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Effect of storage time on sample quality

68
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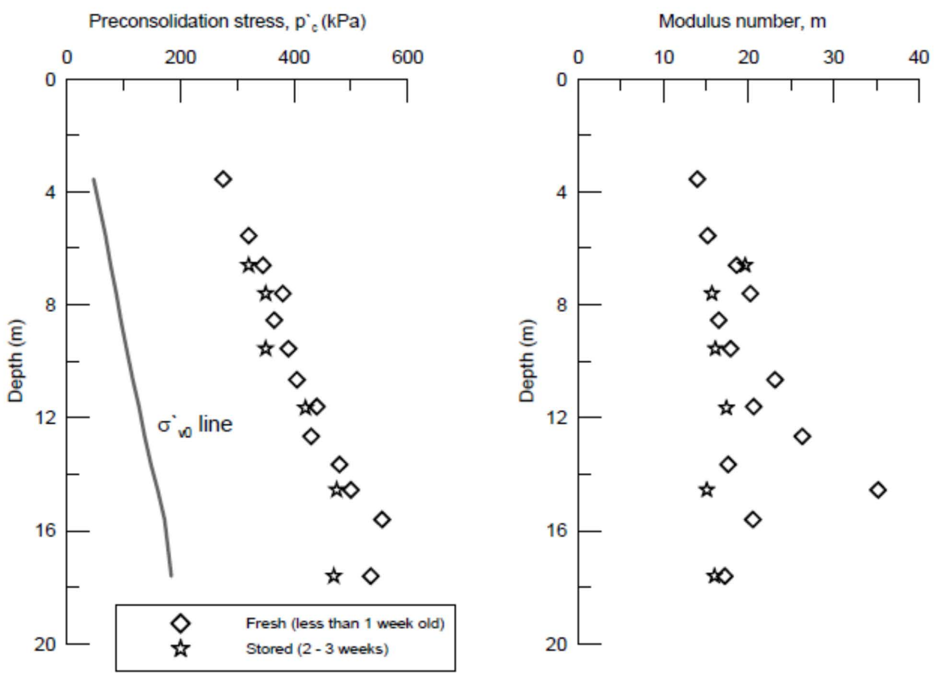

RAPPORT

NIFS
NATURFARE
INFRASTRUKTUR - FLOM - SKRED

Naturfareprosjektet: Delprosjekt Kvikkleire

Effect of storage time on sample quality

Norges vassdrags- og energidirektorat i et samarbeid med Statens vegvesen og Jernbaneverket

2014

Rapport nr. 68/2014
Effect of storage time on sample quality

Utgitt av: Norges vassdrags- og energidirektorat i et samarbeid med Statens vegvesen og Jernbaneverket
Utarbeidet av:
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Summary

This report focuses on the effect of storage time on sample quality in soft and sensitive clay deposits. The report was prepared for the governmental research project "Naturfare, Infrastruktur, Flom og Skred" (NIFS) sub-project 6, which focuses on stability issues in quick clay deposits. The first part of the reports briefly discusses the multiple factors leading to sample disturbance in soft and sensitive clays, and this is followed by a thorough review of available literature and unpublished NGI data documenting the effect of storage time on laboratory derived soil parameters.

Storage of clay samples over time may have a profound effect on the derived mechanical properties of the clays. The most significant mechanical effects over time lead to a decrease in 1) soil stiffness, 2) peak shear strength, 3) preconsolidation stress (p'c), 4) remoulded undrained shear strength, 5) clay sensitivity and in 6) compression index. These changes are attributed to the migration of pore fluids (changes in water content across the sample) and associated changes in stress distribution storage time, drying and moisture loss, to chemical effects and pH changes (due to e.g. oxidation), and also to temperature and humidity changes.

Results presented in this report show that the effect of storage time on the derived mechanical properties of a clay can be fairly important in the early stage of the storage period (i.e. first c. 10 days), especially for samples collected with piston sampler (i.e. 54-72 mm). It is therefore a prudent practice to perform soil testing as soon as possible after sampling.

Sample quality assessment is a vital component of geotechnical design in order to assign confidence levels to laboratory-determined engineering properties. Unfortunately, changes in pore water chemistry are usually not assessed in normal geotechnical testing program. Tests results have shown that relatively small differences in pore water chemistry can lead to changes in e.g. remoulded shear strength of clays. Changes in the pore water chemistry and pH within clay samples should be evaluated if clay samples are to be stored over a longer time period.

Due to the limited capacity in the geotechnical laboratories, clay samples are seldom tested immediately after sampling and the waiting time may vary from days to several months. There is therefore a need to quantify the impact of storage time on the mechanical properties of clays and to provide guidelines to the industry. To this aim, a laboratory testing program is proposed towards the end of the report.

Emneord: sample quality, sensitive clays, soft clays, storage time

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For NGI

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Summary

This report focuses on the effect of storage time on sample quality in soft and sensitive clay deposits. The report was prepared for the governmental research project "Naturfare, Infrastruktur, Flom og Skred" (NIFS) sub-project 6, which focuses on stability issues in quick clay deposits. The first part of the reports briefly discusses the multiple factors leading to sample disturbance in soft and sensitive clays, and this is followed by a thorough review of available literature and unpublished NGI data documenting the effect of storage time on laboratory derived soil parameters.

Storage of clay samples over time may have a profound effect on the derived mechanical properties of the clays. The most significant mechanical effects over time lead to a decrease in 1) soil stiffness, 2) peak shear strength, 3) preconsolidation stress (p'_c), 4) remoulded undrained shear strength, 5) clay sensitivity and in 6) compression index. These changes are attributed to the migration of pore fluids (changes in water content across the sample) and associated changes in stress distribution storage time, drying and moisture loss, to chemical effects and pH changes (due to e.g. oxidation), and also to temperature and humidity changes.

Results presented in this report show that the effect of storage time on the derived mechanical properties of a clay can be fairly important in the early stage of the storage period (i.e. first c. 10 days), especially for samples collected with piston sampler (i.e. 54-72 mm). It is therefore a prudent practice to perform soil testing as soon as possible after sampling.

Sample quality assessment is a vital component of geotechnical design in order to assign confidence levels to laboratory-determined engineering properties. Unfortunately, changes in pore water chemistry are usually not assessed in normal geotechnical testing program. Tests results have shown that relatively small differences in pore water chemistry can lead to changes in e.g. remoulded shear strength of clays. Changes in the pore water chemistry and pH within clay samples should be evaluated if clay samples are to be stored over a longer time period.

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Contents

1 Introduction

The Norwegian Road Authorities (SVV), the Norwegian Water and Energy Directorate and the Norwegian Railway Authorities (JBV) have allocated the Norwegian Geotechnical Institute (NGI) a framework agreement within the governmental research project "Naturfare, Infrastruktur, Flom og Skred" (NIFS) sub-project 6, which focuses on stability issues in quick clay deposits. Within this framework agreement, a work order was issued to study the effect of storage on sample quality.

Both engineering characterization of soils for design and construction, and scientific understanding of natural soil behaviour depend on testing samples from the ground in which disturbance has been minimized. Sample disturbance occurs as a result of many factors associated with sampling, sample transportation, extrusion and sample preparation for laboratory testing. In soft and sensitive clays, soil destructuration can also occur over time in the storage room due to fluid migration and geochemical reactions within the sample. Due to the limited capacity in the geotechnical laboratories, clay samples are seldom tested immediately after sampling and the waiting time may vary from days to several months. The consequence of such delay are seldom fully appreciated and often completely ignored by the engineers, even if it may considerably alter the mechanical properties of the clay samples at hand. There is therefore a need to increase our knowledge and to document the effect of storage time on sample quality.

The present report was prepared after a thorough analysis of literature data and unpublished NGI data, as well as through discussions with project participants during the fall of 2013. A short literature note prepared by Professor Mike Long from the University College Dublin was also available to this project which considerably helped finding relevant literature data. The following persons have contributed to the project through discussions and data collection:

Vikas Thakur – SVV (NIFS contact person)
Yunhee Kim – NGI
Kjell Karlsrud – NGI
Kristoffer Kåsin – NGI
Magnus Rømoen – NGI
Toralv Berre – NGI
Morten Andreas Sjursen – NGI
Mike Long – UCD
Jean-Sebastien L'Heureux – NGI (Project leader)

The following report starts with a short and general review of factors affecting sample quality. Such factors are important to consider as they may bias the effect of storage time. The main objective of this report is to summarise available literature and recent research on the influence of time of sample storage on laboratory derived soil parameters. This is presented in chapter 3. Thereafter, the report gives some recommendations and presents a suggestion for a laboratory testing program to further assess the effect of storage time on sample quality, and this is presented in chapter 5.

2 Causes of sample disturbance in soft and sensitive clay

The fabric and the microstructure have major influence on the mechanical behaviour of soft and sensitive clays. If the bonds that give rise to microstructure are broken, there is disturbance or destructuration. The most significant effects of sample disturbance on measured soft clay engineering parameters have been summarized by e.g. Hight and Leroueil (2003) as follow:

- A decrease in stiffness of the soil inside the limit state curve;
- A decrease in the peak shear strength and in the preconsolidation stress (p'_c), as well as a shrinkage of the entire limit state curve;
- A decrease in the compression index (not always clear).

Undoubtedly, sample disturbance occurs as a result of many factors associated with sampling, sample transportation, sample storage, extrusion and sample preparation for laboratory testing (Figure 1).

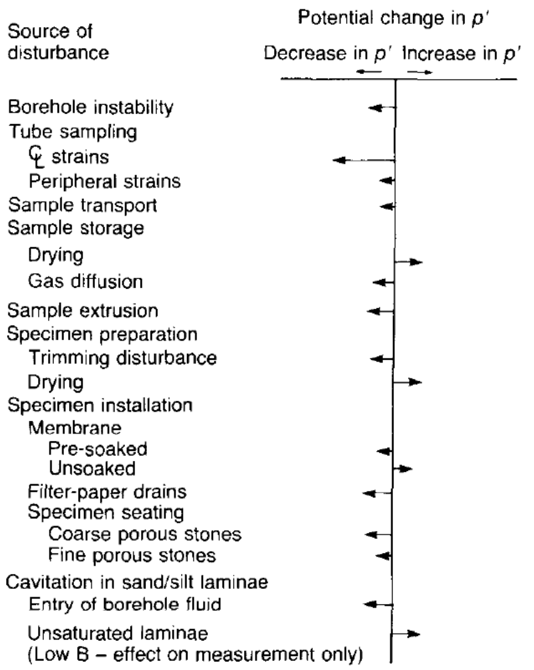


Figure 1: Factors affecting the mean stress in specimen of soft clay (after Hight, 1986).

Following Hvorslev's (1949) fundamental work, which represents the first comprehensive study of the subject of sample disturbance, major contributions were made to this topic in the 1960's through work performed by e.g. Skempton and Sowa (1963), Ladd and Lambe (1963), Noorany and Seed (1965). These studies identified the shear stress release associated with removal of a soil sample from the ground as an unavoidable component of disturbance associated with sampling (Figure 2), quantified the effects of this process on the shear strength measured in the laboratory, and recognized that it could only in part explain the observed behaviour of ''disturbed'' specimens. Over the following decades sampling disturbance continued to be the subject of extensive research. This was directed towards the design of improved samplers (e.g., LaRochelle et al. 1981); the development of reconsolidation procedures for the recovery of the intact behaviour of the soil in the laboratory (e.g., Bjerrum 1973; Ladd and Foott 1974); the establishment of guidelines for appropriate handling (sample storage, specimen preparation, etc.) procedures (e.g., Atkinson et al. 1992); the investigation of the effects of disturbance on various engineering properties through the analysis of laboratory data (e.g., Hight et al. 1992) and/or simulation of the sampling process in the laboratory (e.g., Noorany and Poormand 1973; Clayton et al. 1992; Siddique et al. 1999); and the modeling of the disturbance process through analytical (e.g., Baligh et al. 1987) or numerical (e.g., Budhu and Wu 1992) techniques. Extended work has also been performed to examine the effects of different details of tube sampling geometry, including inside clearance ratio (ICR), outside cutting edge angle (OCA), inside cutting edge angle (ICA) and area ratio (AR) (e.g. Clayton et al. 1998). In general, an increase in the parameters mentioned above leads to increase in peak compressive strain ahead of the cutting edge or an increase in peak extension strain above the cutting edge.

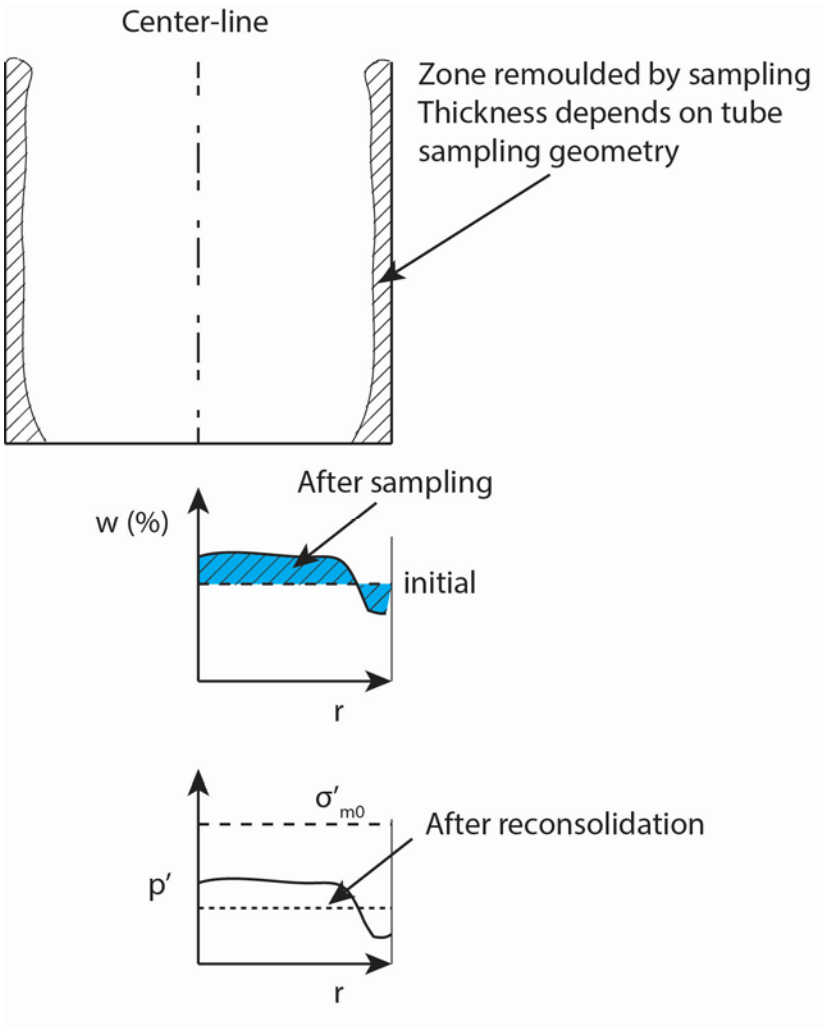


Figure 2: Simplified illustrationof water content and effective stress distribution after tube sampling in normally or lightly overconsolidated clay.

Over the years, investigations carried out on block samples have shown that the properties of sensitive clays are quite different from those measured on the samples obtained from conventional piston samplings techniques, or standard Shelby tube sampling (e.g. Crawford 1963; Conlon 1966; LaRochelle and Lefebvre 1971, Karlsrud and Hernandez-Martinez 2013). Generally, the measured shear strength and the rigidity are higher and the brittleness much better defined than on tube samples. However, sampling of blocks is generally an expensive operation which may become technically problematic or financially prohibitive below some critical depths in soft clays. Therefore, the most common approach of obtaining a sample is by forming a borehole and pushing a tube into the soil.

As described by Baligh et al. (1987), soil disturbance can result in a hypothetical stress path shown in Figure 3 (applied to the centre-line of the sample). Disturbance can occur at each of the stages shown in this figure. Following the history of the sample, basic disturbances occur due to: (i) changes in soil conditions ahead of the advancing borehole during drilling operations; (ii) penetration of the sampling tube and sample retrieval to ground surface; (iii) water content redistribution in the tube (see Figure 2); (iv) extrusion of the sample from the tube; (v) drying and/or changes in water pressures; and (vi) trimming and other activities required to prepare specimens for laboratory testing. Additional disturbances can be significant in special applications. Examples include the expansion of dissolved gases when (very deep offshore) samples are brought to the surface; dynamic effects in hammered samples or during rough handling and transportation; temperature changes in chemically or biologically active deposits, etc.

The main focus of the present study is to evaluate the effect of storage time on sample quality in soft and sensitive clay. However, as seen above, there are many sources of sample disturbance that can be very difficult to separate when looking at the result of a specific test. This must be taken into account when reading the rest of this report. For further documentation of sampling effects, it is referred to Lunne et al. (1997 and 2006).

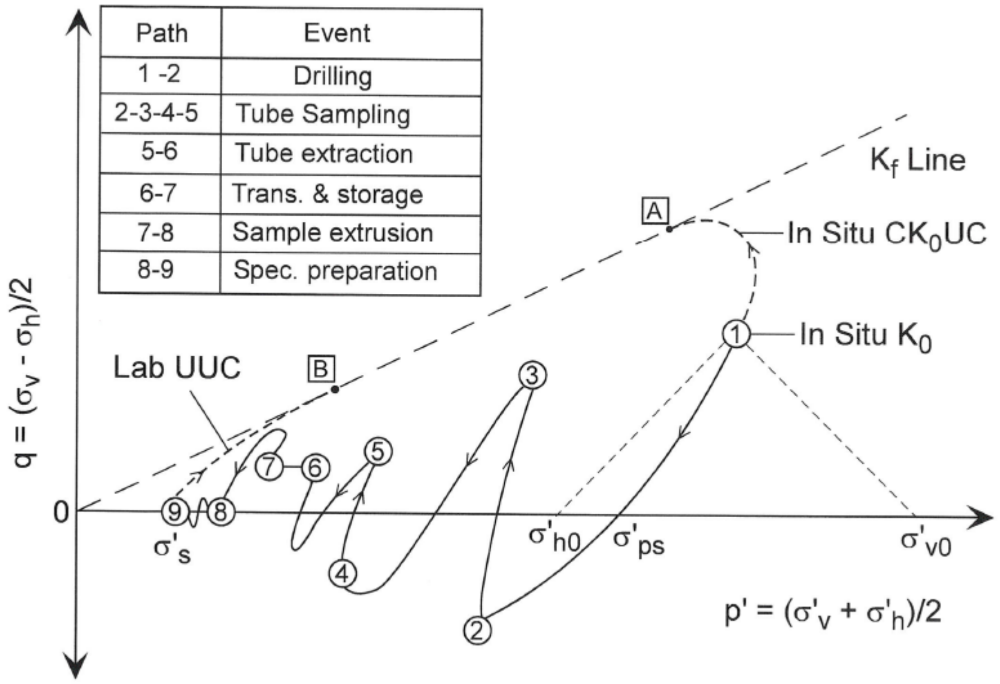


Figure 3: Hypothetical stress path during tube sampling and specimen preparation of centre-line element of low OCR Clay (from Ladd and De Groot, 2003).

3 Effect of storage time

3.1 Impact on index properties

In spite of all due precautions with regards to transport, preparation, trimming and manipulation, the properties of the clay samples may be altered by other phenomena, such as the water migration within the sample and moisture loss on storage. Hvorslev recognized these problems already in the late 1940's. In his work, Hvorslev (1949) showed the importance of sealing techniques for minimizing moisture loss during long-term sample storage (Figure 4). Similar study by Heymann (1998) on London clay is shown in Figure 5. Heymann and Clayton (1999) argues that even a very small loss in water content during storage could lead to very significant changes in effective stress in the sample.

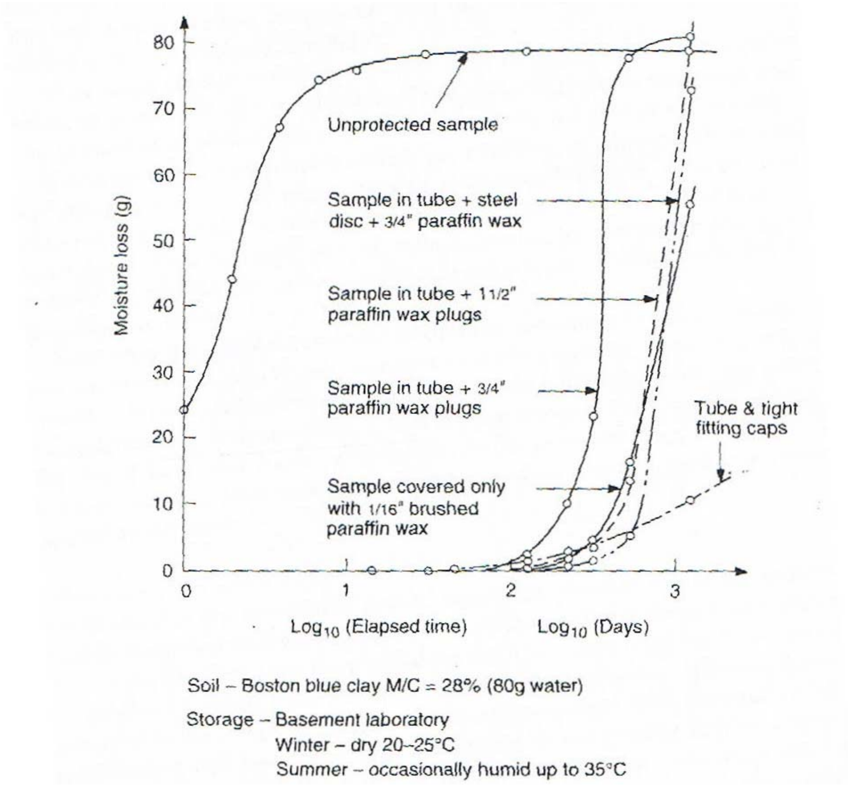


Figure 4: Moisture loss on storage with different sealing methods. Data from Hvorslev (1949). Figure taken from Clayton et al. (1995).

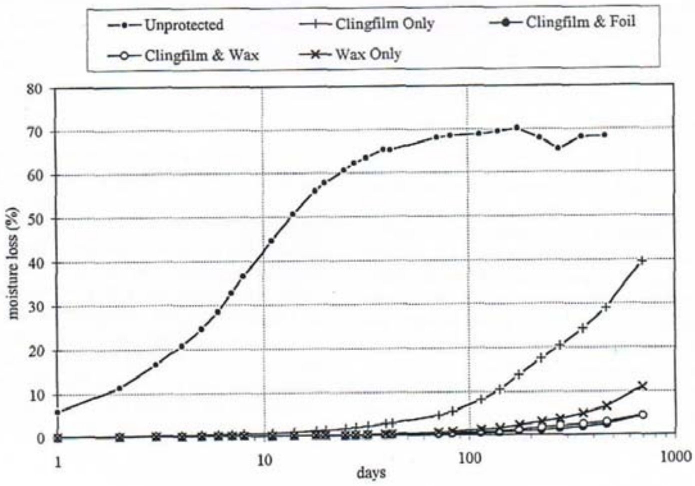


Figure 5: Moisture loss after storage of London clay with different sealing methods from Heymann and Clayton (1999).

Much work has also been done on migration of pore pressures following sampling. The effects are opposite on soft clays and stiff clays. In soft clays the outer layer of soil would have higher pore pressures than the centre immediately after sampling due to the high tube sampling strains that are experienced. This was first noted by Casagrande in 1936. This has been confirmed by a number of researchers (Schjetne 1971; Bjerrum, 1973; Siddique 1990). Schjetne's work is particularly interesting as it involved pore pressure measurement via a hypodermic needle in the sample tube. Bjerrum (1973) showed that the outer 5 mm of extruded Drammen clay samples have water content 3% - 4% lower than in the centre. An examples of some measurements on tube samples of soft clay from Hight (2000) is given on Figure 6. This confirms the general picture suggested by Figure 2.

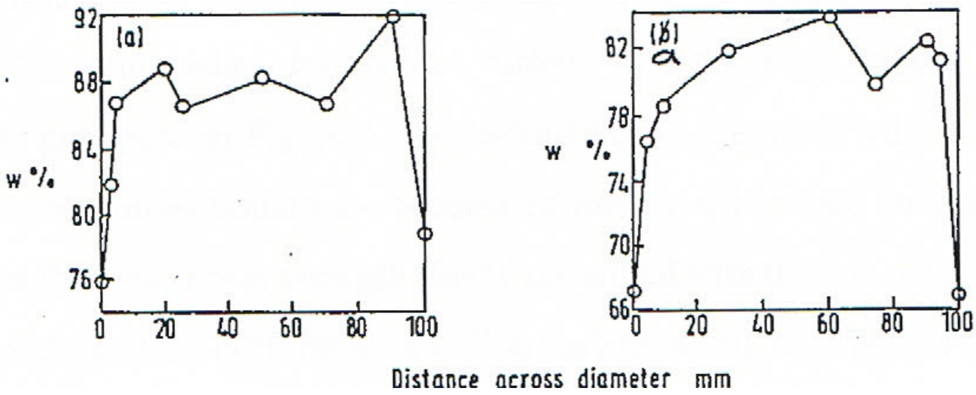


Figure 6: Change in water content across a tube sample of soft clay (Hight, 2000)

The Swedish Geotechnical Institute (SGI) performed a study in 1994 to evaluate the impact of storage time on the properties of Swedish clays (Henriksson and Carlsten, 1994). The clay samples were collected using a 50 mm piston sampler. The samples were tested immediately after sampling and after a storage time varying from 120 to 750 days. As seen from in Table 1, the tested material consisted of either varved clayey silt (samples no. 1, 2, 4) or clay (samples no. 3, 5A-B, 8). Changes in index properties for the Swedish study are reported in Table 1. In general, an increase in the liquid limit (w_L) for the clay samples during the storage period is observed. Such an increase in w_L leads to a decrease in the liquidity index (I_L). Leroueil et al. (1983) have shown that there exists a good correlation between the I_L and the remoulded strength of clays (s_{ur}), which can be expressed as:

1) $$s_{ur}(kPa) = \frac{1}{(I_L - 0.21)^2}$$

Following Eq. (1), a decrease in I_L leads to an increase in remoulded strength. This further explains why a decrease in sensitivity is observed with storage time for the clay samples in Table 1.

One should note that the determination of undrained shear strength based on the Swedish cone method is meant for clay type material. The silt content in samples 1, 2 and 4 (Table 1) leads to natural variations in undrained shear strength and should not be used for conclusions. Moreover, the varved sediments consists of silt and clay lamina which lead to water migration in the samples. This might help explaining the important changes in water content over time in these samples during storage. In comparison, neither the water content nor the density for the pure clay samples in Table 1 changed over time.

Table 1: Effect of storage time on the index properties of a Swedish clay (Henriksson and Carlsten, 1994).

Sample no.	Material type	Storage time (days)	Density	Water content	Liquid limit	Sensitivity	S_u (cone)
1	Varved clayey silt	414	Unchanged	Increase	Increase	Decrease	Increase
2	Varved clayey silt	254	Unchanged	Increase	Increase	Increase	Increase
4	Varved clayey silt	426	Unchanged	Increase / Decrease	Decrease	Decrease	Increase
3	Clay	455	Unchanged	Unchanged	Increase	Decrease	Increase
5A	Clay	120	Unchanged	Unchanged	Unchanged	Decrease	Unchanged
5B	Clay	120	Unchanged	Unchanged	Increase	Decrease	Increase
8	Clay	753	Decrease	Unchanged	Increase	Decrease	Unchanged

LaRochelle et al. (1986) describe a procedure for long-term storage of clay samples, which gives recommendations for sealing compounds, storage temperature, humidity etc. and found it to be an effective means of maintaining various soil index properties with time. Hight et al. (1992) used this procedure for the long-term storage of Laval samples of Bothkennar clay and found no significant decrease in initial sample suction (u_r). Lessard and Mitchell (1985) also found this technique to be effective. However it must be noted that these three studies were performed on high quality samples where redistribution of pore water during storage would be expected to be less significant.

3.2 Impact on mechanical properties

It was quite early recognised that the length of storage time could have a profound effect on the mechanical properties of sensitive marine clays. Bozozuk (1971) analysed the results from consolidation tests on a hand cut block sample stored in a humid room at a temperature of 12°C and relative humidity of 90 to 100 % for about 1.5 years. The samples consisted of sensitive and over-consolidated marine clay from Ottawa, with a w = 52%, I_p = 23, S_t>100 and a clay content of 64%. The results presented in Figure 7 showed that the preconsolidation stress, p'_c, decreased by 4.8% in specimens stored for between 2 months and 17 months.

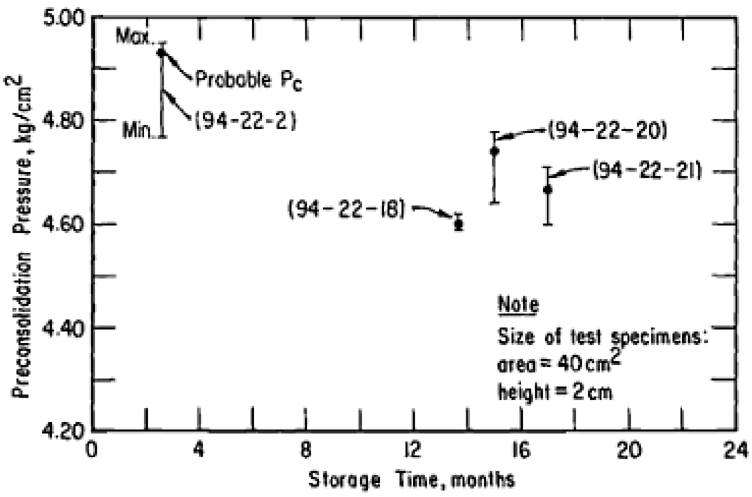


Figure 7: Effect of storage time on the measured preconsolidation pressure from a sensitive and over-consolidated marine clay from Ottawa, Canada (Bozozuk, 1971).

Bjerrum and his co-workers studied the effect of storage time on the geotechnical properties of a quick clay from Ellingsrud in the early 1970's (NGI 1971, Bjerrum 1973). For their study, they brought a triaxial cell in the field and trimmed, mounted and consolidated the quick clay specimens at the site near to the drilling rig. The samples were collected using a 95 mm piston sampler. The results from four CAU triaxial tests are presented in Figure 8. Sample E1-1 and F1-1 were extruded, trimmed and built into the triaxial cell immediately after the sampling, while sample E1-2 and F1-2 were taken from the sampling tube 2 and 3 days later, respectively. All samples were consolidated to their *in situ* stresses. The results show that the peak undrained shear strength was reduced by up to 13.5% when the samples were trimmed and tested 2-3 days after sampling. According to Bjerrum (1973), the internal swelling occurring in the tube could explain the significant reduction in shear strength in the quick clay samples with time. Here, samples E1-2 and F1-2 were allowed to swell due to storage time (i.e. E1-1 and F1-2) (Figure 9), and the reconsolidation to the field stresses did not restore the original structure.

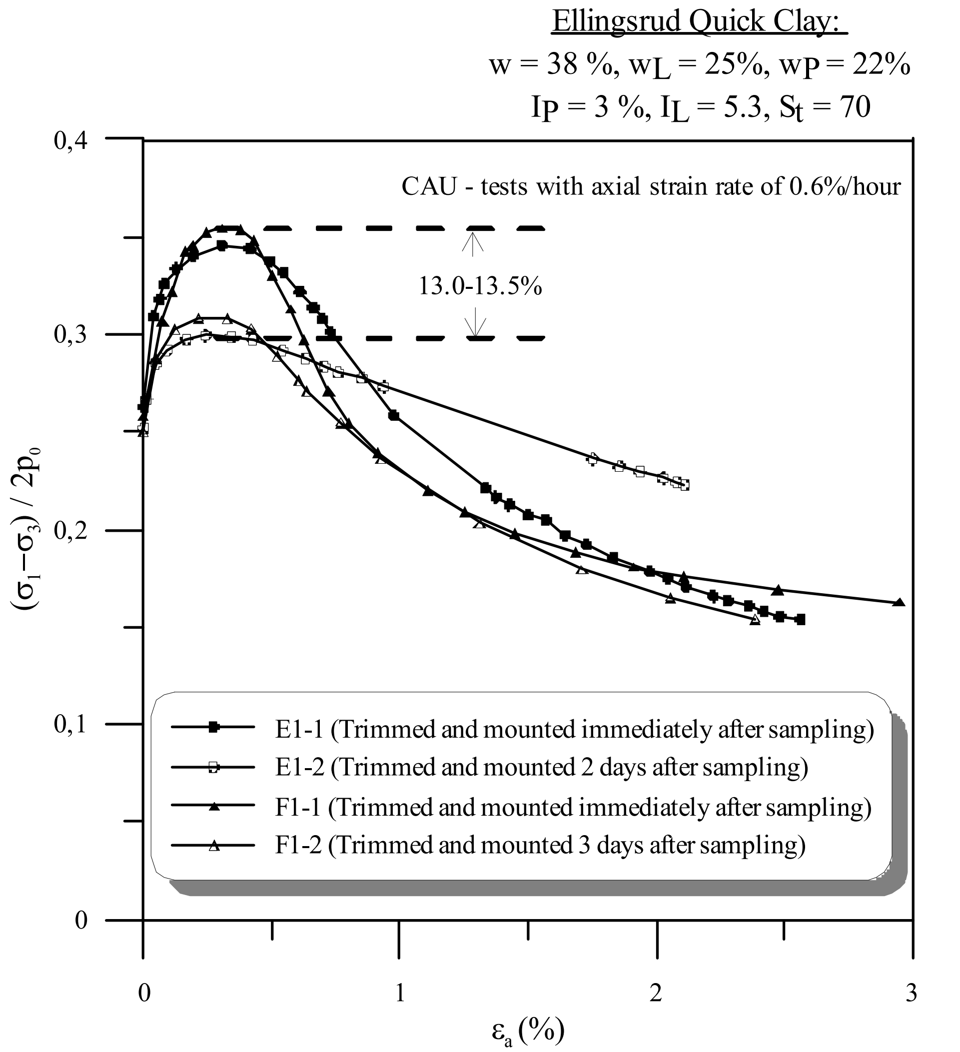


Figure 8: Stress-strain curves obtained in triaxial compression tests on 95 mm piston samples of a quick clay reconsolidated to the field stresses. Samples E1-1 and F1-1 were trimmed and reconsolidated immediately after sampling, while samples E1-2 and F1-2 were tested two and three days after sampling, respectively (data from NGI 1971 and Bjerrum 1973).

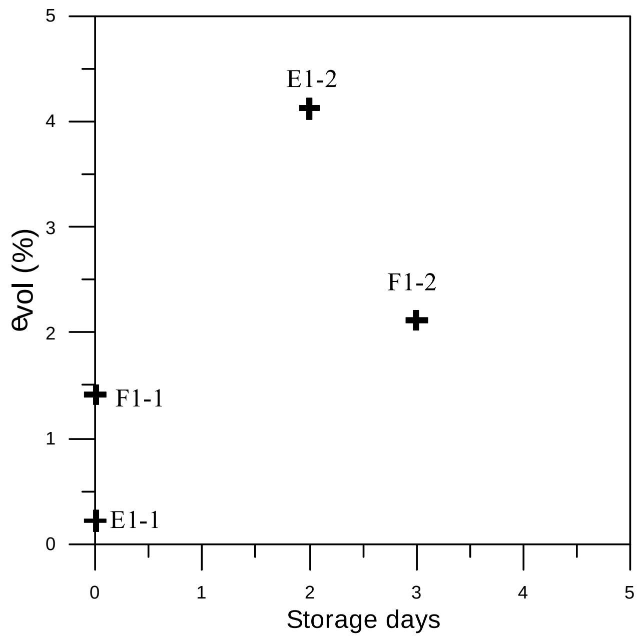


Figure 9: Volumetric changes during the reconsolidation of samples E1-1, E1-2, F1-1, F1-2 from Ellingsrud and presented in Fig 4. Results show an increase in volumetric strain with storage time when reconsolidating to in situ conditions. (data from NGI 1971 and Bjerrum 1973).

Arman and McManis (1976) performed a comprehensive study on the effects of long-term storage on three types of samples (i.e. 305 mm dia. hand cut blocks, 127 mm dia. cores and 71 mm dia. cores) from clay and silty clays from Louisania. All samples were extruded and stored for different times at 22 °C and 100 % relative humidity after the protective coating had been applied. Testing was performed on samples trimmed to 63.5 mm. Up to 10 days, they found no decrease in s_u for all sample types (Figure 10). After 10 days values of s_u for both 127 mm and 71 mm cores deteriorated at an increasing rate (Figure 10). The same did not happen for the block samples. A similar finding was made for the preconsolidation pressure p'_c (Figure 11). The study by Arman and McManis (1976) clearly shows the effect of initial sample quality on the deterioration in undrained shear strength and preconsolidation pressure with storage time.

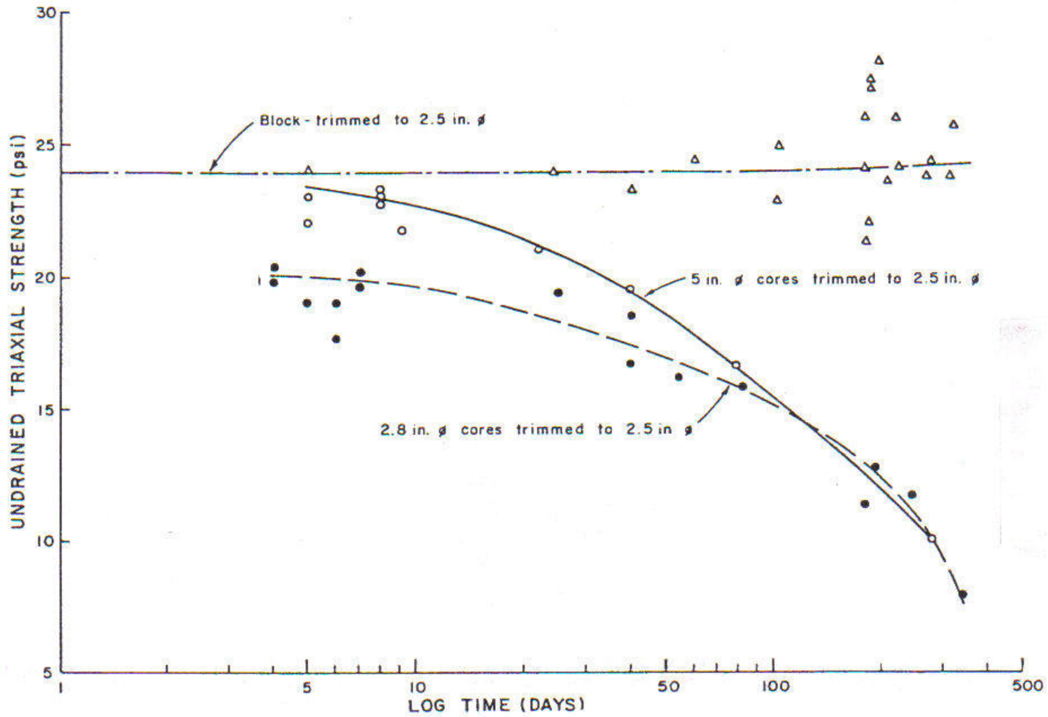


Figure 10: Deterioration in undrained shear strength (s_u) with storage time (Arman and McManis, 1976).

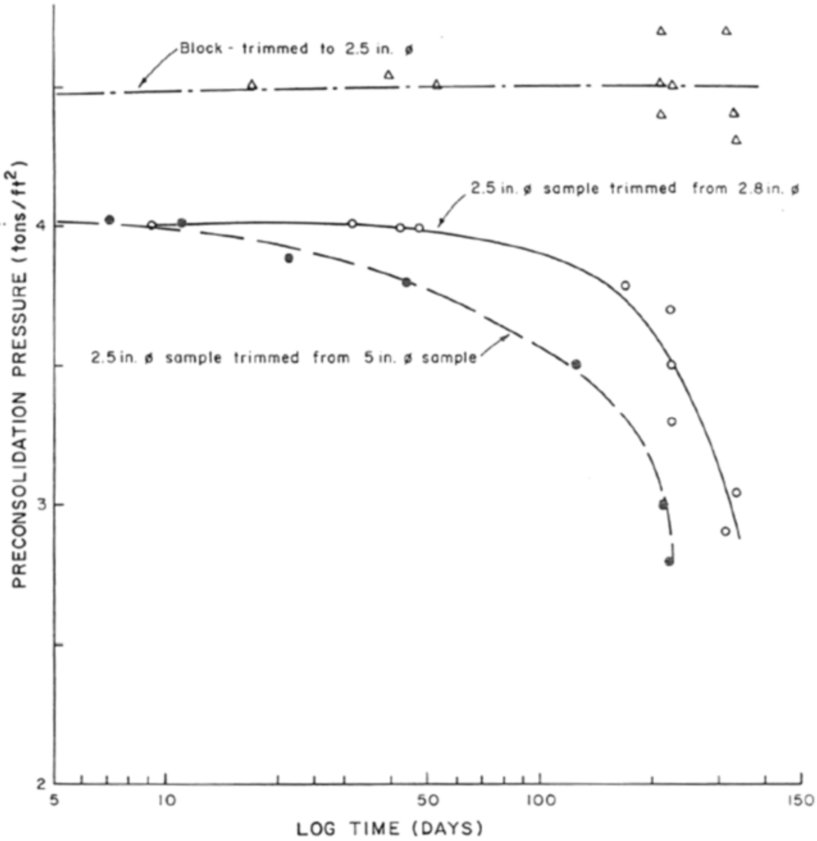


Figure 11: Deterioration in preconsolidation pressure (p'c) with storage time (Arman and McManis, 1976).

La Rochelle et al. (1986) carried out tests on sensitive Champlain clays at various times after sampling. They found that the reconsolidation of the samples back to *in situ* stresses restored much of the strength lost by sampling disturbance. Tests made on block samples, stored for many years in a humid room, showed a decrease in s_u but no effect on p'_c.

A similar study was carried out by Kirkpartick and Khan (1984) on laboratory manufactured normally consolidated, kaolin and illite samples. Lower soil shear strengths, larger strains to failure and appreciable different stress paths to failure were measured in unconsolidated undrained (UU) tests when compared with anisotropically consolidated undrained tests (CAUC). It was found that the discrepancy between UU and CAUC test results increased with increasing storage time. Kirkpatrick et al. (1986), Graham et al. (1987), Graham and Lau (1988) and Graham et al. (1990) extended the above study to overconsolidated kaolin and illite, “underwater” samples of illite, “underwater” samples of grundite and to illite respectively and found more or less the same results, all stressing in particular the importance of anisotropic consolidation prior to shearing. Numerous other studies have demonstrated the inadequacy of the UU test for the measurement of in situ strength.

Over the years, NGI has undertaken numerous sampling campaigns at the Onsøy site in south-eastern Norway. The clay deposit is normally consolidated with some surface weathering and desiccation. In Figure 12, the undrained shear strength obtained from CAUc tests was normalized with respect to the vertical consolidation stress for evaluation of storage time effect on samples collected at various depths. Results from 54 mm, 72 mm and block samples are presented in this figure. The normalized strength obtained from block samples deteriorated 5% from day 25 to day 37 after sampling. For the 72 mm samples, the reduction is larger and up to 10% between day 31 and day 39 after sampling. Results from 54 mm samples show an inverse trend (i.e. strengthening of the clay with time). This is attributed to the initial poor sample quality.

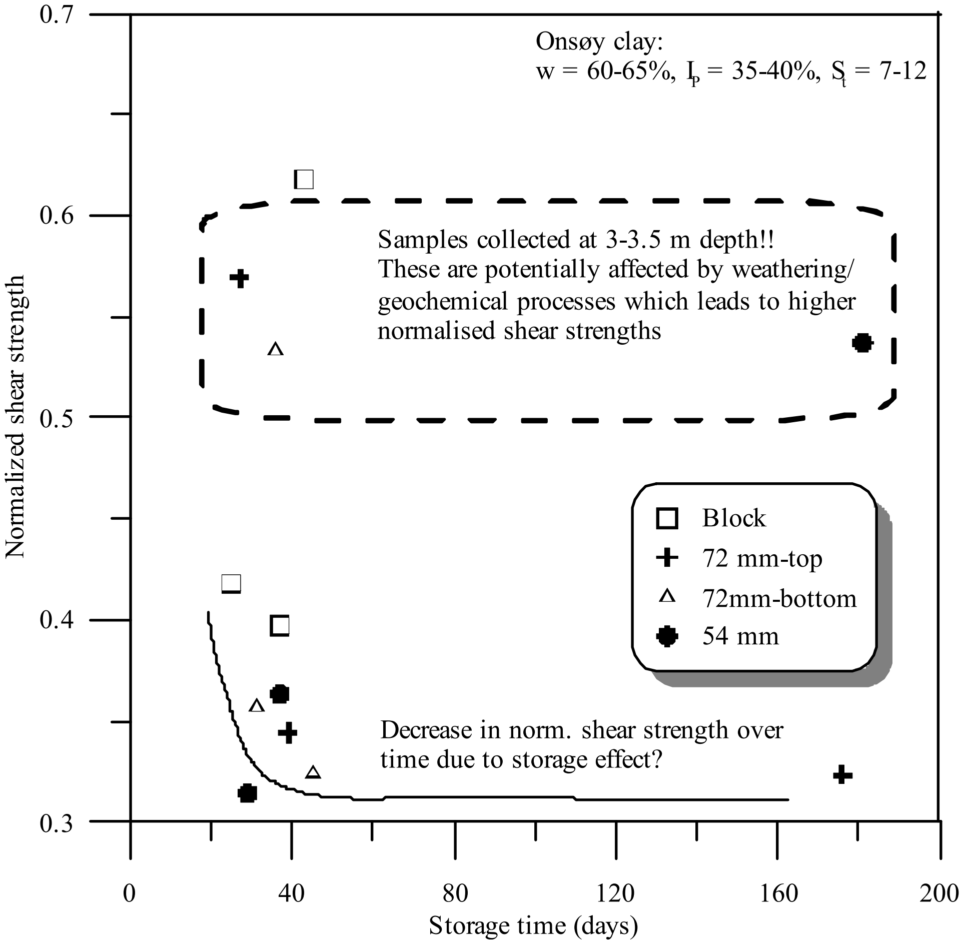


Figure 12: Effect of storage time on the normalized shear strength of Onsøy clay (NGI data).

Rømoen (2005) tested clay samples (54 mm steel piston sampler) from Eberg in Trondheim immediately after sampling and again some 2 to 4 weeks later (Figure 13). The Eberg clay is normally to slightly over-consolidated (OCR from 1.3-2.7) with the following index properties: w = 50-70%, I_P = 10-20%, clay content = 40-60 %, and S_t = 7-10. As seen in Figure 13, the effect of storage time was significant on both the preconsolidation stress p'$_c$ and the modulus number m.

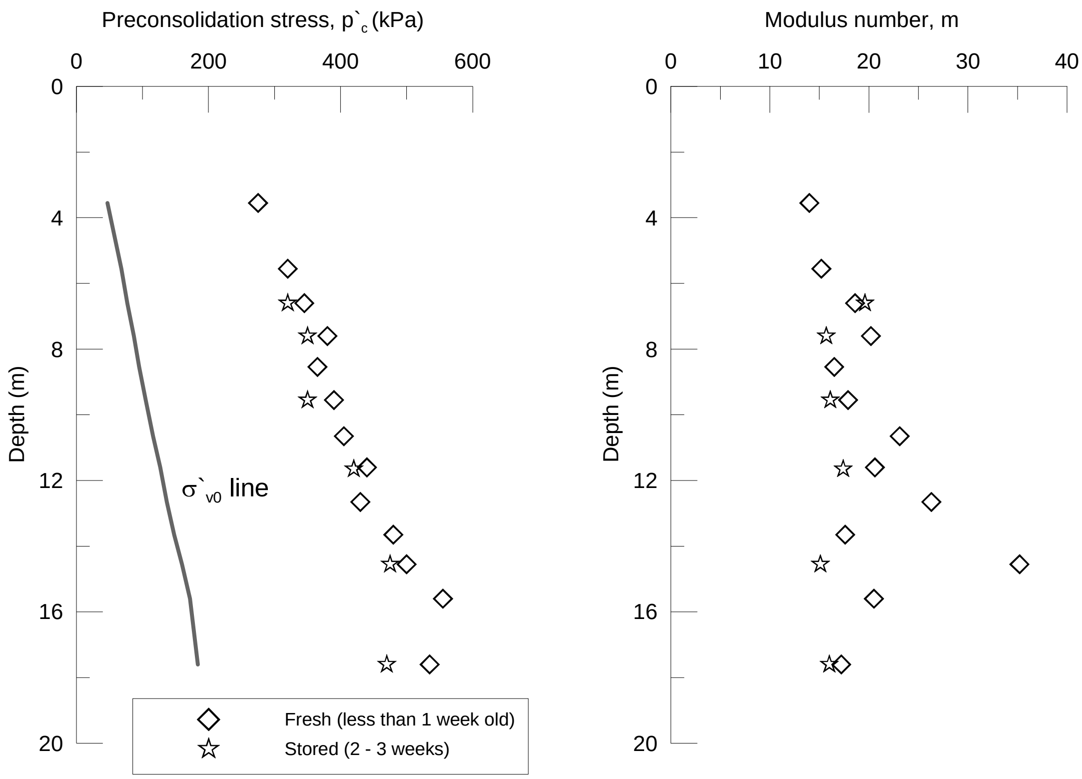


Figure 13: Influence of storage on CRS parameters for Eberg clay (Rømoen, 2005)

In the 1980's, the Norwegian Geotechnical Institute carried out an extensive testing program to characterize the soil conditions in the Troll gas field area, approximately 65 km offshore from the southwest coast of Norway in the Norwegian Sea (NGI 1984, NGI 1988, Lunne et al. 2007). The clays at the Troll gas field site are normally consolidated with a water content nearly equal to its liquid limit. The salt content in the pore fluid is approximately 32 g/L. During the 1987 soil investigation program, several samples were tested offshore immediately after sampling, while some of the samples were sent to the NGI laboratory in Oslo. These samples were tested 1 month after sampling. As seen from Figure 14 and Figure 15, the effect of storage time on the evaluation of p'$_c$ and on the evaluation of the undrained shear strength (CAUc and CCV tests) is hardly noticeable for this clay.

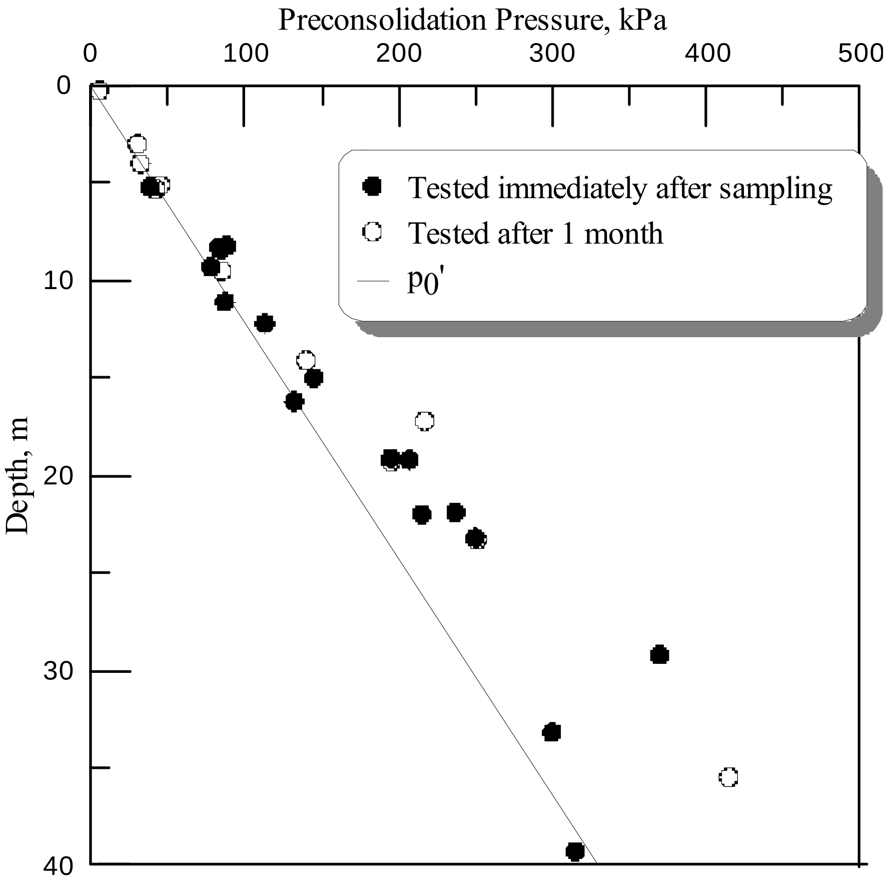


Figure 14: Preconsolidation pressure p'c from CRSc oedometer tests on normally consolidated marine clays from the Troll field area, Norwegian North Sea. The black circles represent test results immediately after sampling (test offshore) and the empty circles are tests results obtained 1 month after the sampling (onshore laboratory) (source: NGI 1988).

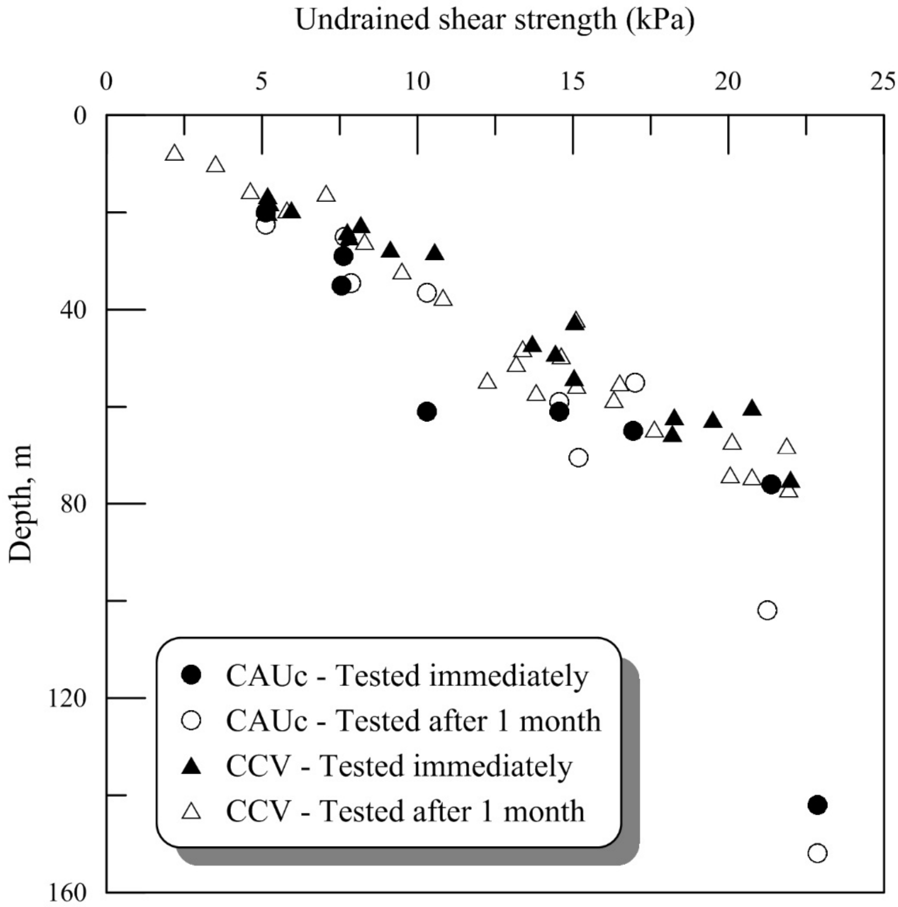


Figure 15: Undrained shear strength results (CAUc and CCV tests) on the normally consolidated clay from the Troll field area, Norwegian North Sea. The black circles represent test results immediately after sampling (test offshore) and the empty circles are tests results obtained 1 month after the sampling (onshore laboratory) (source: NGI 1987).

As presented in chapter 3.1, the SGI performed a study in 1994 to evaluate the impact of storage time on the mechanical properties of Swedish clays (e.g. Henriksson and Carlsten, 1994). Samples from the same depth interval were tested immediately after sampling in March 1985 and during a secondary testing program in March 1987 (i.e. 18 months of storage time). A total of 32 CRS tests were performed to evaluate the effect of storage time on the compressibility of the clays (Figure 16). Each point on this figure represents the percent change in effective preconsolidation stress ($\Delta p'_c$) during the storage period in function of the depth of the samples. Most of the data shows a tendency for p'_c to decrease with storage time. There is also a tendency for samples collected at large depth to be more affected by storage time, but the results are inconclusive. The authors pointed to the natural variations in sediment properties to explain the large discrepancies in the results, but also to variation in laboratory techniques and difficulties in interpretation oedometer test results.

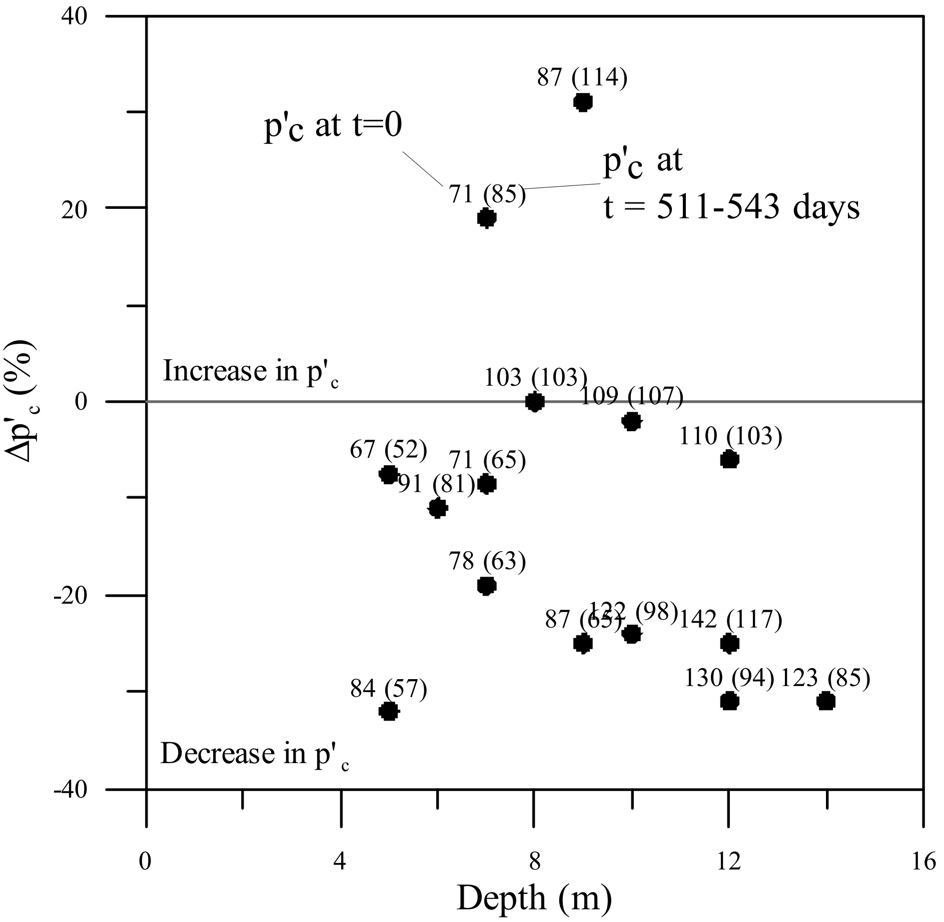


Figure 16: Percent changes in effective preconsolidation stress (p'c) due to storage time in function of sample depth. For all points the storage time varied from 511-543 days and the p'c was estimated from CRS test results. Data is from Henriksson and Carlsten (1994). See text for details.

3.3 Impact on the pore water chemistry

Previous studies have shown that, if the samples are not properly sealed, some aging effects may occur and alter the physiochemical and the mechanical properties of the clay, even though there is no apparent loss of water content with time (e.g. Torrance 1976; Bozozuk 1976; La Rochelle *et* al. 1976; Lessard and Mitchell 1985). There is some evidence that even minute quantities of oxygen are sufficient to initiate the chemical processes causing aging. Changes in pore water chemistry happens over time in a stored clay sample. The reasons for this are related to factors such as oxidation, chemical reactions between the clay sample and wrapping material, and contamination from the drilling fluids (e.g. Torrance 1976). Clays with a high organic content and clays with acids and/or alkali are more prone to chemical reactions and chemical changes during storage time (e.g. Lessard and Mitchell 1985). Also, using aluminium foil to store clay samples is not recommended as the aluminium gets into clay and alters chemical properties.

Bjerrum (1954) found that, for the Norwegian marine clays, a relationship exists between the sensitivity and the salinity; namely, the sensitivity increases as the salinity decreases. In these materials, it also has been found that relatively small differences in the concentration of certain ions, at low but essentially constant pore water salinity, can explain differences in the behavior between otherwise similar soils (e.g. Moum et al. 1971, 1972).

Bjerrum and Rosenqvist (1956) observed an increase in the Atterberg limits of a marine clay from Åsrum, Norway, that was a result of storage time. The plasticity index of a sample rose from 21 % to 27 % over a 2-year period in the room at 18-20 °C temperature and was accompanied by an increase in potassium ion concentration in the pore water, which was attributed to the weathering of the clay minerals. The increase in potassium ions was equivalent to 0·36 g/litre KCl of the pore-water, which explains the observed increase in Atterberg limits.

Söderblom (1969) showed that samples of Swedish clays taken from the Gota River valley lost their original quickness after being stored for 2-4 years. Similar sensitivity reduction was observed *in situ,* as a clay sampled in 1967 at a depth of 1 m below an exposed slide bottom of the 1960 slide at Veston had lost its quickness in the meantime (Söderblom 1969). Quantitative analyses by standard paper chromatography showed that before storage, the quick clay contained mainly Na^+ and SO_4^{2-} in its pore water. After aging, there was a significant amount of Mg^{2+} and Ca^{2+} and a marked increase of SO_4^{2-} (Söderblom 1974). According to Söderblom (1969), "the change from anaerobic to aerobic state and the accompanying changes in the microbial activity may be the most important factor in the storage process."

Torrance (1976) reported the effects, on the pore water chemistry, of 3 months storage under a wide variety of standard and modified storage procedures. The material was a soft Champlain clay with a low salinity and a sensitivity of 10-20. Irrespective of the storage method, the salinity and the percentage of divalent cations (i.e. sodium, calcium, magnesium, and potassium) in the pore water had increased over time. The most conspicuous changes were observed for the clay stored in plastic containers without the protective seal of the wax. According to Torrance, the increase in the concentration of calcium and magnesium in the pore water during aging is probably related to attack on carbonates present in the soil. The main conclusion from Torrance's experiment is that, regardless of the method of storage, chemical changes will increase the concentration of most cations in the pore water during storage time. Torrance (1976) also recommends a storage temperature lower than the mean annual ground temperature to inhibit chemical and biological activity in the samples during storage time.

To better understand the geotechnical and geochemical changes occurring in a quick clay during storage, Lessard and Mitchell (1986) carried out an extensive testing program on the Champlain Sea clay from La Baie, Quebec. After measuring the initial characteristics of the material, samples were stored and tested periodically over a period of 1 year to evaluate the effect of various storage conditions. Quick clay samples stored in the laboratory showed signs of aging regardless of the storage procedure. The remoulded strength and the liquid limit increased with time (Figure 17), whereas the sensitivity, the liquidity index, and the pH decreased. The water content, plastic limit and undisturbed strength remained practically unchanged. The pore water concentrations of calcium, magnesium, and sulfate increased by several fold (Figure 18). Lessard and Mitchell (1986) attributed the aging phenomenon, for the most part, to the oxidation of iron sulfide, which results in the formation of iron hydroxide and sulfuric acid. The production of acid causes the dissolution of calcium carbonate, which increases the concentration of divalent cation in the clay, thereby reducing interparticle repulsion and increasing the remolded strength. The oxidation of organic matter, resulting in the formation of carbonic acid, also contributes to the aging by its effect on the solubility of calcium carbonate.

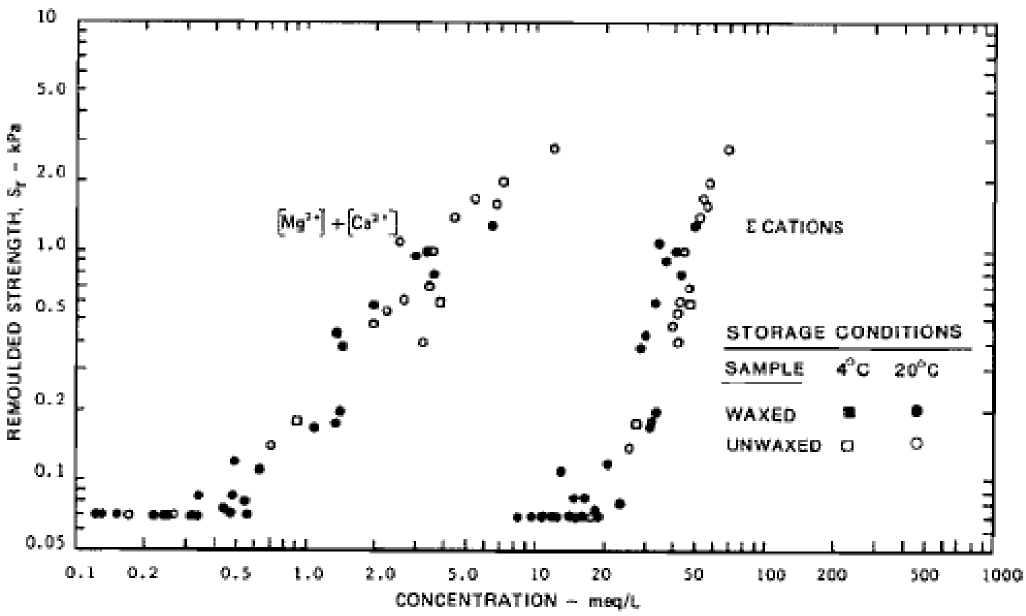


Figure 17: Relationship between remoulded strength and the concentrations of divalent cations and divalent plus monovalent cations in samples sotred under various conditions (from Lessard and Mitchell 1985).

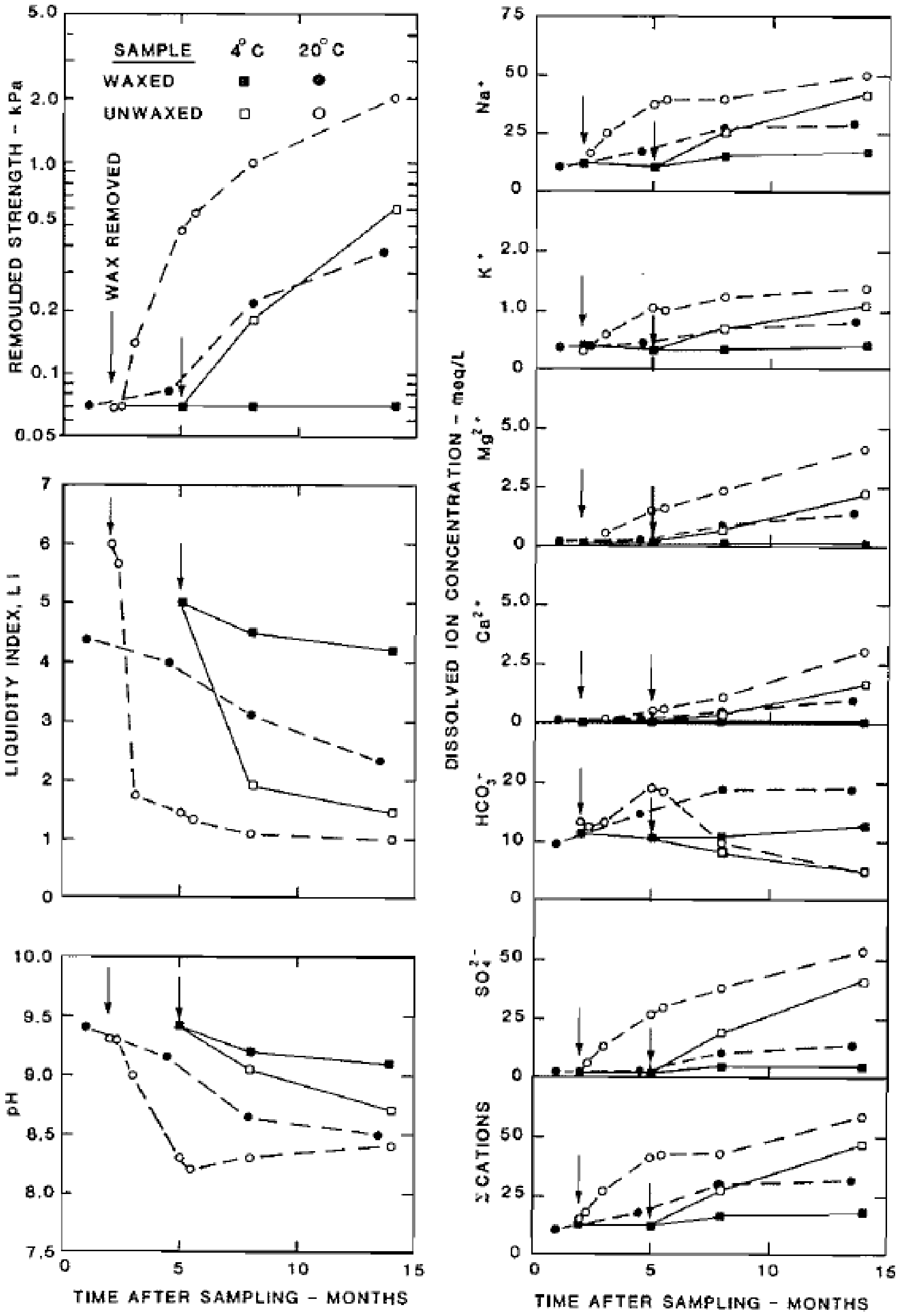


Figure 18: Effect of time on the properties of waxed and unwaxed samples stored in air, at 4°C, and 20°C. The arrows indicate when the wax was removed from the samples (from Lessard and Mitchell 1985).

3.4 Summary of causes and consequences

The main objective of this report was to summarize the available literature and recent research on the influence of time of sample storage on laboratory derived soil parameters. The literature review presented in this chapter shows that the effect of storage time may impact in different ways on the derived mechanical properties of clay samples. A summary of the conclusions from the different studies is presented in Table 2 and 3. In general, the effects of storage time can be attributed to the following processes:

- Migration of pore fluids (changes in water content across the sample) and associated changes in stress distribution
- Drying and moisture loss
- Chemical effects
- Temperature and humidity changes

However, the impact of these processes seems enhanced by several other factors such as e.g., the quality of samples (sampler type, etc.), "extrusion" effects, sealing techniques and the type of clay (plasticity, layering, etc.). For example, the effect of storage time on high quality block samples seems less significant than on a 54 or 72 mm sample since redistribution of pore water during storage is expected to be less important in the block sample. A comparison of the results from clay sites at Onsøy and at Ellingsrud also shows that plastic non-sensitive clays will be less prone to disturbance from storage time than lean sensitive clays.

Results presented in this report show that the effect of storage time on the derived mechanical properties of a clay can be fairly important in the early stage of the storage period (i.e. first c. 10 days), especially for samples collected with piston sampler (i.e. 54-72 mm). It is therefore a prudent practice to perform soil testing as soon as possible after sampling.

Table 2: Summary of conclusions from the different studies presented in the literature review in chapter 3.

Clay site	Sampler	Effect of storage time – Main conclusions	Reference
Eberg clay (Trondheim)	54 mm	• Significant effect on both p'_c and m	Rømoen (2005)
Onsøy clay	54, 72 mm & block	• Block: 5 % reduction in s_u/p'_c from day 25 to 37 day after sampling • 74 mm: 10 % reduction in s_u/p'_c from day 31 to 39 after sampling • 74 mm: No variation in s_u/p'_c after 39 days	NGI data
Troll East clay	70 mm?	• There are no significant difference in soil parameters between tests performed immediately after sampling and after one month	NGI data (1984)
Ellingsrud clay	95 mm	• 15 % reduction in s_u/p'_o after 3 days	Bjerrum (1973)
Louisiana clays	305, 127, 71 mm	• Up to 10 days → no effect on p'_c and s_u • After 10 days → Results show deterioration of s_u and p'_c at an increasing rate. N.B: not for block samples!	Arman & Mcmanis (1976)
Champlain sea clay (Québec)	73 mm (NGI piston sampler) + Laval block samples	• 73 mm: Soft clay → 15 % loss in s_u a few days after sampling (UU tests) • Block samples → reduction of peak strength (10-20%) after long storage period • No effect on p'_c on block samples	La Rochelle et al. (1976)
Champlain Sea clay (Ottawa)	54, 124 mm	• p'_c decreased by 4.8% in specimens stored for between 2 months and 17 months	Bozozuk (1971)
Bothkennar clay	38, 100 mm, Laval block samples	• A reduction in p_i' of approximately 20 % which occurs in the shorter term not in the long term. • There is greater variability of p_i' in 38 mm diameter samples than in 100 mm diameter samples. p_i' : the initial (residual) effective stress measured in all triaxial specimens by applying a cell pressure p_i and monitoring the pore pressure until it came to equilibrium u_i.	Hight el al. (1992)
Champlain sea clay (LaBaie, Quebec)	76 mm of Shelby	• With time, the remoulded strength and liquid limit increased and the sensitivity, liquidity index and pH decreased. • The water content, plastic limit, and undisturbed strength remained practically unchanged.	Lessard & Mitchell (1985)

Table 3: Summary of clay properties for the different sites referred to in the literature review of chapter 3.

Clay site		Sensitivity [-]	Atterberg limit		OCR [-]	p_c' [kPa]	s_u [kPa]	Reference
			Plasticity Index [%]	Liquidity Index [%]				
Eberg clay (Trondheim)		4-12	6.6-10.4	0.2-1.4	2.9-4.5	300-500	50-80	Rømoen (2005)
Onsøy clay		-	36-41	1.1	1.3-2	40-70	16-25	NGI data
Troll East clay	0-25 m	5	32-47	-	1.3-2.2	~100	5-60	NGI data (1984)
	25-52	2	Medium	-	1.3-1.8	~300	50-300	
	>52	-	-	-	2-6	-	400-1000	
Ellingsrud clay		6-140	3-5	2.2-4.8	-	-	18-19	Bjerrum (1973)
Louisiana clays: Stiff, soft, organic and silty clay		-	-	-	-	-	-	Arman & Mcmanis (1976)
Bothkennar (homogenous clay)		-	25-55	~0.7-1.0	Normally to lightly over-consolidated		< 40 kPa	Nash et al. (1992)
Champlain clay	Saint-Alban	14-22	15-28	2-2.4	18-45*		10-21	La Rochelle et al. (1976)
	Saint-Louis	50	23	1.8	102*	164	43	
	Saint-Jea-Vianney	>500	11	2.2	640*	900	240	
	Ottawa	17	22-23	35-50	-	44-62	15	Bozozuk (1971)
	LaBaie	>500	Low	>3			50-70	Lessard & Mitchell (1985)

$^*P_c$-P_o [kPa]

4 Effect of storage time versus sample quality assessment

As mentioned above, the most significant effects of disturbance on the mechanical parameters of soft clays include a decrease in the estimated preconsolidation stress p'_c and the virgin compression index observed in one-dimensional consolidation tests; and poor estimates of shear strength, either high or low depending on the method of consolidation and stress history of the soil. If sample disturbance is severe, none of these effects can be adequately or accurately corrected, leading to potentially significant engineering design errors. Assessing sample quality is therefore a vital component of geotechnical design in order to assign confidence levels to laboratory-determined engineering properties.

The approach in use to assess sample quality in Norway is based on the work by Andresen and Kolstad (1979) and Lunne et al. (1997). The method uses the change in volume a sample undergoes during re-consolidation to *in situ* effective stresses as an indicator of sample disturbance. Lunne et al. (1997) proposed a modified scale for sample quality equal to the change in void ratio normalised by the initial void ratio (Table 4). In this method, the sample quality is associated to changes in void ratio during the consolidation phase ($\Delta e/e_0$); where Δe denotes the change in void ratio from the start of the consolidation process until in *situ* stresses are reached (i.e. p_0'), while e_0 is the initial void ratio at the start of the consolidation process.

Table 4: Sample quality assessment based on the $\Delta e/e_0$ ratio (Lunne et al. 1997)

OCR	$\Delta e/e_0$			
	Very good to excellent	Good to fair	Poor	Very poor
1-2	<0.04	0.04-0.07	0.07-0.14	>0.14
2-4	<0.03	0.03-0.05	0.05-0.10	>0.10
4-6	<0.02	0.02-0.035	0.035-0.07	>0.07
Quality	1	2	3	4

Volumetric strains are equal to axial strains in the oedometer (i.e. $\varepsilon_{vol} = \varepsilon_a$) and $\Delta e/e_0$ can be found by the following equations:

1) $$\Delta e = \varepsilon_{vol}(1 + e_0) = \varepsilon_a(1 + e_0)$$

2) $$e_0 = G_s \cdot w_i$$

where G_s is the particle density, usually in the range 2.65-2.75 and w_i is the water content at the start of the test.

An assessment of the level of destructuration can also be made through measurements of shear wave velocity *in situ* and in the laboratory on recovered samples. Shear wave velocity, V_s, or G_{max} in a given soil depends on the stress state, void ratio and cementing or aging effects. Providing allowances are made for changes in void ratio and differences in stress state, or comparisons are performed at the same stress state, reduction in V_s will indicate damage to the structure of the soil. An example illustrating the different levels of destructuration for different samplers on the soft Boston Blue Clay is presented in Figure 19.

Table 5: Sample quality assessment based on measurements of shear wave velocity in situ and in the laboratory (after Landon et al. 2007). These recommendation were formulated for results obtained on the soft Boston Blue Clay.

Quality class			
1-2		**3**	**4**
Very good to excellent	Good to fair	Poor	Very poor
$V_{vh}/V_{SCPTU} \geq 0.60$		$0.35 \leq V_{vh}/V_{SCPTU} < 0.60$	$V_{vh}/V_{SCPTU} < 0.35$

As shown in chapter 3, when the samples are not properly sealed during storage some aging effects may occur and alter the physiochemical and the mechanical properties of the clay, even though there is no apparent loss of water content with time (e.g. Torrance 1976; Bozozuk 1976; LaRochelle et al. 1976; Lessard and Mitchell 1985). These studies have confirmed the importance and also the difficulties of preventing the detrimental effects of aging of clay during storage. It is important to notice that such physiochemical effects are not considered in the Norwegian sample quality assessment method at the moment. For important geotechnical projects, it is recommended to measure the pH of the clay at the time of sampling or when they are received in the laboratory, and to check it again at time of testing. In effect, the pH is very sensitive to oxidation in the early stages of aging. Furthermore, its measurement is simple and reproducible if the same method is used for all tests. Changes in the pore water chemistry of clay samples could also be evaluated to assess sample quality if clay samples planned stored over a long time period.

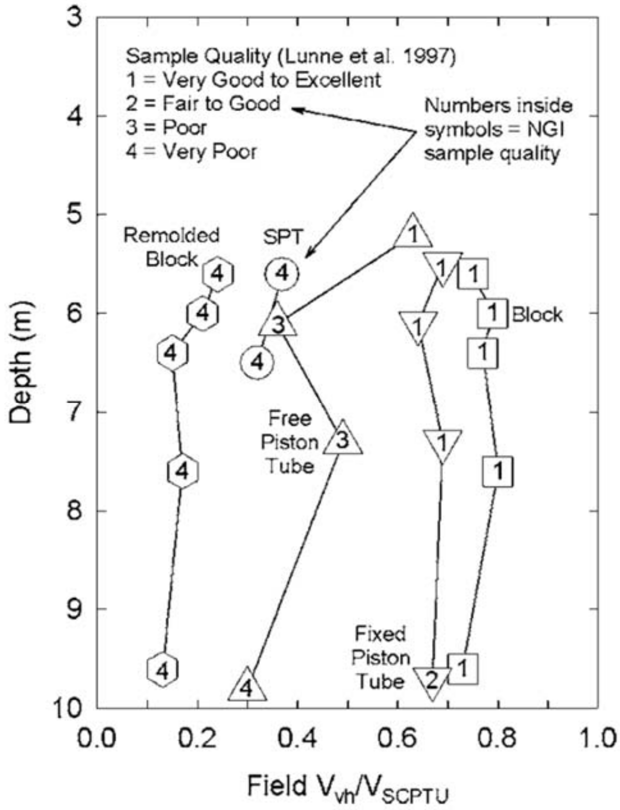


Figure 19: Shear wave velocity ratio (field vs laboratory) with corresponding Lunne et al. (1997) sample quality designations (from Landon et al. 2007)

The impact of storage time on sample quality is clearly affected by the fabric of the soil and its layering. In a layered or laminated clays for example, there will be a mismatch between the suction that can be sustained in the sample following sampling (i.e. removal of total stresses). When the imposed suction exceeds the sustainable suction in the silt/sand layers, it desaturates, giving up its water to the surrounding clay which then swells. The gross fabric of the soil can be evaluated through X-ray imagery and CT-scan photography, in the stages following sampling and after the extrusion process. Such techniques are useful to carefully select samples to be tested in the laboratory, for determining the extent of disturbances from sampling and extrusion processes, and to map the presence of layering and/or anomalies in the samples (Figure 20). Results from X-ray imagery and CT-scan photography should be used to select which samples should be prioritize in a laboratory program, if necessary. Such techniques should be made part of soil testing program in critical foundation or slope stability projects.

Figure 20: Example of x-ray imagery prior to extrusion for gross sample quality evaluation in a layered clay from Finneidfjord. The imagery shows enhanced deformation of layers along the cylinder walls and a failure plane in the loose sandy layers in the mid-section of the sample.

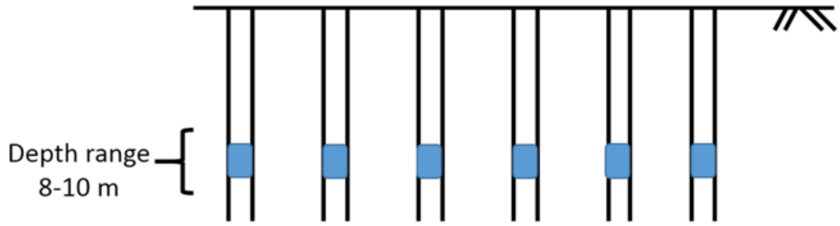
5 Proposed laboratory program

The results presented above shows that there is a need to quantify the impact of storage time on the mechanical properties of clays and to evaluate the amount of time a sample of clay can be stored before the derived mechanical properties are not representative of the original sample. However, such conclusions and recommendations cannot be drawn from the present literature study. The reason for this is that the results in chapter 3 are obtained from studies using e.g. different sampling tools and procedures, sealing techniques, laboratory procedures (i.e. oedometer and triaxial tests), extrusion mode, depth of clay samples and type of clay. One needs to have a certain consistency in the parameters and techniques in order to correctly evaluate the effect of storage time.

To provide more precise guidelines about the effect of sample quality following storage time, a laboratory program devoted to this issue is necessary. Depending on the available funding, the program should focus on at least 2 or 3 sites to evaluate how the clay properties (sensitivity, plasticity, OCR, etc.) may be influenced by the effect of storage time. The selection of the research sites should be steered by available data and knowledge of soil conditions (i.e. Onsøy or Ellingsrud sites) and/or where geotechnical investigation program are already planned (e.g. for road project). This would minimize the cost for such a research project. We recommend collecting at least 6 tubes samples (72 mm) per site, from a depth interval of 8-10 m below terrain. Such depths are representative for most geotechnical problems (foundation and slope stability) and beyond the depth which is affected by weathering processes. The main reasons for recommending 72 mm samples lies in that 1) it offers a balance between good data quality and project economy and 2) it is one of the most commonly use sampling tool in the industry at the moment. The results will therefore have a direct practical meaning. Block samples could be collected to insure control of the data and soil behaviour at selected time intervals at one or more of the study sites. CPTU data would also be an asset.

In the laboratory, the program should involve a panoply of tests including index tests, oedometer (CRS), triaxial (CAUC) tests and pore water analysis (geochemistry and pH). A general overview of the testing program is presented in Figure 21. Testing should be performed often in the early stage of the program to correctly follow changes in mechanical properties. To help assess the overall sample quality it is recommended to make a CT scan of each samples before testing. Sample quality assessment could also be performed by collecting SCPTU data in the field and measurements of S-wave velocity in the lab using bender elements in the triaxial cells. This could help providing a quantitative estimate of samples quality deterioration with time as shown in Figure 19.

Problems associated with sample storage are also often related to the fact that the samples settle in the cylinder tubes with time. It could therefore be interesting to study the effect of sample storage on samples extruded from the cylinder immediately after sampling.



Sample type	Storage time (days)	Type of tests
72 mm	0 – Test in the field	Index tests, Oedometer, Triaxial, Pore water geochemistry and pH evaluations, Vs using bender elements...
	1	
	3	
	10	
	30	
	180	

Figure 21: Potential laboratory program to evaluate the effect of storage time on samples quality. Such program should be performed on at least two sites to evaluate how the clay properties (sensitivity, plasticity, etc.) may influence the effect of storage time on sample quality.

6 Conclusions

The literature review presented in this report shows that storage of clay samples over time may have a profound effect on the derived mechanical properties of the clays. The most significant mechanical may be:

- A decrease in stiffness of the soil inside the limit state curve;
- A decrease in the peak shear strength, preconsolidation stress (p'_c), remoulded undrained shear strength and clay sensitivity.
- A decrease in the compression index.

The main reasons for the changes in mechanical properties observed during the storage time are attributed to:

- Migration of pore fluids (changes in water content across the sample) and associated changes in stress distribution
- Drying and moisture loss
- Chemical effects and pH changes (due to e.g. oxidation)
- Temperature and humidity changes

Results presented in this report show that the effect of storage time on the derived mechanical properties of a clay can be fairly important in the early stage of the storage period (i.e. first c. 10 days), especially for samples collected with piston sampler (i.e. 54-72 mm). Tests results have shown that relatively small differences in pore water chemistry occur rapidly and that this can lead to changes in e.g. remoulded shear strength of clays. It is therefore a prudent practice to perform soil testing as soon as possible after sampling.

Assessing sample quality is a vital component of geotechnical design in order to assign confidence levels to laboratory-determined engineering properties. However, physiochemical effects encountered during storage time are not being considered in the Norwegian sample quality assessment method at the moment. For important geotechnical projects, it is recommended to measure the pH of the clay at the time of sampling or when they are received in the laboratory, and to check it again at time of testing. This would ensure a quality check of the data.

Due to the limited capacity in the geotechnical laboratories, clay samples are seldom tested immediately after sampling and the waiting time may vary from days to several months. As shown here, the consequence of such delay may considerably alter the mechanical properties of the clay samples at hand. There is therefore a need to i) quantify the impact of storage time on the mechanical properties of clays and ii) to evaluate the amount of time a sample of clay can be stored before the derived mechanical properties are not representative of the original sample. To provide such guidelines, a laboratory testing program was proposed in chapter 5. The aim of such a program would be to provide relationships in order to evaluate sample quality deterioration with time, for clays of different consistencies (i.e. different plasticity and sensitivity). To ensure valuable relationships a large number of sample must be collected using the same sampling tools and procedures, sealing techniques, extrusion mode and sample preparation method. Such results and guidelines about the effect of storage time are of uppermost importance to ensure safe design and stability in areas containing sensitive and quick clay deposits.

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