Factors Influencing Time-dependent Deformation Behaviour of Swelling Shales

膨脹性 쉐일의 時間依存的 變形擧動에 影響을 미치는 諸 要素

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Abstract

This paper describes the results of study on major factors influencing time-dependent deformation behaviour of swelling shales. The study was carried out by analyzing all the swell test results available for shales from southern Ontario. Major factors studied are (1) the presence of ambient water, (2) calcite content and (3) the applied stress.

The results of the study on seven shales show that the swelling of shale is associated with the formation of cracks and the absorption of water in these cracks. The magnitude of swelling potential is related linearly to the amount of absorbed water. The presence of calcite inhibits the swelling of shales studied, reducing the swelling to zero at about 30% of calcite content. All the shales studied exhibit the stress-dependent swelling behaviour, though there is a difference in the degree of dependency.

INTRODUCTION

Extensive laboratory testing was carried out on the Queenston shale to study time-dependent deformation behaviour and the results have been reported in Lee [1), 2)]. From this experimental study, it has been observed that factors influencing the swelling behaviour of this shale are ;

(a) the fabric of the sample,
(b) the presence of ambient water,
(c) the mineralogy and
(d) the applied stress.

To generalize the ovservations on these factors, all the existing swell test results of shales from southwestern Ontario, Canada were collected and analyzed in this paper. Sources of these test results are Wai[3)], Lo et al.[4)], Yuen[5)], Lee[6)] and U.W.O. laboratory records.

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Table 1. Summary of time-dependent deformation behaviour of shale formations

Shale Formation	Project or Location	Year of Investigation	Depth (m)	Type of Tests Performed[1]	Stress Dependency Parameter S_V	S_H	Source of Test Results
Collingwood	Duffin Creek	~1974	21.2-25.1	FS	–	–	Wai(1977)
Blue Mt.	Lakeview Deephole	1986	177	FS/SC	0.24	–	Present Study
Georgian Bay	Scotia Plaza	1984	11.5-27.9	FS/SC	–	0.07	〃
	Skydome	1984	11.3-34.5	FS/SC	0.20	0.11	〃
	Lakeview Deephole	1986	14-140	FS	–	–	〃
	John St. Tunnel	1987	11.8-17.9	FS/SC	–	0.08	〃
	Heartlake Tunnel	1977	13.3	FS/SC	–	0.10	Yuen(1979)
	Lakeview	~1974	15.1 15.7	FS/SC	0.32	–	Wai(1977)
Queenston	SABNGS No. 3	1983	6.6-29.9	FS	–	–	Huang & Semec(1983)[2]
	SABNGS No. 3	1984	79.4-121.6	FS/SC	–	0.07	Semec & Huang(1984)[2]
	SABNGS No. 3	1985-1987	95.6-114.3	FS/MSC	0.10	0.07	Huang & Semec(1985)[2] Semec & Huang(1986)[2]
	Hamilton	1987	9.2-25.4	FS/SC	0.02	–	Present Study
	Oakville	1977	3.9-7.4	FS/SC	0.02	0.06	U.W.O. Records
	Halton	1988	4.2-6.6	FS/SC	0.02	–	〃
Power Glen	SABNGS No. 3	1984	66.0-70.3	FS/SC	–	0.04	Present Study
Grimsby	SABNGS No. 3	1984	49.3-60.2	FS/SC	–	0.04	〃
Rochester	Niagara Falls	1976	26.5-31.1	FS/SC	0.04	–	Wai(1977)

NOTE : [1] FS stands for the free swell test, SC stands for the semi-confined swell test and MSC stands for the modified semi-confined swell test.

[2] Tests performed at U.W.O. laboratory for Ontario Hydro(1984–1987 tests performed by author).

Seven shale formations were investigated in the present study and they are (a) the Collingwood shale, (b) the Blue Mountain shale, (c) the Georgian Bay shale, (d) the Queenston shale, (e) the Power Glen shale, (f) the Grimsby shale and (g) the Rochester shale. The list of shale formations, projects and sources of the test results is shown Table 1.

This paper presents the results of the study on factors influencing the swelling behaviour of shales. The effect of ambient water on the swelling behaviour of shales is investigated first. The effect of calcite content is then studied and the effect of the applied stress is lastly discussed for shales studied. Since the effect of the fabric was reported by Lee[2)] and Lo et al.[4)], a further discussion on this will be omitted in this paper.

EFFECT OF AMBIENT WATER

To study the effect of ambient water on the swelling of shale and the structure of test specimen, a cylindrical specimen was prepared and kept in the moist air(100% humidity condition) by storing the specimen in the concrete curing room. The compressional wave velocity and the weight of this specimen were then monitored at appropriate time intervals. The ratio of the wave velocity at any time(V) to the initial wave velocity(V_0) and the ratio of change in weight($\triangle W$: increase in weight in the present study) at any time to the initial weight(W_0) of the specimen are plotted against the elapsed time in Figure 1. In the same figure, the vertical swelling strain from a free swell test is also plotted for better interpretation of test results.

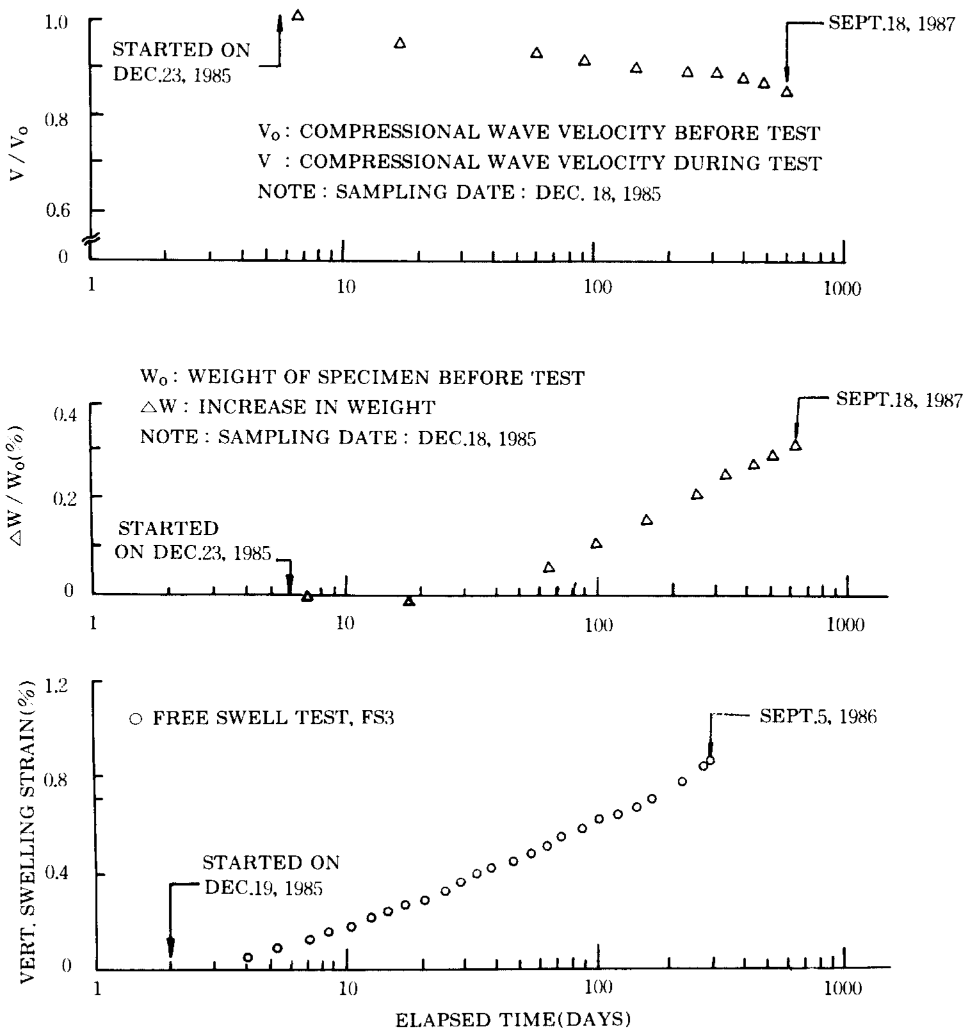


Fig 1. Changes in compressional wave velocity, increase in weight and swelling strain with time, queenston shale, niagara falls

It may be observed that the compressional wave velocity decreases with increasing elapsed time. The decrease in the wave velocity at the end of the 635 day test is about 13% of the initial wave velocity, indicating that cracks have developed in the specimen during test. It is interesting to note that the compressional wave velocity decreases as the specimen swells, implying that the swelling of the specimen is associated with the formation of cracks in the specimen.

The rate of weight change increases with increasing elapsed time. The weight increase at the end of the test is about 0.31% of the initial weight of the specimen. The weight of the specimen increases as the specimen swells, indicating that the swelling of the specimen is associated with the amount of water absorbed, in cracks formed during the swelling.

In order to verify the above observations, two shale samples, one from the Queenston shale and the other from the Blue Mountain shale, were visually inspected before and after free swell test. From the inspection of the specimen after free swell test, the pattern of cracking is easily noticed due to the dark lines on the light surface(Figure 2). The dark colour in these lines is mainly due to the presence of the water, while the light-coloured portion on these samples is the dry surface of the sample. When these samples were inspected visually before the test, there was no sign of cracks on the surface of these samples. Therefore, these cracks were developed and filled with water during the test, as the test specimen swelled. The results of the visual inspection confirm that the swelling of the shales is associated with the formation of cracks and the increase in the amount of water absorbed.

It is also interesting to note that these two shales show a different pattern of cracks, as shown in Figure 2. The Blue Mountain shale exhibits a brick-layer pattern of crack, while the Queenston shale shows a more random pattern of cracks. These crack patterns are consistent with the fabric of these shales discussed in Lee[2]. The Blue Mountain shale has a strong clay fabric with preferred orientation of horizontal layering, while the Queenston shale shows a less distinctive clay fabric compared to the Blue Mountain shale.

To extend this observation to other shales, the ratio of the increase in weight after test ($\triangle W$) to the initial weight (W_O) of the sample is plotted against the vertical swelling potential of three shales and three shaly limestones in Figure 3. It may be observed that the amount of water absorbed(ie. increase in weight of the specimen) increases almost linearly with the increase in the vertical swelling potential of swelling rocks studied. From the observations made in Figures 1, 2 and 3, it may be generalized that the swelling of shale is associated with the formation cracks and the amount of water absorbed in these cracks.

THE EFFECT OF CALCITE CONTENT

The importance of mineralogy on swelling behaviour of shales from southwestern Ontario has been studied in detail and reported in Lee[2]. It has been found from this study that the swelling of shales from this region is not attributed to minerals like pyrite, anhydrite or swelling clay minerals. It has also been shown that shales studied contain some amount of calcite as non-clay minerals.

The effect of cementation by calcite on inhibiting the swelling of shales was illustrated

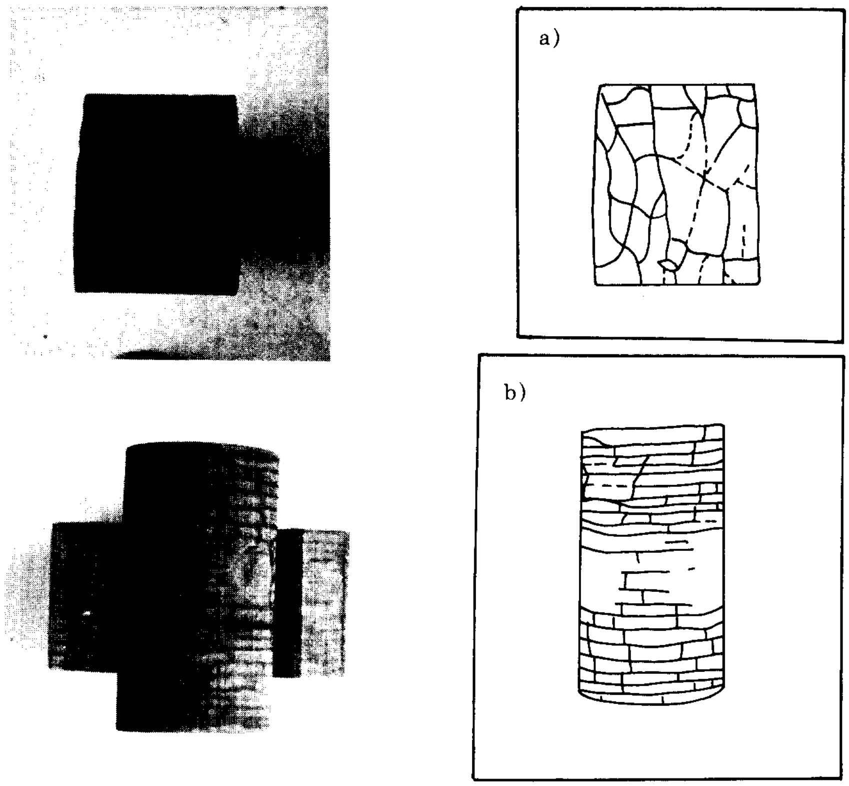


Fig 2. Sample photos showing crack patterns of
a) Queenston shale sample and
b) Blue Mountain shale sample
(After free swell test)

by Lo et al[4]. It was shown that the swelling potential decreased with increasing calcite content, based on the test results on a relatively limited number of shale formations. To establish an approximate correlation generally applicable to shales from this region, the swelling potentials from all the existing test results are plotted against the corresponding calcite content of the samples. Considering the effect of sampling depth on the swelling behaviour of shales, the test results are divided into two groups ;

(a) One group containing test results from shallower depth than 40 m below ground surface, and

(b) The other group comprising test results from depth greater than 40 m.

In Figure 4, the test results from the shallow depth are presented. From the examination of the test results in this figure, the following observations may be made :

(a) There is a general trend of decrease in both horizontal and vertical swelling potentials with increasing calcite content.

(b) For a shale having a calcite content exceeding 30%, the swelling potential is essentially zero.

(c) Some of test results fall above the approximate limit lines for both horizontal and

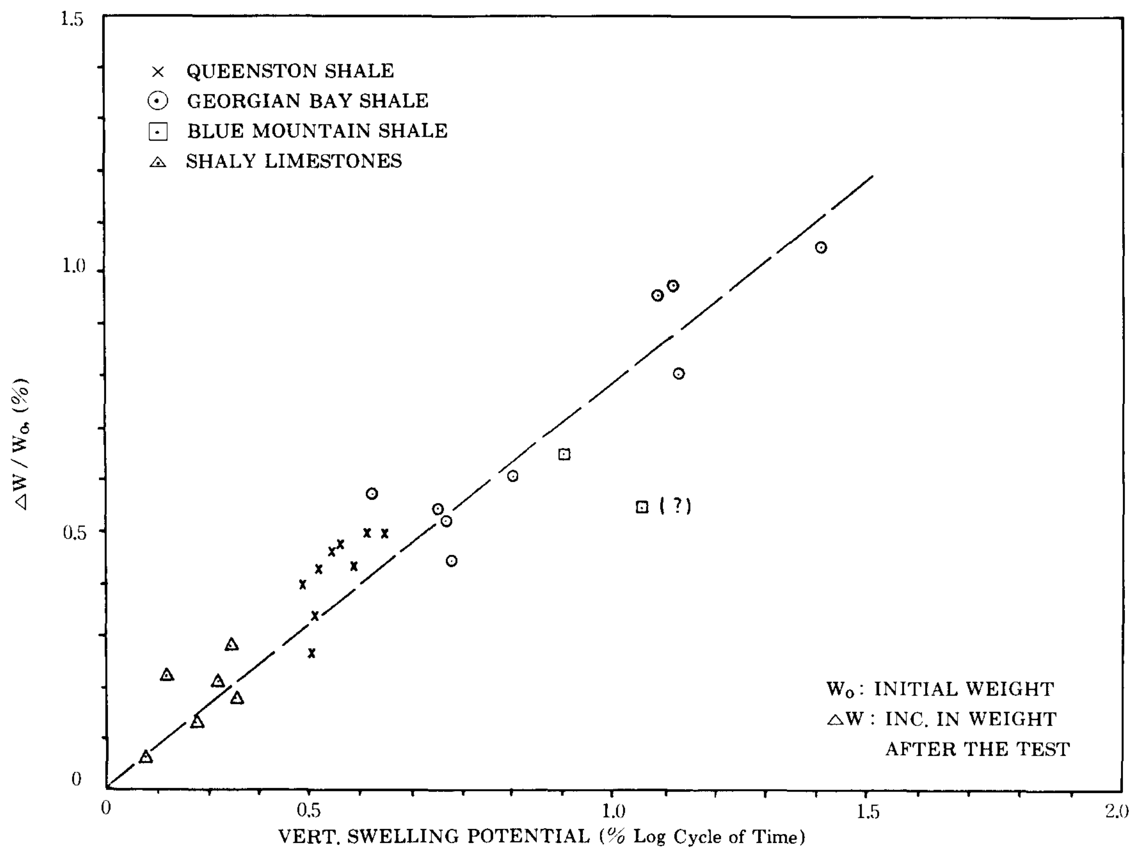


Fig 3. Relationship between vertical swelling potential and increase inweight of the specimen after test

vertical swelling potentials given by Lo et al[4].

From the above observations, it is now evident that the appoximate limit lines suggested by Lo et al.[4] may have to be revised for better correlation between the swelling potential and the calcite content. New upper limit lines covering almost all the data points are drawn in Figure 4 for the horizontal and the vertical swelling potentials of the sample. It may be noted that the main engineering usage of the correlation is to provide an assessment of the swelling of the shale in the preliminary stage of a project, not a quantitative application of the data.

The vertical and the horizontal swelling potentials from the deeper depth are plotted against the corresponding calcite content of the sample and the results are found in Lee[6]. All the ovservations made above are found to be valid.

THE EFFECT OF THE APPLIED STRESS

The stress-dependency of the swelling behaviour of shaly rocks was well demonstrated by Lo et al[4]. Using the test results for shales (two formations) and shaly limestones (two formations), they observed that both horizontal and vertical swelling potentials decreased with

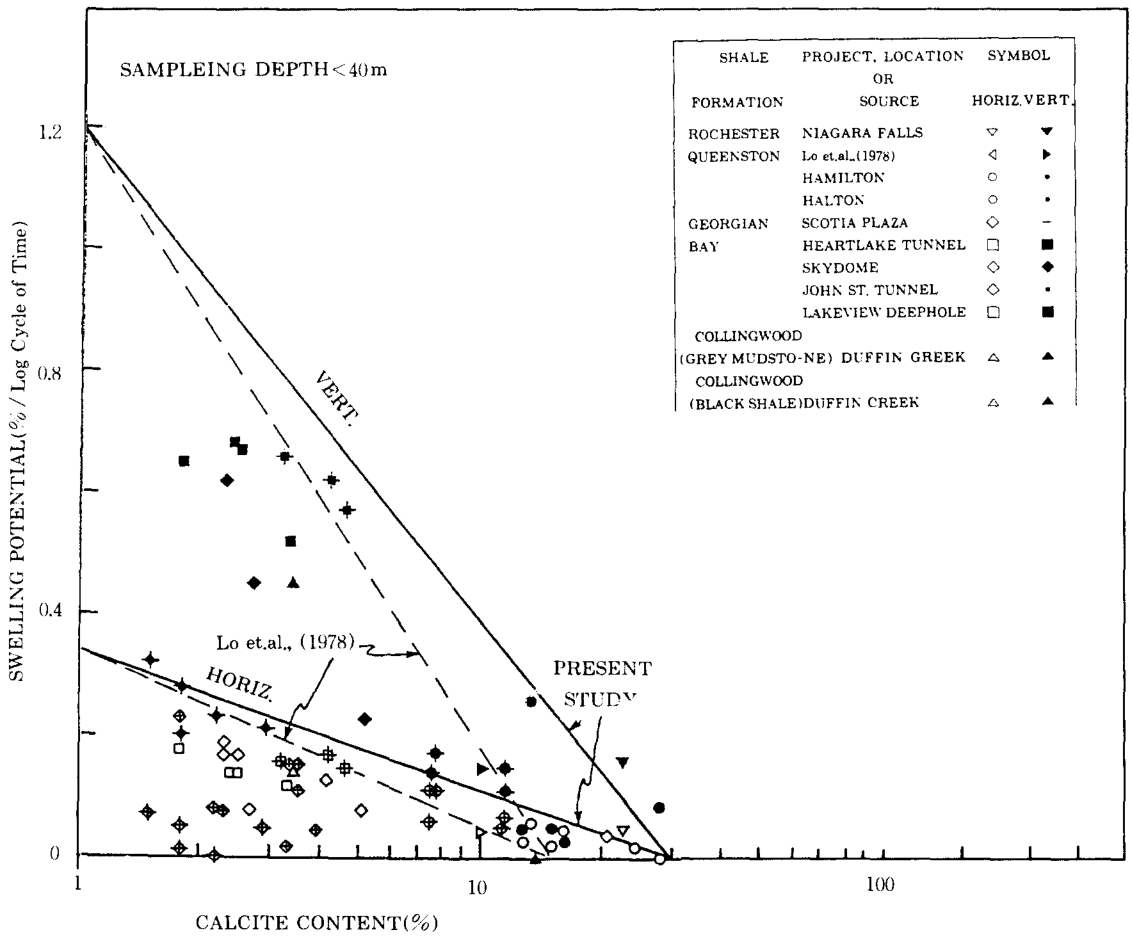


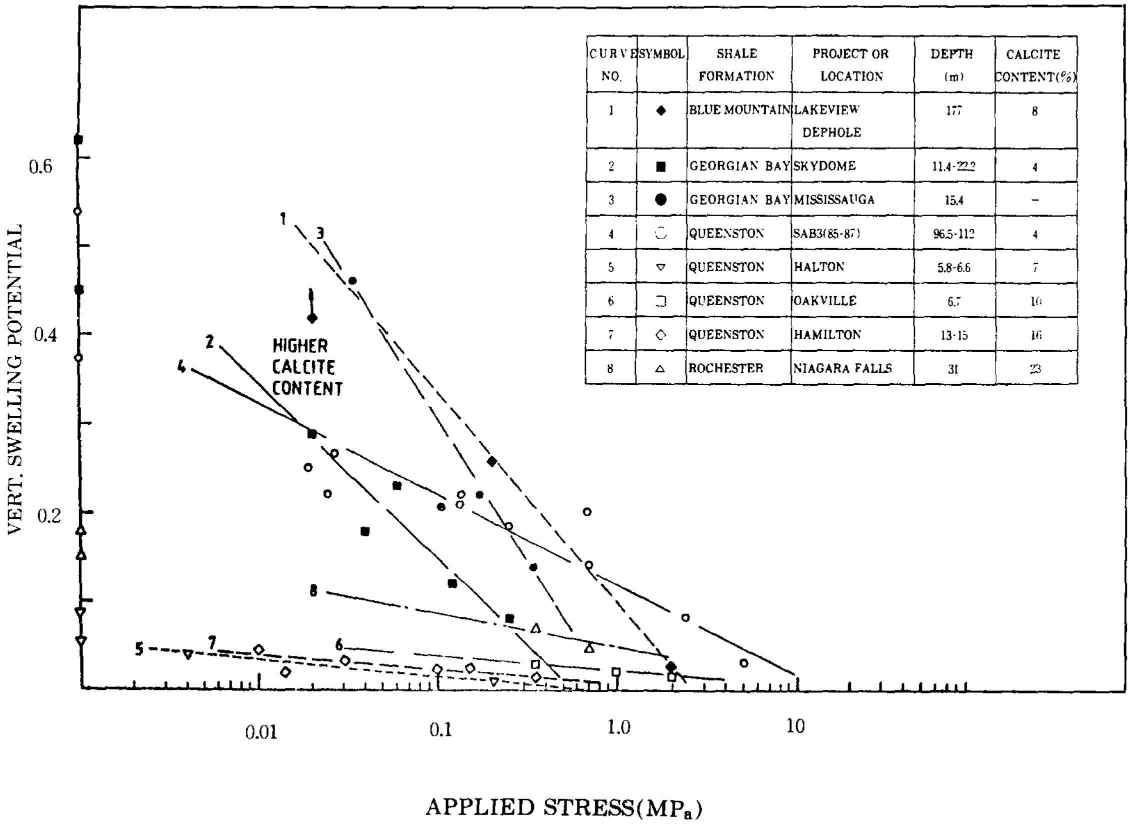
Fig 4. Effect of calcite content on swelling potentials of shale samples from depth shallower than 40m

increasing applied stress.

To investigate a gereral pattern of the stress-dependency of swelling behaviour of shales, the swelling potentials from semi-confined swell tests are plotted against logarithm of the applied stress . Vertical swelling potentials are plotted aganist the applied stress in Figure 5 for shales from southern Ontario. For a clearer discussion of the test results, the stress-dependency parameter, S, is defined as the slope of the curve in the plot of the swelling potential versus logarithm of applied stress. Upon examining the test results presented in Figure 5, the following observations are made :

(a) The vertical swelling potential from all the shale formations studied generally decreases linearly with increasing applied stress in the semi-log plot.

(b) The rate of decrease in swelling potential, that is, the stress-dependency parameter, S, is substantially different for shales tested. The Georgian Bay shales show the stress-dependency parameter in the range of 0.20 to 0.32, indicating that vertical swelling potentials



CURVE NO.	SYMBOL	SHALE FORMATION	PROJECT OR LOCATION	DEPTH (m)	CALCITE CONTENT(%)
1	◆	BLUE MOUNTAIN	LAKEVIEW DEPHOLE	177	8
2	■	GEORGIAN BAY	SKYDOME	11.4-22.2	4
3	●	GEORGIAN BAY	MISSISSAUGA	15.4	–
4	○	QUEENSTON	SAB3(85-87)	96.5-112	4
5	▽	QUEENSTON	HALTON	5.8-6.6	7
6	□	QUEENSTON	OAKVILLE	6.7	10
7	◇	QUEENSTON	HAMILTON	13-15	16
8	△	ROCHESTER	NIAGARA FALLS	31	23

Fig 5. Effect of applied stress on vertical swelling potential of swelling shales, southern ontario

are strongly stress—dependent. The values of S for the Queenston shale samples from Halton, Oakville, and Hamilton and the Rochester shale are one roder of magnitude lower, ranging from 0.02 to 0.04. The Wueenston shale from Niagara Falls shows the stress—dependency parameter falling in between these two(S=0.1).

(c) High stress-dependency parameter of the Georgian Bay shale and the Blue Mountain shale may be attributed to the effects of the fissility and the fabric on the shale after sampling. (d) Difference in the stress-dependency parameter between the Queenston shale from SABNGS No. 3 site and that from other areas may be attributed to different calcite content, and possibly to different magnitude of stress relief due to sampling process.

The horizontal swelling potential is plotted against the applied stress in Figure 6 for shales from southern Ontario. From the examination of the test results shown in Figure 6, the following observations are made :

(a) As in the case of vertical swelling potential, the horizontal swelling potential from all the shales studied decreases with increasing applied stress linearly in the semi-log plot.

(b) The Georgian Bay shale shows strong stress-dependency in the horizontal swelling potential. The stress-dependency parameter, S, ranges from 0.07 to 0.11.

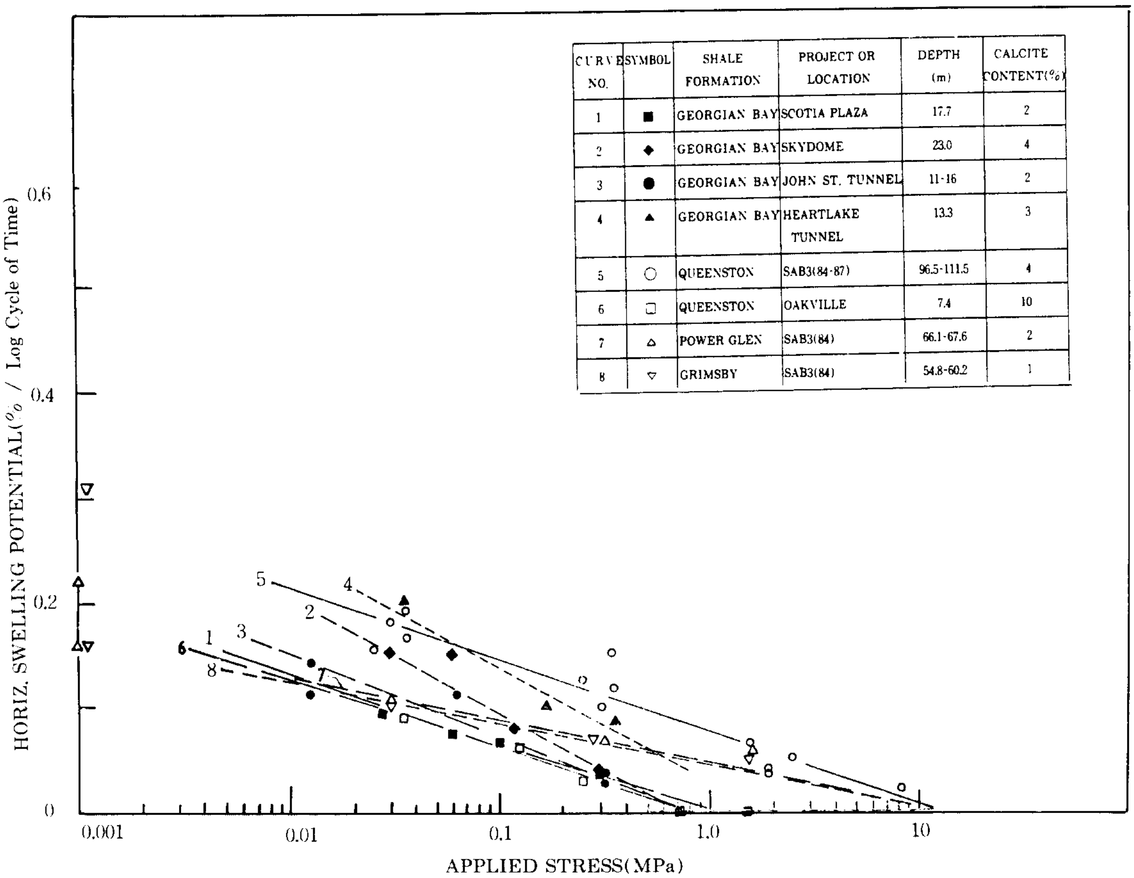


Fig 6. Effect of applied stress on horizontal swelling potential of swelling shales, southern ontario

(c) The stress-dependency parameter for the Power Glen shale and the Grimsby shale is 0.04, indicating that the swelling potentials of these shales are weakly stress-dependent.

(d) The Queenston shales from Niagara Falls and Oakville show the intermediate stress--dependency of the swelling potential, ranging from 0.06 to 0.07.

(e) In general, the stress-dependency parameter in the horizontal direction is smaller than that in the vertical direction for the same shale formation, mainly due to the anisotropic swelling behaviour of these shales as discussed in Lee[2]

The stress-dependency parameters in the vertical and horizontal directions S_V and S_H are summarized in Table 1.

CONCLUSIONS

From the results of the study of all the existing data on the seven shales from southwestern Ontario, the following conclusions may be drawn :

(a) The swelling of shale is associated with the formation of cracks in the specimen and the absorption of water in these cracks. It has been established that the amount of absorbed water during the test can be related linearly to the magnitude of swelling potential.

(b) In general, both horizontal and vertical swelling potentials decrease with increasing calcite content, regardless of the sampling depth. For a shale having a calcite content exceeding 30%, no swelling is expected to occur in both horizontal and vertical directions.

(c) Both horizontal and vertical swelling potentials generally decrease with increasing applied stress. Both horizontal and vertical swelling potentials of the Georgian Bay shale are strongly stress-dependent, while those of the Queenston shale are moderately stress-dependent.

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要　　旨

本稿는 膨脹性 쉐일들의 時間依存的變形擧動에 影響을 미치는 主要素들에 關한 研究結果에 대해서 說明한다. 本研究에서는 南部온타리오주의 쉐일들에 대한 蒐集可能한 모든 膨脹實驗結果를 分析하였다. 調査한 主要素은 (1) 周邊水의 存在 (2) 方解石의 量과 (3) 作用荷重이었다.

研究 結果로 보면 쉐일의 膨脹은 龜裂이 發生한후 이 龜裂에 周邊水들이 吸收되는 것과 關係가 있는 것으로 밝혀졌다. 吸收된 물의 量과 膨脹可能性指數의 크기는 直線的인 關係를 보인다. 方解石은 調査한 쉐일의 膨脹을 抑制하는데, 약 30% 以上의 方解石을 含有하면 쉐일은 膨脹하지 않는 것으로 나타났다. 調査한 모든 쉐일이 程度의 差異는 있지만 應力 依存的 膨脹性擧動을 보였다.

REFERENCES

1. Lee, Y.N., Time-dependent deformation behaviour of Queenston shale, *J. of Korean Society of Geotechnical Engineers,* Vol. 5, No.2, 1989 PP 57～72
2. Lee, Y.N., Mineralogy and fabric of four swelling shales, *Proc. of 1989 Fall Seminar, Korean Society of Geotechnical Engineers,* 1989, PP Ⅱ-1～Ⅱ-25
3. Wai, R.S.C., *Time-dependent deformation of some shaly rocks,* M.E.Sc. Thesis, Univ. of Western Ontario, London, Canada, 1977
4. Lo, K.Y., Wai, R.S.C., Palmer, J.H.L. and Quigley, R.M., Time-dependent deformation of shaly rocks in southern Ontario, *Can. Geotech. J.,* Vol. 15, 1978, PP 537～547
5. Yuen, C.M.K., *Rock-structure time interaction in lined circular tunnels in high horizontal stress field,* Ph. D. Thesis, Univ. of Western Ontario, London, Canada, 1979
6. Lee, Y.N., *Stress-strain-time relationship of Queenston shale,* Ph. D. Thesis, Univ. of Western Ontario, London, Canada, 1988
7. Huang, J.H.S. and Semec, B.P., Sir Adam Beck-Niagara Generating Station No.3, 1983 geotechnical investigation results and evaluation. *Oritario Hydro Report No. 83511,* 1983.
8. Semec, B.P. and Huang, J.H.S., Sir Adam Beck-Niagara GS No.3, 1984 geotechnical investigation results and evaluation, *Ontario Hydro Report No. 84478,* 1984
9. Huang, J.H.S. and Semec, B.P., Sir Adam Beck-Niagara GS No. 3, 1985 geotechnical investigation results and evaluation, *Ontario Hydro Report No. 85403,* 1985
10. Semec, B.P. and Huang J.H.S., Sir Adam Beck-Niagara GS No.3, 1986 geotechnical investigation results and evaluation, *Ontario Hydro Report No. 86279,* 1986

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