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# Gypsum cementation and yielding in plastic clay

## Cimentation du gypse et écrouissage d'une argile plastique

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ABSTRACT
Low (8 m high) dykes on soft plastic clay in SE Manitoba failed intermittently over many years. The clay is smectitic and cemented with gypsum. Tests showed that clay at an unstable section was more brittle and anisotropic than at a nearby stable section. Both sections had noticeably less gypsum than nearby unloaded clay. Tests examined the impact of pore fluid chemistry on mechanical properties of reconstituted clay from the site. Yielding appeared to be controlled by cementation bonding and by environmental effects. Stress-strain behaviour, and softening from peak to post-peak and then to residual strength, was influenced by ionic strength and the Na/Ca ratio.

RÉSUMÉ
Des ruptures de digues de faible hauteur (8 m) construites sur des argiles plastiques molles du Sud-Est du Manitoba ont été observées de façon sporadique au cours des années. L'argile est constituée de smectite cimentée par du gypse. Des essais ont montré que le comportement de l'argile de la section instable était plus fragile et anisotrope que celui de l'argile d'une section stable située à proximité. Le contenu en gypse dans l'argile de ces deux sections était nettement plus faible que celui d'une section d'argile identique mais non chargée. L'influence de la chimie du fluide interstitiel sur les propriétés mécaniques a été examinée en laboratoire sur des spécimens d'argile reconstitué. Les résultats ont montré que l'écrouissage était contrôlé par les liens de cimentation et les effets environnementaux. Le comportement en contraintes-déformations et le radoucissement du pic au post-pic et jusqu'à la résistance résiduelle sont influencés par la résistance ionique et le rapport Na/Ca.

## 1 INTRODUCTION

The Winnipeg River flows north-westwards from Lake of the Woods at the Manitoba-Ontario border into the south-east corner of Lake Manitoba. In the early decades of the 20th century, the river was developed to provide hydroelectric power for the growing city of Winnipeg. The topography through which the river flows is relatively flat and water-retaining dykes were used to increase the capacity of the reservoirs. Figure 1 shows the powerhouse at Seven Sisters Generating Station and the low-head dykes extending upstream on either side of the reservoir. The generating station is approximately 110 km northeast of Winnipeg, Manitoba and is operated by Manitoba Hydro.

Figure 1: Powerhouse, forebay, and retaining dykes, Seven Sisters Generating Station

The dyke system was initially constructed in 1929. The heights and lengths of the dykes were increased in the late 1940s. The dykes consist of clay fill beneath a rip-rap shell. Their average height is approximately 7.0 m, the width of the crest is approximately 4.3 m, and the total length about 13 km. Although the dykes are low, they rest on a thin layer of soft, highly plastic 'foundation' clay (about 3 – 4m thick), which has some challenging properties. The project dealt largely with the properties of the foundation clay and not with the less-plastic compacted clay fill in the dykes.

When the dykes were raised in the 1940s, engineers were concerned about possible instability because of the soft foundation clay and the lack of good borrow material. At that time, the most likely mechanisms of instability were believed to involve either a circular slide surface through the embankment and foundation, or a lateral spreading of the dyke due to the weak foundation soil. Minor slides and other movements occurred during construction. These were believed due to steep construction slopes or other unusual conditions and did not cause immediate concern.

Following construction, a series of slides occurred at irregular intervals up to the present. Generally, subsidence of the 'dry'-side slope was preceded by crest settlement and cracking near the 'wet'-side shoulder. In some cases, bulging was observed at the toe. Engineers who worked on these dykes included Peterson et al. (1960), Casagrande (1959), Bjerrum (1969) and Liu and Dubois (1996). Garinger et al. (2004) gave a recent account of a testing and modeling program that led to the present study. None of the instabilities led to uncontrolled loss of water. The operator, Manitoba Hydro, has been proactive in preventing further instabilities by constructing granular berms at locations that were considered at risk.

## 2 RECENT STUDY

Garinger et al. (2004) studied the stability of a section that had previously failed and a section that had remained stable. They examined the mechanical (stress-strain) properties of the foundation clay at these two sections and also at a third (background) location that had not been subjected to dyke loading.

### 2.1 *Soil properties*

Hydrometer tests on the foundation soil showed the clay size fraction ranging from 95% to 99% in the foundation clay. Clay minerals account for between 67% and 81% of the total composition of broadly similar Lake Agassiz clay in Winnipeg, where the clay size fraction consists of approximately 75% montmorillonite, 10% illite, 10% kaolinite and 5% quartz (Loh and Holt 1974, Baracos 1977). The remaining soil fraction consists primarily of silt-sized particles composed of limestone and dolomite. It also contains localized nodules of white amorphous gypsum. The clay is extensively fissured (nuggety) near the surface and fissures extend through the clay to the underlying till (Baracos 1977, Graham et al. 1983).

Figures 2 and 3 show results from consolidated undrained triaxial compression tests on specimens from the unstable and stable sections respectively. The results are plotted as deviator stress $q = (\sigma_1-\sigma_3)$ *versus* mean effective stress $p' = (\sigma'_1+2\sigma'_3)/3$. The results show specimens that are markedly strain softening after peak shearing resistance had been reached, with the specimens from the unstable section (Figure 2) showing more softening than those from the stable section (Figure 3). The post-peak p′,q paths follow closely to the paths before failure.

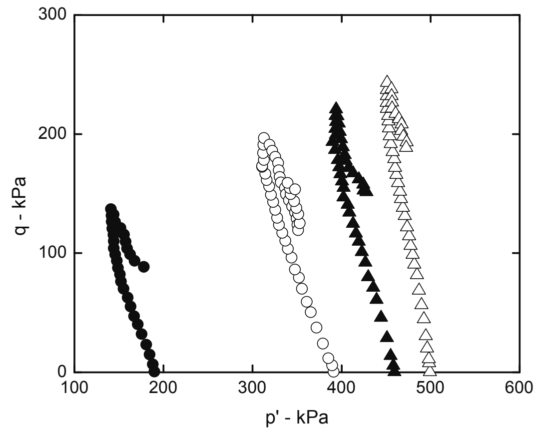


Figure 2: Stress paths (p′,q) from TXC tests – unstable section.

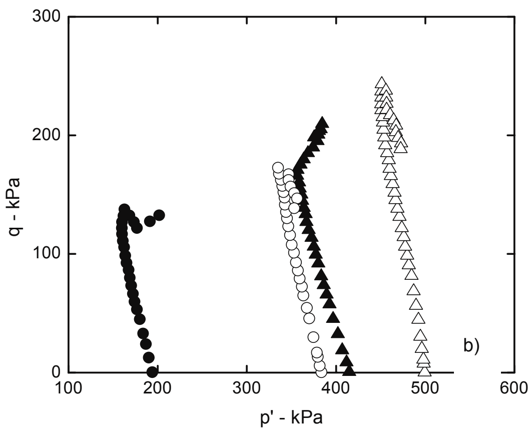


Figure 3: Stress paths (p′,q) from TXC tests – stable section.

Thus, while the material is strain softening, it is not highly sensitive. This is confirmed by the morphology of the slides, which tend to slump rather than develop as flow slides. In Figures 2 and 3, the pre-failure stress paths are frequently remarkably straight, suggesting that the clay can effectively be modeled as an elastic plastic material (Graham et al. 1983).

However, the straight sections of these p′,q plots are not vertical, so the material is anisotropic (Graham and Houlsby 1983). It is noticeable that clay at the unstable section (Figure 2) appears more anisotropic than at the stable section (Figure 3).

Figure 4 shows representative stress-strain curves for specimens from the stable, unstable and background locations. The specimens were all consolidated to an effective isotropic consolidation pressure of 200 kPa. The ‘stable’ and ‘unstable’ specimens had about the same strengths and were somewhat stronger than the ‘background’ specimen. More notable, was the much higher strain-softening rate (increased brittleness) of the ‘unstable’ specimen after peak failure.

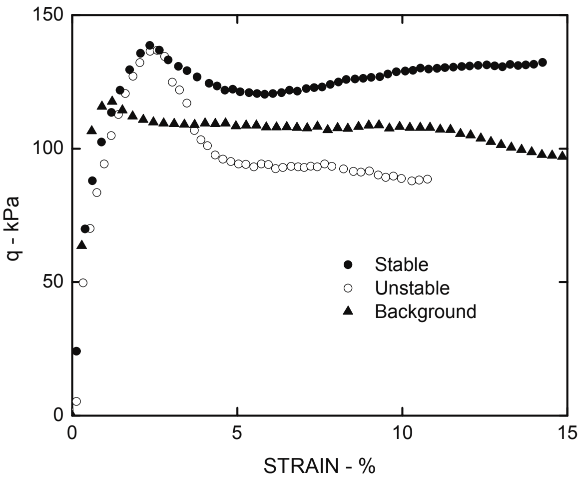


Figure 4: Stress-strain curves and post-peak strain softening from TXC tests.

The post-peak strengths were often ambiguous, with just a short section of approximately constant deviator stress and pore water pressure before the specimens developed strongly-defined shear planes and moved toward residual strength. It is appreciated that achieving residual strength in lightly overconsolidated clays in triaxial tests is unusual, but the values obtained for $\phi'_r$ from the triaxial tests agreed quite closely with equivalent values from direct shear tests. Table 1 shows values of the strain softening rate, post-peak friction angle and residual friction angle for the foundation clay. The friction angles are very low. In Table 1, they have been taken as corresponding to an effective cohesion intercept $c' = 0$.

Table 1: Strain softening rates and angles of shearing resistance $\phi'$ (degrees) from triaxial tests on foundation clay.

| Section | Strain softening rate* | Post-peak Strength (degrees) | Residual strength (degrees) |
|---|---|---|---|
| Back-ground | 11 | 13 | 11 |
| Stable | 14 | 13.5 | 11 |
| Unstable | 51 | 13 | 10 |

* Post-peak strain softening kPa/ degree strain

2.2 *Stability analysis.*

Slope stability analyses were done using the commercial application SLOPE-W. From other experience in Lake Agassiz clays, the stabilities were calculated using strength envelopes with $c' = 5$ kPa and slightly lower values of $\phi'$ than those shown in Table 1. Values of $\phi'$ were chosen to produce essentially the same shearing resistance as Table 1 in the range of stresses in the foundation clay. This is an approximate way of modeling the curvature of strength envelopes in smectitic soils. For stability analysis, the less-plastic fill material was modeled as $c' = 20$ kPa, $\phi' = 23°$. Pore water pressures were estimated using a steady-state seepage analysis in SEEP-W, with average reservoir levels, and measured values of hydraulic conductivity (Garinger 2002). Only small differences were found between the results of circular and non-circular failure surfaces.

Table 2 shows results from the circular failure surface analyses. Two approaches were used to estimate the inter-slice force inclinations $\theta_i = \lambda(f(x)$. The first was a General Limit Equilibrium (GLE) Solution with $\theta_i$ = constant (Spencer solution). The second used a finite element (FE) solution (SIGMA-W) with linear elasticity to evaluate stress distributions along the sides of the slices, and from these, the values of $\theta_i$. Calculations were done using both post-peak strengths (Rivard and Lu 1978) and residual strengths.

Table 2: Values of safety factors for post-peak and residual strengths.

| Case | Foundation Strength | Unstable Section | Stable Section |
|---|---|---|---|
| 1* | Post-peak | 1.16 | 1.23 |
| 2* | Residual | 0.97 | 0.98 |
| $3^+$ | Post-peak | 1.15 | 1.21 |
| $4^+$ | Residual | 0.97 | 1.01 |

* General limit equilibrium, f(x) = constant
$^+$ Interslice force inclination from FEM

Using both post-peak and residual strengths, there were only small differences between the results from the GLE and FE solutions. In terms of post-peak strengths, the unstable section produced lower safety factors than the stable section. This is probably due to the slightly thicker layer of soft clay at the unstable section (Garinger et al 2004). Both safety factors were above unity. At residual strength, both sections had safety factors very close to unity. In other words, if the stable and unstable sections were operating with post-peak strengths, (developed by the fissure structure), they would both be stable. Creep straining would probably be noticeable at the unstable section. If both sections were operating at residual strengths, both of them would be unstable. Some other mechanism had to be found to explain why some sections of the dyke moved rapidly towards instability, while others remained stable over periods of fifty years.

The observations of strain softening (Figures 2, 3 4) and the observation of gypsum in the clay suggests that gypsum cementation might be leaching from the clay by natural seepage beneath the dykes. The seepage, and therefore the leaching, would be controlled by irregular sand and silt 'partings' that are known to exist in the clay. Leaching would produce a quasi-stable microstructure in the clay that could be disturbed by creep strains and would vary locally with time.

2.3 *Pore fluid chemistry.*

Specimens of pore fluid were obtained by extrusion from a saturated paste prepared from samples of the foundation clay at the three different locations described earlier. They were subjected to the test program outlined by Garinger et al. (2004) for $Na^+$, $Ca^{2+}$, $Mg^{2+}$, $Cl^-$, $S0_4^{2-}$, $HCO_3^-$, and electrical conductivity EC. All cation concentrations increased with increasing depth, probably due to weathering effects extending downwards from the ground surface. Concentrations in the background location were noticeably higher than at the two dyke sections, and the stable section had concentrations slightly higher than the unstable section. The (monovalent-divalent) ratio $Na^+/Ca^{2+}$ decreased with depth; with the background, stable and unstable sections having increasingly higher ratios. Because of our interest in gypsum ($CaSO_4{\cdot}2H_2O$), we will examine here only the results of the tests for $Ca^{2+}$ and $SO_4^{2-}$. Further information can be found in Man et al. 2003.

Table 3: Selected results from analysis of pore fluid chemistry. Values in parentheses ( ) are outside the ranges identified in the background section.

| Location | $Ca^{2+}$ (mg/L) | $SO_4^{2-}$ (mg/L) | EC (µS/cm) | Na/Ca |
|---|---|---|---|---|
| Background | 125-680 | 290-1250 | 1460-4160 | 0.27-0.51 |
| Stable | (28)-280 | (51)-672 | (546)-3520 | 0.34-(0.95) |
| Unstable | (30)-172 | (81)-324 | (772)-1650 | (0.68)-(2.10) |

In Table 3, lower values of ionic concentrations and electrical conductivity come from shallow depths just below the bottom of the fill material in the dyke, and larger values come from greater depths (Man et al. 2003, Garinger et al. 2004). Table 3 shows marked diminution of gypsum at the stable and unstable sections, with many values lying well below corresponding values at the background location. Electrical conductivities are reduced and Na/Ca ratios are increased.

Figure 5 shows values of the Ion Activity Product IAP with depth at the three locations. Groundwater at the background section was supersaturated with respect to gypsum in the bottom half of the deposit, while gypsum in the groundwater beneath the dykes was noticeably closer to the chemistry of the forebay water.

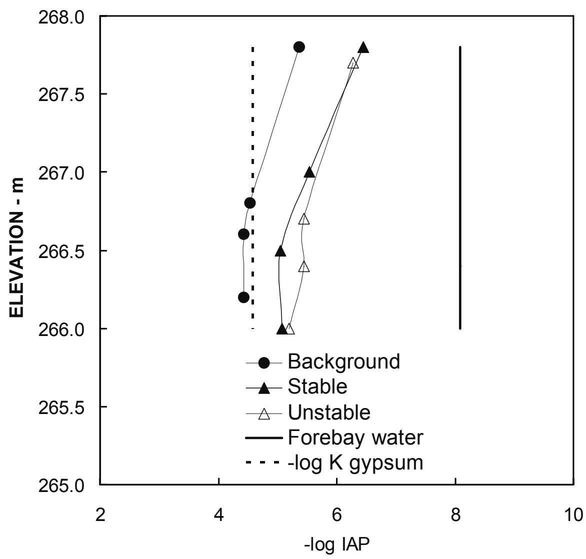


Figure 5: Ion Activity Product Versus depth at Seven Sisters.

The results of the chemistry tests supported the earlier suggestion that leaching had removed gypsum, which can be a cementing agent between the soil particles. The results did not, however, directly address the question of the increased brittleness, strain softening and anisotropy at the unstable section. In other words, observations of chemical change did not by themselves support the hypothesis of changes in mechanical (stress-strain) behaviour.

## 3 RECONSTITUTED SPECIMENS WITH DIFFERENT PORE FLUIDS

To establish the effects of chemical change on mechanical properties, and to obtain homogeneous samples with consistent properties, tests were done on four blocks of reconstituted soil, prepared with different pore fluid geochemistry. These were prepared from oven-dried and pulverized clay from the background section at Seven Sisters. The reconstituted specimens were prepared by oven-drying, pulverizing and rehydrating the soil under vacuum in a mechanical mixer. Sufficient water was used to obtain a water content approximately twice the liquid limit. The slurries were subsequently consolidated one-dimensionally to a vertical effective pressure of 225 kPa in a 254 mm diameter cylinder with top and bottom drainage. This produced initial undrained shear strengths of about 35 kPa, sufficient to permit trimming of triaxial specimens. Four blocks of reconstituted soil were prepared with different pore fluids as follows:

(a) deionized water to provide a 'baseline' condition for comparisons,
(b) gypsum-rich water (2 g/L) to model the background conditions at Seven Sisters,
(c) acidified deionized water (6.5 g/L $H_2SO_4$) to reduce effects of carbonate cementation, and
(d) sodium-enriched brine (50 g/L NaCl in deionized water) to potentially reduce the effects of gypsum cementation, increase ionic strength, and increase the Na/Ca ratio.

A further set of tests is currently in progress with an artificially leached soil and the results will be presented later. Initial water contents and specific volumes were similar for all batches of soil, suggesting similar initial microstructures.

After consolidation was complete, 50 mm diameter x 100 mm long triaxial specimens were carefully trimmed from the 'cakes' and subjected to a series of triaxial stress paths to examine the effects of gypsum cementation on the elastic-plastic properties (specifically the yielding behaviour) of the clay. The tests included stress-controlled probes along a variety of stress paths, oedometer tests, and isotropically consolidated CID and CIŪ tests.

## 4 TEST RESULTS

### 4.1 *Consolidation*

Figure 6 compares oedometer results from the reconstituted and natural clays. There is good agreement between specimens of natural clay from the background and unstable locations. There is also good agreement between the four sets of reconstituted specimens. This reflects a high level of consistency in the specimens and good quality control. There is also good agreement between the starting voids ratios for the two sets of tests.

Two observations caused some surprise. First, the reconstituted specimens appeared to be more compressible and showed stronger evidence of destructuration in post-yield compression than the natural specimens. Usually natural specimens are much more compressible than reconstituted

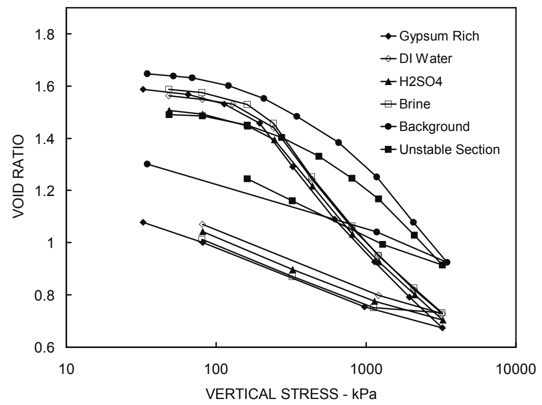


Figure 6: Oedometer tests on natural and reconstituted specimens.

specimens (Graham and Li 1985). Here, however, despite careful sampling and trimming, it is likely that the natural specimens had received some destructuring as a result of freezing-thawing effects and sampling disturbance (Graham and Au (1985). Second, the considerable differences in the pore fluid used for making the reconstituted specimens appeared to have had remarkably little effect on the compression behaviour of the specimens. All four specimens showed clear evidence of yielding, considerable compression during post-yield straining, and subsequent plastic hardening that had broadly similar compression rates (compression index) as the natural specimens. It is believed that this similarity of behaviour is due to the presence of gypsum, possibly in the form of mineral particles in the clay as well as cementation. (The IAP results in Figure 5 show that the pore fluid in the background clay is gypsum-saturated. At other sites in Lake Agassiz clay, it is common to see white- or tan-coloured nodules or localized partings of gypsum.)

### 4.2 *Yielding:*

With a soil that seemed to be cemented, it was clearly desirable to examine whether yielding would be affected by changes in pore fluid chemistry and other influences. Figure 7 shows yield loci for gypsum-rich reconstituted clay and for natural clay from the background and unstable locations. Yielding was interpreted from changes in slope of various plots of stress *versus* strain in stress-controlled loading along stress paths with various controlled values of $\Delta q/\Delta p'$. Usually, yielding was relatively easy to identify and consistent yield states were obtained from different stress-strain plots. The results are broadly similar to those seen for other careful sampled natural clays, see for example Graham et al. (1983, 1989). Of particular interest here is the generally similar shape of the yield loci for reconstituted gypsum-rich reconstituted clay and the natural background clay. (Specimens made with different pore fluids showed only small differences in their $p'_y$,$q_y$ yield stresses.) The reconstituted clay appeared to have slightly higher values of $q_y$ and lower values of $p'_{y\ iso}$ than the background clay. This may be affected by a combination of aging and fissuring. The unstable section had a higher $p'_{y\ iso}$, perhaps because of the dyke loading, and was generally flatter in shape, more like the Winnipeg clay reported by Graham et al. (1983).

Asymmetric yield loci like those shown in Figure 7 have been associated with anisotropic elasticity (Graham et al. 1989). It is therefore important to examine their traces, not only in p′,q (stress) plots, but also in p′,V (compression space). Figure 8 shows $p'_y$ *versus* $V_y$ data corresponding to the $q_y$,$p'_y$ data in Figure 7. The traces are 'hooked' and not straight as in Cam Clay, where the elasticity is assumed to be isotropic. The reconstituted soil prepared with brine displayed significantly greater compressibility at yield compared to the other

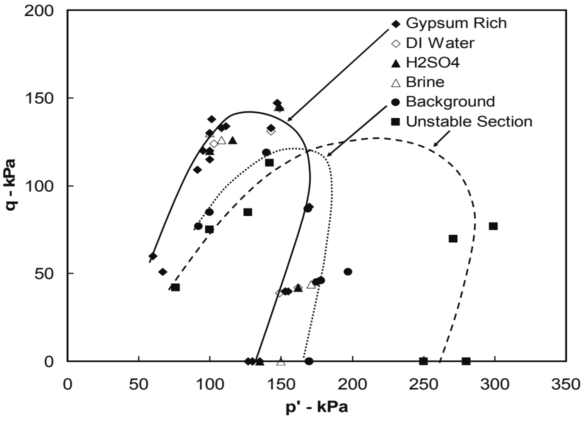


Figure 7: Yield loci for gypsum-rich reconstituted clay and natural clay from the background and unstable locations

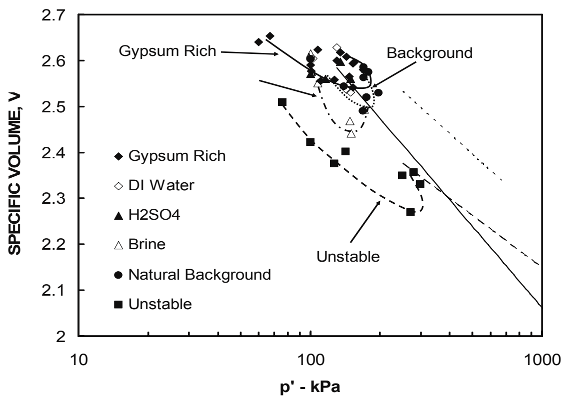


Figure 8: Traces of yield loci in p′- specific volume space for gypsum-rich reconstituted clay and natural clay from the background and unstable locations.

reconstituted soils that had less notable differences in pore fluid chemistry. At large strains, the 1-D NCLs move towards a hardening law with constant slope.

Figures 6, 7, and 8 suggest that reconstituted gypsum-rich clays can model the natural clay at Seven Sisters and provide the benefit of increased uniformity. While the strengths and yield stresses in $p'_y$,$q_y$ space did not vary much with the chemistry of the pore fluid of the initial slurry, some differences were noted in post-peak behaviour. Figure 9 shows stress-strain results from four specimens that were all saturated with gypsum at the beginning of the test but which had different pore fluid chemistry. All had closely similar strengths, and all softened markedly by about the same amount in post-peak straining. However, there were differences in the strains at which softening began. The specimens made with deionized water and acidized ($H_2SO_4$) water softened first at axial strain $\varepsilon_1$ of around 8%. The specimen made with brine (having an elevated $Na^+/Ca^{2+}$ ratio), started softening at 12%, while the gypsum-enhanced specimen started softening at about 15%. This may represent some differences in the amount of cementation bonding.

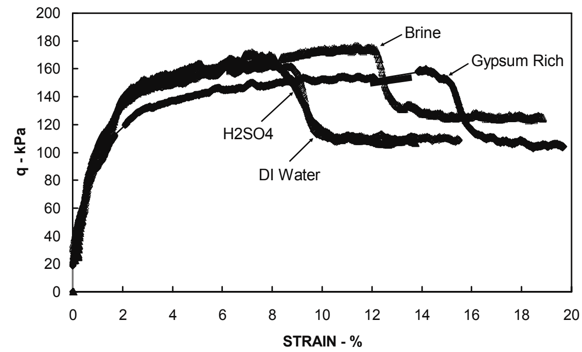


Figure 9: Differences in post-peak softening with differences in pore fluid chemistry.

## 5 CONCLUDING COMMENTS

The tests have led to some interesting conclusions about the effects of soil chemistry and pore fluid chemistry on the mechanical properties of this smectitic clay. The tests show it has been possible to make consistent specimens of cemented clay in the laboratory. In this project, the results may be controlled as much by the chemistry of the solids in the clay as by the chemistry of the pore fluid used to make the slurry from which the specimens were formed. (This has also been observed in other smectitic clays, notably the sand-bentonite mixtures used by Atomic Energy of Canada for nuclear waste disposal, Martino et al. 2003.)

Geochemistry appears to influence different parts of stress-strain behaviour. Yielding is controlled by primary cementation in the material, but this can be affected by strain disturbance, whether caused by embankment loading, desiccation or freezing-thawing, as likely happened at Seven Sisters. Additional testing is now being done to examine the effects of freezing and thawing. Volume changes, particularly destructuring, are affected by the ratio of monovalent to divalent ($Na^+/Ca^{2+}$) cations. Softening from peak strength to post-peak strength (destructuring), and from post-peak strength to residual strength, are influenced by the amount of cementing minerals, by ionic strength, and by the ($Na^+/Ca^{2+}$) ratio.


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