Time-dependent Deformation Behaviour of Queenston Shale

퀸스톤 쉐일의 時間依存的 變形擧動

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要 旨

本稿는 膨脹性 岩石들의 時間依存的變形의 測定을 위한 實驗裝置와 實驗結果에 關해서 說明한다. 새로운 實驗裝置들은 改善된 一軸壁縮下의 膨脹試驗, 一軸 引張下의 膨脹試驗과 二軸 應力下의 膨脹試驗을 위해서 製作하였다. 本 實驗裝置들은 岩盤掘鑿時 地盤에 作用하는 單純化된 應力狀態下에 있는 岩盤의 時間依存的 變形을 세 垂直方向에서 測定한다. 지난 몇년간에 걸쳐서 얻은 實驗結果에 依하면 本 實驗裝置들은 成功的으로 作動하는 것으로 나타났다.

實驗結果로 보면, 퀸스톤 쉐일(Queenston shale)의 自由變形條件下에서의 時間依存的 變形 擧動은 層理面과 垂直인 方向에서는 層理面과 平行인 方向에서보다 약간 더 많은 膨脹이 일어나는 異方性的 擧動을 보인다. 한 方向에 應力을 받을 때에는 應力이 作用하는 方向은 물론 그와 垂直되는 方向의 膨脹性變形이 抑制된다.

Abstract

This paper describes the design and construction aspects of time-dependent deformation test apparatus for swelling rocks and presents the test results obtained using these apparatus. These tests are modified semi-confined swell test, swell test under uniaxial tension and swell test under biaxial stress. These apparatus measure the time-dependent deformations in three orthogonal directions of the test specimen under simplified field stress conditions. The test results obtained from these test apparatus for the last several years show that these apparatus have performed satisfactorily.

The test results show that the time-dependent deformation behaviour of the Queenston shale is cross-anisotropic with higher swelling in the vertical direction (normal to bedding plane) than in horizontal direction (parallel to bedding plane) under free swell condition. The applied stress in one direction suppresses the swelling deformation in that direction as well as that in the orthogonal directions.

Introduction

It is well recognized that the knowledge on time-dependent deformation behaviour of shaly rocks is essential for the design and construction of underground structures built in swelling

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rocks. Time-dependent deformations in the form of heave and/or lateral inward movement have been observed in tunnels constructed in different parts of the world. For example, invert heave amounting to about 30 cm in 30 years was measured in tunnels in Switzerland and floor heave up to 45cm in 3 years in tunnels in Germany (Lo and Yuen[1]). Various degrees of distress have been reported for underground structures constructed in rocks exhibiting time-dependent deformation and subject to high initial horizontal stresses. In some tunnels, the distress was so severe that expensive remedial measures had to be undertaken. Short and long-term problems in open excavation and tunnels built in swelling rocks under high initial stresses have been summarized by Lo and Yuen[1]

To study the time-dependent deformation behaviour of swelling rocks and their swelling mechanism, an extensive experimental investigation has been carried out by the author. The main emphasis was directed towards the effects of the internal factors (e.g., fabric, mineralogy and salinity) and the external factors (e.g., the applied stress and stress system) on swelling behaviour of some shales from southern Ontario, Canada. For the study on the effect of the applied stress and stress system on swelling behaviour, three new test apparatus were designed and constructed by the author.

In this paper, three new methods of laboratory testing for time-dependent deformation of shales are described. Results of tests on the Queenston shale rockcores are presented. It is shown that these results are generally consistent with field behaviour. The effect of the stress system on swelling strain is briefly discussed.

Methods of Testing

To study the swelling behaviour of shales from southwestern Ontario, two simple but useful types of test methods, free swell test and semi-confined swell test, have been used extensively sine the early 1970s. It has been found however that the existing test methods are not adequate for the study of swelling behaviour in three dimension under the representative stress condition in the field. For this reason, three new test apparatus were designed and constructed for the measurement of time-dependent deformation in three orthogonal directions for the study of the swelling behaviour of shaly rocks. Details of these apparatus are described below:

Modified Semi-confined Swell Test

This test is to simulate the stress condition of the element where the dominant stress is the uniaxial compressive stress. In the existing test apparatus, the axial deformation alone is monitored by dial gauge. To measure the time-dependent deformations in three orthogonal directions, the existing semi-confined swell test apparatus has been modified as shown in Figures 1 and 2. This test apparatus consists of loading hanger, loading support frame, and deformation monitoring system. The dial gauge (reading to 0.001mm), sitting on the top cross bar of the loading hanger, monitors the sample height during the test, giving the axial deformation of the specimen. Lateral deformations are measured by strain gauges mounted on the cantilever beam. On both sides of the cantilever beam (12.5×63.5×1.57mm), two strain gauges, type CEA-06-250UW-120 (Micro-Measurement Co., U.S.A) are mounted to monitor deflections of

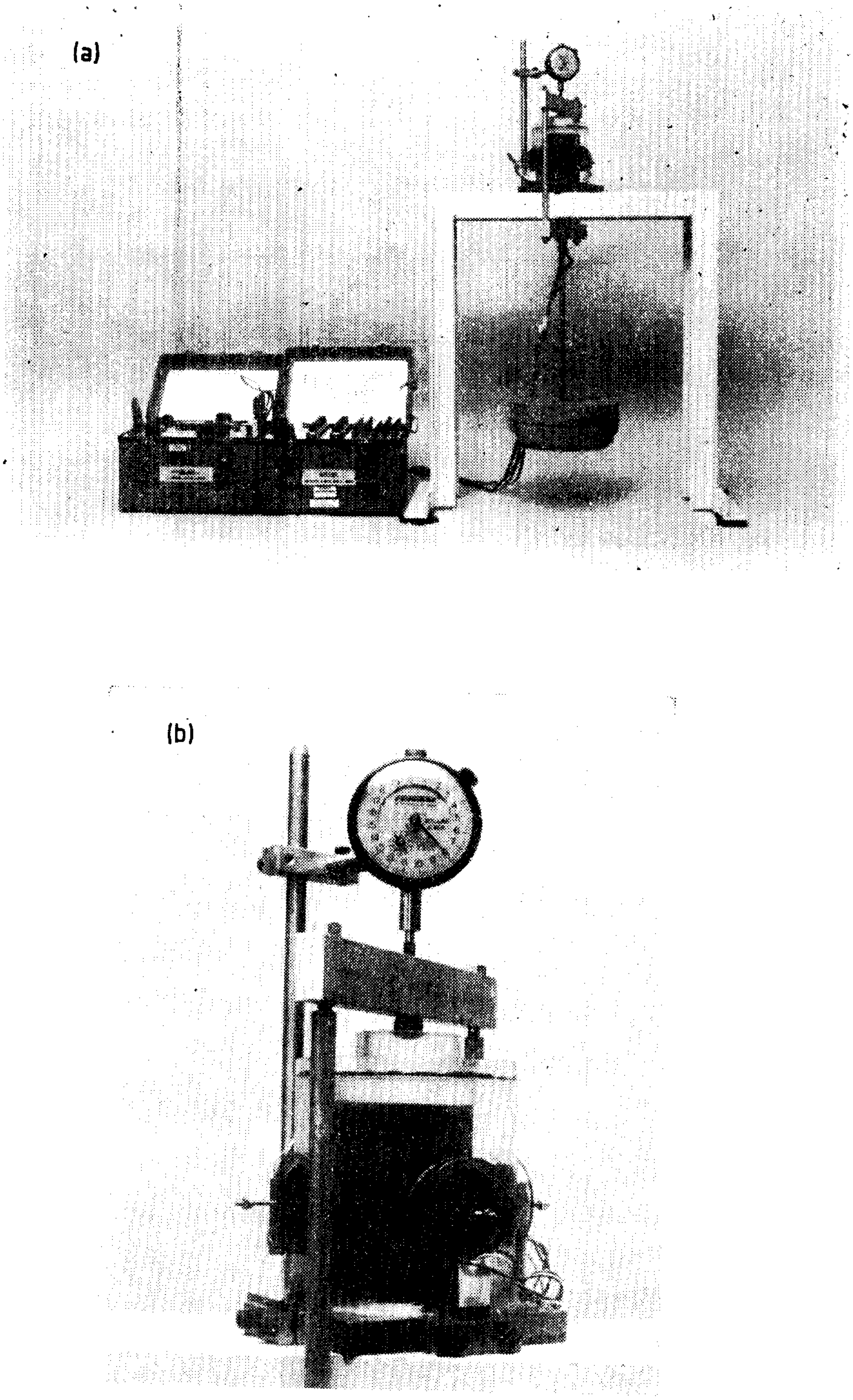


Fig. 1. Modified semi-confined swell test; (a) overall test arrangement and (b) details

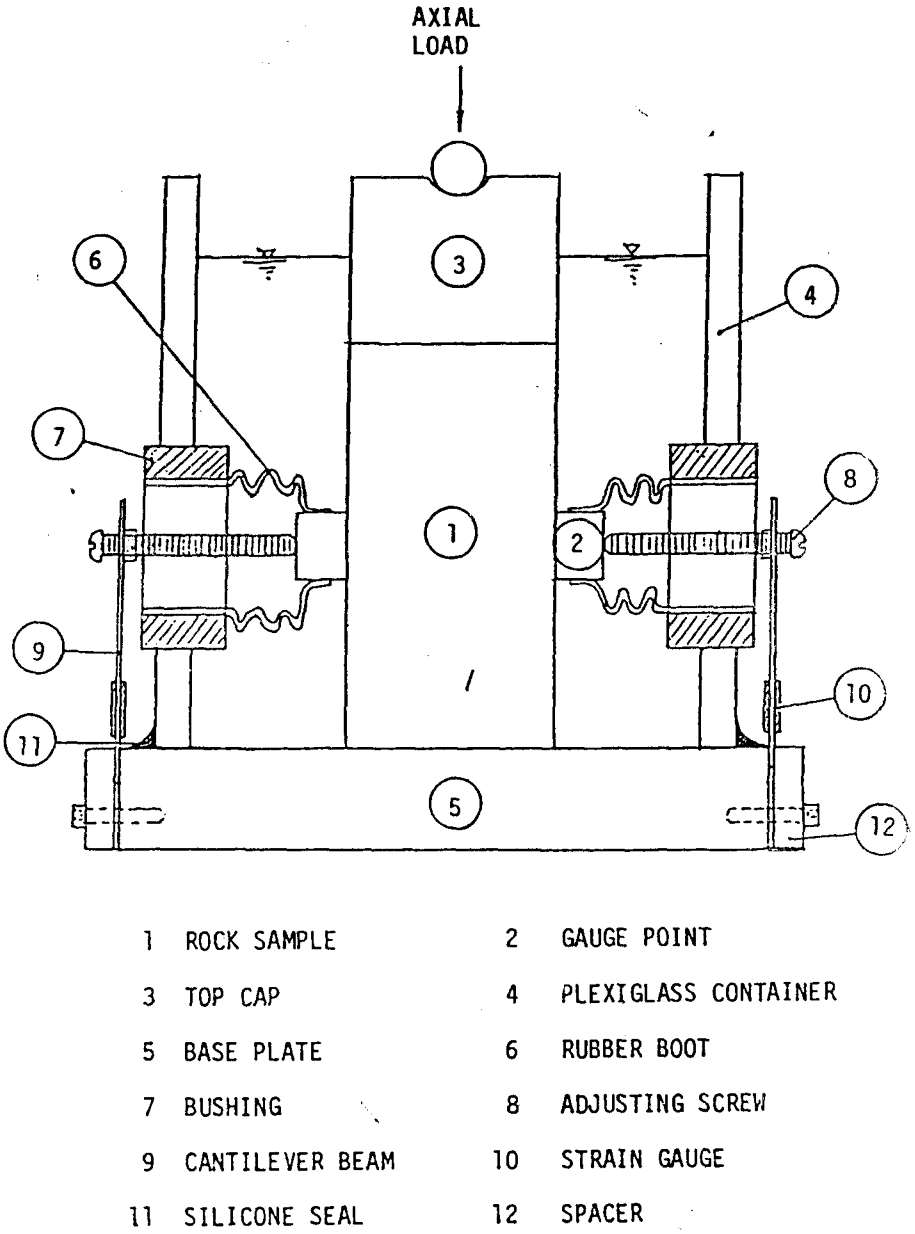


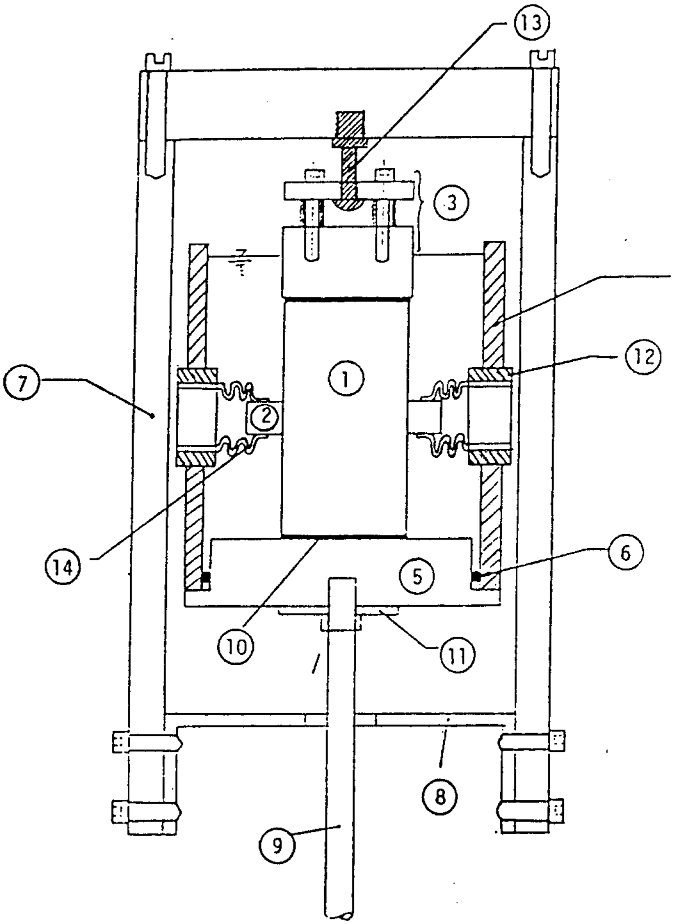
Fig. 2. Section view of modified semi-confined swell test set-up

the beam caused by the swelling of the specimen in the lateral direction.

A specially designed container was constructed to isolate the lateral deformation monitoring system from the cell water surrounding the specimen.

Swell Test Under Uniaxial Tension

This test is designed to simulate the stress condition of an element where the dominant stress after the excavation is a tensile stress. To study the effect of the applied tensile stress on time-dependent deformation behaviour, a new test apparatus has been designed and constructed as shown in Figure 3. This test set-up is composed of three main parts; loading support frame. loading cap assembly and container, and deformation monitoring system. The loading support frame is similar to that of the modified semi-confined swell test except that there are two additional parts added; four dial gauge support anchors and the upper loading support frame. The design of the loading cap assembly is adopted from that for the triaxial extension test developed by Bishop and Henkel[2] in which details of this assembly can be found. All the lateral deforma-



1 ROCK SAMPLE
2 GAUGE POINT
3 LOADING CAP ASSEMBLY
4 PLEXIGLASS CYLINDER
5 BASE PLATE
6 'O' RING
7 UPPER LOADING SUPPORT FRAME
8 LOWER LOADING SUPPORT FRAME
9 THREADED HANGER ROD
10 BODY FILLER MATERIAL
11 AXIAL DIAL GAUGE SUPPORT BAR
12 BUSHING
13 BAYONET CATCH
14 RUBBER BOOT

Fig. 3. Details of test arrangement for swell test under uniaxial tension

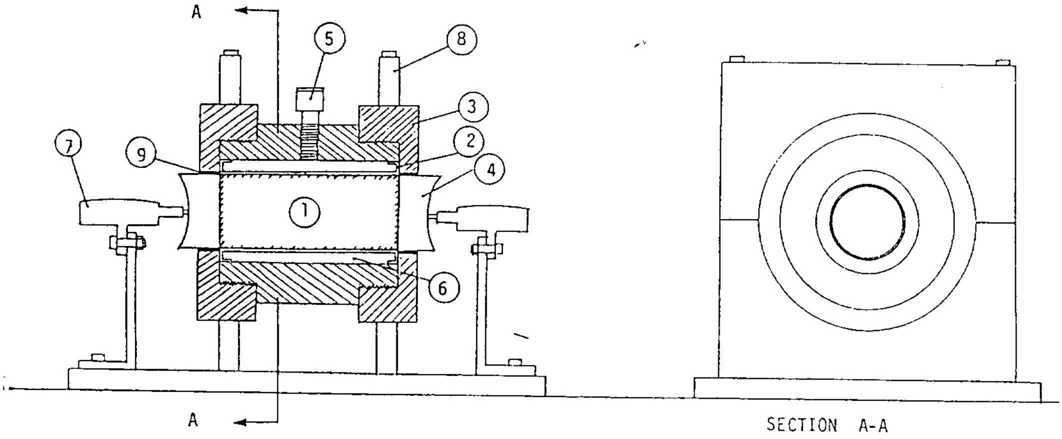
tions of the test specimen are monitored by four dial gauges whose stems are brought into contact with gauge points. The axial deformation of the test specimen is monitored by two dial gauges mounted on the axial dial gauge support plate.

In this test, the test specimen is glued onto the loading cap assembly and the base plate in order to apply tensile stress. The bonding material selected is a body filler material used in automobile repair work and recommended for the direct tensile strength test of rocks in ASTM D2936-78. Since the specimen has to be glued onto the base and the loading cap, the plexiglass cylinder of the container is designed to be detchable from the base using an ‘0’ ring at the base.

Swell Test Under Biaxial Stress

This test simulates the stress condition of an element where post-excavation stresses are approximately same in two principal stress directions. The main components of this test set-up are the Hoek cell, hydraulic pump and deformation monitoring system, as shown in Figure 4. The Hoek cell is used to apply a uniform pressure to the cylindrical surface of the test specimen. Descriptions of the Hoek cell may be found in Hoek and Brown.3) A uniform pressure is supplied by a hydraulic pump having a capacity of 30 MPa. Longitudinal deformation is monitored by dial gauge (reading to 0.001 mm) and strain gauges mounted on the specimen. For the measurement of diametric changes, strain gauges are mounted on the specimen and very thin lead wires are used to fit the available annular space between the Hoek cell and the specimen. These strain readings are monitored by a switch and balance unit and a strain indicator.

End caps are placed at both ends of the test specimen to prevent a local failure of the cylindrical surface of the rock under a high hydraulic pressure. However, these end caps should not restrict the longitudinal deformation of the specimen. This is achieved by filling the annular space between the end cap and the Hoek cell with the vacuum grease. Further, the vacuum grease in the annular space prevents the sample from being dried up.



1	ROCK SAMPLE	2	RUBBER JACKET	3	CELL BODY
4	END CAP	5	OIL INLET	6	OIL CHAMBER
7	DIAL GAUGE	8	CLAMPING PLATES	9	VACUUM GREASE

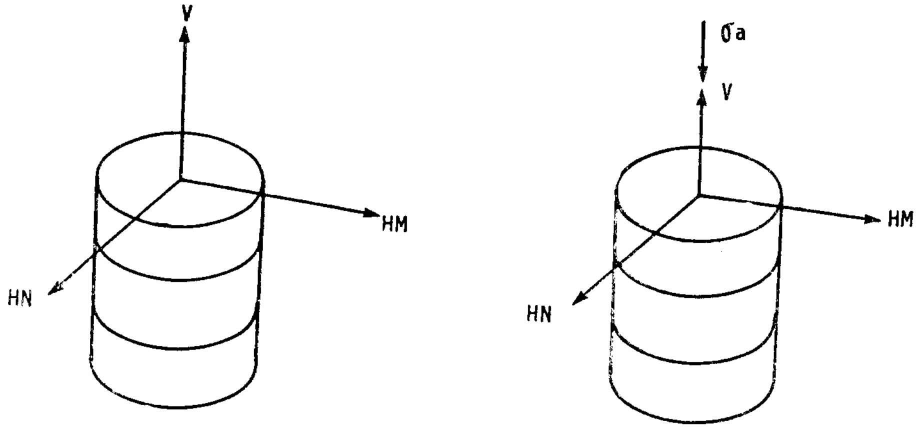
Fig. 4. Arrangement of swell test under biaxial stress

Sample Preparation

In general, test specimens for time-dependent deformation tests were prepared from oriented rockcores in three principal stress directions as shown in Figure 5. The core orientation work was carried out by scribing E-hole (diameter 38mm) wall and then orienting this scribe mark. Details of the core orienting are reported in Lee.[4)] Based on the known orientation of scriber mark and the "known" direction (N 45 E) of the secondary major principal stress from borehole NF-4 (Semec and Huang[5)]), the line of the major principal stress direction was drawn on rockcores. After orienting cores, free swell test specimens were prepared by mounting gauge points in three principal stress directions. All nine modified semi-confined swell test specimen were recored from HQ3 size (nominal diameter of 61.1mm) rockcores in three principal stress directions; vertical, two (HM and HN) principal stress directions in horizontal plane.

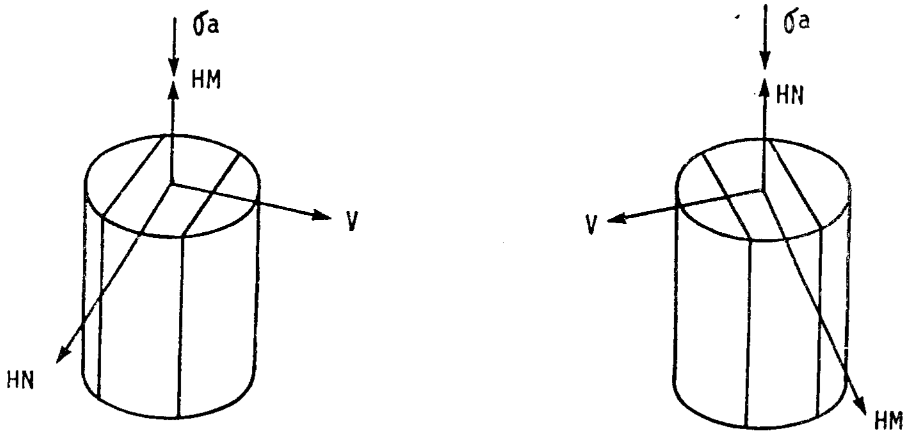
Description of Queenston Shale Tested

The Queenston shale rockcores studied were mainly obtained from one deep borehole NF4A



(a) Free swell test specimen ($\sigma_a=0$)

(b) Modified semi-confined swell test-vertical(V) specimen



(c) Modified semi-confined swell test-horizontal(HM) specimen

(d) Modified semi-confined swell test-horizontal(HN) specimen

Fig. 5. Various specimen orientations with respect to the applied stress

(115m deep) made for the feasibility study of a new hydraulic power plant, known as Sir Adam Beck Niagara Generating Station No. 3 (SABNGS No. 3). The general properties and strength and deformation properties obtained from the present study are summarized as follows:

General Properties

Over the depths of investigation from 80m to 122m where the twin tunnels may be located, the water content lies between 2.0% to 2.9% with an average value of 2.6%. The unit weight averages 26.7 KN/m^3, ranging from 26.4 KN/m^3 to 26.8 KN/m^3. The specific gravity is 2.82. The porosity is approximately 7%. The calcite content varies from 3% to 7% which is lower than values obtained at other sites of the Queenston shale formation in the Niagara Peninsula. The salinity of the pore fluid is in the range of 108mg/l to 265mg/l. There is no significant trend of variation with depth of water content, unit weight, calcite content or salinity, as shown in Figure 6.

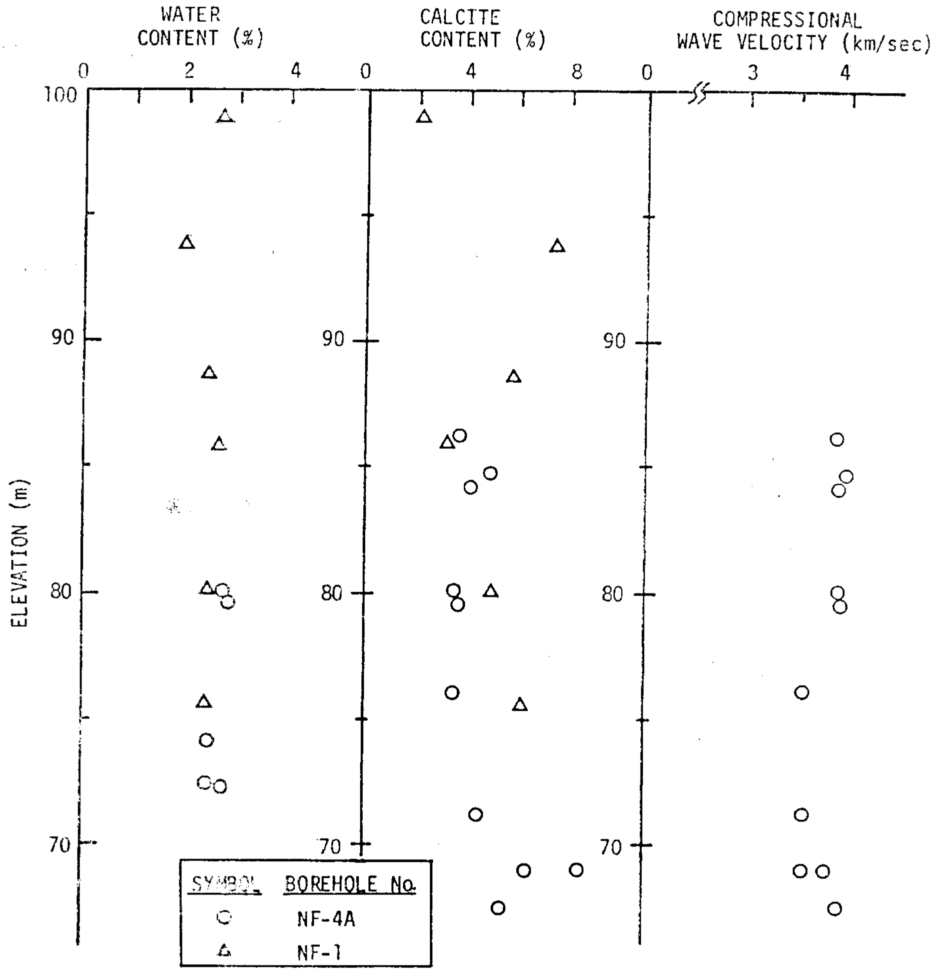


Fig. 6. Variation of water content, calcite content and compressional wave velocity of Queenston shale samples, SABNGS No. 3, Niagara Falls

Strength and Deformation Properties

The uniaxial strength from vertical specimens is approximately 25 MPa and from horizontal specimens 26 MPa. The vertical and horizontal elastic moduli are approximately 9 GPa and 13GPa respecively. The Poisson's ratio for the effect of vertical stress on horizontal strain is 0.35, while the Poisson's ratio for the effect of horizontal stress (in HM direction) on vertical strain is 0.40. The Poisson's ratio for the effect of horizontal stress on horizontal strain is 0.26. It is evident therefore that while the strength behaviour appears isotropic, the deformation behaviour is moderately anisotropic. The compressional wave velocities of vertical and horizonal specimens are approximately 3.6km/sec and 4.0km/sec respectively. The vertical and horizontal dynamic moduli from these wave velocity measurements are approximately 22 GPa and 30 GPa, resulting in a comparable ratio of horizonal to vertical moduli to the corresponding ratio of static moduli.

The tensile strengths determined from splitting (Brazilian) tests are 4.6 MPa and 3.4 MPa respectively for fracture across and along bedding planes.

Results of Time-dependent Deformation Tests

Free Swell Test Results

A total of nine free swell tests were carried out on oriented rockcores from depths between 94 to 113m below ground surface. Typical free swell test results are shown in Figure 7. It may

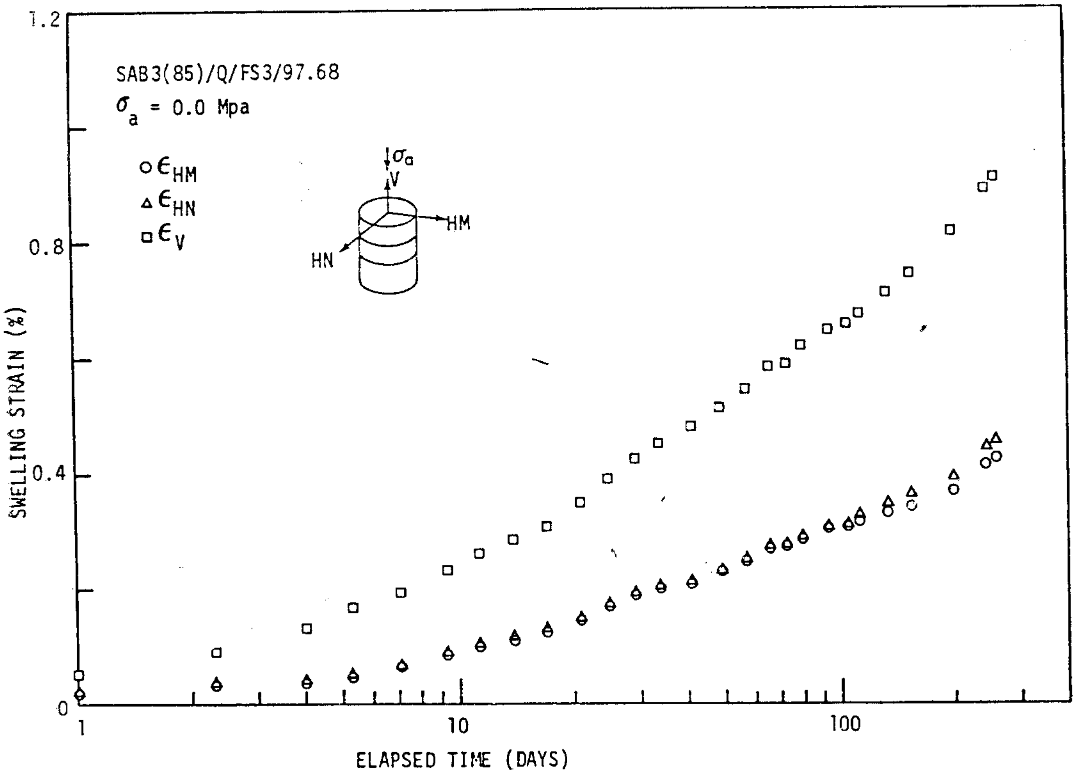


Fig. 7. Typical results of free swell test for the Queenston shale, Niagara Falls, Canada

be observed from this figure that all the strains (plotted in semi-logarithm scale) in three orthogonal directions increase with time for the entire test period of about 270 days. It is particularly interesting to note that horizontal strains in the secondary principal stress directions (HM and HN direction respectively) are virtually identical to each other, indicating that the swelling behaviour in the horizontal plane is isotropic as observed in the other shales from this region. The same observation may also be made on the other free swell test results reported in Lee.[4]

Directions and magnitudes of the initial horizontal stress at this site were determined using the hydrofracturing technique and reported in Semec and Huang.[5] At depths between 93.9 and

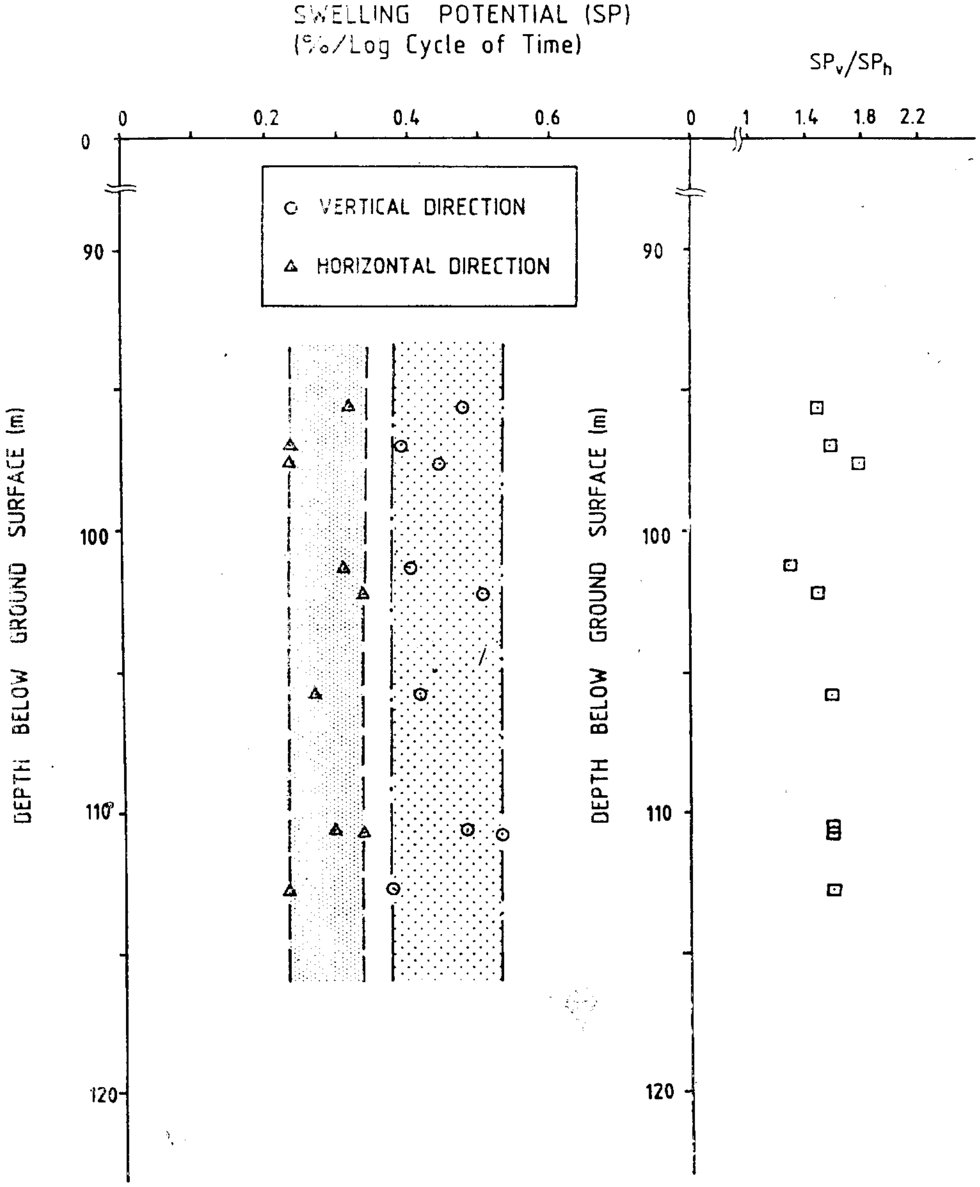


Fig. 8. Variation of swelling potentials of free swell test specimens, Queenston shale

110.3 meters in Borehole NF4, next to NF4A, the results indicate that the major principal horizontal stress is 7.9 MPa and the minor principal stress is 5.2 MPa. Although these results require independent verification as regards magnitude and direction, the results imply that, in the horizontal plane, time-dependent deformation is not sensitive to the precise magnitude of the high horizontal stress.

It may be also observed that swelling potential, defined as swelling strain per log cycle of time and normally taken as strain between 10 and 100 days, in the vertical direction is moderately higher than those in the horizontal directions. The results on the other specimens show the same trend and support the above observation, as shown in Figure 8. In this figure, the swelling potentials in all three directions are plotted against the depth of sampling, together with the ratio of vertical to horizontal swelling potentials. The swelling potential from horizontal samples ranges from 0.24 to 0.34 with an average value of 0.29. The vertical swelling potential is about 1.3 to 1.8 (average of 1.6) times higher than horizontal swelling potential, reflecting the moderate effect of shale fabric. It is also interesting to note from this figure that the swelling potential in the horizontal direction does not show any trend of variation with depth. The same observation can be extended to the vertical swelling potential of the Queenston shale.

The Results of Modified Semi-confined Swell Test

In Figure 9, typical results of the modified semi-confined swell test are shown for a vertical specimen. The applied stress in this test is 0.132 MPa in the vertical direction. Under this stress,

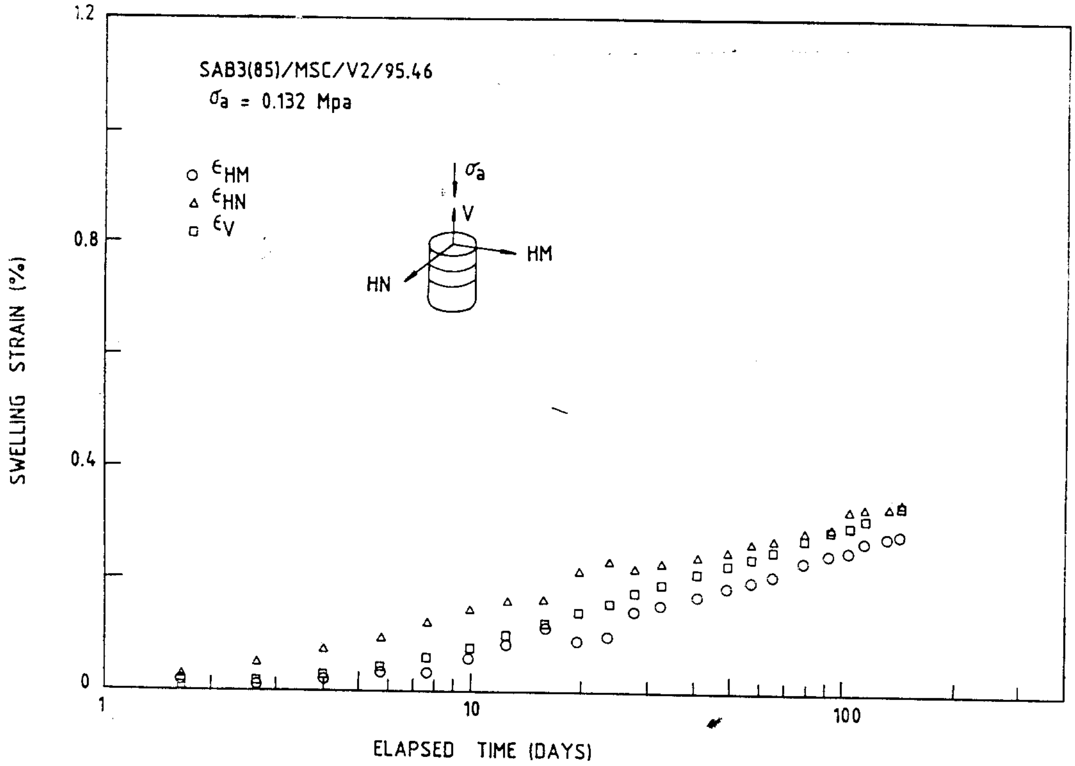


Fig. 9. Typical results of modified semi-confined swell test for the Queenston shale, Niagara Falls, Canada

the vertical swelling potential is reduced to 0.22 from 0.45 (obtained from the free swell test in Figure 7). The reduction effect of applied stress on swelling potential in that direction may be better presented in Figure 10. In this figure, the swelling potentials under applied stress are plotted against logarithm of the applied stress, σ_a for the Queenston shale. Swelling potentials of specimens prepared in the vertical and horizontal directions decrease linearly with increasing applied stress in the semi-log plot. The rate of decrease in swelling potential of vertical specimen is slightly higher than that of horizontal specimen.

It may be also observed from Figure 9 that both horizontal swelling potentials in HM and HN directions, normal to the direction of applied stress, are also reduced to 0.18 from 0.24, indicating that the applied stress in the vertical direction suppresses the swelling in the horizontal directions. The suppression effect of the applied stress on both axial and lateral strains may be further illustrated in Figure 11. In this figure, swelling potentials in the V,HM and HN directions are ploitted against the applied stress for vertical specimens. Swelling potentials in all three directions decrease with increasing applied stress, suggesting that the applied stress suppresses the swelling strain not only in the direction of the applied stress (V direction), but also in the orthogonal directions (HM and HN directions). This suppression effect of axial stress on lateral strains is analogous to Poisson's effect in the conventional uniaxial compression test.* The same observations may be made on the test results of HM and HN samples, as shown in Lee.4)

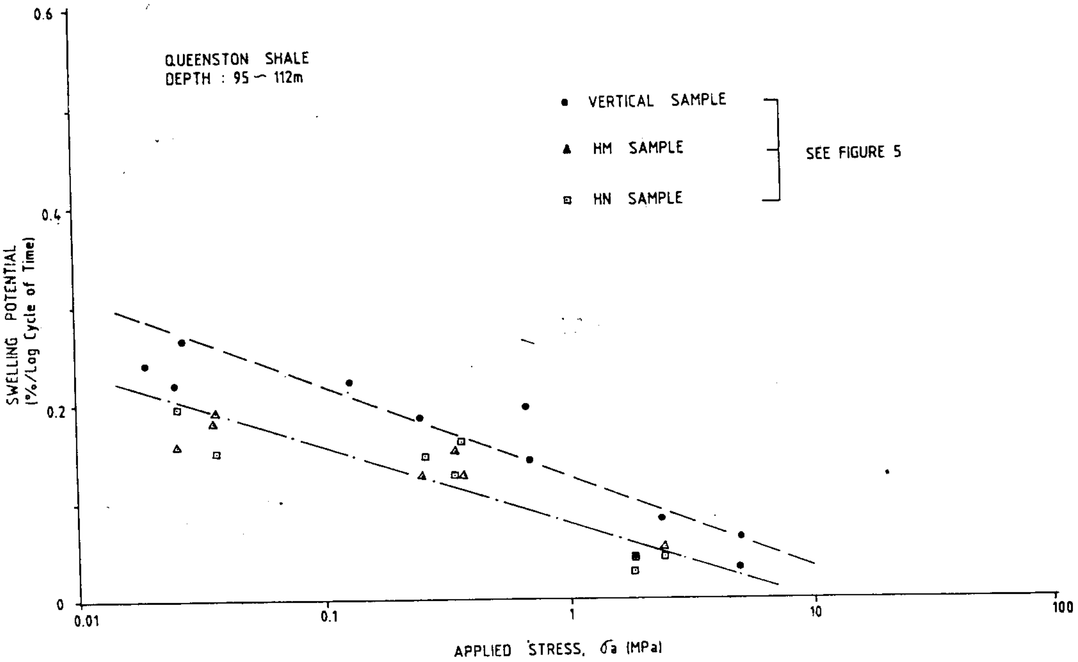


Fig. 10. Effect applied stress on reduction of swelling potential in the direction of applied stress

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* The analogy is made here to describe the effect of the applied axial stress on the orthogonal strains. It should be noted, however, that, in the time-dependent deformation test, the effect of the applied stress is manifested in restricting the swelling of the specimen in orthogonal directions, while in the uniaxial compression test, the effect is exhibited in the expansion of the specimen in lateral directions.

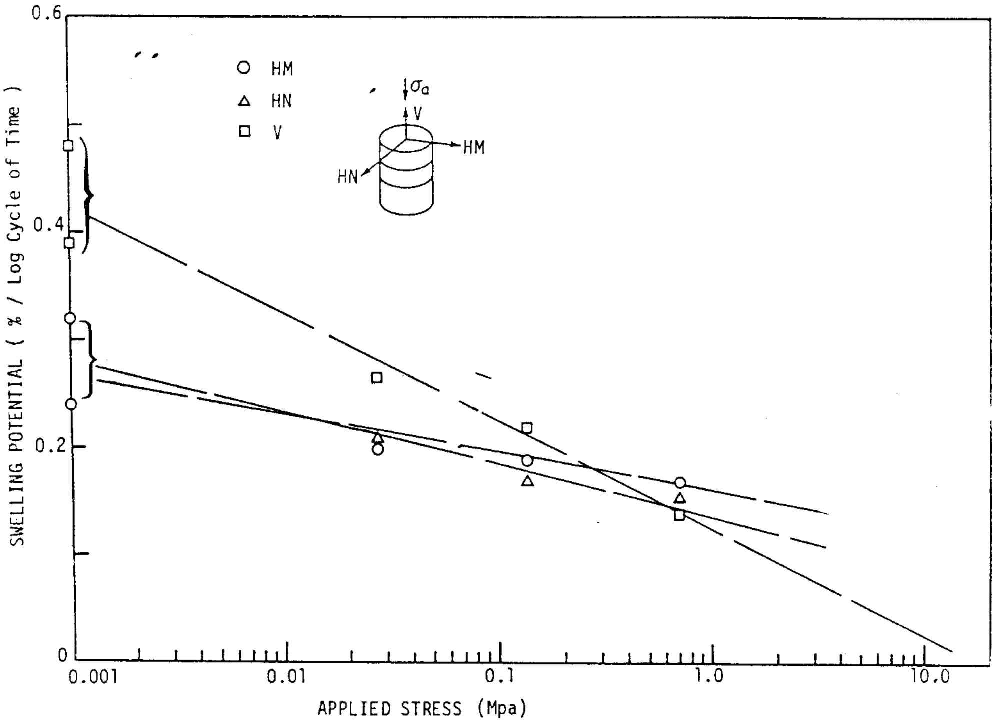

Fig. 11. Effect of applied stress on swelling potentials of the oriented Queenston shale samples, Niagara Falls, Canada

The Results of Swell Test Under Uniaxial Tension

The results of the swell test under uniaxial tension are shown in Figure 12. The HN specimen was subjected to a constant tensile stress of 0.2MPa, about 5% of the tensile strength obtained by the Brazilian tensile strength test, and the specimen failed 25 days after loading. In this 25 day period, the specimen swelled slightly in the direction of the applied stress, while strains in orthogonal directions are practically constant before the failure. The swelling potential in the applied stress direction is 0.05, compared to 0.24 from free swell test. The tensile failure of the specimen may be attributed to the formation and propagation of cracks with time. The presence of cracks in the specimen after free swell test has been observed from visual inspection and reported in Lee.[4]

The Result of Swell Test Under Biaxial Stress Condition

In Figure 13, the vertical swelling strain from the swell test under biaxial stress condition is plotted against the elapsed time. In this test, the hydraulic pressure of 4.5MPa applied to the cylindrical surface, while there was no stress applied in the longitudinal direction. It may be observed that the vertical swelling strain under the applied stress increased with the elapsed time up to about 100 days when the horizontal crack opened up and the swelling strain increased rapidly thereafter. The vertical swelling potential from this test is 0.20, compared to 0.45 from free swell test. The test results suggest that the applied stress on the cylindrical surface restricts

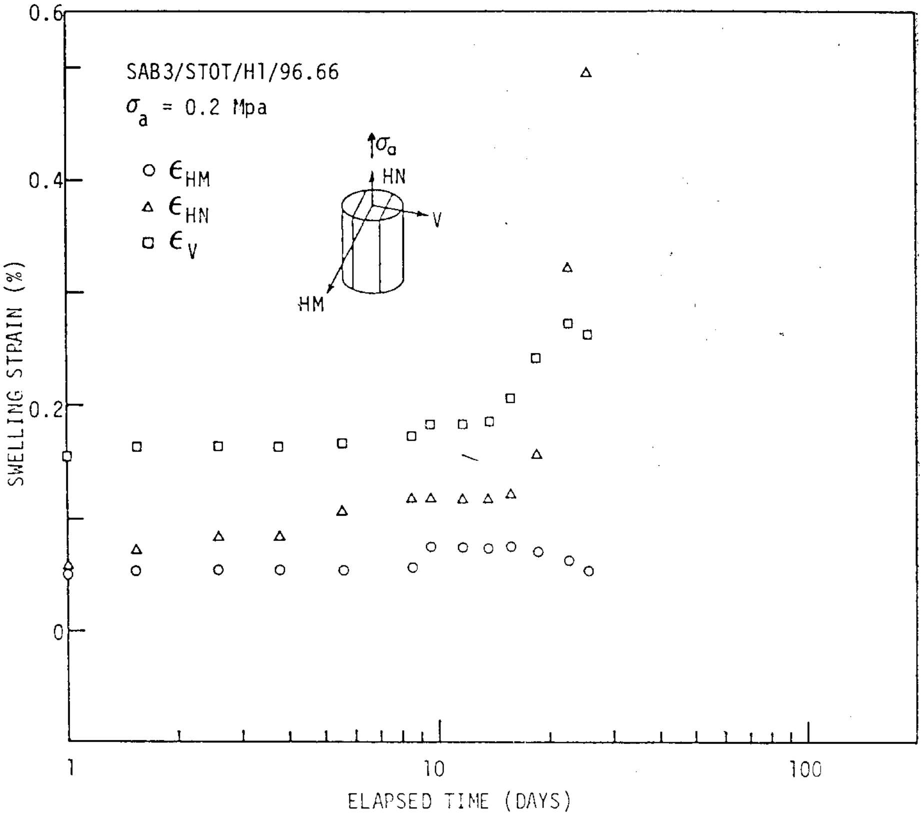

Fig. 12. Results of swell test under uniaxial tensile stress, Queenston shale, Niagara Falls, Canada

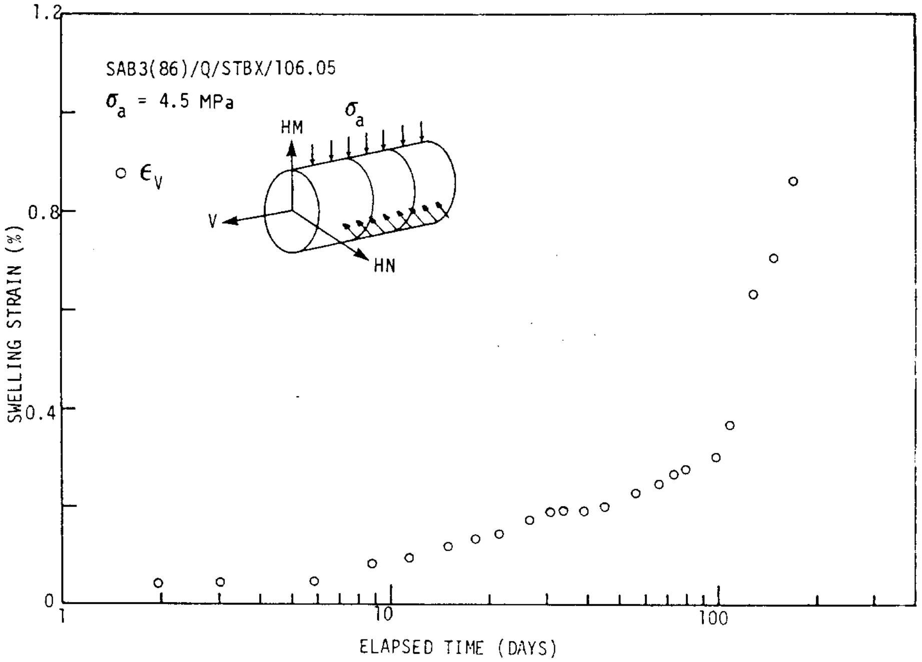

Fig. 13. Results of swell test under biaxial stress on the Queenston shale sample, Niagara Falls, Canada

the swelling in the longitudinal direction due to Poisson's effect.

Effect of Stress System Applied

The suppression effect of the applied stress on swelling strain may be further illustrated in Figure 14. In this figure, the vertical swelling strains from free swell test (FST), modified semi-confined test (MSC) and swell test under biaxial stress (STBX) are plotted against the elapsed time. The specimen under zero stress(FST) shows the highest manitude and rate of vertical swelling strain. In the MSC test, vertical swelling strain is substantially reduced from that of the FST specimen under the applied stress of 5 MPa in the vertical direction. However, the vertical swelling strain of STBX specimen under a uniform lateral stress of 4.5 MPa is still substantial, compared to that of the MSC specimen.

In MSC and STBX, the applied stress is about same magnitude, but in different directions of application, thus showing the suppression effect of stress applied in different directions on swelling strain in vertical direction. By comparing these two test results, it may be observed that, under the applied stress, the swelling strain is reduced substantially in the direction of the applied stress, but suppressed moderately in the direction normal to the applied stress. Therefore, it may be important to consider swelling behaviour in three orthogonal directions under different stress systems for the development of constitutive relationship of the Queenston shale.

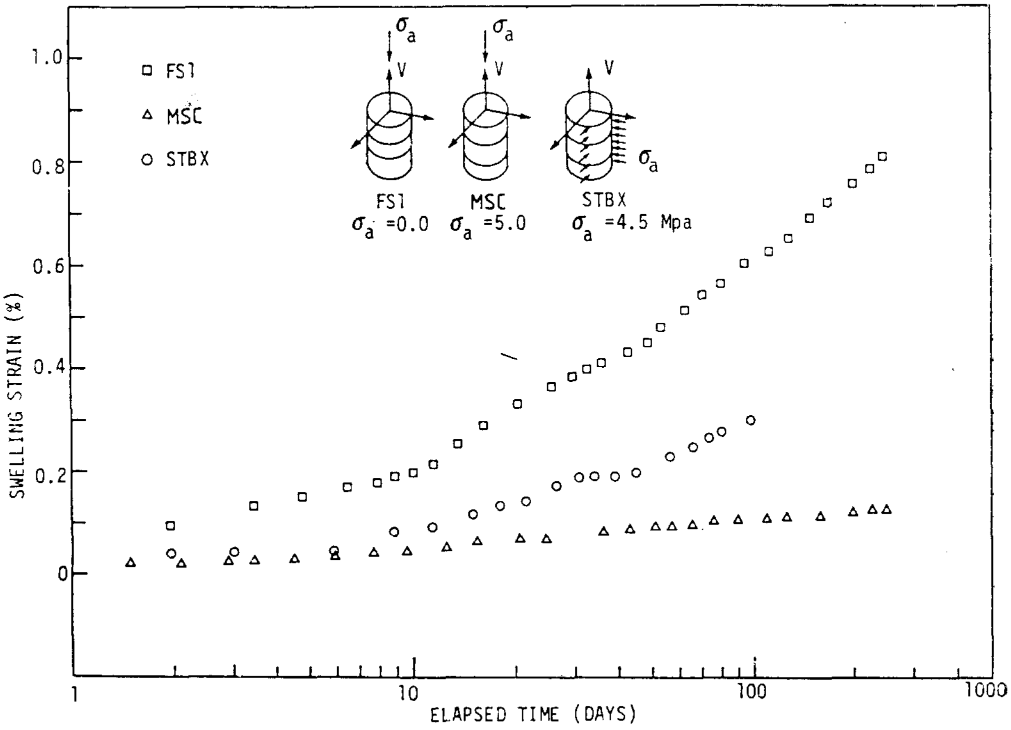

Fig. 14. Effect of stress system on vertical swelling strain

Summary and Conclusion

To study swelling behaviour of shales, three new test apparatus have been developed for the measurement of time-dependent deformation under stress states representative of field condition. These are modified semi-confined swell test, swell test under uniaxial tension and swell testunder biaxial stress field. Results of tests obtained over the years indicate that these tests are repeatable and reliable. From the results of this extensive test program, the following conclusions may be drawn:

(a) The horizontal swelling potential of the Queenston shale is isotropic. Within the range of sampling depths from 94 to 113m, there is no significant variation in horizontal swelling potential with depth. The average horizontal swelling potential is 0.29, ranging from 0.22 to 0.34.

(b) The vertical swelling potential is about 1.6 times higher than the horizontal swelling potential, reflecting the effect of fabric of the rock.

(c) The application of a stress in one principal direction not only suppresses the swelling in that direction, but also reduces the swelling in the orthogonal directions.

(d) For specimens prepared in the vertical and horizontal directions, swelling potentials in the direction of applied stress decrease linearly with increasing applied stress in the semi-log plot.

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