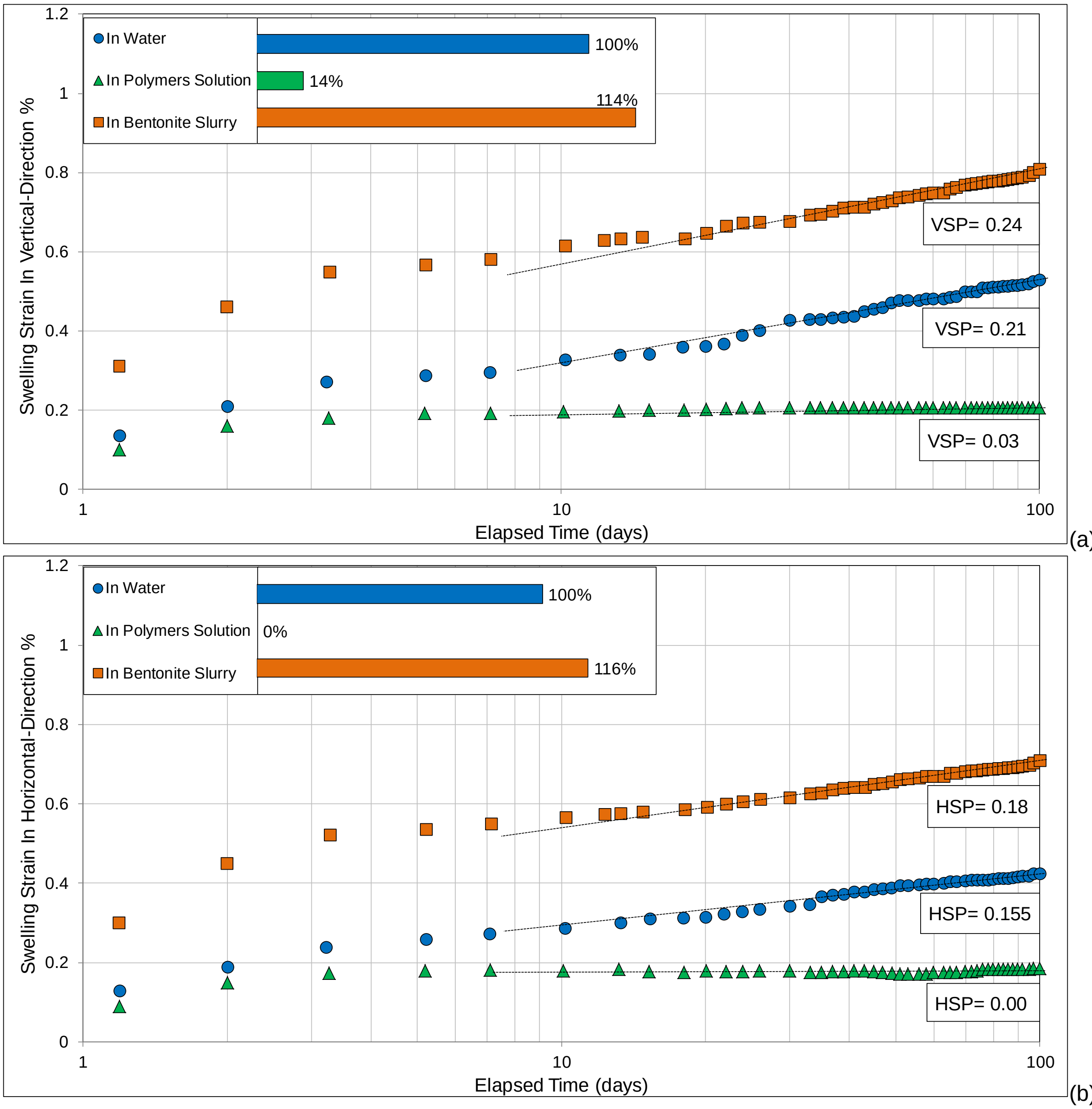

Figure 3. Typical results of the free swell tests performed on Milton Qeenston shale from depth ≈18 m-33 m below natural ground level: a) Vertical strains, b) Horizontal strains

Table 2. Average swelling potential of Milton Queenston shale

Ambient fluid	HSP (rate of strain%/log cycle of time)	VSO (rate of strain%/log cycle of time)	Moisture Content (%)	Pore Water salinity before test (g/L)	Pore Water salinity after test (g/L)	Decrease in pore salinity (%)	Calcite content (%)
Water [5]	0.110 - 0.210 (0.155)	0.120 - 0.240 (0.190)	2.0 – 3.01 (2.67)	73.7 - 149.7	21.9 - 76.2	48 - 70	15.0 - 30.3
0.8% Polymers solution [5]	0.000 - 0.060 (0.027)	0.020 - 0.100 (0.065)	2.14 – 3.02 (2.55)	70.2 - 232.9	47.5 - 173.0	26 - 36	13.4 - 29.3
8% Bentonite slurry [3]	0.130 - 0.200 (0.170)	0.226 - 0.240 (0.235)	2.30 – 2.53 (2.46)	118.3 - 148.6	20.4 - 34.8	77 - 86	12.1 - 29.3

Note: value in [ ] represents number of performed tests, value in ( ) represents the average swelling potential.

fluid, the test was repeated for a minimum three times in order to have representative average value of the swelling potential for each of the tested Queenston shales. The lubricant fluids used in the drilling process, such as polymers solution and bentonite slurry in addition to water, were adopted in this research. The concentrations of these solutions were the same as those used in the field. The polymers solution was 0.8% of polymers to water, while the bentonite solution was 8% of bentonite to water, by weight. In order to explain the swelling behaviour of Queenston shales in the adopted ambient fluids, additional tests were performed on each of the free swell test specimens, such as the moisture content, pore water salinity, and calcite and dolomite contents using Chittick apparatus and following the procedure described in Dreimanis (1962). The pore water salinity was calculated by mixing the powdered sample with distilled water and centrifuging the mixture. The conductivity of the resulted supernatant was measured and converted to the pore water salinity using a calibration chart for NaCl solutions (Lee 1988).

3 RESULTS

The results of the free swell tests performed on the Queenston shale samples from Niagara and Milton in Southern Ontario are summarized in Table 1 and Table 2. The tables also include the results of calcite content and pore water salinity before and after performing the free swell test and the percentage reduction in the pore water salinity. The presented results include the swelling potential in the vertical and horizontal directions, measured with respect to the rock bedding. The vertical swelling potential (VSP), and the horizontal swelling potential (HSP) represent the rate of the swelling strain of the Queenston shale specimens in the vertical and horizontal directions, respectively, measured in a log cycle of time, as defined by Lo et al. (1978). They defined the cycle of time as the time between day 10 to day 100 from the beginning of the free swell test. Based on the test procedure described by Lo et al (1978), the swelling strains of the specimen during the first 9 days are usually ignored. The specimen during this period is considered under adjustment between the in-situ and the laboratory conditions. As the installation process of a pipeline using micro-tunnelling technique may last for several weeks, swelling deformation in the tunnel aperture may occur. In addition to the free swell test results, the aforementioned tables include the results of the pore water salinity of the Queenston shale specimens measured before and after performing the free swell tests with the percentage decrease in the pore water salinity. The calcite content of each specimen was also measured and also presented. The Queenston shale samples tested herein were collected from borehole in Niagara tunnel from depth: 125 m -137 m, and from borehole in Milton, Ontario from depth: 18 m – 33 m below the natural ground level. Typical free swell test results of Queenston shale specimens from Niagara and Milton are also presented in Figure 2 and Figure 3, respectively. In these figures, the swelling strains in the vertical and horizontal directions for each Queenston shale specimen are presented in part (a) and part (b) of each figure, respectively. The VSP and the HSP are presented as doted straight lines that best represent the swelling strain curves between day 10 and day 100, and their values are presented next to each curve. In order to illustrate the variation in the swelling strains of the Queenston shales in water, and in lubricant fluids (i.e. polymers solution, and bentonite slurry), a bar chart representation was added to the presented figures. The bar charts represent the variation in the resulted strains excluding the first 9 days (i.e. VSP and HSP) of Queenston shales in the lubricant fluids, as percentages of those in water.

4 DISSCUSSION

The results revealed that, in comparison to water, there was a considerable variation in the swelling strains of the tested Queenston shales when the lubricant fluids were used as ambient fluids in the free swell tests. The polymers solution produced the lowest swelling strains in all of the tested Queenston shale samples, in both directions, compared to water and bentonite slurry. The polymers solution significantly reduced the VSP and HSP of Niagara Queenston shale samples by 87%, and 84%, and Milton Queenston shale by 66%, and 83%, respectively, compared to water. The bentonite slurry caused decreases in the VSP and the HSP of Niagara Queenston shale by 33%, and 14%, respectively; conversely, the bentonite slurry caused increases in Milton Queenston shale VSP by 24% and the HSP by 10%, respectively. The percentage decrease in the pore water salinity of the specimens after the free swell test period was more evident in water than in other fluids for Niagara Queenston shales. In Milton Queenston shale, the percentage decrease in the pore water salinity was the highest in the specimens tested in the bentonite slurry, and this might explain the increased swelling of Milton Queenston shale in bentonite slurry.

From the above discussion, it can be concluded that adopting lubricant fluids in the micro-tunnelling process through swelling rocks, such as Queenston shale, can significantly change the swelling behaviour of these shales. Compared to water, the polymers solution was very effective in supressing the swelling strains of both Niagara and Milton Queenston shales. On the other hand, the bentonite slurry had a moderate influence in reducing the swelling of Niagara Queenston shale. However, the swelling behaviour of Milton Queenston shale in the bentonite slurry needs further investigation.

5 SUMMARY AND CONCLUSIONS

As part of a comprehensive research program, the presented work examines the influence of lubricant fluids that are used in the drilling process, on the swelling characteristics of Queenston shales of Southern Ontario. In this work, a number of the free swell tests were performed on Queenston shale samples collected from Niagara and Milton in Southern Ontario. The free swell tests were performed in three ambient fluids: water, polymers solution, and bentonite slurry. The adopted lubricant fluids were of the same polymers and bentonite concentrations of those fluids used at working sites. From the results of the performed testing program, the following conclusions can be drawn:

1) The swelling behaviour of Queenston shale of Southern Ontario in lubricant fluids, such as the polymers solution, and the bentonite slurry, can be significantly different from their swelling behaviour in water.

2) Compared to water and bentonite slurry, the polymers solution considerably reduced the swelling strains of both Niagara and Milton Queenston shales in both vertical and horizontal directions. This finding can have significant value in the drilling industry, where the polymers solution can be used to supress the swelling strain of the Queenston shale. Micro-tunnelling technique is a clear example, where installing a pipeline using this technique can last for several weeks.

3) The bentonite slurry reduced the swelling strains of Niagara Queenston shale in both vertical and horizontal directions, but it caused a slight increase in the swelling strains of Milton Queenston shale. However, more detailed investigation is required to clarify the behaviour of Queenston shale in bentonite slurry.

Based on the results of this testing program, it is recommended to expand this study to investigate the swelling behaviour of other types of sedimentary swelling rocks from Southern Ontario and other parts of Canada in the lubricant fluids.

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REFERENCES

ASTM. 2008. Standard practices for preparing rock core as cylindrical test specimens and verifying conformance to dimensional and shape tolerances. ASTM standard D4543-08. ASTM International, West Conshohocken, Pa.

Al-Maamori, H.M.S., El Naggar, H., and Silvana, M. 2014. A Compilation of the Geo-Mechanical Properties of Rocks in Southern Ontario and the Neighbouring Regions, *Open Journal of Geology*, **4**, 210-227. Doi. 10.4236/ojg.2014.45017.

Bowen, C.F.P., Hewson, F.I., MacDonald, D.H. and Tanner, R.G. 1976. Rock squeeze at Thorold Tunnel, *Canadian Geotechnical Journal*, **13**(2): 111-126. Doi: 10.1139/t76-013.

Dreimanis, A. 1962. Quantitative Gasometric Determination of Calcite and Dolomite by Using Chittick Apparatus, *Journal of Sedimentary Petrology*, **32**(3): 520 - 529.

Einstein, H.H. and Bischoff, N. 1975. Design of tunnels in swelling rocks. Proceedings of the 16th Symposium on Rock Mechanics, University of Minnesota, Minneapolis, MN, PP. 185-195.

Hawlader, B.C., Lee, Y.N. and Lo, K.Y. 2003. Three-dimensional stress effects on time-dependent swelling behavior of shaly rocks, *Canadian Geotechnical Journal*, **40**(3): 501-511. Doi:10.1139/t03-006

Hefny, A., Lo, K.Y. and Huang, J.A. 1996. Modelling of long-term time-dependent deformation and stress-dependency of Queenston shale. Canadian Tunnelling 1996, The Tunnelling Association of Canada, pp. 115-146.

Lee, Y.N. 1988. Stress-strain-time relationship of Queenston shale. Ph.D. thesis, Civil and Environmental Engineering Department, The University of Western Ontario, London, ON.

Lee, Y.N. and Lo, K.Y. 1976. Rock squeeze study of two deep excavations at Niagara Falls. Rock Engineering, Proceedings of the Specialty Conference for Foundations and Slopes, Boulder, Colorado, 15-18 August 1976. American Society of Civil Engineers, New York, **1**, pp. 116-140.

Lee, Y.N. and Lo, K.Y. 1993. The swelling mechanism of Queenston shale. Canadian Tunnelling 1993, The Tunnelling Association of Canada, pp. 75-97.

Lo, K.Y. 1978. Regional distribution of in situ horizontal stresses in rocks of Southern Ontario, *Cnadian Geotechnical Journal*, **15**(3): 371-381. Doi:10.1139/t78-034

Lo, K.Y. and Hefny, A.M. 1999. Measurements of Residual Expansion Rates Resulting from Alkali-Aggregate Reaction in Existing Concrete Dams. *ACI Materials Journal*, **96**(3): 339-345.

Lo, K.Y. And Yuen, C.M.K. 1981. Design of Tunnel Lining In Rock for Long Term Time Effects, *Canadian Geotechnical Journal*, **18**(1): 24-39. Doi. 10.1139/t81-004

Lo, K.Y., Wai, R.S.C., Palmer, J.H.L. and Quigley, R.M., 1978. Time-dependent deformation of shaly rocks in Southern Ontario. Canadian Geotechnical Journal, **15**(4): 537-547. Doi. 10.1139/t78-057.

Morison, W.G. 1957. Rock squeeze investigation. Ontario Hydro Research Division Report No.57-13, Toronto Power Generating Station, Ontario Hydro Research Division, Toronto, Ontario.