

# Evaluating the feasibility of using guanidinium salts as a means of in-situ soil strengthening

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## ABSTRACT

There are a variety of engineering problems for which conventional geotechnical solutions are either impractical or ineffective; thus, the need for a multi-disciplinary approach has become apparent. When it comes to slope stability, challenging sites are found worldwide in clayey soils and weak rocks. In Saskatchewan and eastern Alberta, particular problems are associated with shallow soil deposits in highly plastic smectitic clays, clayey tills, and in weak shales with lenses of highly plastic smectitic clay. Given the extremely low residual shear strengths of these materials, shallow creeping failures are common and threaten infrastructure such as roads, bridges, and pipelines. The current research is intended to evaluate the feasibility of modifying the porewater chemistry of such soil deposits using guanidinium chloride ( $C(NH_2)_3Cl$ ) to effect mineralogical alteration through ion exchange, as a means of in situ soil strengthening.

The effect of guanidinium on geotechnical properties (relevant to slope stability) for various local soils has been evaluated through batch tests and lab-scale treatment trials. Using four local prairie soils, the effect that guanidinium salts have on soil behaviour was evaluated through testing of index properties, x-ray diffraction, and residual shear strength.

## RÉSUMÉ

Il existe une variété de problèmes d'ingénierie pour lesquels les solutions géotechniques classiques sont peu pratiques ou inefficaces; ainsi, la nécessité d'une approche multidisciplinaire est devenue évidente. En ce qui concerne la stabilité des pentes, les sols argileux et les roches fragiles se rencontrent partout dans le monde. En Saskatchewan et dans l'est de l'Alberta, des problèmes particuliers sont associés aux dépôts de sol peu profonds dans des argiles smectitiques hautement plastiques, des tills argileux et dans des schistes faibles à lentilles en argile smectitique hautement plastique. Compte tenu de la résistance extrêmement faible au cisaillement de ces matériaux, les défauts de fluage superficiels sont fréquents et menacent des infrastructures telles que les routes, les ponts et les pipelines. Les recherches actuelles ont pour objectif d'évaluer la faisabilité de modifier la chimie de l'eau interstitielle de tels dépôts en utilisant du chlorure de guanidinium ( $C(NH_2)_3Cl$ ) pour effectuer une altération minéralogique par échange d'ions, comme moyen de renforcer les sols in situ.

L'effet du guanidinium sur les propriétés géotechniques (relatives à la stabilité des pentes) de divers sols locaux a été évalué à l'aide de tests par lots et d'essais de traitement en laboratoire. En utilisant quatre sols locaux des Prairies, l'effet des sels de guanidinium sur le comportement du sol a été évalué en testant les propriétés de l'indice, la diffraction des rayons X et la résistance au cisaillement résiduelle.

Shallow slope failures are prevalent throughout Saskatchewan and eastern Alberta due to the presence of highly plastic smectitic clay lenses within clayey till formations. These clay lenses tend to be rich in montmorillonite and, with the exception of the sediments deposited from Lake Agassiz, are likely derived from short-lived pro-glacial lakes that formed during the retreat of ice sheets (Quigley, 1980). Due to the frequency of this sort of failure and their often highly publicized nature (i.e. the 2016 oil spill in the North Saskatchewan River that resulted from a pipeline rupture), an alternative approach to typical geotechnical solutions is being investigated (CBC Saskatoon, 2019). This altered approach is one based upon geochemistry, specifically the mineralogical alteration of smectitic soils via the use of guanidinium salts.

Preliminary results of batch style laboratory testing have indicated that guanidinium salts lead to lower liquid limits and an increase in the residual angle of shearing resistance,  $\phi'_{RES}$ . The latter of these two properties is of particular interest for the aforementioned shallow slope failure problems. Guanidinium salts are readily dissolved

and biodegraded in naturally occurring surface water (Mitchell, 1987). This property of organic salt makes it an excellent candidate for potentially being used as an in situ treatment method for slow moving landslides.

## 1.1 Literature Review

The nature and composition of the minerals within a soil are key factors governing the soil's mechanism of shear (Lupini, et al., 1981; Skempton, 1985). The three clay minerals that traditionally receive the most attention, in order of increasing activity, are: kaolinite, illite, and montmorillonite. The focus of the work presented here is on montmorillonite soils, and therefore much of the discussion will be made regarding this specific type of clay mineral. Montmorillonite is a 2:1 phyllosilicate comprised of successive links of aluminum octahedrons (Gibbsite Sheets) and silicon tetrahedrons. Figure 1 provides a schematic of a montmorillonite mineral. Weak Van der Waal bonds hold each mineralogical unit together, and therefore each unit is easily separated and susceptible to

the intrusion of water and other cations. (Mitchell & Soga, 2005).

The structure and interlayer bonds forming the montmorillonite mineral lead to high levels of isomorphic substitution. Isomorphic substitution is a process whereby cations of lesser valence are exchanged for cations of higher valence within the crystalline structure of the mineral. This substitution leads to a net negative charge on the surface of the clay mineral, and this negative surface charge results in repulsive forces amongst the clay particles (Mitchell & Soga, 2005; Terzaghi et al., 1995). The resulting negative surface charge may be satisfied by the rearrangement of cations within the clay crystal structure, but more commonly via the uptake of excess cations present in a solution (Garrison, 2004).

The cations required to once again achieve electrical neutrality are often exchangeable, and the quantification of these exchangeable cations is termed the Cation Exchange Capacity (CEC). CEC is expressed in terms of milliequivalents per 100 g of dry clay (Laird, 1987; Mitchell & Soga, 2005; Sparks, 1999). This phenomenon means that soils that undergo more isomorphic substitution will have higher CEC values, and will be more sensitive to their surrounding porewater.

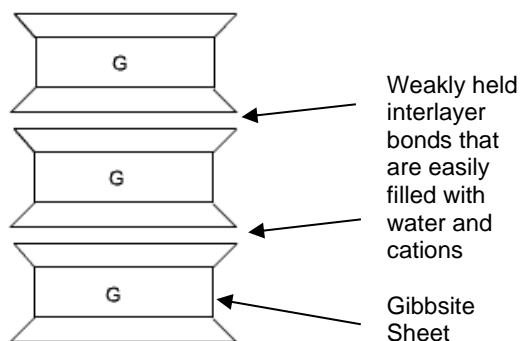


Figure 1: Montmorillonite mineralogical unit.

The diffuse double layer (DDL, and for smectitic minerals the interlayer), govern the properties of a clayey soil. The DDL is a layer of bound water that forms around a clay particle in the presence of solution. The DDL forms as a response to the surface of the clay particles being negatively charged. This negative charge attracts cations within solution to the surface of the clay particle, but these cations are simultaneously drawn back into solution by the anions in the bulk solution (Mitchell & Soga, 2005; Sparks, 1999).

The effects that porewater chemistry have on the  $\phi'_{RES}$  were first evaluated by Kenney (1967). His work involved subjecting natural soils to Sodium, Potassium, and Calcium ( $\text{Na}^+$ ,  $\text{K}^+$ , and  $\text{Ca}^{2+}$ ) cationic solutions. He concluded that  $\phi'_{RES}$  was heavily influenced by the porewater chemistry surrounding the clay, and that the following three factors led to an increase in  $\phi'_{RES}$ : 1.) cations of a higher valence ( $\text{Ca}^{2+} > \text{K}^+$ ), 2.) cations of greater polarizability ( $\text{K}^+ > \text{Na}^+$ ), and 3.) a higher concentration of ions within the pore water.

Ramiah, et al. (1971) followed the work of Kenney (1967) by investigating the residual shear strength of soils after the treatment of flocculants and dispersing agents.

The study concluded that the flocculating agent led to a higher  $\phi'_{RES}$  ( $31^\circ$ ) when compared with the dispersing agent ( $\phi'_{RES} = 28^\circ$ ).

Moore (1991) suggested that in soils with a high clay fraction, the residual shear strength is influenced by the nature of the clay minerals (i.e. particle size, shape and surface area) and the type, valency and concentration of cations in the porewater. In his discussion following this paper, Moore (1992) proposed that the increase in residual shear strength and decrease in plasticity with increased salt concentration and cation valency is due to an increase in the strength of the interparticle bonding. He also recommended that more representative residual shear strengths would be obtained if naturally occurring groundwater from sampling sites was used during testing.

Anson & Hawkins (1998) performed liquid limit and ring shear testing on pure kaolinite and sodium montmorillonite. Their testing procedure involved subjecting the soils to various concentrations of calcium chloride that were representative of the ground water chemistry from soils collected from a calcareous mud rock from the Fuller's Earth Formation.

Their testing concluded that the pure kaolinite was not as affected by an increase in concentration of calcium chloride in the porewater, in comparison to the sodium montmorillonite. They observed a steep decline in the liquid limit of the montmorillonite when comparing the liquid limit of the soil using low concentrations of calcium chloride versus distilled deionized (DDI) water. Their ring shear tests produced similar findings, as pure kaolinite was, again, not affected to the same extent as the montmorillonite soil. The ring shear testing was performed at five different normal stresses. For the montmorillonite soil, all normal stress increments indicated approximately a  $5^\circ$  increase in  $\phi'_{RES}$  when modifying the porewater fluid with calcium chloride salts.

Anson & Hawkins (1998) attributed the increase in residual shearing angle to a collapse of the interlayer, and DDL, due to the addition of calcium chloride to the soil's porewater. When the DDL is collapsed, the repulsive forces between clay particles are lessened, and more face to face aggregation is achieved. This rise in face to face aggregation increases the frictional resistance of the clay particles, and therefore gives way to a higher  $\phi'_{RES}$ . This explanation of the increase of  $\phi'_{RES}$  provided by Anson & Hawkins (1998) corroborates the findings and suggested theories of Kenney (1967), Ramiah, et al. (1971), and Moore (1991).

### 1.1 Prior Research on Guanidinium Salts

The work described in this paper continues a study initiated at the University of Saskatchewan by Pu (2018) which analyzed the effects that guanidinium have on natural Saskatchewan smectitic soils. Prior to this, only a single study has focused on the effects of guanidinium salts on highly plastic soils. This study showed that adding guanidinium salts to porewater leads to a reduction in swell potential and plasticity, and an increase in hydraulic conductivity and both peak and residual shearing angles (Minder, 2013, 2016; Minder & Puzrin, 2017; Minder, Puzrin, & Plötze, 2016; Pu, 2018). The studies conducted

by Minder (previously mentioned studies) used only processed uniform commercially sourced clay materials.

To address this gap in research, batch style testing was performed on four prairie soils: Battleford Till, Floral Till, Whitecourt Clay, and Regina Clay. Testing commenced with characterization of the porewater composition of the four soils. A synthetic porewater solution was then prepared for each soil. This synthetic porewater solution was then used in conjunction with various concentrations of guanidinium salts at concentrations of 0.1 Molar (M), 0.25 M, 0.5 M, 1 M, 2 M, and 4 M. Regina Clay had additional liquid limit test done using a 0.05 M guanidinium salt solution, to confirm the results that were obtained at the 0.1 M concentration. Soil samples were allowed to equilibrate with the porewater for a minimum of 16 hours prior to testing.

The first two soils tested were Battleford and Floral Tills sourced near Saskatoon. These soils have the lowest montmorillonite contents of the four soils tested. X-ray diffraction (XRD) data from Christiansen (1971) indicates that both soils are mostly kaolinite and illite. Whitecourt Clay was taken from east-central Alberta, and no published quantitative XRD analysis is available for this soil; however, based on testing that will be presented later, it appears that the clay fraction is mostly illite. Regina Clay has the highest activity of the four soils and its clay fraction is composed of 53% montmorillonite, 35% Illite, and 12 % kaolinite (Fredlund, 1975). Particle size analyses are shown in Figure 2.

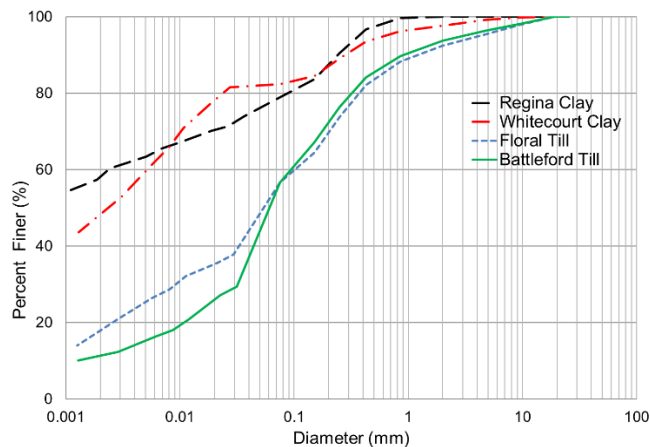


Figure 2: Particle size distribution of Regina Clay, Whitecourt Clay, Floral Till, and Battleford Till.

## 2 METHODOLOGY

### 2.1 Porewater Chemistry

Porewater characterization for each soil was carried out using porewater samples squeezed from freshly collected bulk samples. Analysis of cations was carried out using inductively coupled plasma mass spectrometry (ICP-MS). Anions were determined using ion chromatography (IC) and the pH, EC, TDS, and alkalinity of each porewater sample were measured. Measuring pH, EC, and TDS allowed for simple comparison of the synthetic porewater solutions that were made later for testing purposes.

### 2.2 Liquid Limit Testing

Liquid limit testing was conducted using a fall cone apparatus, rather than a Casagrande cup, as it has been shown to yield more consistent values for clayey soils (Koumoto & Houlsby, 2001). Synthetic porewater solutions were made for each soil sample, and then combined with guanidinium salts at concentrations of 0.1 Molar (M), 0.25 M, 0.5 M, 1 M, 2 M, and 4 M. Regina Clay had additional liquid limit test done using a 0.05 M guanidinium salt solution, to confirm the results that were obtained at the 0.1 M concentration. Soil samples were allowed to equilibrate with the porewater for a minimum of 16 hours prior to testing.

### 2.3 CEC Testing

The CEC of each soil was determined using the methylene blue spot test. The decision to use the methylene blue test was based on the simplicity of the test and given that the method provides the most representative results for clayey till sediments, as suggested by literature (Holden et al., 2012). The procedure followed was a slightly modified version of the procedure outlined by Santamarina et al. (2002) and Cokca & Birand (1993).

The methylene blue test consisted of titrating a 0.01 N methylene blue solution into a soil slurry in 0.5 mL increments. After each 0.5 mL increment, a drop of the solution was deposited onto a filter paper to check for the presence of a blue "halo" surrounding the drop. When a clearly defined halo formed around the drop, the test was complete as the methylene blue had replaced all of the soil's exchangeable cations (Yukselen & Kaya, 2008). The amount of methylene blue added to the clay suspension was then equivalent to the CEC.

Kahr & Madsen (1995) recommend the use of sodium hexametaphosphate as a dispersing agent prior to testing; however, it was found that this extra step led to inconsistent results when compared with those obtained from the standard methylene blue test procedure. Figure 3 shows a filter paper that was used for CEC testing, where the blue halo can be seen.

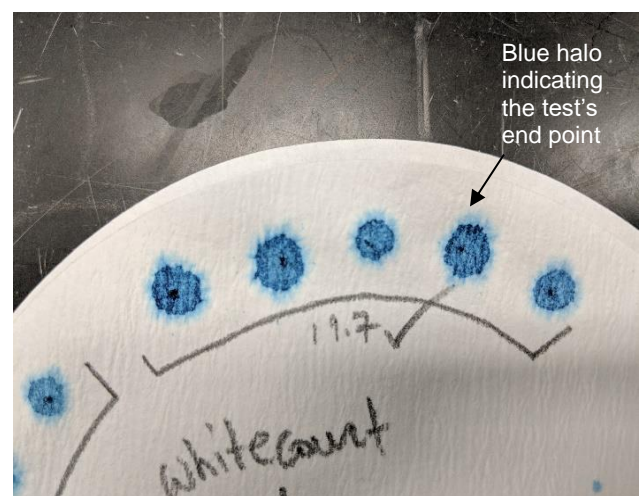


Figure 3: Filter paper displaying the results of methylene blue testing for Whitecourt Clay.

## 2.4 X-Ray Diffraction Analysis

Qualitative XRD analysis was performed on untreated and treated Regina Clay samples. The Millipore transfer method outlined by Drever (1973) was used to prepare the oriented samples. The Millipore transfer method was chosen as the technique to achieve preferred orientation since the method easily accommodates saturating samples with cationic species (Moore & Reynolds, 1989).

Soil samples were dispersed by a mechanical mixing apparatus into 100 mL of a 5g/mL sodium hexametaphosphate solution. Following dispersion, an additional 200 mL of distilled deionized water was added, and the slurry was placed in an ultrasonic bath for 15 minutes. After 15 minutes, the slurry was decanted and centrifuged for 3 three minutes at 1000 RPM. Using equations provided by Moore and Reynolds (1989), it was determined that these specifications would separate out all particles larger than 2  $\mu\text{m}$ , with the smallest settled particles having a diameter of 1.7  $\mu\text{m}$ . After centrifuging, the supernatant (process yield) was decanted.

For untreated slurry samples, this supernatant collected after centrifuging could be tested immediately. Treated samples were spiked with either a 0.1 M or 1.0 M guanidinium salt solution and were left to age for a minimum of 24 hours prior to being tested.

In summary, incident x-rays are diffracted by the various atomic/crystalline planes present in a soil sample. By knowing the wavelength ( $\lambda$ ) of these x-rays, the spacing ( $d$ ) between each crystalline plane can be determined by Bragg's Law (shown in Equation 1, below). The reader is referred to Mitchell & Soga (2005) for a detailed explanation regarding the physics governing the mechanism by which XRD is used to determine the mineralogical composition of soils.

$$n\lambda = 2d \sin\theta \quad [1]$$

After determining the interlayer spacing, this value can be used in tandem with the angle of the reflected x-ray beam, with respect to the incident beam to identify the species of minerals present within a soil sample. Figure 4 provides a useful schematic of the XRD process.

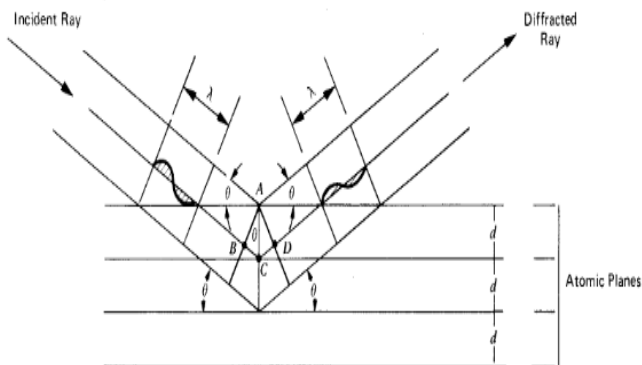


Figure 4: Schematic of the XRD process used to determine soil mineralogy. From Mitchell & Soga (2005).

The XRD analysis performed in this research used Copper radiation and evaluated all samples from 3 to 50 degrees  $2\theta$ , with a step size of 0.17  $2\theta$ . After an initial scan, all samples were glycolated to help resolve the smectitic peaks and further quantify the effects of guanidinium salts.

## 2.5 Ring Shear Testing

Pu (2018) conducted ring shear testing using a Bromhead ring shear apparatus on a Regina Clay sample (apparatus shown in Figure 5). The sample was prepared near its liquid limit using a synthetic porewater. The bath surrounding the sample was filled with the synthetic porewater, and the sample was consolidated to a vertical stress of 100 kPa. Once the reconstituted sample was consolidated, it was sheared at a rate 0.0038 mm/min. After reaching the sample's residual shear strength with the synthetic porewater, a 1.0 M guanidinium salt solution was applied to the sample by changing the bath solution in the container. After achieving a new residual shearing resistance, the 1.0 M bath was exchanged for a 0.4 M. This procedure was repeated several times, varying the porewater bath composition between a 1.0 and 0.4 M guanidinium solution and the synthetic porewater solution.

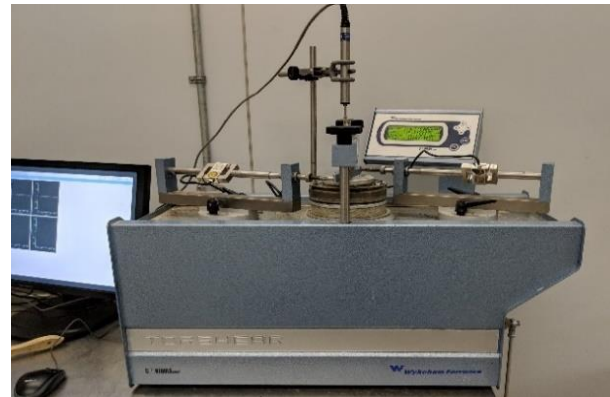


Figure 5: Bromhead ring shear apparatus used for measuring the angle of residual shearing resistance.

## 3 RESULTS AND DISCUSSION

### 3.1 Porewater Chemistry

Figure 6 shows a piper plot relating normalized values of the ions present within each porewater. The two ternary plots are indicative of the cationic and anionic compositions. The points on the diamond plot are made at the intersection of a fictitious line extending from corresponding points on each ternary plot.

As shown, calcium comprises a minimum of 50% of the cations within each porewater, while sulphate was the most prominent anion in each sample.

### 3.2 Liquid Limit Testing

The plot in Figure 6 shows the liquid limits of Regina Clay, Whitecourt Clay, Floral Till, and Battleford Till after various

treatments of different concentrations of guanidinium. Regina Clay was the most sensitive to the guanidinium treatments, having its liquid limit decline from 80% to 43%. This was an expected result, as it is known that the clay is approximately 50% montmorillonite (Fredlund, 1975). The exponential decrease in the liquid limit of the Regina Clay at guanidinium concentrations of 0.1 M to 0.5 M matches the findings of the liquid limit testing performed by Anson & Hawkins (1998). This sharp decline in liquid limit can be attributed to the collapse of the large amount of interlayer swelling that montmorillonite is capable of in the presence of water.

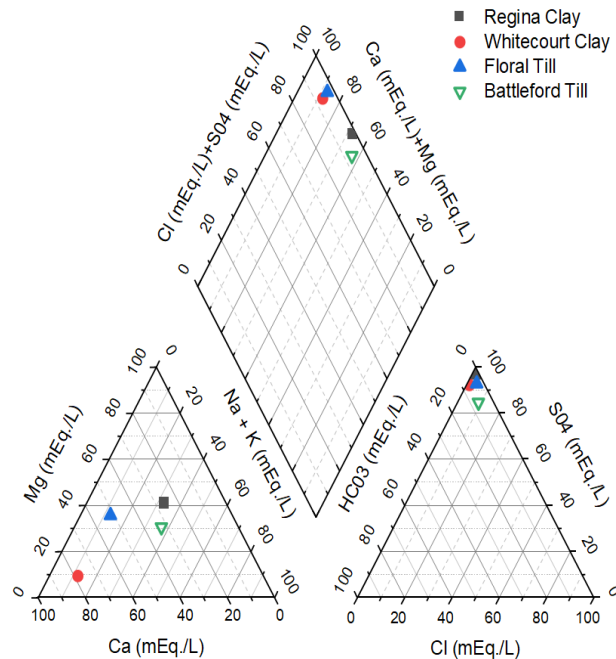


Figure 6: Piper plot of porewater compositions.

The other three soils were not affected nearly as much as the Regina Clay, but all three show a trend in how their liquid limits decrease. Since these other three soils are lacking in smectitic minerals, the decrease in liquid limit is solely due to a collapse of the DDL. This trend also explains why the Regina Clay joins the pattern of the other three soils after the initial sharp decline in liquid limit. Once the interlayer has been collapsed, the only way to further reduce the liquid limit is by collapsing the DDL.

One may also note that there was a slight increase in the liquid limits for the Battleford Till, Floral Till, and Regina Clay at the first concentration of guanidinium testing. This was an expected result for the two tills, as past research has produced similar results when testing soils rich in kaolinite (Anson & Hawkins, 1998). This slight increase in liquid limit is possibly due to an increase in the dielectric permittivity of the pore water solution. The initial increase in liquid limit for Regina Clay was unexpected; however, the increase may be a result of a similar phenomenon as experienced by both tills.

### 3.3 CEC Testing

Table 2 shows the results from the CEC testing of the four prairie soils. Regina Clay and Whitecourt Clay had the highest CEC values, which was expected given the clay content of each of these soils. The assumption that the Whitecourt Clay is mostly illite is partially verified from this testing, as Regina Clay and Whitecourt Clay have approximately the same clay fraction, but their CEC values differ by nine milliequivalents per litre. Of the four clays tested, Regina Clay was the only soil for which literature could be found to verify the test results. Fredlund (1975) reported a CEC value of 31 mEq./L in his report, which is in good agreement with the value of 29 mEq./L.

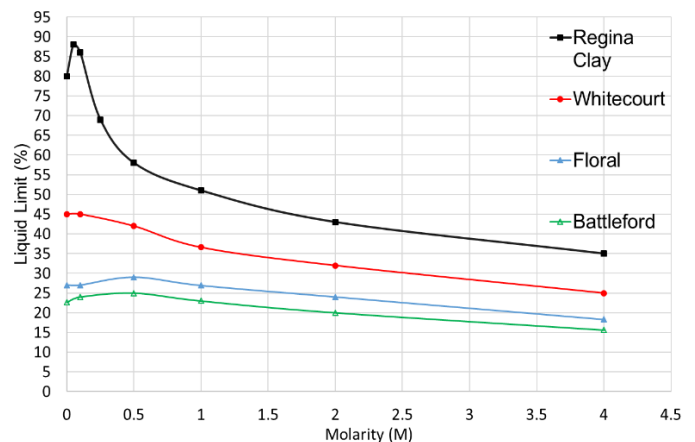


Figure 7: Results of liquid limit testing. Note: a molarity of 0 indicates tests completed with a synthetic porewater solution.

Table 2: Characterization of clay mineralogy

Soil	% Clay	% Smectite	CEC (mEq/L)
Regina Clay	58	53% <sup>1</sup>	29, 31 <sup>1</sup>
Whitecourt Clay	59	N/A	20
Floral Till	25	<5% <sup>2</sup>	9
Battleford Till	15	<5% <sup>2</sup>	6

<sup>1</sup> Fredlund (1975), <sup>2</sup> Christiansen (1971)

### 3.4 XRD Testing

Figures 8 and 9 show the results of the qualitative XRD analyses. Figure 8 compares glycolated and non-glycolated Regina Clay samples. The non-glycolated XRD trace shows clear evidence of illite/smectite interlayering, as indicated from 5° to 9° 2θ and the broad shoulder surrounding the quartz peak at 26.6° 2θ. Glycol solvation of this sample revealed the smectitic peak at 5.17° 2θ (17.01 Angstroms, Å) and confirmed the presence of the chlorite at 6.2° 2θ (14.2 Å). The trace also indicates the sample contains illite and kaolinite, as shown by the 10 Å peak at 8.8° 2θ, and the 7.2 Å peak at 12.5° 2θ, respectively.

Figure 9 compares XRD traces from Regina Clay samples treated with 0.1 M and 1.0 M guanidinium solutions with that of an untreated sample. Although both samples were analyzed in their non-glycolated forms, only glycolated samples have been presented, as the illite/smectite interlayering that was evident in Figure 8 makes observing peak shifts difficult. The XRD trace in Figure 9 shows a large shift in the 17.01 Å smectite mineral peak, providing clear evidence of interlayer collapse within the smectite mineral for both the 0.1 M and 1.0 M treated samples.

These results confirm the mechanism by which the liquid limit exponentially decreased when exposing the soil to a guanidinium salt solution. Figure 9 also suggests that if the strength and plasticity characteristics of the soil are to be dominated by the interlayer, drastic alterations to the soil's engineering properties should be capable with relatively low concentrations of guanidinium salts being added to the soil's porewater.

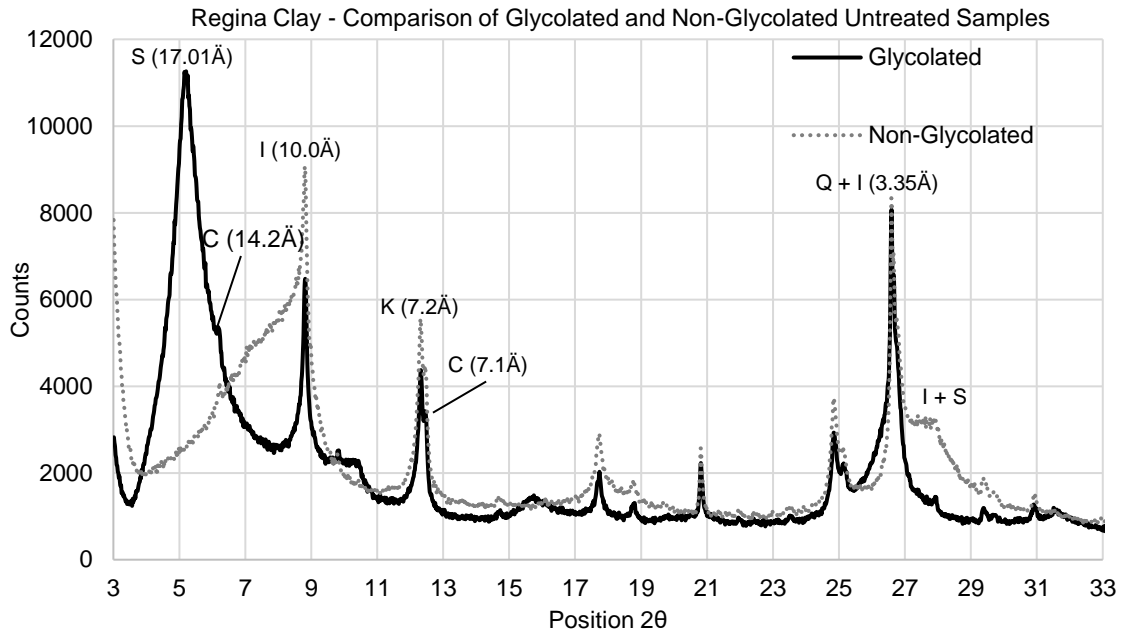


Figure 8: Comparison of glycolated and non-glycolated XRD traces for Regina Clay.

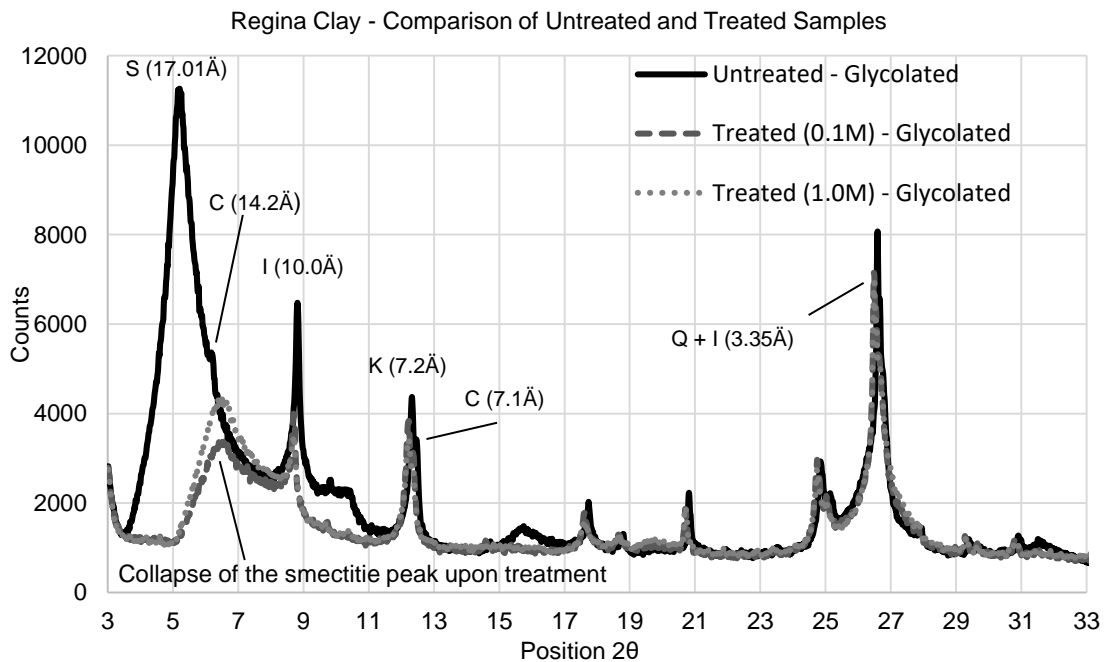


Figure 9: Comparison of treated and untreated XRD traces for Regina Clay

### 3.5 Ring Shear Testing

A plot of shear strength versus displacement for Regina Clay is shown in Figure 10. The orange lines in the plot represent the time at which the sample bath was changed. The figure has been annotated such that the angle of residual shearing resistance for each bath composition has been stated. As shown, the introduction of guanidinium to the system increases  $\phi'_{RES}$  from  $7.7^\circ$  to  $12.1^\circ$ . After reducing the concentration of guanidinium in the bath,  $\phi'_{RES}$  dropped less than  $1^\circ$  to  $11^\circ$ .

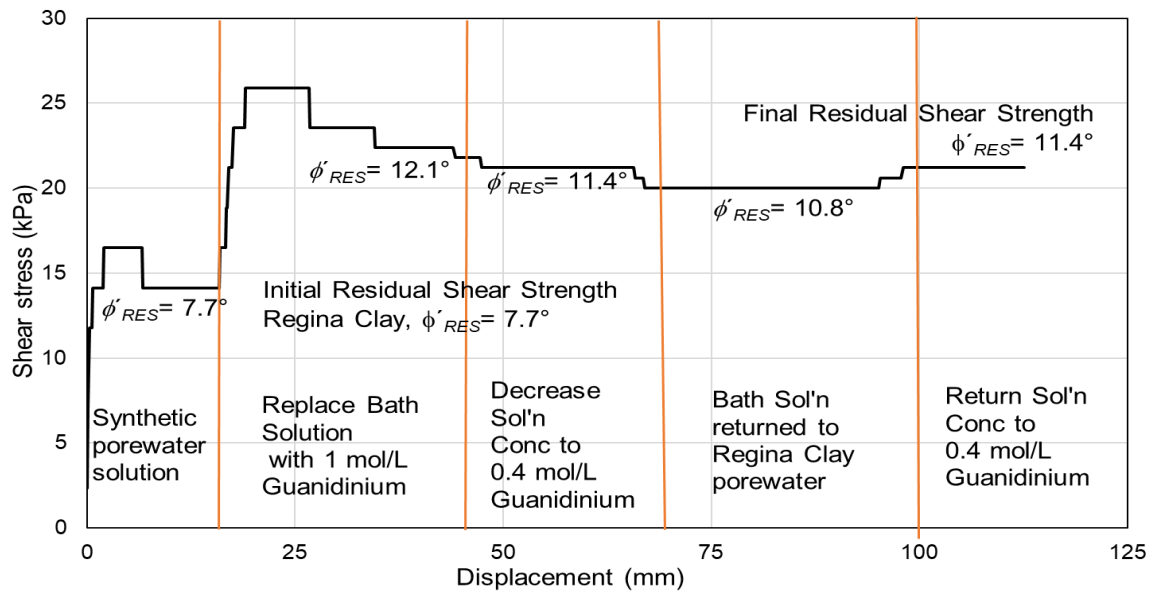


Figure 10: Plot of shear stress (kPa) vs. displacement (mm) for Regina Clay with a 100 kPa normal force. From Pu (2018).

Upon replacing the sample bath with the synthetic porewater solution, it was found that the angle of residual shearing resistance remained higher ( $10.8^\circ$ ) than the value measured prior to treatment with guanidinium salts.

The results of this test suggest that the increase in  $\phi'_{RES}$  is disproportional to the concentration of guanidinium in the system; and furthermore, that a large increase in residual shear strength is experienced at very low concentrations of guanidinium salts. This finding supports the results of the liquid limit and XRD testing, as both of those experiments revealed significant changes in the behaviour Regina Clay at very low concentrations of guanidinium.

#### 4. CONCLUSION

Four prairie soils were subjected to batch style testing to determine their insitu porewater compositions and cation exchange capacities. The soils were further classified by a particle size analysis and index testing. The liquid limits of the four soils were then evaluated using various concentrations of guanidinium salt solutions. Regina Clay showed the largest change in liquid index properties when subjected to guanidinium salts as it displayed a decrease in liquid limit from 80% to 43% (shown in Figure 7). This large decrease is attributed to a collapse of interlayer spacing between montmorillonite minerals within the clay.

The other three soils experienced minor declines in their liquid limits, all of which were attributed to a function of their DDLs collapsing.

CEC testing of the four soils revealed that Regina Clay had the highest exchange capacity (29 mEq. /L), followed by Whitecourt Clay (20 mEq. /L), Floral Till (9 mEq. /L), and lastly Battleford Till (6 mEq. /L). These values are indicative of not only the clay fractions of the soils, but also the types of clay minerals present within each soil. Regina Clay and

Whitecourt Clay have nearly identical clay fractions, but the difference in CEC values leads to the conclusion that Whitecourt Clay is lacking in montmorillonite, while Regina Clay is known to contain a large amount of this expansive mineral (Fredlund, 1975).

Qualitative XRD analysis was performed on treated, untreated, glycolated, and un-glycolated samples of Regina Clay. The XRD traces confirmed the effects shown in the liquid limit testing, as a large peak shift in the smectite mineral peak was observed at low concentrations of guanidinium. This finding verifies that the effects of guanidinium beyond concentrations of 0.1 M are solely due to the collapse of the DDL, and that alterations to the soil's interlayer may be achieved at low concentrations of guanidinium.

The ring shear testing performed by Pu (2018) investigated the effects of guanidinium with respect to the angle of residual shearing resistance for Regina Clay. It was found that an increase of  $4.7^\circ$  was observed when the sample bath was spiked with a 1.0 M guanidinium salt solution. Upon removing guanidinium from the sample bath, it was found that  $\phi'_{RES}$  remained at a higher value ( $10.8^\circ$ ) than what was originally measured ( $7.7^\circ$ ). These results suggest that the effects of guanidinium treatment may be permanent. In addition, the ring shear test confirmed that the effects of guanidinium on clays is

disproportional to the concentration of guanidinium in the system. The results of the liquid limit test, XRD analysis, and ring shear experiment all suggest that low concentrations of guanidinium are capable of yielding large changes in the engineering properties of high plasticity clays.

Guanidinium salts have a strong effect on soils rich in montmorillonite; specifically, a significant reduction in plasticity and a sizeable increase in residual shear strength are observed. Since guanidinium salts are biodegradable within natural water, there is potential for their use in developing a new insitu treatment method for common slope stability problems associated with weak clay/shale lenses.

Future research plans to further evaluate changes in residual shear strength due to guanidinium salts, and to address the issues associated with data resolution (which are evident in Figure 10). In addition, future testing plans to evaluate potential alterations to hydraulic conductivity, pore-size, and consolidation properties of both expansive and non-expansive clayey soils.

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