Laboratory setup to evaluate the improvement of geotechnical properties from potassium chloride saturation of a quick clay from Dragvoll, Norway

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

TE Helle, RN Bryntesen, & H Amundsen
Norwegian University of Science and Technology, Trondheim, Norway
& Norwegian Public Roads Administration, Trondheim, Norway
A Emdal, & S Nordal
Norwegian University of Science and Technology, Trondheim, Norway
P Aagaard
Department of Geoscience – University of Oslo, Oslo,Norway

ABSTRACT
This laboratory study comprises testing of soft leached quick clay samples under three storage conditions; wrapped in plastic, submerged in de-aired water and submerged in a potassium chloride slurry. The main purpose is to reveal the potential of improving the soil strength by introducing salt ions to the soil in order to enable future use of unsafe clay areas. To enhance the precision of the study, the clay samples are taken by use of a miniature version (sample diameter 160 mm) of the Sheerbrooke block sampler to reduce the sample disturbance to a minimum. The clay is tested by index, triaxial and oedometer testing. Adding KCl to the clay, a 25 % increase is found in the undrained shear strength whereas the remolded undrained shear strength dramatically increased from <0.5 to 4 kPa. Further, increase in soil plasticity, preconsolidation pressure and stiffness is noticeable.

RESUME
Cette étude de laboratoire comprend des essais sur échantillons d'argile sensible lessivée ayant été conservés sous trois conditions ; enveloppés dans du plastique, submergés dans de l'eau désaérée et submergés dans une suspension de chlorure de potassium. Le but principal étant de révéler le potentiel d'amélioration de la résistance du sol par introduction d'ions de sel dans le sol afin de permettre l'utilisation future de zones argileuses à risque. Pour améliorer la précision de l'étude, les échantillons d'argile sont prélevés par l'utilisation d'une version miniature (diamètre d'échantillon 160mm) de l'échantillonneur Sherbrooke afin de réduire au minimum la perturbation de l'échantillon. L'argile est testée par indice, par triaxial et à l'œdomètre. En ajoutant du KCl à l'argile, une augmentation de 25% de la résistance au cisaillement non drainée a été observée tandis que la résistance au cisaillement non drainée du sol remanié a augmenté de façon importante de <0.5 à 4 kPa. De plus, une augmentation de la résistance a été constatée, ainsi qu'un accroissement de la plasticité du sol, de la pression de préconsolidation et de la rigidité.

1 INTRODUCTION

Potassium chloride (KCl) improves the geotechnical parameters in highly sensitive, low-saline clays (Moum et al. 1968; Eggestad and Sem 1976; Helle et al. 2013). In Norway, quick clay is defined by its remolded shear strength equal to or less than 0.5 kPa (Norwegian Geotechnical Society 1982). A field experiment where salt wells were installed in a quick clay deposit at Ulvensplitten, Oslo, Norway, was carried out in 1972 in order to improve the geotechnical properties prior to excavation (Eggestad and Sem 1976). Recent new investigations in the same area show that the effect remains thirty to forty years later, and the method is suggested to be applicable as ground improvement to prevent large landslides (Helle et al. Submitted, 2015). Installing salt wells in soft natural clay slopes is a challenge due to the marginal safety of the slope. This calls for moderate weight equipment and new technology development for a cost effective solution.

Using KCl as ground improvement is time consuming, and it takes a couple of years to improve the clay volume surrounding the salt well even though the salt wells have a center to center distance of 1.5 m (Eggestad and Sem 1976). In soils with a hydraulic conductivity of less than $1x10^{-10}$ m/s, the transport mechanism is dominated by diffusion, i.e. chemical transport from high concentration to low concentration (Appelo and Postma 2005; Mitchell and Soga 2005). The obtained improvement on the geotechnical properties and the time it takes, depend on the initial pore water chemistry and ion distribution in the adsorbed positions on the clay mineral surface, water-filled porosity, temperature and tortuosity, all of which are site specific.

Prior to installing salt wells in quick clay areas it is necessary to quantify the effect on the geotechnical properties. As diffusion is time consuming, a laboratory setup for quantifying the effect quickly is needed. As time and method of sample storage highly affects the geotechnical properties, it is important to also evaluate the laboratory results with respect to storage effects. A laboratory setup and a testing regime for quantifying the necessary data prior to stabilizing quick clay areas with KCl is proposed in this paper.

2 BACKGROUND

2.1 Geochemistry in quick clays

The pore water in clays deposited in marine environment originally had seawater salt content (~30-35 g/l). The ion composition was similar to the depositional environment i.e. highly dominated by sodium (Na^+) in the pore water as well as in the adsorbed positions on the clay mineral surface. Leaching and diffusion decreased the salt content and changed the ion composition in the pore water (Rosenqvist 1946). A salt content of less than 5-10 g/l may develop quick clay (Bjerrum et al. 1969). Leached clays with a salt content of less than 1 g/l may behave as a liquid when remolded (Bjerrum et al. 1969; Moum et al. 1971). However, low salt content does not necessarily imply quick clay as the specific ion composition at low salt content highly affects the geotechnical properties (Moum et al. 1971).

Clay minerals are negatively charged, attracting cations from the pore water to maintain neutral charge. The adsorbed ions are affected by available ions in the pore water. Potassium (K^+) has higher exchanging power than Na^+, but less than Mg^{2+} and Ca^{2+} (Løken 1970; Appelo and Postma 2005; Mitchell and Soga 2005). The pore water composition in quick clays is dominated by Na^+, whereas the adsorbed positions are dominated by divalent ions such as magnesium (Mg^{2+}) and calcium (Ca^{2+}) introduced by the leaching water and weathering of the soil minerals (Moum et al. 1971). According to Mitchell and Soga (2005), introducing high concentration of monovalent ions, such as K^+, to the pore fluid will even so replace Mg^{2+} and Ca^{2+} on the mineral surface. K^+ has a higher beneficial impact on the undrained and remolded shear strength as well as the Atterberg limits than Na^+, Mg^{2+} and Ca^{2+} (Løken 1968). KCl is highly soluble in water and easily available, consequently it is highly applicable for ground improvement.

2.2 Storage effects on quick clay samples

Long term storing of soft clay over time may cause oxidation of the samples. Oxidation lead to changes in the chemical composition of the pore water as well as in the adsorbed positions on the clay mineral surface (Torrance 1976; Lessard and Mitchell 1985). Torrance (1976) and Lessard and Mitchell (1985) report increased salinity and increased percentage of divalent ions in the pore water as a result of storage, possibly due to dissolution of carbonates releasing Mg^{2+} and Ca^{2+} to the pore water. As divalent ions have higher exchanging power than monovalent ions, these may be adsorbed on the mineral surface releasing Na^+ and K^+ to the pore water. Increased salinity reduces the repulsive forces between the clay particles, improving the geotechnical properties of the clay (Rosenqvist 1946; Rosenqvist 1953; Bjerrum 1955; Rosenqvist 1955; Løken 1968; Moum et al. 1968; Løken 1970; Quigley 1980; Torrance 1983).

Storage over time may cause migration of water and loss of moisture (Hvorslev 1949). This may be prevented by wrapping samples in clingfilm combined with waxing, or clingfilm and foil (La Rochelle et al. 1986; Heymann and Clayton 1999). La Rochelle et al. (1986) dipped the clingfoil in a wax compound prepared from equal weight of paraffin wax and vaseline prior to wrapping it around specimens cut out from larger samples. The clingfilm was evened out with the hands to avoid trapped air bubbles. The pH did not change due to storage, indicating that the technique prevents oxidation of the clay specimens. The stored clay specimens also maintained their natural water content and Atterberg limits over a time period of eight years.

Even though wrapping the samples in wax and clingfilm will prevent moisture loss, the geotechnical properties will change due to loss of its in situ overburden pressure. Bjerrum (1973) found a decrease in peak shear strength with 13.0-13.5 % within 2-3 days due to increased internal swelling in quick clay samples from the Oslo area. A decrease in the preconsolidation pressure (p_c') of 4.8 % was found in block samples of overconsolidated sensitive marine clay stored for 2 to 17 months (Bozozuk 1971).

3 METHOD

The NTNU research site at Dragvoll in Trondheim, Norway, is located 159 m above current sea level. The marine limit in the Trondheim area is 175-180 m above current sea level (Kjemperud 1981; Hafsten 1983). The clay deposit is up to 40 m thick in the area (Hafsten and Mack 1990).

3.1 Storage procedure

NTNU has developed a down-sized Sheerbrooke block sampler to easily extract samples of high quality. The sample has a diameter of 160 mm, and height of 250 mm.

Fourteen mini block samples covering the depth in the range of 3.25 m to 8.95 m were extracted from the quick clay NTNU research site Dragvoll (Table 1). Six of these were used for reference measurement of the soil properties. Four were stored in de-aired water before testing, and four were stored in KCl-slurry using a cell shown in Figure 1. All samples were wrapped in clingfilm directly after extraction from the ground, and stored in the cold storage chamber at approximately 7 ºC for up to 2 months. The variety of storage time was due to capacity problems at the laboratory. However, the stored samples from the same depths are tested within the same week.

All cells were filled with de-ionized, de-aired water. The samples stored in de-aired water were submerged wrapped in clingfilm to avoid diffusion of ions from the clay into the reservoir. The samples stored in KCl-slurry were covered by KCl to ensure high concentration throughout the time of storage as well as rapid migration of the concentration front into the sample. The solute concentration of KCl in the storage cells was about 3500 meq/l (~260 g/l).

Table 1. Storage time of samples used in the study. Amount of days stored in clingfilm prior to testing in the laboratory, and prior to submerging the samples in de-aired water or KCl-slurry. Total days of storage is the sum of days in clingfilm and days stored in the storage cells

Storage	Depth (m)	Clingfilm[1] (days)	Cells (days)	Total (days)
Reference	3.25-3.50	41		41
Reference	4.00-4.25	45		45
Reference	4.50-4.75	52		52
Reference	7.70-7.95	28		28
Reference	8.45-8.70	3		3
Reference	8.70-8.95	4		4
De-aired water	3.75-4.00	61	47	108
De-aired water	4.75-5.00	41	68	109
De-aired water	5.55-5.80	41	82	123
De-aired water	8.20-8.45	35	102	137
KCl	3.50-3.75	61	42	103
KCl	4.25-4.50	61	62	123
KCl	5.05-5.30	41	76	117
KCl[2]	7.45-7.70	35	96	131

[1] days the samples were stored in the cold storage room wrapped in clingfilm prior to submerged in cells

[2] leakage in cell. Consequently only partially stored in KCl-slurry

3.2 Laboratory tests

The mini-block samples were sectioned as shown in Figure 2. Fall cone undrained and remolded shear strength, water content, Atterberg limits, pH and ion composition in the pore water were determined in sections 1 to 3 shown in Figure 2c. CAU Triaxial and CRS oedometer tests were carried out on all samples.

Mineralogy was determined by x-ray diffraction analysis (XRD). The pore water was extracted from the clay by centrifuge, and filtered using a syringe filter of 45 µm prior to analysing the ion composition.

The concentration of ions in the pore water was analyzed at the laboratory at the Department for Geosciences at the University in Oslo. The cations were analyzed using a Dionex ICS-1000 Ion Chromatography System (ICS-1000). The anions were analyzed using a Dionex ICS-2000 Ion Chromatography System (ICS-2000). The alkalinity was determined by HCl-titration in Metrohm 702 SM Titrino. pH was measured in the pore water by the Methrom 702 SM Titrino at 25 ºC.

4 RESULTS

4.1 Soil description

The soil at Dragvoll is characterized as clay with a clay content (particle size < 2 µm) of 24-28 % down to 6 m depth, and of approximately of 38 % at 7-9 m depth.

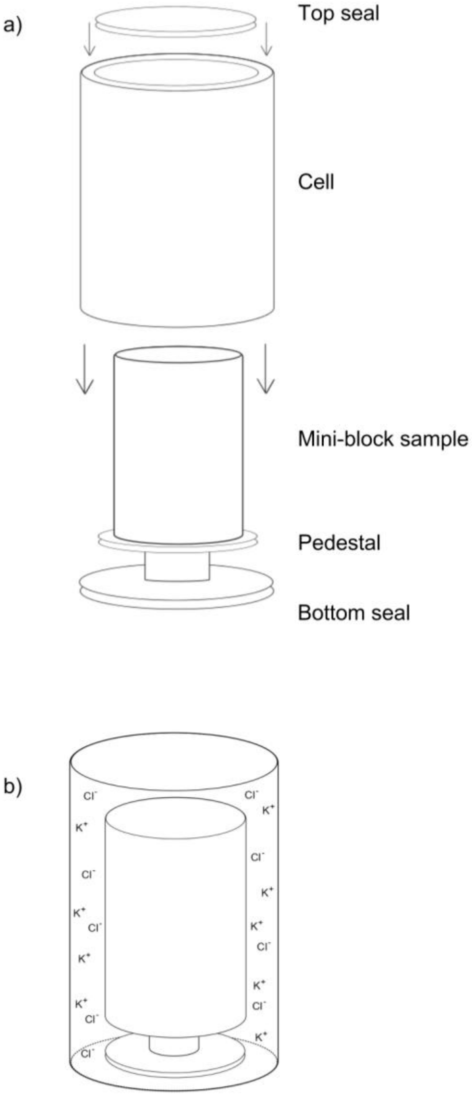

Figure 1 Storage cell used for the samples submerged in de-aired water and KCl-slurry. a) construction parts and b) sample submerged in KCl

The clay deposit is intersected with horizontal silt layers. Shells, shell fragments and drop stones were occasionally observed in the samples. The clay mineralogy is dominated by illite; 45 % in the top soil and 35 % at around 8 m depth. The amount of chlorite is generally around 14 %. Below 4.5 m, 2-3 % of the bulk mineralogy consisted of calcite.

4.2 Pore water chemistry

Horizontal cutting revealed discoloration with a lighter grey almost yellow colour along the circumference and along the thickest siltlayers throughout the samples stored wrapped in clingfilm, submerged in de-aired water. The discoloration was also evident in the reference samples stored for around 40 days. This may be an indicating of

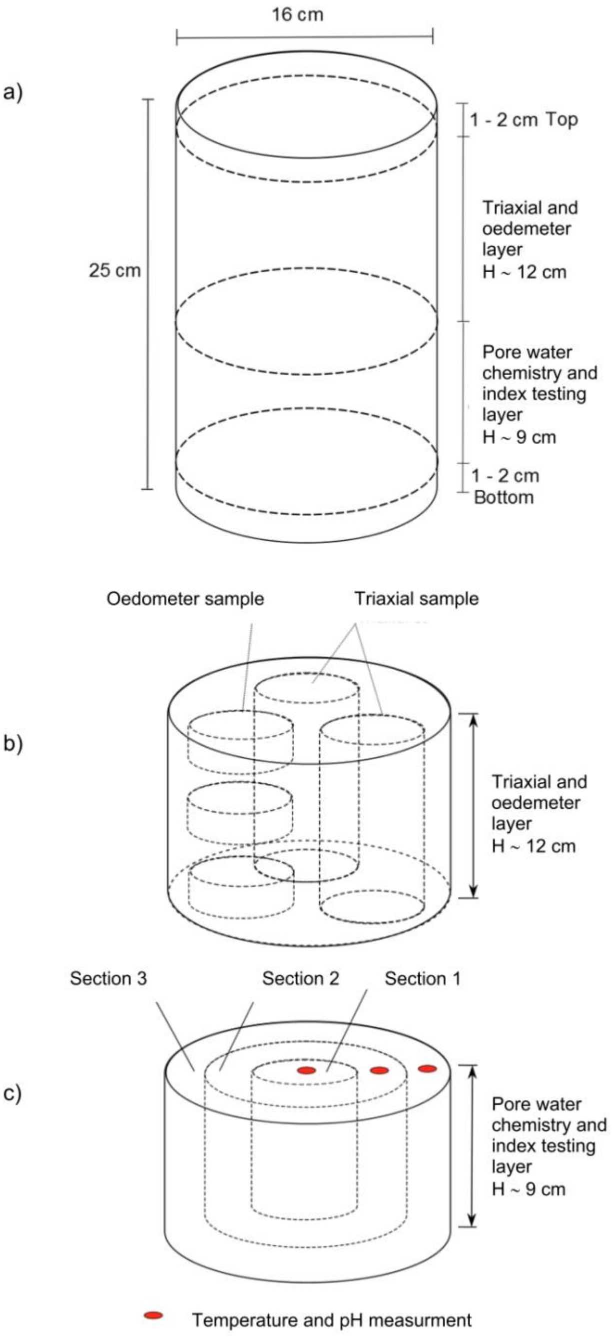

Figure 2. Sectioning of mini-block sample. A couple of cm in the top and bottom was removed (a). Approximately 12 cm was used for triaxial and oedometer testing (b). The remaining 9 cm was used for index testing, pH and pore water chemistry (c)

oxidation. The oxidation may have occurred in the time from extracting the samples until submerging the samples in the storage containers. Furthermore, some oxygen may have been trapped within the clingfilm contributing to oxidation of the samples. The samples stored in KCl did not have this discoloration. The sulphate concentration (SO_4^{2-}) is increased in section 2 and 3 compared to section 1 in the reference sample, and throughout the samples stored submerged in either water or KCl-slurry (Figure 4g). The increased concentration of SO_4^{2-} may be a result of oxidation of pyrite (FeS_2) to ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}), ultimately precipitating as $Fe(OH)_3$ causing the slightly yellow discoloration of the circumference of the clay sample (Lessard and Mitchell 1985).

The pH in the reference samples compared to the ones submerged in de-aired water wrapped in clingfilm is almost unchanged (Figure 3). However, pH in the samples stored in KCl is decreased below 8. This may be caused by the de-aired water holding a lower pH, or due to oxidation of pyrite forming sulfuric acid (Lessard and Mitchell 1985). The decrease in pH may have caused dissolution of calcite releasing Ca^{2+} to the pore water.

The alkalinity (Figure 4f) at the occurring pH is governed by bicarbonate (HCO_3^-). The drastic drop in alkalinity in the samples stored in KCl may be explained by the high concentration of Cl^- entering the pore water, suppressing bicarbonate out of the system as well as bicarbonate being neutralized by sulfuric acid (Lessard and Mitchell 1985).

The cation concentrations change in the samples stored in de-aired water compared to the concentrations in the reference sample. Na^+ increase by approximately 5 meq/l in the deepest samples. K^+ and Mg^{2+} is increased by approximately 0.4 meq/l and 0.1 meq/l respectively, whereas Ca^{2+} is doubled by an increase of 0.7 meq/l. Storing the samples in KCl-slurry, the concentration of K^+ (Figure 4b) and chloride (Cl^-) (Figure 4e) is increased to the solute concentration in the storage container, of approximately 3500 meq/l (~260 g/l). As K^+ enters the adsorbed positions on the clay mineral surface, Na^+, Mg^{2+} and Ca^{2+} is released increasing the concentration in the pore water (Figure 4a, c and d).

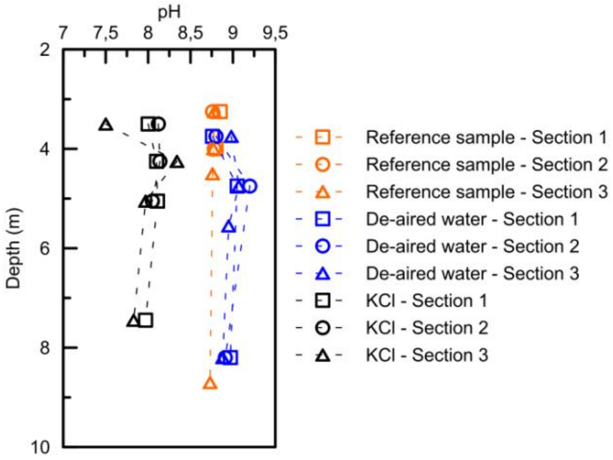

Figure 3. pH in sections 1-3

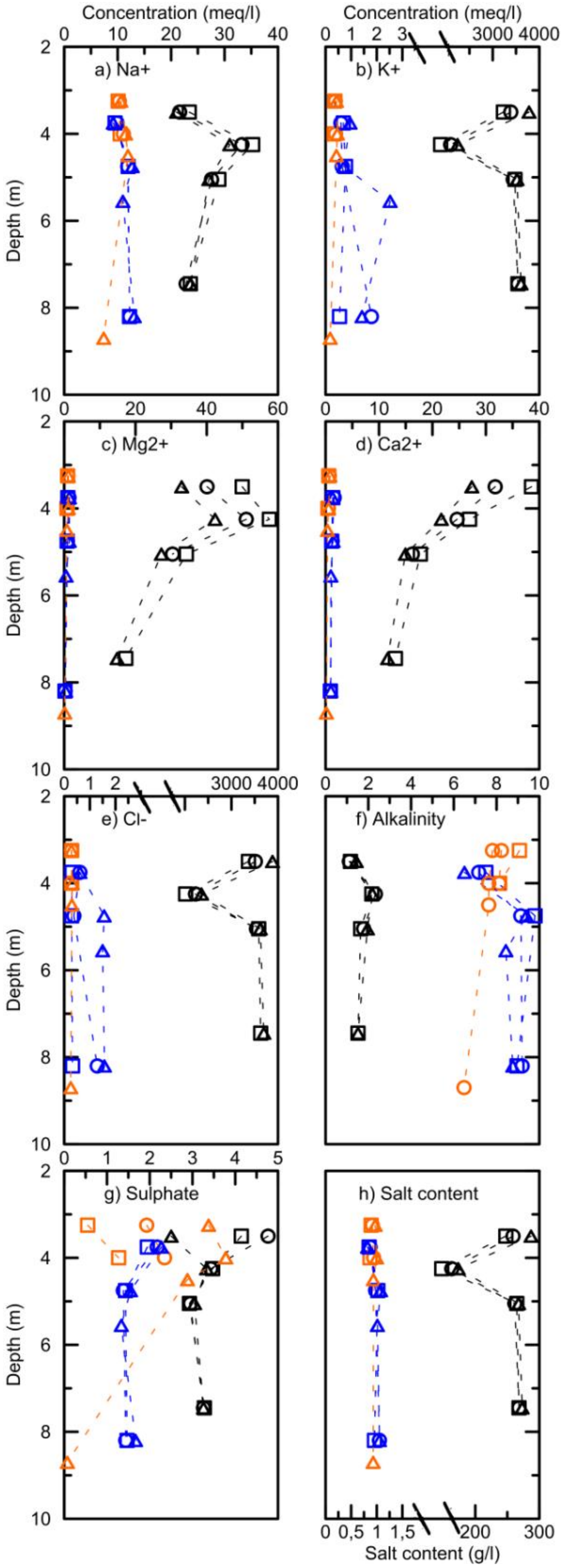

Figure 4. Ion composition in pore water over time for section 1 and 2. a) Sodium, b) potassium, c) magnesium, d) calcium, e) chloride, f) alkalinity, g) sulphate and h) total salt content. Legend as in Figure 3

4.3 Geotechnical properties

The circumference of the sample is the most disturbed part due to handling during sampling, oxidation and swelling due to unloading. The data from section 3 is never the less included as some of the samples have their index tests carried out in the top lid of the sample. However, most emphasis is made on interpreting data from Section 1 and 2. The clay is in-homogenous with depth due to an uneven distribution of horizontal silt layers affecting the results. Results clearly deviating from the lot due to occurence of silt layers are ruled out.

Storage effects have affected the geotechnical properties. However, storing the samples wrapped in clingfilm submerged in de-aired water seem to retain the fall cone undrained and remolded shear strength (Figure 5), water content and the Atterberg limits (Figure 6). However, considering the triaxial (Figure 7) and oedometer tests (Figure 8) the degradation of the geotechnical properties is considerable.

Storing the samples in KCl increase the fall cone undrained shear strength slightly compared to the reference sample. The remolded shear strength however, is increased from 0.1 kPa to as much as 6.4 kPa. The liquid limit is increased to the natural water content, whereas the plastic limit is practically unchanged. The density in the samples stored in KCl increased due to the increased salt content. The reduced water content in these samples may be due to higher content of solids. Osmoses may also have contributed to reduced water content. The liquidity index (IL) in the reference samples is in the range of 1.6 to 4.6, whereas the samples stored in KCl has an IL in the range of 0.5-0.9. IL is, however, greatly affected by the water content. Calculating IL in the samples stored in KCl using the water content from the reference sample increases IL to the range of 0.8-1.5. The plasticity index in the reference sample is in the range of 2.8-10.4 %, whereas it in the KCl-treated clay is increased to the range of 10.0-17.4 %; from low plasticity to medium plasticity.

Figure 7 and 8 present triaxial and oedometer results from 4 m to 5 m depth. The triaxial undrained peak strength for the samples stored in de-aired water increased compared to the reference sample (Figure 7); from 20 kPa to 22.5 kPa. However, the residual strength in this case was decreased to less than the residual strength in the reference sample. By storing the quick clay in KCl, the peak shear strength increased to 25 kPa, which is an increase of 25 % compared to the reference sample. The residual strength increased far beyond the residual strength of the reference sample; from 13.5 kPa to 22 kPa at 5 % strain.

The oedometer modulus (M) is unaltered from the reference sample storing the sample in de-aired water; around 2 MPa (Figure 8a). M increase to around 5 MPa in the sample stored in KCl. The apparent preconsolidation pressure (pc’) increase from around 90 kPa to around 120 kPa in the KCl-treated clay. The occurring strains at the same effective stress (σ’) show that increased time of storage decrease the stiffness of the specimen (Fig. 8b). However, the stiffness of the KCl-treated clay is increased and the specimen deforms far less at the same σ’.

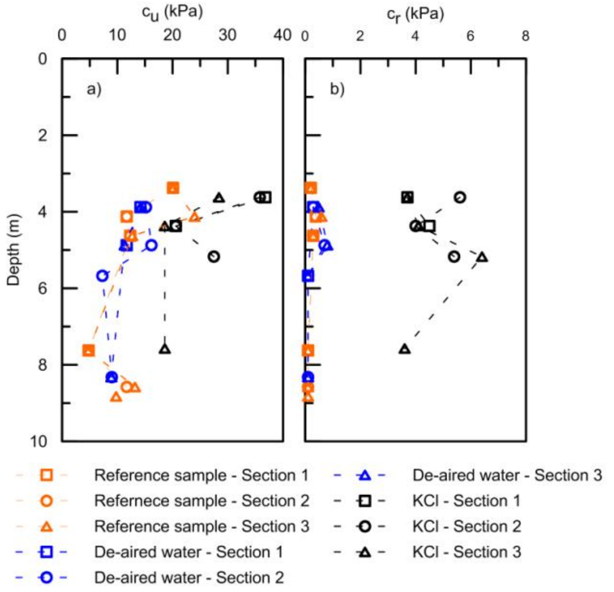

Figure 5. Fall cone a) undrained shear strength and b) remolded shear strength sections 1-3

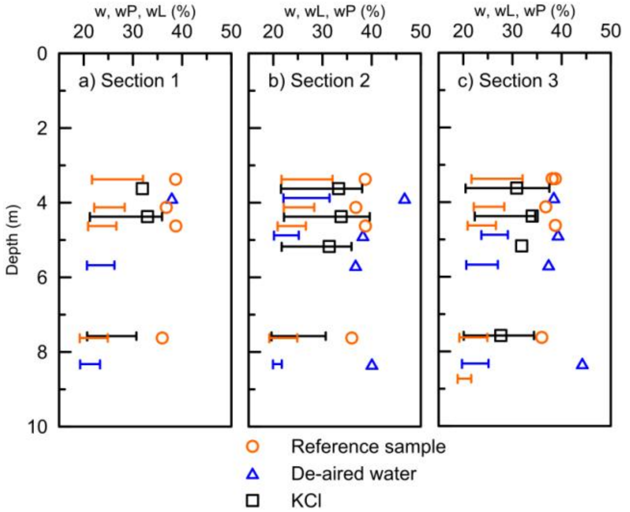

Figure 6. Water content and Atterberg limits sections 1-3

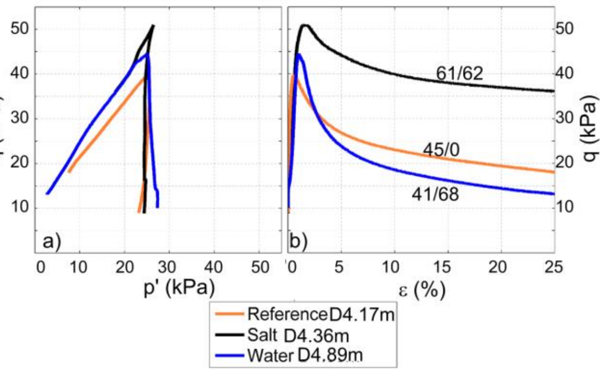

Figure 7. CAU triaxial test on reference sample and samples stored in de-aired water and KCl from 4.17-4.89 m depth. a) Deviatoric (q) versus mean effective stress (pm'), and b) deviatoric stress versus strain (ε). Days stored in clingfilm/days stored in cell is marked in figure b

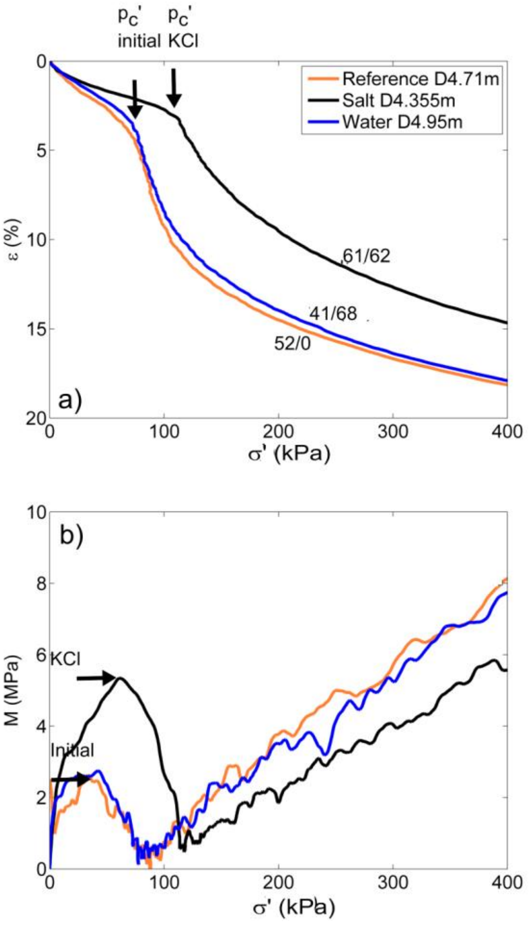

Figure 8. CRS oedometer tests on samples from 4.4-5.0 m depth. a) Strain (ε) versus effective stress (σ'). b) Oedometer modulus (M) versus effective stress. Days stored in clingfilm/days stored in cell is marked in figure a. Preconsolidation pressure (p_c') and oedometer modulus is marked by arrow

5 DISCUSSION AND RECOMMENDATIONS

Submerging the whole mini-block sample rather than small specimens in KCl-solution, index, oedometer and triaxial tests can all be carried out on the same block. This includes testing of mineralogy and pore water chemistry. Storing parallel samples submerged in de-aired water and KCl as well as testing one sample from the same depth directly after extraction is necessary to evaluate the improved geotechnical properties as a result of adding KCl. Storing the samples wrapped in clingfilm submerged in de-aired water, the samples seem to retain the index parameters. The pore water chemistry is, however, affected by storage, probably due to oxidation.

The reference samples and the ones wrapped in clingfilm submerged in de-aired water are of low plasticity and highly sensitive with a remolded shear strength of 0.1-0.4 kPa in sections 1-2. The samples stored in KCl have completely changed their behavior to medium plasticity and medium to low sensitivity, with a remolded shear strength of 3.7-5.6 kPa in sections 1-2.

Quick clays retain their water content during leaching (Bjerrum 1967). Re-introducing high salt content by submerging quick clay samples in KCl decreases the water content. However, the samples submerged in KCl has increased density compared to the reference samples. This indicates that the decreased water content may be a result of increased weight of solids which again reduce the porosity. Due to submerging the samples in KCl-slurry, osmoses may have contributed to decreasing the water content.

Losing the in situ overburden pressure, the clay sample expands which greatly affects the parameters determined by triaxial and oedometer testing. Testing the reference samples directly after extraction, may result in higher undrained peak strength. Decreasing time of storage as well as storing the samples at their in situ overburden pressure may result in a larger undrained peak strength increase due to increased concentration of K^+.

Even though storage time clearly affects the triaxial and oedometer parameters determined for the quick clay samples, a clear outcome of storing the samples in KCl is increased undrained peak strength, significantly increased residual strength and significantly reduced compressibility as a result of increased plasticity due to increased salt content. These findings are in agreement with Bjerrum (1967), where clay treated with KCl developed an increased resistance against deformation as the plasticity and shear strength increased.

6 CONCLUSIONS

Quantifying the improved geotechnical properties as a result of treating the clay with KCl is possible using a modification of the described laboratory setup. Determining fall cone undrained and remolded shear strength, water content, density, grain size distribution, Atterberg limits, mineralogy, pore water chemistry, cation exchange capacity (CEC) and exchangeable ions should be carried out, as well as triaxial and oedoemeter tests. The following laboratory setup is suggested:

a) Determine the initial condition of the clay directly after sample extraction from the ground
b) Store at least one sample from the same depth wrapped in clingfilm, submerged in de-aired water at in situ overburden pressure in a cold storage chamber
c) Store at least one sample from the same depth in supersaturated KCl solution (KCl+de-aired water) at in situ overburden pressure in a cold storage chamber

To delimit undesirable storage effects, the samples in b) and c) should be stored for as short time as possible. Geochemical simulations may provide information on how K^+ is distributed in the soil volume with time, both in the pore water and on the mineral surface. These calculations can be carried out by for instance the computer program PHREEQC. The improved geotechnical behavior found in c) must be evaluated considering the storage effect found in b).

Helle et al. (Submitted 2015) investigated the long-term effect of treating quick clay with KCl. The improved geotechnical properties regarding fall cone undrained and remolded shear strength and Atterberg limits remain 30-40 years after installing salt wells filled with KCl. Due to its beneficial effect on the remolded shear strength, liquid limit and plasticity, it appears to be well suited for stability measures in quick clay areas as well as for settlement reductions under constructions.

ACKNOWLEDGEMENTS

The authors express their sincere gratitude to Jan Jønland and Gunnar Winther at NTNU Geotechnical Research Group for their great effort during sampling and laboratory work as well as construction of storage containers. The tidy work by Mufak Naoroz at the laboratory at the University in Oslo analyzing the pore water chemistry on small sample volumes is highly appreciated. The work is funded by the Norwegian research program “Naturfare - infrastruktur, flom og skred (NIFS)”.

REFERENCES

Appelo, C., and Postma, D. 2005. Geochemistry. groundwater and pollution. 2nd edn. Balkema, Leiden, Netherlands.

Bjerrum, L. 1955. Norske marine leirers geotekniske egenskaper. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 7.

Bjerrum, L. 1967. Engineering geology of Norwegian normally-consolidated marine clays as related to settlements of buildings. *Geotechnique*, 17: 81-118.

Bjerrum, L., Løken, T., Heiberg, S., and Foster, R. 1969. A field study of factors responsible for quick clay slides. *In proceedings of 7th ICSMFE*, 2, Mexico 1969. pp 531-540.

Bozozuk, M. 1971. Effect of sampling, size, and storage on test results for marine clay. *Sampling of Soil and Rock, American Society for Testing and Materials, Special Technical Publication no. 493*: 121-131.

Eggestad. A.. and Sem. H. 1976. Stability of excavations improved by salt diffusion from deep wells. *In proceedings of the European conference on soil mechanics and foundation engineering*, 6, Vienna, March 1976, pp. 211-216.

Hafsten, U. 1983. Shore-level changes in South Norway during the last 13,000 years, traced by biostratigraphical methods and radiometric datings. *Norsk geografi tidsskrift*, 37: 63-79.

Hafsten, U. and Mack, G. 1990. Den postglaciale landskapsutviklingen på Dragvoll universitetsområde, Trondheim. Norks Geografisk Tidsskrift, 44(3): 131-148.

Helle. T.E., Gjengedal. I., Emdal. A., Aagaard. P., and Høydal. Ø. 2013. Potassium chloride as ground improvement in quick clay areas – A preliminary study. *In Landslides in sensitive clays: From Geosciences to risk management*. Edited by J.-S. L'Heureux. A. Locat. S. Lerouil. D. Demers. and J. Locat. Springer Dordrecht Heidelberg New York London. pp. 63-74.

Helle, T.E., Nordal, S., Aagaard, P., and Lied, O.K. Submitted 2015. Long-term effect of potassium chloride treatment on improving the soil behavior of highly sensitive clay – Ulvensplitten, Norway. Submitted to *Canadian Geotechnical Journal*.

Henriksson, M., and Carlsten, P. 1994. Lagringstidens inverkan på prøver tagna med standardkolvprotagare. Available from Statens geotekniska institute. Varia 430

Heymann, G. and Clayton, C.R.I. 1999. Block sampling of soil: Some practical considerations. In Geotechnics for Developing Africa. Edited by Wardle, Blight and Fourie. Balkema, Rotterdam. pp. 331-339.

Hvorslev, M.J. 1949. Subsurface exploration and sampling of soils for civil engineering purposes. Waterways Experiment Station, USA.

Kjemperud, A. 1981. A shoreline displacement investigation from Frosta in Trondheimsfjorden, Nord-Trøndelag, Norway. *Norsk geologisk tidsskrift*, 61: 1-15.

La Rochelle, P., Leroueil, S., and Tavenas, F. 1986. A technique for long-term storage of clay samples. *Canadian Geotechnical Journal*, 23: 602-605.

Lessard, G., and Mitchell, J.K. 1985. The causes and effects of aging in quick clays. *Canadian Geotechnical Journal*, 22: 335-346.

Løken. T. 1968. Kvikkleiredannelse og kjemisk forvitring i norske leirer. Available from Norwegian Geotechnical Institute, Oslo, Norway. *NGI Publication no. 75.*

Løken, T. 1970 Recent research at the Norwegian Geotechnical Institute concerning the influence of chemical additions on quick clay. In proceedings of the Geologiska Föreningen i Stockholm, Förhandlingar 92(2). pp 133-147.

Mitchell. J.K.. and Soga K. 2005. Fundamentals of soil behavior. 3rd edn. John Wiley & Sons Inc. New Jersey, USA.

Moum, J., Sopp. O.I., and Løken T. 1968. Stabilization of undisturbed quick clay by salt wells. Available from Norwegian Geotechnical Institute, Oslo, Norway. *NGI Publication no.* 81.

Moum, J., Løken, T., and Torrance, J.K. 1971. A geochemical investigation of the sensitivity of a normally consolidated clay from Drammen, Norway. *Geotechnique*, 21(4): 329-340.

Quigley, R.M. 1980. Geology, mineralogy and geochemistry of Canadian soft soils: A geotechnical perspective. Canadian Geotechnical Journal 9: 261-285.

Rosenqvist, I.T. 1946. Om leirers kvikkaktighet. Available from the Norwegian Public Road Administrations, *Meddelelsen fra Vegdirektøren*, No. 3. pp. 29-36.

Rosenqvist, I.T. 1953. Consideration on the sensitivity of Norwegian quick-clays. Geotechnique 3: 195-200.

Rosenqvist, I.T. 1955. Investigations in the clay-electrolyte-water system. Available from Norwegian Geotechnical Institute, Oslo, Norway. NGI Publication no. 9.

Torrance, J.K. 1976. Pore water extraction and the effect of sample storage on the pore water chemistry of Leda clay. *Soil Specimen Preparation for Laboratory Testing, American Society for Testing and Materials, Special Technical Publication no. 599*: 147-157.

Torrance, J.K. 1983. Towards a general model of quick clay development. Sedimentology, 30: 547-555

Torrance, J.K. 1988. Mineralogy, pore-water chemistry and geotechnical behaviour of Champlain Sea and related sediments. *In The Late Quaternary development of the Champlain Sea Basin.* Edited by N.R. Gadd. Geological Association of Canada, Special Paper 35: 259–275.