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## Reference

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## ABSTRACT

The effects of storage duration on the sample quality of 54-mm piston samples were investigated by an extensive laboratory study. A soft clay deposit in Central Norway was used as a research site—the Tiller site. The soft clay deposit consists of two types of leached marine clay, a low-sensitivity and high-sensitivity soft clay. In total, 21 boreholes were drilled, and four samples were retrieved from each borehole between 5 m and 11 m in depth, two samples from each layer. Immediately after the sampling, the thin-walled stainless steel sampling tubes were sealed airtight and stored at the temperature of 4°C, slightly lower than the ground temperature. The storage duration varied between 0 days to 603 days, and the laboratory testing was conducted periodically, using the same equipment and test procedures. Results indicate a reduction of undrained shear strength, preconsolidation pressure, and constrained modulus with increasing storage duration. The reduction in the material properties and sample quality is rapid for the high-sensitivity soft clay, but marginal for the low-sensitivity soft clay samples. The effects of storage duration seem to be caused by physical processes taking place within the sample, as no significant changes were observed in the measurements of the water content, Atterberg limits, remolded shear strength, and pore water chemistry during the storage of the samples. In light of the laboratory results and the existing literature, an attempt has been made to explain the cause of the observed changes of the material properties and sample quality during storage of soft clay samples.

## Keywords

sample disturbance, soft clay, piston sample, storage, sensitive clay, quick clay

# Introduction

The applicability of engineering parameters for geotechnical design is linked to the quality of soil sampling and testing. Over the years, a significant effort has been made to improve and refine sampling techniques. The literature, e.g., Hvorslev (1949); Berre, Schjetne, and Sollie (1969); Bjerrum (1973); Leroueil et al. (1979); Lefebvre and Poulin (1979); La Rochelle et al. (1981); Lacasse, Berre, and Lefebvre (1985); Baligh, Azzouz, and Chin (1987); Hight et al. (1992); Lunne, Berre, and Strandvik (1997); Clayton and Siddique (1999); Hight (2001); Long (2003); Ladd and DeGroot (2003); Nagaraj et al. (2003); Hight and Leroueil (2003); Leroueil and Hight (2002); DeGroot, Poirier, and Landon (2005); Long (2006); DeGroot and Landon (2007); Donohue and Long (2009, 2010); Karlsrud and Hernandez-Martinez (2013); Gylland et al. (2013) and Amundsen, Thakur, and Emdal (2015), confirms that soft clays, such as Norwegian soft clays, are prone to sample disturbance, especially when sampled using tube and piston samplers. Several different stages during the acquisition of a soft clay sample, e.g., drilling, sampling, transport, storage, extrusion, and handling of the sample prior to testing, may have a negative effect on sample quality (e.g., Kallstenius 1971; Bozozuk 1971; Arman and McManis 1976; La Rochelle et al. 1976; La Rochelle, Leroueil, and Tavenas 1986; Tanaka 2000; Long 2002; Amundsen et al. 2015, 2017).

Despite the overwhelming evidence of high levels of sample disturbance induced by the conventional tube and piston samplers, they are still commonly used in soft soils (e.g., Pytten, Flobak, and Ottesen 2017). In geotechnical practice, the collected samples are rarely tested immediately after the sampling. The storage duration may be in the order of days, weeks or months. Stress relief during storage triggers a local redistribution of pore water within the sample (e.g., Kimball 1936; Schjetne 1971; Rowe 1972; Clayton, Matthews, and Simons 1995) and a possible exsolution of dissolved gas. Furthermore, physicochemical changes in the pore water may happen during storage (e.g., Torrance 1976 and Lessard and Mitchell 1985). A limited number of studies, which are listed in **Table 1**, suggest that sample storage may lead to a reduction in the undrained shear strength and preconsolidation pressure, among other effects. However, there is insufficient data to draw a robust conclusion as to how storage affects soft clay samples in terms of their strength, consolidation properties, and sensitivity (ratio between the undrained and remolded shear strength). This is especially the case for high-sensitivity soft clay of low plasticity.

This article studies the effects of storage based on the results from an extensive laboratory test program. The samples for this study were retrieved with the use of a 54-mm fixed-piston sampler (Andresen and Kolstad 1979) from a marine soft clay deposit at Tiller in Central Norway, which is well known to be challenging to sample because of its low plasticity (e.g., Sandven 1990; Sandven, Ørbech, and Lunne 2004; Gylland et al. 2013; Emdal et al. 2016; Amundsen et al. 2017). The experimental program consisted of storing and testing samples of high-sensitivity quick clay (QC) and low-sensitivity clay (LSC). The samples from both clays were retrieved and stored in thin-walled stainless steel tubes at 4° C. Some of the clay samples were tested immediately after sampling, while others were stored for up to 603 days. The variation in the material properties was investigated with the use of triaxial and oedometer tests, and an extensive amount of index and pore water chemistry testing, using the sample equipment and procedures. Finally, an attempt has been made to explain the cause of the observed effects of storage.

**TABLE 1**

Observed effects of storage; summary of previous work.

| Year | Reference | Site | NC/OC | $I_p$, % | $S_t$ | Storage Period | Major Changes |
|---|---|---|---|---|---|---|---|
| 1971 | Bozozuk (1971) | Ottawa (CAN) - BL | | 12 | 100 | 17 months | 5 % ↓ in $\sigma'_c$ |
| 1973 | Bjerrum (1973) | Ellingsrud (NOR) - T (95 mm) | NC | 3 | 70 | 3 days | 15 % ↓ in $c_u$ |
| 1976 | La Rochelle et al. (1976) | St-Louis (CAN) - BL | NC | 23 | 50 | 6 years | 10–15 % ↓ in $c_u$ |
| | | St-Jean-Vianney(CAN) - BL | | 11 | 500 | 6 years | 13–21 % ↓ in $c_u$ |
| 1976 | Arman and McManis (1976) | Louisiana (USA) - BL | OC | | | 10 months | 3–5 % ↑ in $c_u$ |
| | | T (71-127 mm) | OC | | | 11 months | 62 % ↓ in $c_u$; 29 % ↓ in $\sigma'_c$ |
| 1977 | Svaan (1977) | Østre Berg (NOR) - T (54 mm) | NC/OC | 16 | 9.5 | 7 months | 69 % ↓ in $c_u$ (UC) |
| | | Risvollan (NOR) - T (54 mm) | OC | 13 | 8.6 | 7 months | 32 % ↓ in $c_u$ (FC) |
| 1984 | Kirkpatrick and Khan (1984) | Illite | NC | 40 | low | 1 month | 53 % ↓ in $c_u$ |
| | | Kaoline | NC | 30 | low | 1 month | 64 % ↓ in $c_u$ |
| 1985 | Lessard and Mitchell (1985) | La Baie (CAN) - BL (20°C) | | 5.3 | 500 | 14 months | 130 % ↑ in $I_p$; 90 % ↓ in $I_L$; 169 % ↑ in sum of cations |
| 1986 | La Rochelle, Leroueil, and Tavenas (1986) | St-Alban (CAN) - BL | | 22–32 | | 3 years | No significant change in $w$, $I_p$, $I_L$, pH |
| | | St-Jean-Vianney (CAN) - BL | | 6 | | 3 years | |
| 1988 | Graham and Lau (1988) | Illite | NC | 32 | low | 7 days | 14 % ↓ in $c_u$ |
| 1994 | Henriksson and Carlsen (1994) | Swedish clay - T (50 mm) | NC | | | 18 months | 10 % ↓ in $c_u$ |
| 2005 | Rømoen (2005) | Berg (NOR) - T (54 mm) | OC | 7–10 | 4–10 | 2–3 weeks | 5–12% ↓ in $\sigma'_c$; 0–23% ↓ in $M_0$ |
| 2014 | L'Heureux and Paniagua (2014) | Onsøy (NOR) - T (54 mm) | NC | 30–50 | 5 | 4 months | 6–9 % ↓ in $c_u$ |
| 2015 | Amundsen Thakur, and Emdal (2015) | Klett (NOR) - BL | NC | 4 | 304 | <1 day | 18–23 % ↓ in $c_u$; 21–38 % ↓ in $\sigma'_c$ |
| 2017 | Amundsen et al. (2017) | Tiller (NOR) - BL | NC | 9–10 | 280 | 2 days | 5 % ↓ in $c_u$; 4 % ↓ in $\sigma'_c$ |

*Note*: ↓ = reduction and ↑ = increase. T/BL = Tube/Block; NC/OC = normally and overconsolidated; $I_p$ = plasticity index; $I_L$ = liquidity index; $w$ = water content; $S_t$ = sensitivity ($S_t = c_u/c_{ur}$, where $c_u$ is undrained shear strength and $c_{ur}$ is remolded shear strength from Fall Cone test); $\sigma'_c$ = preconsolidation pressure; $c_u$ = undrained shear strength (triaxial shear test, compression); and $c_u$ (UC) = undrained shear strength from Unconfined Compression test.

## Test Site and Methodology

The test site is located about 129 m above sea level and 13 km south from Trondheim City in the area called Tiller, which has been used previously for research projects by the Norwegian University of Science and Technology (NTNU) for several decades (e.g., Sandven 1990; Sandven, Ørbech, and Lunne 2004; Gylland et al. 2013; Amundsen et al. 2017). The test site area is covered with a marine deposit that has been deposited during the retreat of the glacial ice cover about 11,000 years before present (Reite, Selnes, and Sveian 1982). The uplift of the marine clay above the sea level led to freshwater leaching of the dissolved salt in the pore water, which caused the formation of the highly sensitive QC. The landscape is characterized by erosion with several hollow areas visible from large landslides that occurred in the past; e.g., the Tiller landslide, located about 4 km south of the test site, occurred in 1816 (Helland 1898). However, no major landslides have occurred in the surrounding area in recent time.

For this study, a rectangular plot of relatively flat forest land, about 8 m by 12 m, was used. Two relatively homogeneous layers of slightly overconsolidated clay were chosen for the investigation of storage duration effects: an LSC from 4–8 m and a high-sensitivity QC from 8–13 m. The sampler that was used in this study was the NGI 54-mm fixed-piston sampler (Andresen and Kolstad 1979). The sample length was 80 cm, the internal and external diameters of the sampling tube were 54 mm and 57 mm, and the cutting angle was 10° with no inside clearance. Total, 21 boreholes were formed by the NTNU drillers, with the same equipment and sampling techniques, and four samples were taken from 5 m and 11 m depths, two from each layer. Immediately after the sampling, the thin-walled stainless steel sampling tubes were sealed airtight. Shortly after, the samples were transported in the tubes about 12 km to the NTNU laboratory, where they were either tested immediately as reference samples or stored vertically at 4°C for up to 603 days.

The reference samples from the LSC and QC layers represent the geotechnical properties of the clay prior to storage and are used to find the in situ range of the natural variation of parameters, see **Table 2**. The methodology of this work is to compare the test results of the stored and reference samples with an aim to evaluate the effects of storage on sample quality and geotechnical parameters. In addition, two reference mini-block samples were taken with a downsized Sherbrooke block sampler, the mini-block sampler (NTNU, Trondheim, Norway) (Emdal et al. 2016).

## LABORATORY TESTING

All laboratory testing was conducted at the geotechnical laboratory at NTNU using the same extrusion, handling, and testing techniques. The samples were extruded the same day as they were tested. The extrusion was carried out horizontally at room temperature, onto a special tray for 54-mm samples. After the extrusion from the tubes, the samples were divided with the use of a thin wire saw, and the following geotechnical properties were determined at room temperature: natural water content ($w$), plasticity limit ($w_p$), liquid

**TABLE 2**

Geotechnical properties of the Tiller clay reference samples.

| | | LSC | | | QC | | |
|---|---|---|---|---|---|---|---|
| Test | Parameter | No. of Tests | Mean | Range of Values | No. of Tests | Mean | Range of Values |
| Index tests | w, % | 31 | 37.4 | 32.0–43.2 | 12 | 40.4 | 37.1–43.8 |
| | $I_p$, % | 7 | 15.1 | 10.5–19.0 | 5 | 7.2 | 5.4–8.9 |
| | $I_L$, % | 8 | 1.2 | 1.0–1.8 | 3 | 2.6 | 2.0–2.9 |
| | Organic content, % | 5 | 0.3 | 0.3–0.7 | 7 | 0.4 | 0.2–0.7 |
| Pore water chemistry | pH | 5 | 8.1 | 8.0–8.4 | 6 | 8.8 | 8.7–8.9 |
| | Sum of cations, meq/L | 3 | 11.2 | 10.2–13.0 | 3 | 9.7 | 9.1–10.7 |
| Fall cone test (FC) | $c_u$, kPa | 15 | 29.7 | 24.0–34.3 | 9 | 23.4 | 21.1–28.9 |
| | $c_{ur}$, kPa | 15 | 2.8 | 2.3–3.1 | 10 | 0.1 | 0.1 |
| Unconfined compression test (UC) | $c_u$, kPa | 5 | 24.2 | 20.5–26.4 | 3 | 23.1 | 20.7–26.6 |
| | $\varepsilon_f$, % | 5 | 4.4 | 3.5–5.0 | 3 | 4.7 | 3.5–6.0 |
| Oedometer test (CRS) | $\Delta e/e_0$ | 3 | 0.044 | 0.029–0.55 | 2 | 0.060 | 0.060–0.110 |
| | $\sigma'_c$, kPa | 3 | 162.3 | 157–165 | 2 | 168 | 166–170 |
| | $M_0$, MPa | 3 | 6.7 | 5.8–7.2 | 2 | 4.4 | 4.3–4.5 |
| | $M_0/M_L$ | 3 | 5.5 | 2.9–9.6 | 2 | 3 | 2.9–3.1 |
| Triaxial test (CAUC) | $\Delta e/e_0$ | 2 | 0.049 | 0.049 | 2 | 0.065 | 0.061–0.069 |
| | $c_u/\sigma'_{v0}$ | 2 | 0.6 | 0.57–0.63 | 2 | 0.43 | 0.41–0.44 |
| | $\varepsilon_f$, % | 2 | 2.0 | 1.7–2.4 | 2 | 1.6 | 1.4–1.9 |
| | $D$ | 2 | 0.03 | 0.00–0.05 | 2 | −0.24 | −0.29–0.18 |
| | $c$, kPa | 2 | 5.1 | 5.0–5.2 | 2 | 4.1 | 2.3–5.9 |
| | $\varphi$, degrees | 2 | 29.2 | 27.9–30.3 | 2 | 30.5 | 29.2–31.8 |

limit ($w_L$), salt content, pH, pore water chemistry (extracted with the use of a centrifuge), bulk unit weight ($\gamma$), undrained and remolded shear strength ($c_u$ and $c_{ur}$) from the Swedish fall cone (FC) test, $c_u$ from the Unconfined Compression Test (UC) and clay content. In addition to these testes, Constant Rate of Strain (CRS) oedometer tests and Consolidated Anisotropically sheared with Undrained Compression (CAUC) triaxial tests were conducted. The laboratory procedures for the oedometer and triaxial tests were similar to those described by Sandbækken, Berre, and Lacasse (1986), Lacasse and Berre (1988), ASTM D4186-06, *Standard Test Method for One-Dimensional Consolidation Properties of Saturated Cohesive Soils Using Controlled-Strain Loading*, and ASTM D4767-11, *Standard Test Method for Consolidated Undrained Triaxial Compression Test for Cohesive Soils*. The preconsolidation pressure ($\sigma'_c$) was determined by using an approach proposed by Janbu (1963).

## Results and Discussion – Sample Quality, Shear Strength, and Deformation Behavior

In order to examine whether the geotechnical properties had been affected by the storage duration, triaxial and oedometer tests were carried out on the reference samples during the sampling day as well as after various time periods. The results are shown in **Figs. 1–4**, and a detailed list of the results is in **Tables 3** and **4**. The index properties of the stored samples are summarized in **Table 5**.

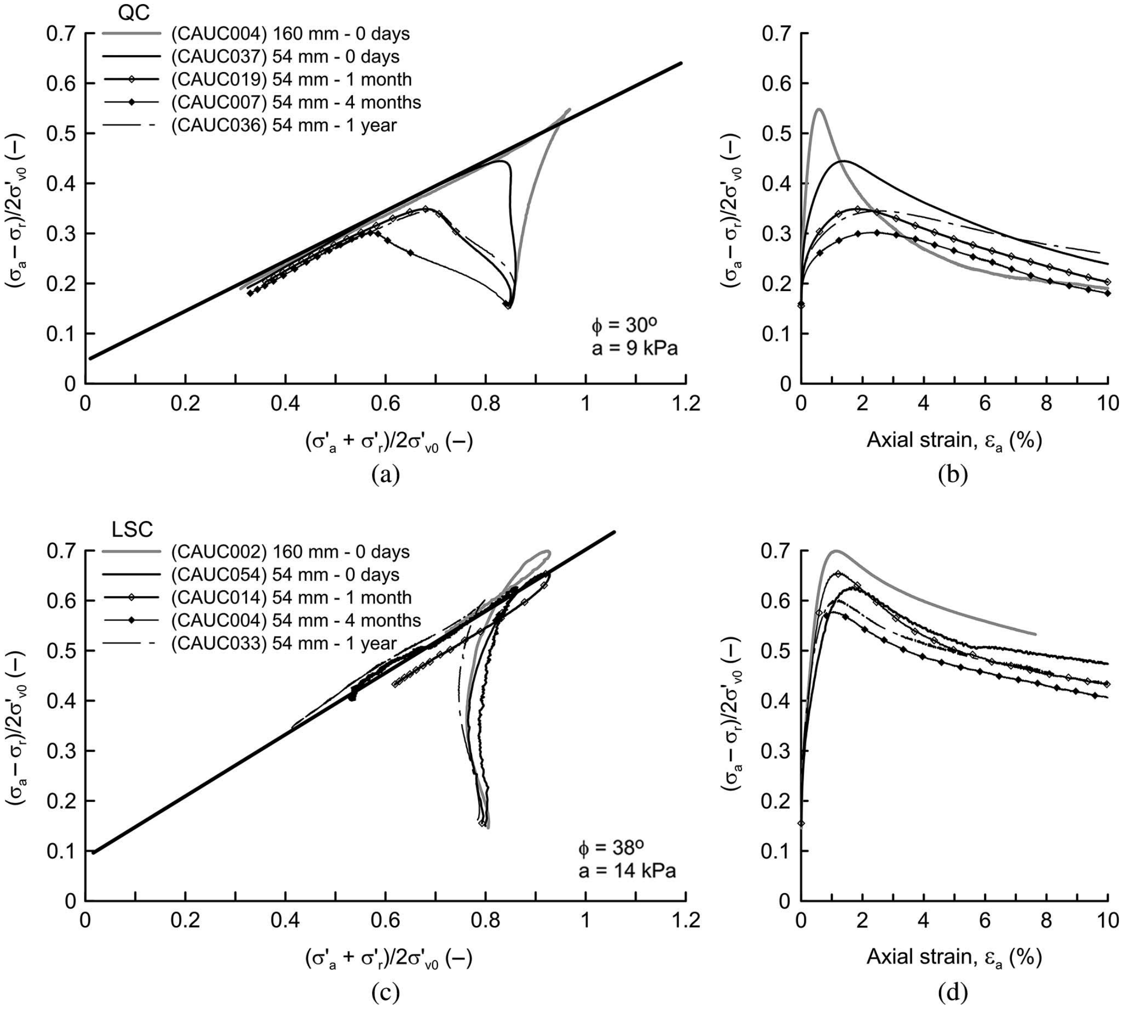
### SAMPLE QUALITY

The evaluation of the sample disturbance of soft clays has been the topic of a significant amount of research, which resulted in several sample quality assessment criteria. In this article, two methods have been used: the normalized void ratio during reconsolidation, the $\Delta e/e_0$ criterion (Lunne, Berre, and Strandvik 1997), and the $M_0/M_L$ criterion (Karlsrud and Hernandez-Martinez 2013), where $M_0$ is the maximum constrained modulus before the $\sigma'_c$ and $M_L$ is the minimum constrained modulus after the $\sigma'_c$.

The inflicted disturbance during the sampling has a great influence on how well the soil structure of the sample will be preserved during storage. An immediate testing of a 54-mm piston sample after the sampling may produce test results that are closer to a block sample (see **Fig. 1a**). However, when the storage duration increases, a large decrease in strength could be unavoidable. It is emphasized that the effects of storage are only visible in samples of originally good quality, and major sampler-induced disturbances will dominate the test results, regardless of the storage period.

Based on the laboratory data from triaxial and oedometer tests, shown in **Fig. 3**, the magnitude of the sample disturbance, as indicated by the $\Delta e/e_0$ criterion, was found to increase rapidly during the storage of the QC samples, compared to the LSC samples. The LSC specimens show a limited reduction in sample quality, as indicated by the $\Delta e/e_0$ criterion, during the first 5 months in storage, about a 0–22 % decrease, compared to a 17–65 % decrease for the QC (see **Fig. 3a** and **b**). The effect of long-term storage duration on the LSC and QC samples seems to be a slightly stiffer stress-strain response during reloading in the odometer tests, which leads to a reduction in the $\Delta e/e_0$ of the stored samples.

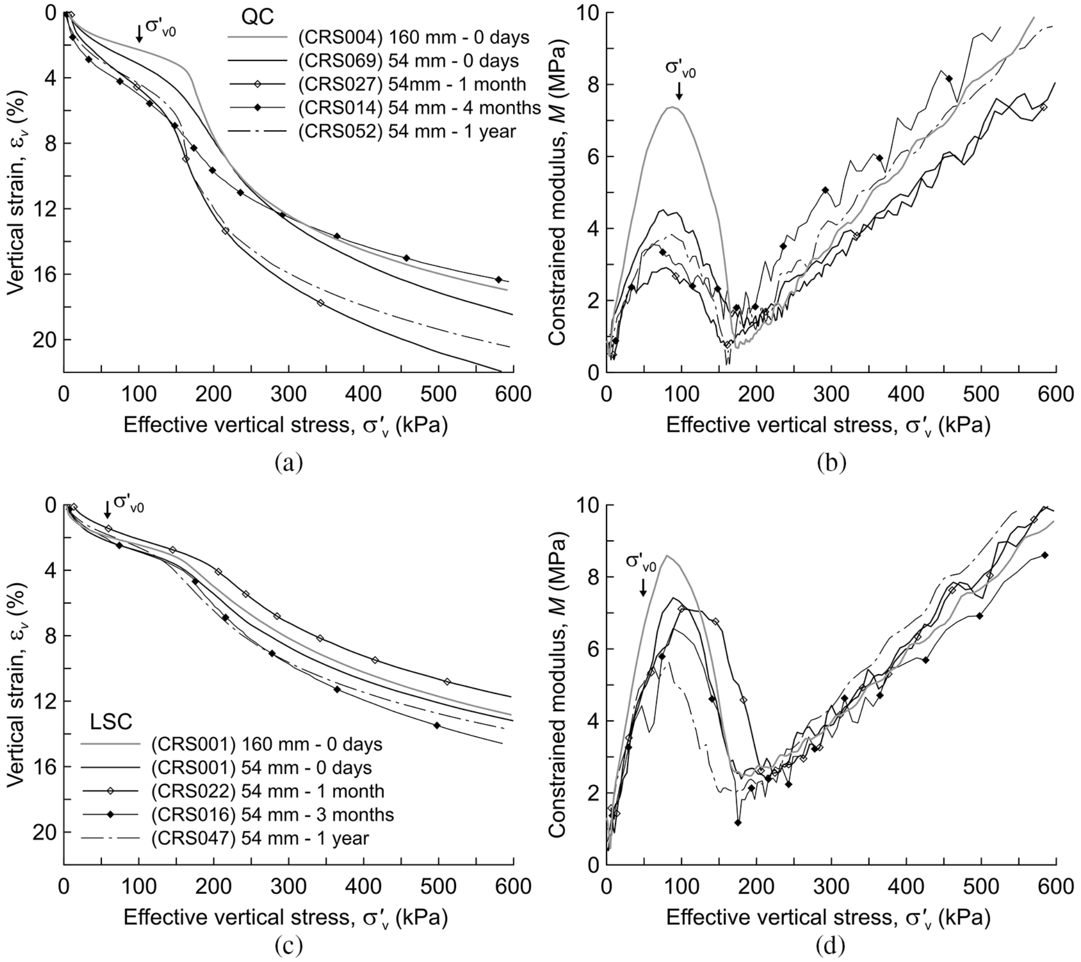
**FIG. 1** A selection of results from CAUC triaxial tests conducted on 160-mm mini-block samples and 54-mm piston samples from (a,b) QC and (c,d) LSC. For a complete list, see **Table 3**.



## SHEAR STRENGTH BEHAVIOR

The degradation of the sample quality has apparent detrimental effects on the effective stress path and the peak undrained shear strength, $c_u$, as shown in **Fig. 1**. The comparison between the reference mini-blocks and reference 54-mm samples, marked as "0 days" in **Fig. 1**, shows that the QC is more prone to the initial piston sampler-induced disturbance than the LSC. After a month in storage, the disturbance in the QC piston samples develops further and causes a significant change in the effective stress path (see **Fig. 1a**) and a rapid $c_u/\sigma'_{v0}$ reduction of about 18 % (see **Fig. 4a**). Further storage of 4 months reduces the strength with 27 % of the reference QC sample. The LSC samples, however, do not degrade at the same rate as the QC. The first signs are visible after about 3–5 months, when the $c_u$ reduces by about 7 % (see **Fig. 4a**), but it has a minimal effect on the effective stress path (see **Fig. 1c**).

**FIG. 2** A selection of results from CRS triaxial tests conducted on 160-mm mini-block samples and 54-mm piston samples from (a,b) QC and (c,d) LSC. For a complete list, see **Table 4**.



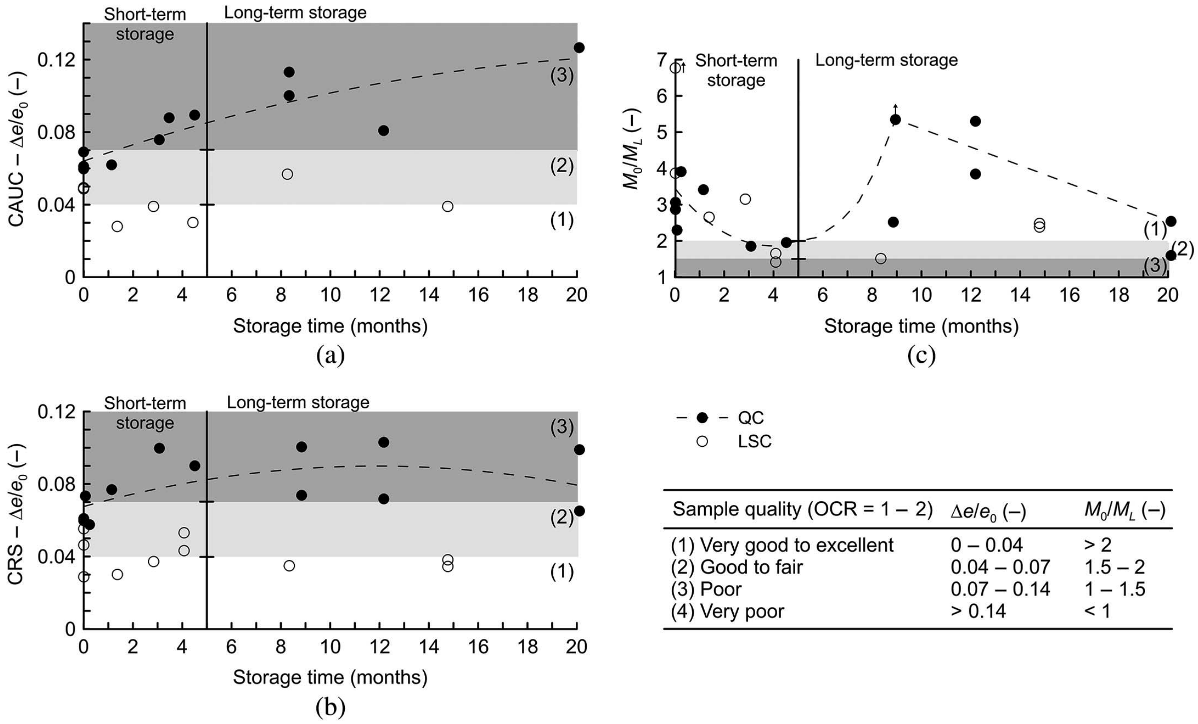
(a) (b)

(c) (d)

In addition to the increasing $\Delta e/e_0$ and decreasing $c_u$, several other indicators of sample quality reduction have been observed in the test results of stored samples: an increasing $\varepsilon_f$ (see **Fig. 4a**), less pronounced strain softening (see **Fig. 1b**), and decreasing dilatancy parameter ($D = (\Delta p - \Delta u)/\Delta q$) (see **Fig. 4b**). However, regardless of the increasing sample disturbance ($\Delta e/e_0$) during storage, the Mohr-Coulomb failure line does not seem to be significantly affected by it (see **Fig. 1** and **Table 3**), indicating that the friction angle and cohesion are not altered by the degree of sample disturbance. Similar observations were also reported by Skempton and Sowa (1963).

The effects of storage on the shear strength behavior have been reported in the literature, see **Table 1**, by e.g. La Rochelle et al. (1976), who observed a 10–21 % decrease in the $c_u$ after long-term storage of block samples. For the 54-mm samples of the Tiller QC, such a decrease occurred already after a month in storage. Therefore, it is important to emphasize that the effects of storage may occur faster in the smaller diameter samples than in block samples. Even when the results show a small difference between a piston and a mini-block sample tested at the sampling day, the discrepancies will become larger with time (see **Fig. 1a** and **b**).

**FIG. 3** Effect of storage on sample quality of QC and LSC. (a) CAUC triaxial tests and (b,c) CRS oedometer tests. For a detailed list, see **Tables 3** and **4**. Sample quality is assessed based on the Delta $e/e_0$ (Lunne, Berre, and Strandvik 1997) and $M_0/M_L$ (Karlsrud and Hernandez-Martinez 2013).



(a)

(c)

(b)

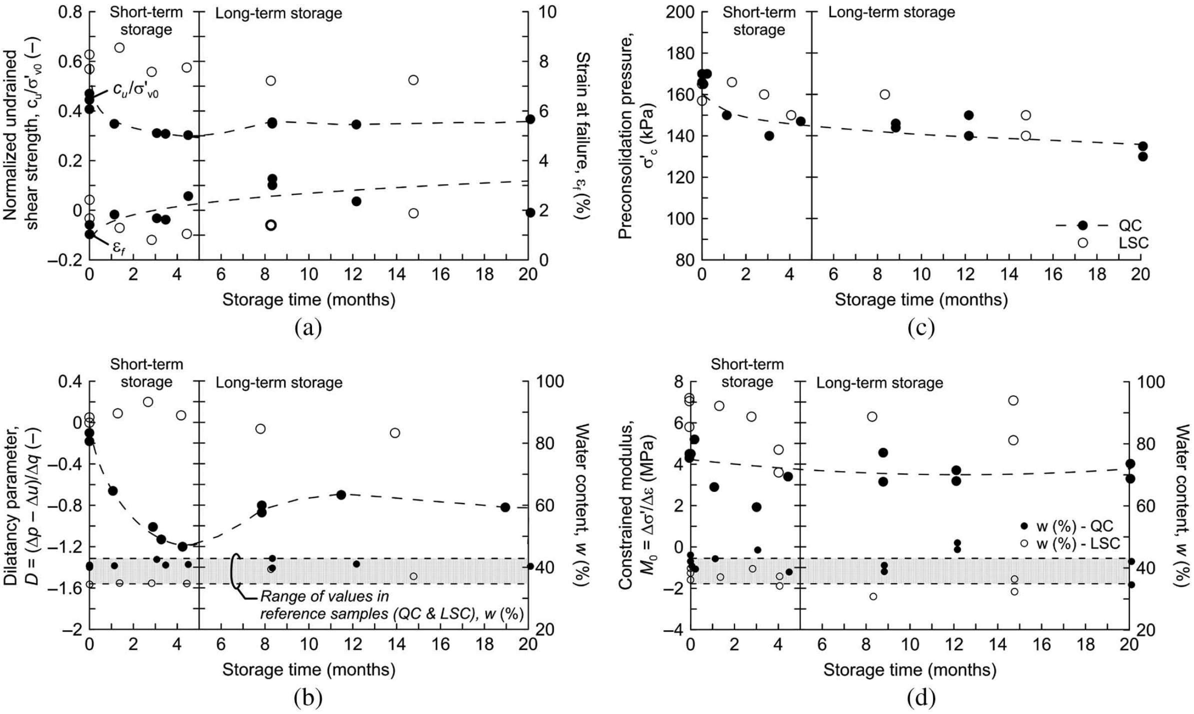
| Sample quality (OCR = 1 – 2) | $\Delta e/e_0$ (–) | $M_0/M_L$ (–) |
|---|---|---|
| (1) Very good to excellent | 0 – 0.04 | > 2 |
| (2) Good to fair | 0.04 – 0.07 | 1.5 – 2 |
| (3) Poor | 0.07 – 0.14 | 1 – 1.5 |
| (4) Very poor | > 0.14 | < 1 |

When comparing the Tiller clay results to the only extensive long-term study available, to the authors' knowledge, conducted on tube samples of Louisiana clay (Arman and McManis 1976), a similar trend is observed during the first months in storage (see **Fig. 5a**). During long-term storage, the Louisiana clay continues to lose its strength with age, without major changes in water content or density, but the Tiller QC samples exhibit an increasing trend after three months. A possible explanation for the discrepancies could be the storage conditions; the Tiller clay samples were stored in the sampling tubes until they were extruded on the testing day. However, the Louisiana clay samples were extruded and sealed with a protective coating on the sampling day prior to storage. This indicates that long-term storage within the sampling tubes prevents the soil samples from further loss of strength. Therefore, it may be advantageous to store the samples within the sampling tubes and extrude them only when they are ready to be tested. This corresponds with the recommendations of Ladd and DeGroot (2003).

## PRECONSOLDIATION PRESSURE

During short-term storage of less than 5 months, the preconsolidation pressure, $\sigma'_c$, decreased by on average by 2–17 % in the QC samples and 1–8 % in the LSC samples, as shown in **Fig. 4c**. Similar observations were reported by Bozozuk (1971), Arman and McManis (1976), La Rochelle et al. (1976), and L'Heureux and Paniagua (2014). The results indicate that the $\sigma'_c$ is less influenced by an increasing amount of disturbance ($\Delta e/e_0$) than the $c_u$ measurements shown in **Table 6**. From this observation, it is concluded

**FIG. 4** Effects of storage on material parameters from (a,b) CAUC triaxial tests and (c,d) CRS oedometer tests conducted on QC and LSC. For a detailed list, see **Tables 3** and **4**. The range of the water content is based on the results in **Table 2**.



(a) (c)
(b) (d)

that one can find an estimate for the preconsolidation pressure even though the sample has some degree of disturbance. It will, however, reduce with increasing sample disturbance. This is in agreement with the results of Hight and Leroueil (2003). The value of the $M_0$ modulus, however, was significantly influenced by the degree of disturbance (see **Figs. 2b** and **4d**), since it is derived from the strain during recompression ($M_0 = \Delta\sigma'/\Delta\varepsilon$).

During long-term storage of more than 5 months, the $\sigma_c'$ continues with a tendency to decrease with time. After more than a year, it has decreased by about 23 % for the QC and 14 % for the LSC (see **Fig. 4c**). However, the decreasing tendency of the QC is less rapid compared to the first month of storage. This indicates that the clay undergoes major changes shortly after the sampling. Thereafter, the process slows down.

When comparing the Tiller clay test results to the Louisiana clay in **Fig. 5b**, a decreasing trend in normalized $\sigma_c'$ is observed for all three clays, regardless of their sensitivity.

## Results and Discussion – Index Properties and Pore Water Chemistry

From the conducted triaxial and oedometer tests, it was observed that the $c_u$, $\sigma_c'$, and $M_0$ decrease during storage, accompanied by an increase in volume change during reconsolidation to an estimate of in situ stresses. This indicates a decreasing sample quality. Therefore, a significant amount of index tests have been evaluated, in addition to a

**TABLE 3**

Summary of CAUC triaxial test results. Triaxial specimen diameter—54 mm and height—100 mm. The consolidation stresses are $\sigma'_a = \sigma'_{v0}$ and $\sigma'_r = K'_0 \cdot \sigma'_{v0}$ ($\gamma = 19$ kN/m$^3$, $K'_0 = 0.7$). Backpressure is 250–300 kPa. Strain rate—1.5 %/h.

| Storage, days | Test No. | $\sigma'_a$, kPa | $\sigma'_r$, kPa | $w$, % | $\gamma$, kN/m$^3$ | $c_u$, kPa | $\varepsilon_f$, % | $u_f$, kPa | $D$ | tan $\varphi$ | $\varepsilon_{vol}$, % | $\Delta e/e_0$ | $c_u/\sigma'_{v0}$ | $u_f/\sigma'_{v0}$ | $c_u/\sigma'_c$[b] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSC | | | | | | | | | | | | | | | |
| 0 | CAUC002[a] | 58.8 | 41.6 | 37.8 | 18.9 | 41.1 | 1.1 | 14.7 | −0.04 | 0.75 | 1.65 | 0.032 | 0.70 | 0.25 | 0.27 |
| 0 | CAUC054 | 54.2 | 38.0 | 40.4 | 18.6 | 34.0 | 1.7 | 14.0 | 0.05 | 0.59 | 2.62 | 0.049 | 0.63 | 0.26 | 0.23 |
| 0 | CAUC049 | 57.8 | 40.0 | 34.5 | 19.1 | 32.9 | 2.4 | 11.7 | 0.00 | 0.49 | 2.39 | 0.049 | 0.57 | 0.20 | 0.22 |
| 41 | CAUC014 | 55.1 | 38.0 | 34.9 | 19.1 | 36.1 | 1.3 | 10.6 | 0.09 | 0.65 | 1.38 | 0.028 | 0.66 | 0.19 | 0.24 |
| 85 | CAUC010 | 63.0 | 37.3 | 34.9 | 19.2 | 35.1 | 0.8 | 6.8 | 0.20 | 0.50 | 1.93 | 0.039 | 0.56 | 0.11 | 0.23 |
| 133 | CAUC004 | 55.3 | 37.8 | 34.8 | 19.0 | 31.8 | 1.1 | 12.8 | 0.07 | 0.59 | 1.48 | 0.030 | 0.57 | 0.23 | 0.21 |
| 248 | CAUC047 | 70.3 | 47.9 | 37.1 | 18.5 | 36.7 | 1.4 | 20.1 | −0.06 | 0.58 | 2.98 | 0.057 | 0.52 | 0.50 | 0.24 |
| 443 | CAUC034 | 56.3 | 39.9 | 37.1 | 18.6 | 29.6 | 1.9 | 16.6 | −0.10 | 0.60 | 1.99 | 0.039 | 0.53 | 0.29 | 0.20 |
| QC | | | | | | | | | | | | | | | |
| 0 | CAUC004[a] | 97.0 | 67.1 | 40.0 | 19.1 | 53.1 | 0.6 | 26.4 | −0.02 | 0.58 | 2.51 | 0.047 | 0.55 | 0.27 | 0.30 |
| 0 | CAUC037 | 87.7 | 61.1 | 40.7 | 18.2 | 39.0 | 1.4 | 27.5 | −0.18 | 0.62 | 3.26 | 0.061 | 0.44 | 0.31 | 0.23 |
| 0 | CAUC058 | 110.6 | 77.0 | 41.8 | 18.1 | 45.0 | 1.9 | 36.0 | −0.29 | 0.56 | 3.70 | 0.069 | 0.41 | 0.33 | 0.24 |
| 7 | CAUC038 | 95.8 | 65.1 | 39.9 | 18.4 | 45.0 | 1.0 | 23.0 | −0.10 | 0.53 | 3.15 | 0.060 | 0.47 | 0.24 | 0.25 |
| 34 | CAUC019 | 91.5 | 63.0 | 40.5 | 18.7 | 31.9 | 1.8 | 32.6 | −0.66 | 0.61 | 3.29 | 0.062 | 0.35 | 0.36 | 0.18 |
| 92 | CAUC012 | 91.8 | 62.8 | 42.5 | 18.6 | 28.5 | 1.7 | 32.4 | −1.01 | 0.53 | 4.12 | 0.076 | 0.31 | 0.35 | 0.16 |
| 104 | CAUC008 | 91.8 | 62.6 | 40.7 | 19.1 | 28.3 | 1.6 | 35.0 | −1.13 | 0.59 | 4.68 | 0.096 | 0.31 | 0.38 | 0.16 |
| 135 | CAUC007 | 92.9 | 63.1 | 40.9 | 18.4 | 28.1 | 2.6 | 38.2 | −1.20 | 0.63 | 4.77 | 0.089 | 0.30 | 0.41 | 0.16 |
| 250 | CAUC045 | 89.6 | 60.8 | 42.8 | 17.9 | 31.8 | 3.0 | 35.2 | −0.87 | 0.34 | 5.46 | 0.100 | 0.35 | 0.39 | 0.18 |
| 250 | CAUC046 | 94.5 | 66.1 | 39.8 | 18.2 | 33.0 | 3.3 | 36.0 | −0.80 | 0.26 | 5.96 | 0.113 | 0.35 | 0.38 | 0.19 |
| 365 | CAUC036 | 92.6 | 64.5 | 41.0 | 18.3 | 32.0 | 2.4 | 32.1 | −0.70 | 0.50 | 4.32 | 0.081 | 0.35 | 0.35 | 0.18 |
| 603 | CAUC043 | 89.9 | 59.3 | 40.3 | 18.6 | 33.0 | 1.9 | 31.0 | −0.82 | 0.67 | 6.71 | 0.127 | 0.37 | 0.34 | 0.19 |

*Note*: [a] Reference samples from 160-mm diameter mini-block sampler; [b] $\sigma'_c = (\text{Depth} + 19.87)/0.169$.

thorough analysis of the pore water chemistry, in an attempt to explain the processes that cause the observed changes in the geotechnical properties. Because of a large number of tests, the mean values of the results have been plotted according to storage period in **Figs. 6** and **7**. The list of mean values, along with the corresponding number of tests, are shown in **Table 5**. The geotechnical properties of the reference samples are in **Table 2**.

The natural water content of the Tiller clay has been shown to vary within the sample prior to storage, as shown in **Fig. 6a** and **b**. And throughout the storage period of more than a year, the average water content of the samples remained within the range of reference samples, indicating no loss of moisture. Similarly, the $I_p$ and $I_L$ remained relatively constant (see **Fig. 6c–f**). Similar studies conducted by Svaan (1977) and La Rochelle, Leroueil, and Tavenas (1986) showed that the loss of moisture can be avoided; however, the changes in the Atterberg limits can be more challenging to prevent, because of access to oxygen during storage.

In addition to the loss of moisture and changes in Atterberg limits, an inadequate sealing can be revealed from discrepancies in the pore water chemistry. The results in **Fig. 6g–j** indicate that the samples were sealed properly, as no significant changes in pore water chemistry during storage were observed. Similar results were reported by Lessard and Mitchell (1985) for a sample stored for 14 months in the Shelby tube and by La Rochelle, Leroueil, and Tavenas (1986) for waxed samples stored at 8–9°C. Torrance (1976) observed that the extraction of a sample from the ground exposes the soil to the air and aging due to oxidation will start. An airtight sealing may prevent this process;

**TABLE 4**

Summary of CRS oedometer test results. Oedometer specimen diameter—54 mm and height—20 mm. Strain rate—1.0 %/h.

| Storage, days | Test No. | $\sigma'_{v0}$, kPa | $w$, % | $\gamma$, kN/m$^3$ | $\sigma'_c$, kPa | OCR[b] | $M_0$, MPa | $M_L$, MPa | $m$ | $\sigma'_{ref}$, kPa | $\varepsilon_{vol}$, % | $\Delta e/e_0$ | $M_0/M_L$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| LSC | | | | | | | | | | | | | |
| 0 | CRS001[a] | 59.1 | 39.4 | 18.1 | 162 | 2.7 | 11 | 1.3 | 19.2 | 123 | 1.66 | 0.032 | 8.8 |
| 0 | CRS002 | 56.5 | 38.4 | 18.4 | 165 | 2.9 | 5.8 | 1.5 | 20.2 | 128 | 2.87 | 0.055 | 3.9 |
| 0 | CRS067 | 57.4 | 39.9 | 17.2 | 157 | 2.7 | 7.2 | 0.8 | 16.9 | 109 | 1.52 | 0.029 | 9.6 |
| 0 | CRS001 | 64.6 | 36.2 | 18.6 | 165 | 2.6 | 7.1 | 2.4 | 20.4 | 100 | 2.33 | 0.046 | 2.9 |
| 41 | CRS022 | 53.8 | 37.0 | 18.9 | 165 | 3.1 | 6.8 | 2.6 | 20.2 | 100 | 1.53 | 0.030 | 2.7 |
| 85 | CRS016 | 53.8 | 39.7 | 18.2 | 160 | 3.0 | 6.3 | 2.0 | 16.3 | 52 | 1.96 | 0.037 | 3.2 |
| 122 | CRS030 | 53.8 | 34.2 | 18.8 | 150 | 2.8 | 4.7 | 3.3 | 21.0 | 36 | 2.11 | 0.043 | 1.4 |
| 122 | CRS031 | 54.3 | 37.3 | 18.5 | 150 | 2.8 | 3.6 | 2.2 | 20.8 | 103 | 2.71 | 0.053 | 1.7 |
| 250 | CRS034 | 54.3 | 30.8 | 19.3 | 160 | 3.0 | 6.3 | 4.2 | 21.9 | 30 | 1.62 | 0.035 | 1.5 |
| 443 | CRS047 | 53.8 | 36.4 | 18.5 | 140 | 2.6 | 5.2 | 2.1 | 20.9 | 84 | 1.74 | 0.034 | 2.5 |
| 443 | CRS048 | 54.3 | 32.4 | 18.9 | 155 | 2.8 | 7.1 | 3.0 | 22.2 | 69 | 1.82 | 0.038 | 2.4 |
| QC | | | | | | | | | | | | | |
| 0 | CRS004[a] | 98.2 | 41.9 | 18.2 | 167 | 1.7 | 7.3 | 0.8 | 21.7 | 138 | 2.99 | 0.055 | 8.7 |
| 0 | CRS069 | 107.4 | 42.8 | 17.4 | 170 | 1.6 | 4.5 | 1.5 | 17.5 | 127 | 3.30 | 0.060 | 3.1 |
| 0 | CRS006 | 81.7 | 42.1 | 17.9 | 166 | 2.0 | 4.3 | 1.5 | 17 | 97 | 3.30 | 0.061 | 2.9 |
| 2 | CRS007 | 100.6 | 40.6 | 18.2 | 165 | 1.7 | 4.5 | 2.0 | 20.1 | 115 | 3.90 | 0.073 | 2.3 |
| 7 | CRS057 | 98.8 | 39.6 | 18.3 | 180 | 1.8 | 5.2 | 1.3 | 21.4 | 118 | 3.03 | 0.058 | 3.9 |
| 34 | CRS027 | 89.8 | 43.0 | 18.0 | 150 | 1.7 | 2.9 | 0.9 | 18.9 | 120 | 4.20 | 0.077 | 3.4 |
| 92 | CRS019 | 90.3 | 45.8 | 18.3 | 140 | 1.6 | 1.9 | 1.0 | 19.4 | 44 | 5.60 | 0.100 | 1.9 |
| 135 | CRS014 | 89.8 | 38.7 | 19.0 | 147 | 1.6 | 3.4 | 1.7 | 18.6 | 86 | 4.68 | 0.090 | 2.0 |
| 265 | CRS039 | 89.8 | 38.8 | 18.4 | 144 | 1.6 | 4.6 | 0.5 | 20.3 | 116 | 3.84 | 0.074 | 9.1 |
| 265 | CRS040 | 90.3 | 40.8 | 18.1 | 146 | 1.6 | 3.2 | 1.3 | 22.6 | 128 | 5.36 | 0.100 | 2.5 |
| 365 | CRS051 | 90.7 | 45.9 | 17.6 | 140 | 1.5 | 3.2 | 0.8 | 20.5 | 99 | 5.79 | 0.103 | 3.8 |
| 365 | CRS052 | 91.2 | 48.1 | 17.5 | 150 | 1.6 | 3.7 | 0.7 | 20.9 | 117 | 4.12 | 0.072 | 5.3 |
| 603 | CRS060 | 89.4 | 42.1 | 17.9 | 135 | 1.5 | 3.3 | 1.3 | 20.9 | 89 | 5.35 | 0.099 | 2.5 |
| 603 | CRS061 | 90.3 | 34.6 | 19.0 | 130 | 1.4 | 4.0 | 2.5 | 22.3 | 53 | 3.03 | 0.062 | 1.6 |

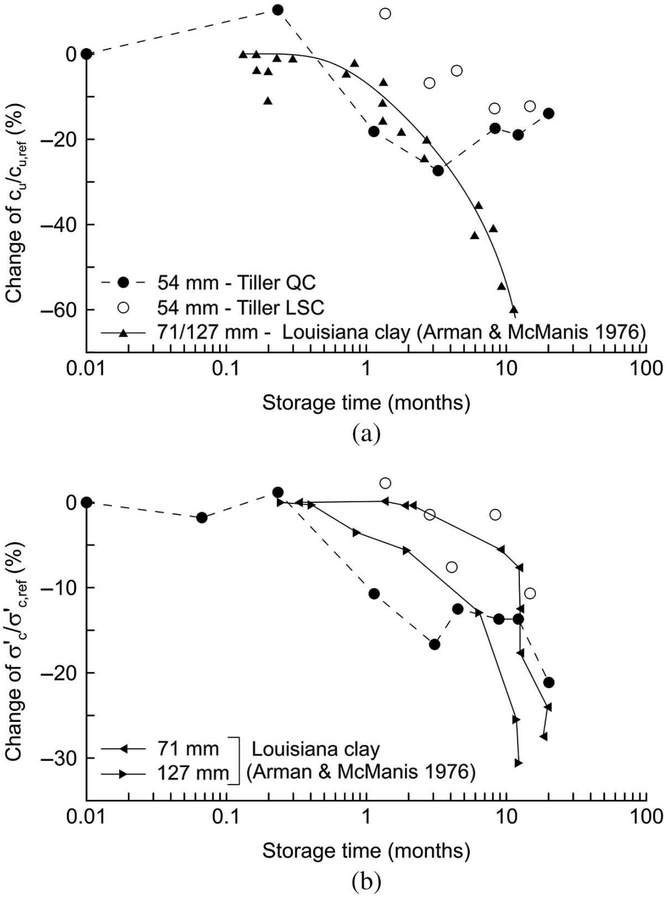
*Note*: [a] Reference samples from 160-mm diameter mini-block sampler; [b] OCR - overconsolidation ratio.

however, the implementation of this technique depends on the operator, and therefore aging due to imperfect sealing could be expected (Torrance 1976). Lessard and Mitchell (1985) observed that sample storage at 20°C might cause significant changes in $I_p$, $I_L$, and the pore water chemistry, see **Table 1**, and should be avoided.

The $c_u$ (FC and UC) of the LSC samples shows no clear time dependence, see **Fig. 7b** and **f**. The $c_u$ (FC) of the QC samples, however, decreased with 21 % after 4 months in storage, and after more than a year the $c_u$ continued to decrease to 23–49 %, see **Fig. 7a**. It is worth mentioning that after about five months in storage, the clay samples became more challenging to extrude with full cross-section, with some of the clay remaining in the tube (no changes in the pore water chemistry were observed). The decreasing trend of the $c_u$ (FC) could have been caused by disturbance during the extrusion of the samples after long-term storage. It is possible that the strength of the QC does not change significantly during storage while it is in the sampling tube—as with LSC samples. However, the initially remolded clay in the outer zone of the sample has been reconsolidating during storage and developed a stronger bond with the surroundings (sampling tube), which has caused an additional disturbance during the extrusion. Hence, the decreasing $c_u$ (FC) might be caused by an increasing strength of the outer zone of the sample during storage.

**FIG. 5**

Change of the normalized (a) undrained shear strength ($c_u/c_{u,ref}$) and (b) preconsolidation pressure ($\sigma'_c/\sigma'_{c,ref}$) during storage. $c_{u,ref}$ and $\sigma'_{c,ref}$ are from a reference sample or a mean value from several samples with the least amount of storage duration.



The $c_u$ (UC) of the QC shows a 40 % decrease during the first three months in storage; thereafter, the strength seems to increase back to the range of the measured strength in reference samples, as shown in **Fig. 7e**. A similar trend was reported by Svaan (1977) for a lightly overconsolidated LSC. The clay exhibited a decrease in $c_u$ (FC and UC) of about 31–67 % after 2–3.5 months in storage, which increased after 6 months. These observations indicate that soil samples may go through time-dependent quality deterioration, after which the soil structure starts to recover because of a possible restructuring of the sample during storage (Leroueil and Vaughan 1990), which presumably causes the decreasing values of the $\varepsilon_f$ (UC) in **Fig. 7g** and **h**.

## Discussion – Water Migration and Pore Pressure Equalization

The index tests and pore water analysis conducted on the stored samples indicate that the clay was stored in airtight sampling tubes with no chemical changes or losses in moisture. However, in spite of all precautions taken with regards to transport, storage, and handling, the properties of the clay samples were altered during storage. With the samples seemingly

**FIG. 6**

Variation in the index properties and the pore water chemistry during storage.

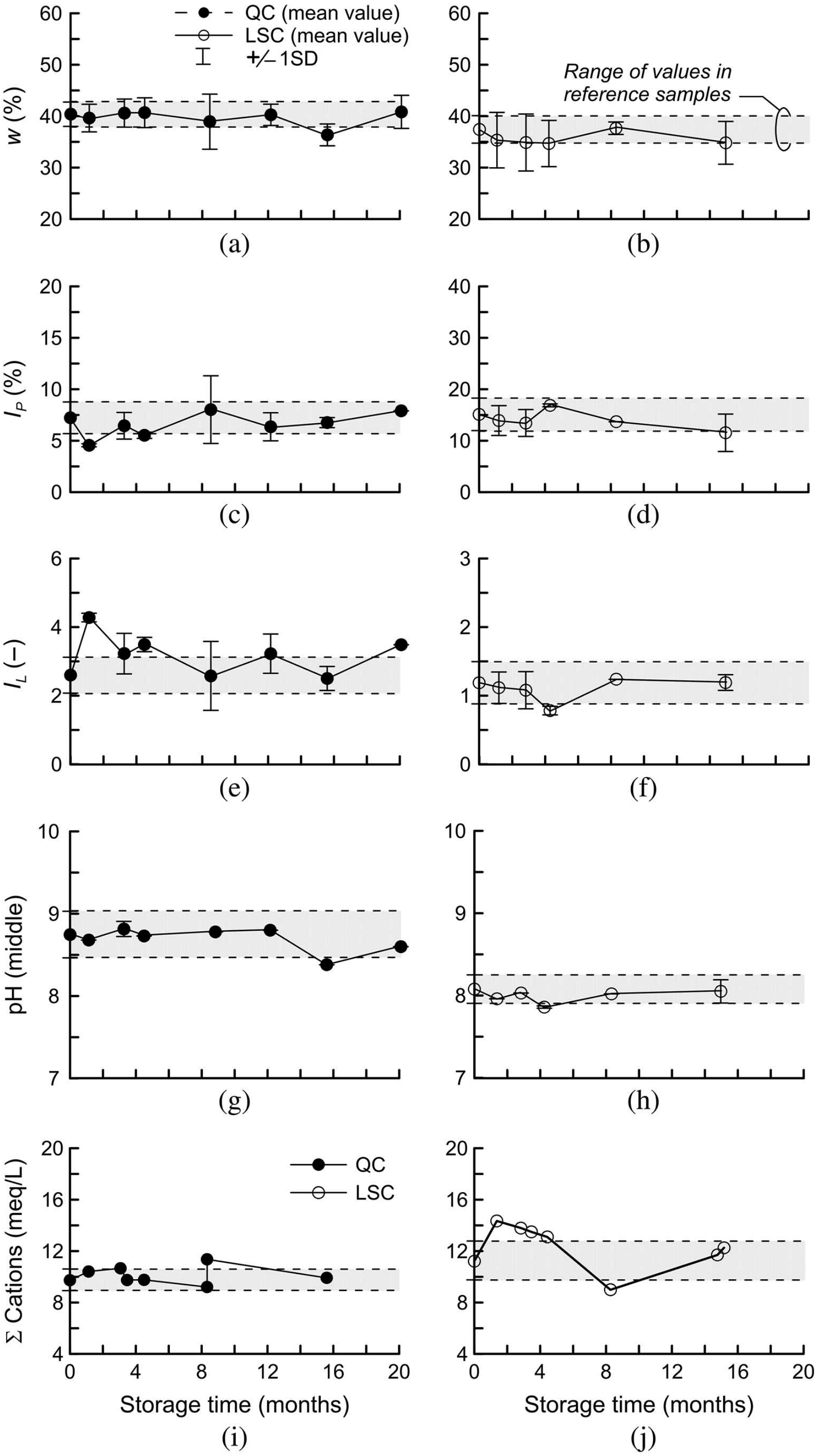
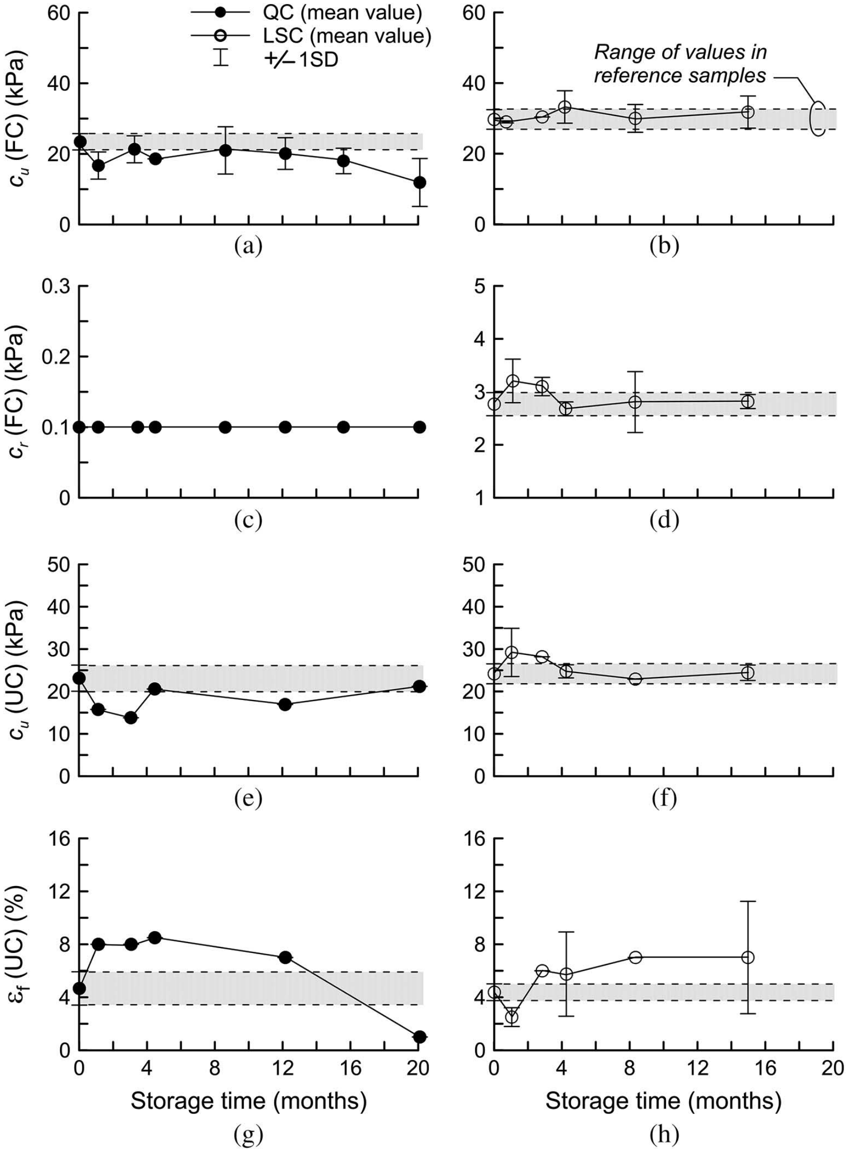


**FIG. 7**

Variation in the index properties during storage.



uninfluenced by external factors, it is likely that the storage duration effects are caused by physical processes taking place within the sample, such as internal water migration.

In the reference samples of the QC and LSC, a cross-sectional water migration between the periphery and the core was already observed less than one hour after the sampling, shown in Fig. 8, where the specimens were collected immediately after the extrusion from the sampling tube.

The samples were stored vertically inside the sampling tubes. Interestingly, a longitudinal water migration was observed in only two of the samples. Fig. 9a and b show how the measured water content of the samples that were stored for four months deviates from the water content of the reference samples, which were tested on the day of the sampling.

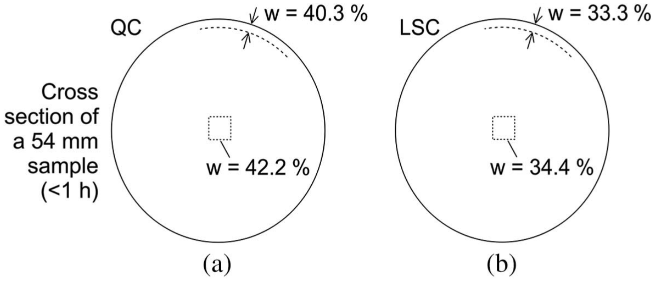
**TABLE 5**

Variation in the index properties during storage.

| Storage, months | | w, % | $I_p$, % | $I_L$, % | pH | $c_u$, kPa | $c_{ur}$, kPa | $c_u$ (UC), kPa | $\varepsilon_f$ (UC), % |
|---|---|---|---|---|---|---|---|---|---|
| LSC | | | | | | | | | |
| 0 | No. of tests | 31 | 7 | 8 | 5 | 15 | 15 | 5 | 5 |
| | Mean | 37.4 | 15.1 | 1.2 | 8.1 | 29.7 | 2.8 | 24.2 | 4.4 |
| 1 | No. of tests | 9 | 4 | 4 | 1 | 2 | 5 | 2 | 2 |
| | Mean | 35.3 | 13.9 | 1.1 | 8.0 | 29.0 | 3.2 | 29.2 | 2.5 |
| 3 | No. of tests | 5 | 3 | 3 | 1 | 1 | 3 | 1 | 1 |
| | Mean | 34.9 | 13.4 | 1.1 | 8.0 | 30.4 | 3.1 | 28.2 | 6.0 |
| 4 | No. of tests | 7 | 3 | 3 | 2 | 4 | 5 | 2 | 2 |
| | Mean | 34.7 | 16.9 | 0.8 | 7.9 | 33.2 | 2.7 | 24.7 | 5.8 |
| 8 | No. of tests | 8 | 1 | 1 | 1 | 4 | 4 | 1 | 1 |
| | Mean | 37.7 | 13.7 | 1.2 | 8.0 | 30.0 | 2.8 | 22.9 | 7.0 |
| 15 | No. of tests | 16 | 6 | 6 | 2 | 6 | 6 | 2 | 2 |
| | Mean | 34.8 | 11.5 | 1.2 | 8.1 | 31.8 | 2.8 | 24.4 | 7.0 |
| QC | | | | | | | | | |
| 0 | No. of tests | 12 | 5 | 3 | 6 | 9 | 10 | 3 | 3 |
| | Mean | 40.4 | 7.2 | 2.6 | 8.7 | 23.4 | 0.1 | 23.1 | 4.7 |
| 1 | No. of tests | 3 | 2 | 2 | 1 | 3 | 3 | 1 | 1 |
| | Mean | 39.6 | 4.6 | 4.3 | 8.7 | 16.7 | 0.1 | 15.8 | 8.0 |
| 3 | No. of tests | 8 | 6 | 6 | 2 | 2 | 6 | 1 | 1 |
| | Mean | 40.6 | 6.5 | 3.2 | 8.8 | 21.3 | 0.1 | 13.8 | 8.0 |
| 4 | No. of tests | 4 | 2 | 2 | 1 | 1 | 3 | 1 | 1 |
| | Mean | 40.7 | 5.5 | 3.5 | 8.7 | 18.6 | 0.1 | 20.6 | 8.5 |
| 8 | No. of tests | 8 | 5 | 5 | 1 | 5 | 5 | 1 | 1 |
| | Mean | 38.9 | 8.0 | 2.6 | 8.8 | 21.0 | 0.1 | 24.2 | 6.0 |
| 12 | No. of tests | 7 | 3 | 3 | 1 | 3 | 3 | 1 | 1 |
| | Mean | 40.3 | 6.4 | 3.2 | 8.8 | 20.1 | 0.1 | 16.9 | 7.0 |
| 16 | No. of tests | 7 | 3 | 3 | 1 | 3 | 3 | – | – |
| | Mean | 36.4 | 6.8 | 2.5 | 8.4 | 18.0 | 0.1 | – | – |
| 20 | No. of tests | 4 | 1 | 1 | 1 | 2 | 3 | 1 | 1 |
| | Mean | 40.8 | 7.9 | 3.5 | 8.6 | 11.9 | 0.1 | 21.2 | 1.0 |

**FIG. 8**

Water migration within 54-mm piston samples. Water content in the cross section of (a) QC and (b) LSC samples (tested immediately after the sampling).

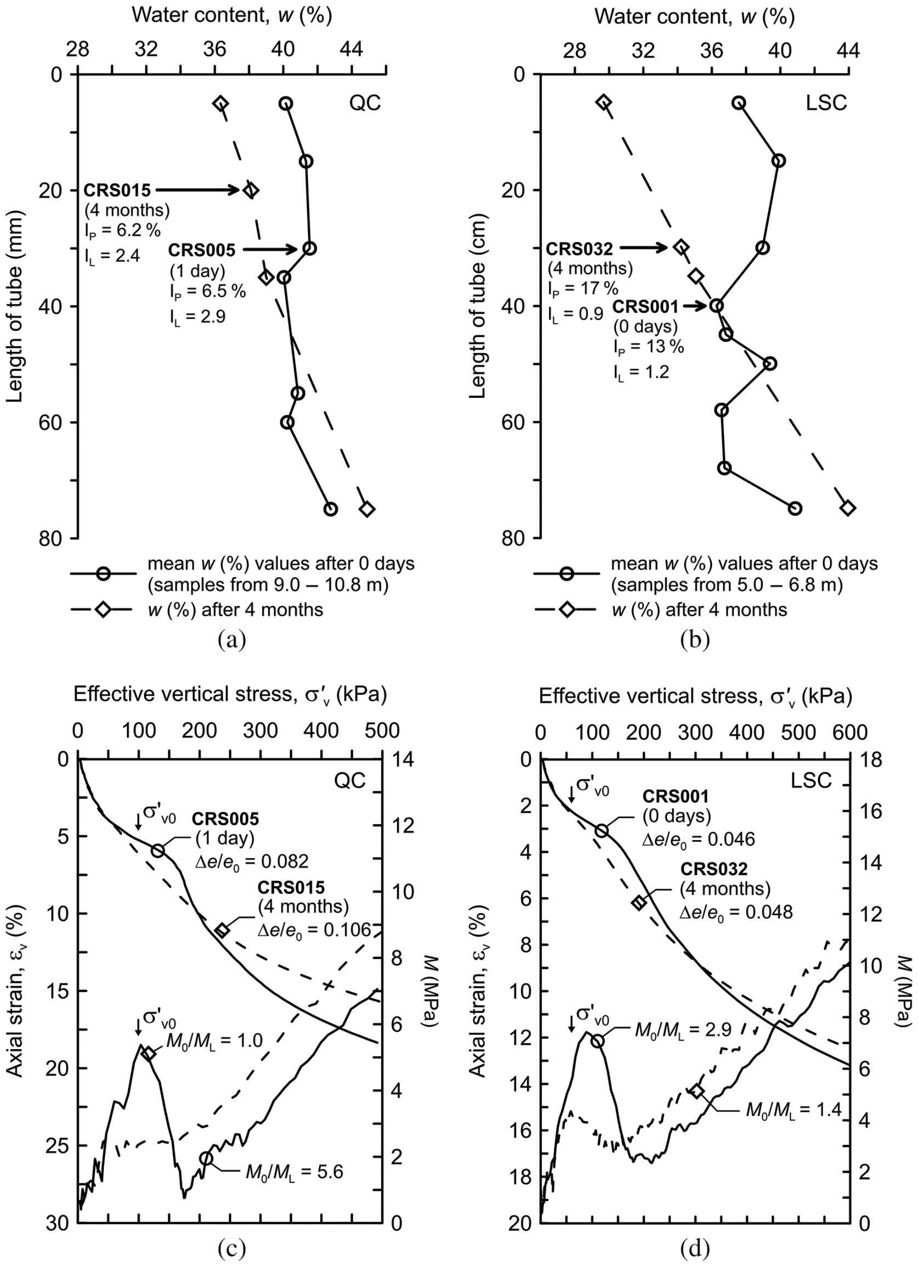


(a) (b)

The results from the oedometer tests in Fig. 9c and d show that the quality ($\Delta e/e_0$ and $M_0/M_L$) has reduced significantly. This indicates that the water migration, followed by the swelling of the soil structure, has resulted in a poorer sample quality after four months in storage. The pore water chemistry of the samples was within the range of the reference samples, indicating an airtight seal.

The results reported in Tables 3 and 4 show similar degradation of the sample quality with storage duration as the samples in Fig. 9, but no longitudinal redistribution was measured in these samples. This observation indicates that the water migration, in the samples listed in Tables 3 and 4, has occurred at a small/local scale, such as between

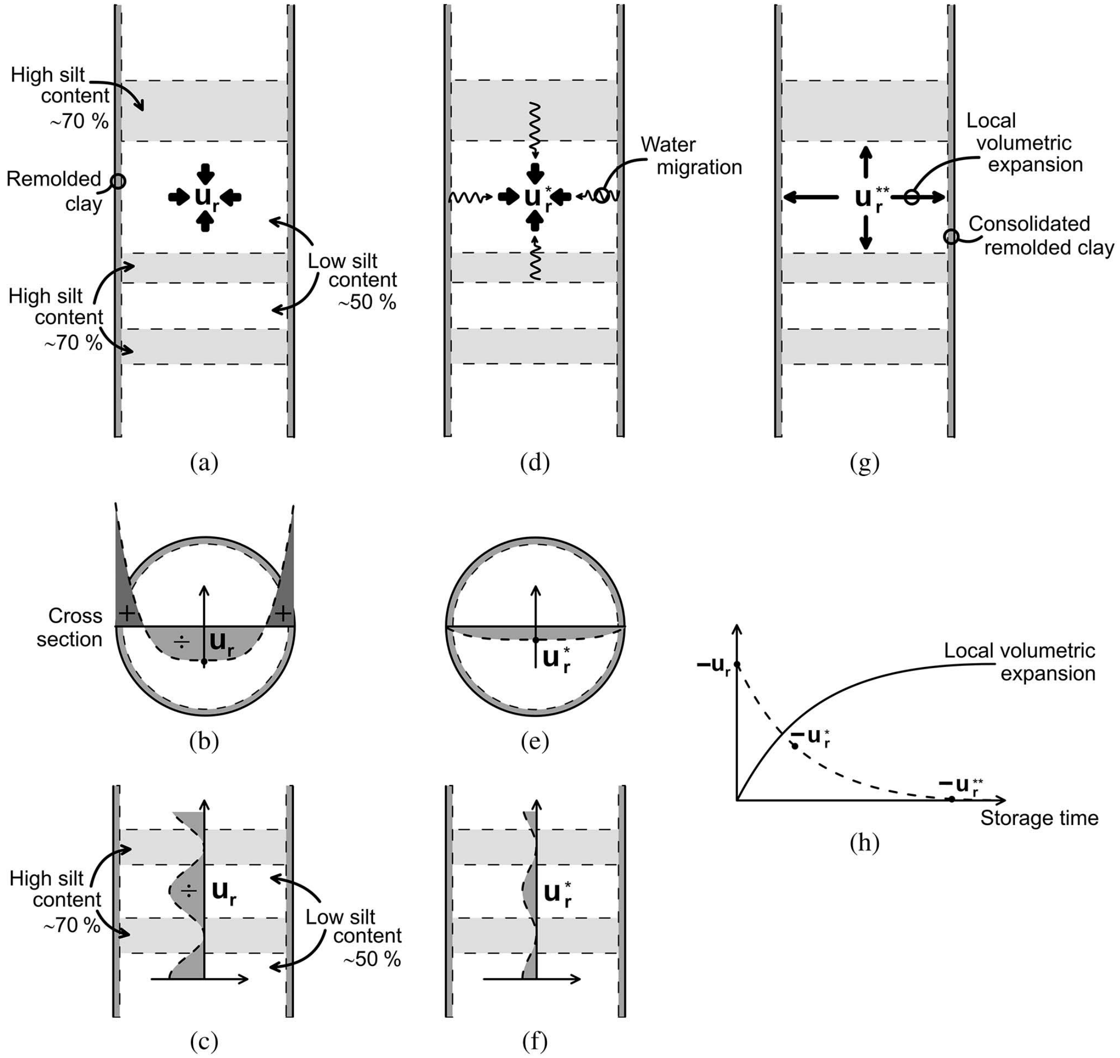
**FIG. 9** (a,b) Longitudinal water migration in stored samples and (c,d) its effects on CRS oedometer test results. Initial water content is presented as mean values of several samples that were tested at the sampling day.



layers of coarser material. In fact, the Tiller clay consists of many thin shifting clay layers with different index properties. For instance, Amundsen et al. (2017) showed that within a distance of less than 5 cm, the natural water content decreased from 46 % to 34 %, the silt content increased from 42 % to 58 %, and the plasticity index decreased from 13 % to 9 %. Since there is such rapid variation, localized water migration within the sample could be a possible explanation for the observed degradation of sample quality during storage.

Fig. 10 illustrates a hypothetical idealized sketch of a layered saturated sensitive clay sample in a thin-walled 54-mm diameter tube immediately after sampling as well as during storage. A longitudinal section of the tube in Fig. 10a shows a zone of remolded clay at the periphery of the sample, which is caused by the sampling tube. The remolded clay

**FIG. 10** Sketch of pore water pressure equalization within a layered saturated sensitive clay as a longitudinal and cross section of a sampling tube during storage. (a,c) Immediately after sampling, (d,f) shortly after sampling, and (g) during long-term storage. (h) An idealized dissipation of the residual pore water pressure ($u_r$), with accompanying local volumetric expansion, during storage.



contains free water with presumably positive pressure, as shown in a cross-section of the tube in **Fig. 10b**. The undisturbed core develops a negative pore pressure (residual pore pressure, $u_r$) as a reaction to the reduction of the total stresses after sampling. Theoretically, the negative pore pressure in the sample after unloading should be equal to the in situ mean effective stress (Ladd and Lambe 1963). However, the measured values of the residual pore pressure in natural clays are much lower (Amundsen et al. 2017). This is especially true for a layered material with coarse grained layers, wherein the pore pressure is close to zero (see **Fig. 10c**).

The distance between regions of the sample cross-section with positive and negative pore pressure is very short in a 54-mm diameter tube (see **Fig. 10b**). Therefore, the migration of water, which starts immediately after the sampling, may occur quickly, as was observed in the Tiller clay in **Fig. 8a** and **b**. The undisturbed core pulls in water from the surroundings and expands while the remolded clay reconsolidates (see **Fig. 10d** and **g**). During the volumetric expansion of the undisturbed core, the negative pore pressure dissipates (see **Fig. 10e** and **f**) shortly after the sampling, as was measured during field tests in high-sensitivity clays (Schjetne 1971 and Amundsen et al. 2017). **Fig. 10h** illustrates a hypothetical decrease in residual pore pressure with local volumetric expansion during storage.

The described hypothesis for the development of disturbance during storage emphasizes that even when a sampling tube is completely sealed, the sample will not be stored undrained. In fact, the pore pressure gradient will induce water migration, resulting in local volumetric changes that will inflict further disturbance. The volumetric changes in the soil structure during storage will cause destructuration and result in poorer sample quality. This effect is time dependent and may occur during short- or long-term storage, depending on the type of soil and its properties, such as permeability and stress history. Graham and Lau (1988) showed, with reconstituted clay samples, that even a short drained storage of 1–7 days could rapidly reduce the $c_u$ and induce poorer sample quality. It is possible to reduce this effect by using a large diameter sampler. However, stress relief will unavoidably occur, and the inhomogeneity of the natural clays may contribute to the water migration, causing the material to swell.

An attempt was made to measure the residual pore pressure in the reference samples just after sampling, with a low air entry ceramic stone. However, most of the measured values were very low or zero. The best response was found to be about −4 kPa, similar to the in situ test measurements in the Tiller clay (Amundsen et al. 2017). These observations, together with the measured water migration along the cross-section of the sample (see **Fig. 8a** and **b**) and its inhomogeneity (Amundsen et al. 2017), confirm that the described mechanism of internal water migrations and pore pressure equalization can be a reasonable explanation for the rapid deterioration of the quality of QC samples (see **Figs. 1**–**3**).

## Discussion – Restructuration of Clay Samples during Storage

The microstructure of natural clay develops over time during the post-deposit processes, because of the combined effects of consolidation, thixotropy, cementation, etc. (e.g., Leroueil et al. 1979; Tavenas and Leroueil 1987; Leroueil and Vaughan 1990; Leroueil and Hight 2002). The microstructure can be damaged during, e.g., sampling by shear and volumetric strains, and destructing can occur, which leads to a decrease in stiffness and peak strength, as well as an increase in compressibility (Leroueil et al. 1979). Over time, however, a destructured material may recover some of its structure without any major changes in water content (Leroueil and Vaughan 1990).

Destructuring of the Tiller clay samples has been observed during the short-term storage (see **Fig. 4**); however, during the long-term storage, the observed trends indicate restructuring of the soil with time. The signs of restructuring are visible in the triaxial test results of the QC, where $c_u$ increases with storage after a large destructuring during the short-term storage (see **Fig. 4a**). The $M_0$ modulus from the oedometer tests of the LSC samples increases (see **Fig. 4d**) together with the assessed sample quality (see **Fig. 3b**). However, based on the reducing $\sigma'_c$ (see **Fig. 4c**), the soil is restructuring to a lower stress state and will not be completely restored within the time of laboratory testing (Casagrande 1932).

A negative effect of restructuring was observed during the extrusion of samples that had been stored for longer than five months. It was more difficult to extrude an intact sample from the sampling tube because of the soil in the outer zone of the sample becoming attached to the tube. The extrusion caused additional sample disturbance, which reduced the $c_u$ (FC) of the clay (see **Fig. 7a**).

## Conclusions

The effects of storage will develop based on the amount of initial disturbance a sample has experienced during sampling and its inhomogeneity. A shallow sample of LSC of medium/high plasticity experiences less disturbance than a deep QC sample of low plasticity. The amount of remolded and destructured soil, along with the pore pressure gradients that develop within the tube during the sampling, will determine how quickly any significant storage duration effects will occur. The samples will simply not be stored completely undrained, and the water migration within the sampling tube will inflict further disturbance. In general, it is not recommended to postpone the laboratory testing of soil samples.

The sample quality has been observed to decrease quickly in stored QC samples, which has a negative effect on the peak undrained shear strength, preconsolidation pressure, and $M_0$ modulus. It is therefore recommended to open and test samples of normally or lightly overconsolidated QC of low plasticity during the sampling day. A storage period of a month or more can cause significant reduction in sample quality and geotechnical parameters of low-plasticity QC samples. The quality of the overconsolidated LSC samples of medium plasticity has a decreasing tendency during storage, but the negative effect on the geotechnical properties is less significant compared to the QC samples. The change in the geotechnical properties of the LSC during storage is smaller than the range of natural variation in reference samples. This allows for longer storage duration of three to five months for the LSC samples. The major results are summarized in **Table 6**.

The LSC and QC samples may be stored in airtight sealed tubes for a longer period if only parameters, such as the remolded shear strength, water content, and Atterberg limits, need to be determined. These properties are independent of the soil structure and are not influenced by the disturbance or restructuring. However, these properties will be influenced by changes in the pore water chemistry; therefore, sampling tubes with an air gap between the soil and the sealing cap or extruded samples should be tested as soon as possible. Storage of extruded samples is not recommended, but if it is unavoidable, one should seal the sample or the specimen airtight to avoid any loss of water. Poorer sample quality could be expected from the stored extruded samples or specimens, especially when testing normally consolidated sensitive clays of low plasticity.

**TABLE 6**

Effect of storage on geotechnical properties of the Tiller clay.

| | Short-Term Storage, <5 months | | Long-Term Storage, >5 months | |
|---|---|---|---|---|
| Parameters | LSC | QC | LSC | QC |
| $\sigma'_c$ | ↓ 1–8 % | ↓ 2–17 % | ↓ 1–14 % | ↓ 11–23 % |
| $M_0$ | ↓ 6–46 % | ↓ 23–56 % | ↑ 6–23 % | ↓ 9–28 % |
| $\Delta e/e_0$ | ↑ 0–22 % | ↑ 22–65 % | (↓ 12–21 %) | ↑ 8–71 % |
| $c_u/\sigma'_{v0}$ | ↓ 4–7 % | ↓ 18–29 % | ↓ 12–13 % | ↓ 14–19 % |
| $\Delta e/e_0$ | – | ↑ 17–37 % | – | ↑ 24–94 % |
| $\varepsilon_f$ | – | ↑ 2–57 % | – | ↑ 16–99 % |

Based on the observations in this study, the following remarks can be drawn:

- Soil samples should be sealed airtight and stored inside the sampling tubes at in situ temperature.
- Triaxial and oedometer tests should preferably be performed on the same day as the sampling, as this will minimize the storage effects. If this is not possible, one should be aware that the sample quality degrades with time.
- It is recommended to test QC samples within 1–2 weeks. If possible, one should avoid storage times longer than a month.
- Testing the soil samples at a field laboratory should be considered when sampling soils that are vulnerable to disturbance.
- LSC samples can be stored for up to 1–4 months.
- The friction angle and cohesion are less affected by sample disturbance than the peak undrained shear strength.
- The preconsolidation pressure can be found even though the sample has some degree of disturbance, but it will be lower than for a sample tested shortly after sampling. The $M_0$ modulus will be significantly altered.
- Tests that do not require an intact soil structure can be performed even after prolonged storage times.

The authors would like to emphasize that these remarks are valid for the studied material and that the effects of storage are visible in samples of initially good quality. In disturbed samples, the effect of storage may not be seen.

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