Effect of Temperature on Measured Strength Parameters from Variations in Both Storage and Testing Temperatures

Kathrine Buene Gangenes

Civil and Environmental Engineering
Submission date: July 2017
Supervisor: Gustav Grimstad, IBM
Co-supervisor: Arnfinn Emdal, IBM
Tom Lunne, NGI

Norwegian University of Science and Technology
Department of Civil and Environmental Engineering
# Abstract:

The effect of temperature on laboratory tested mechanical properties of clay has been debated for many years. The fact that soil parameters are affected by variations in temperature is generally agreed upon, resulting in recommendations regarding storage of sampled test specimens. Decrease of testing temperature has been shown to have a significant effect, with increases in preconsolidation pressure ($p_c$) and $(s_u)$ of around 10% per 10°C. As of yet, there are no standardized corrections or recommendations made towards testing temperatures used.

In this work tests have been performed on cohesive clay samples from the Lilleby site in Trondheim, Norway. Selected index tests, CRSC oedometer tests and CAUC triaxial shear tests have been run in parallel, for two different storage periods, storage temperatures, and test temperatures. By examining trends across these permutations of the test environment, the goal has been to provide additional data on clay used in a typical construction projects.

The results of this work show clearly that the testing temperature has an effect on measured mechanical properties, on the order of 9% for $p_c$ and 6% for $s_u$. The effects of storage temperature are less pronounced, and the same is the case for the storage duration. Findings are discussed in the context of previous literature, and some recommendations for further work are made.

# Keywords:

1. Effect of temperature
2. Strength parameters
3. Lilleby
4. Mini-block samples

Katherine Buene Gangenes
MASTER DEGREE THESIS

Spring 2017

for

Kathrine Buene Gangenes

EFFECT OF TEMPERATURE ON MEASURED STRENGTH PARAMETERS FROM VARIATIONS IN BOTH STORAGE AND TESTING TEMPERATURES.

BACKGROUND

During sampling, transportation, storage and laboratory testing of soil material, the specimens are often subjected to temperature variations from in situ temperatures to room temperatures. Determined soil parameters are affected by temperature variations, where soil strength may decrease approximately 10% with a 10 degrees’ Celsius increase in temperature. Some research on the field has been done by i.e. Norwegian Geotechnical Institute (NGI) on both reconstituted clay and clay from various consulting projects. The aim of this master thesis is to supplement this research by studying temperature effect on a clay sampled from the Lilleby site using the mini-block sampler.

TASK

Parallel undrained triaxial compression tests and constant rate of strain consolidation tests with two different testing temperatures, storage lengths and storage temperatures are to be executed. NTNU’s climate room is used for this. Storage durations are approximately 0 and 170 days. Both storage and testing temperatures are either close to in situ temperatures of 6 degrees Celsius, or close to normal room temperatures of 21 degrees Celsius. Some index tests on Atterberg limits and shear strengths from falling cone tests are also to be performed for both storage durations, and storage and testing temperatures.

The thesis will be presented as a scientific report using the introduction, methods, results, and discussion (IMRaD) organizational structure. Test results of all tests performed are added as attachments.

Professor in charge:
Gustav Grimstad (NTNU)

Other supervisors:
Tom Lunne (NGI) and Arnfinn Emdal (NTNU)

Department of Civil and Environmental Engineering, NTNU
Date: 11.01.2017 (revised: 15.06.2017)
Preface

The work presented in this report makes up my master thesis within geotechnical engineering, as part of a master degree in civil engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim, Norway. The subject of this work was initiated in cooperation with Section Head Morten A. Sjursen and Expert Adviser Tom Lunne at Norwegian Geotechnical Institute (NGI), and Professor Gustav Grimstad at NTNU. This master thesis constitutes a work load of 30 SP credits, or one semester of study.

The subject of this thesis is to supplement recent research associated with NGI by examining the effects of temperature on soft clay samples from Lilleby. The samples were extracted using the mini-block sampler developed by the Geotechnical Division at NTNU. Testing was performed in the division's climate room, to ensure a controlled environment. Professor Gustav Grimstad has served as the primary advisor, with additional supervisors NGI Expert Adviser Tom Lunne and Assistant Professor Arnfinn Emdal.

The work was carried out during the spring semester of 2017, in the period from the 15th of January until the 9th of July. While originally due the 11th of June, complications with laboratory test equipment, causing a delay of two months devoted to troubleshooting problems, and delivery was therefore postponed for one month.

What was intended as a short period of familiarizing myself with test equipment and procedures, very soon became a prolonged process of repeated troubleshooting, attempted mending and retesting. Much of the equipment, the triaxial test apparatus in particular, had a number of defects, such as multiple leakages, blockages, apparent motor problems, software errors, measuring artifacts, and more. In addition, due to problems with determining the eigen deformation of the original CRS oedometer compression apparatus placed in the climate room,
this device needed to be sent to an external workshop and needed replacement. These problems were compounded by the fact that most of the equipment had to be stationed in the climate room.

Trondheim, 2017-07-08

[Signature]

Kathrine Buene Gangenes
Acknowledgements

I would like to thank my supervisor, Professor Gustav Grimstad, for all his assistance, guidance and constructive discussion related to both artifacts and results found during troubleshooting and official laboratory testing. Assistant Professor Arnfinn Emdal has also assisted greatly with understanding deviations and challenges with equipment and calculations. A special thanks to NGI Expert Adviser Tom Lunne for his invaluable help and support throughout the semester, showing remarkable attentiveness in spite of the geographical distance between us.

Several other faculty members at NTNU have been available for questioning during my troubleshooting period, providing interesting and useful suggestions and help on where to start solving the many problems encountered. Special thanks to Senior Engineer Per A. Østensen for invaluable help during the troubleshooting of software and equipment, and Senior Engineer Karl I.V. Kvisvik and Staff Engineer Espen Andersen for extracting my mini-block samples, giving guidance on handling laboratory test equipment and procedures, and helping with replacing pieces of equipment. I would also like to thank Phd. Candidate Helene A. Amundsen for many useful and worthwhile hints and recommendations on understanding and solving artifacts encountered.

My studies at NTNU would not have been the same without the many dear friends and fellow students I’ve been surrounded by. My last year ”was a blast”, much due to “Geogjengen 2017” and the wonderful environment we have had both outside and inside the study halls. A special thanks goes to Anders Lindgård and Christian S. Oftstad for valuable discussions and camaraderie during this masters period, especially during hard times in the climate room.

I would also like to thank my family and friends for supporting me and keeping me motivated during my studies, especially my parents Kjellaug and Jørgen Eivind, whom I would never have reached this far without. A huge thanks to my
dear and close friend Susanne for support and proofreading.

Finally, I would like to thank my best friend and boyfriend Olav Emil, for exce-
ceptional help and guidance with streamlining the presentation of large amounts
of data in \LaTeX{}. His assistance during the opening of the two latter block samples
was also invaluable, as well as the amount of general support and guidance he
has given me throughout both good and hard times. Lastly, he has provided
tremendous patience and support regarding structuring and proofreading for this
report.
Summary

The effect of temperature on laboratory tested mechanical properties of clay has been debated for many years. The fact that soil parameters are affected by variations in temperature is generally agreed upon, resulting in recommendations regarding storage of sampled test specimens. Decrease of testing temperature has been shown to have a significant effect, with increases in $p'_c$ and $s_u$ of around 10% per 10°C. As of yet, there are no standardized corrections or recommendations made towards testing temperatures used.

In this work tests have been performed on cohesive clay samples from the Lilleby site in Trondheim, Norway. Selected index tests, CRSC oedometer tests and CAUC triaxial shear tests have been run in parallel, for two different storage periods, storage temperatures, and test temperatures. By examining trends across these permutations of the test environment, the goal has been to provide additional data on temperature effects on clay used in typical construction projects.

The results of this work show clearly that the testing temperature has an effect on measured soil properties, on the order of 9% for $p'_c$ and 6% for $s_u$. The effects of storage temperature are less pronounced, and the same is the case for the storage duration. Findings are discussed in the context of previous literature, and some recommendations for further work are made.
Sammendrag

Effekten av temperatur på laboratoriemålte mekaniske egenskaper av leire har vært oppe for debatt i flere år. Det faktum at jordparametre blir påvirket av temperaturvariasjoner er generelt akseptert, noe som har resultert i anbefalinger angående lagringstemperatur av opptatte leirprøver. Det er kjent at en reduksjon i testtemperatur har en tydelig effekt, hvor verdier for $p'_c$ og $s_u$ kan øke rundt 10% per 10 °C endring i temperatur. Det finnes ennå ingen standardiserte korreksjoner eller anbefalinger med tanke på hvilke testtemperaturer som brukes.

Formålet med oppgaven er å gjennomføre utvalgte rutineundersøkelser, CRSC ødometerforsøk og CAUC treaksielle skjærerforsøk på leire fra et anleggsområdet på Lilleby i Trondheim. Ved å utføre parallele forsøk på to ulike temperaturer for to ulike lagringslengder med to ulike lagringstemperaturer, har målet med oppgaven vært å bidra med ytterligere data om temperatureffekt på typisk leire man møter på i anleggsarbeid.

Resultatene fra arbeidet som er gjennomført viser tydelig at testtemperaturen har en effekt på målte verdier for ulike jordparametre, med rundt 9% økning for $p'_c$ og rundt 6% for $s_u$. Effekten av lagringstemperatur er langt mer begrenset, i likhet med effekten sett for lagringstid. Observasjonene blir diskutert i kontekst av tidligere litteratur om omnet, og noen anbefalinger for fremtidig arbeid gis.
Contents

Acknowledgements iii
Summary v
Sammendrag vii

1 Introduction 1
  1.1 Problem Formulation . . . . . . . . . . . . . . . . . . . . . . . . . . 2
  1.2 Outline . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 3

2 Background 5
  2.1 State of the art . . . . . . . . . . . . . . . . . . . . . . . . . . . . . 6

3 Sample quality 11
  3.1 Material classification . . . . . . . . . . . . . . . . . . . . . . . . . . 11
  3.2 Sources of disturbance . . . . . . . . . . . . . . . . . . . . . . . . . . 13
    3.2.1 Effect of storage time . . . . . . . . . . . . . . . . . . . . . . . 15
  3.3 Sample disturbance . . . . . . . . . . . . . . . . . . . . . . . . . . . 15

4 Methodology 19
  4.1 Sampling and storage . . . . . . . . . . . . . . . . . . . . . . . . . . . 19
    4.1.1 Mini-block samples from Lilleby . . . . . . . . . . . . . . . . . 22
  4.2 Opening of mini-block samples . . . . . . . . . . . . . . . . . . . . . 24
  4.3 Laboratory testing . . . . . . . . . . . . . . . . . . . . . . . . . . . . 28
    4.3.1 Water content testing . . . . . . . . . . . . . . . . . . . . . . . 32
    4.3.2 Atterberg limits . . . . . . . . . . . . . . . . . . . . . . . . . . . 33
    4.3.3 Fall cone testing . . . . . . . . . . . . . . . . . . . . . . . . . . . 38
CONTENTS

4.3.4 CRSC oedometer testing ........................................ 39
4.3.5 CAUC triaxial shear testing ..................................... 47

5 Test results ................................................................. 59
5.1 Water content results .................................................. 60
5.2 Atterberg limit results .................................................. 61
5.3 Fall cone test results .................................................... 62
5.4 CRSC oedometer test results ......................................... 64
5.5 CAUC triaxial test results ............................................. 68

6 Discussion ................................................................. 73
6.1 Heterogeneity of Lilleby clay ......................................... 73
6.2 Index tests ............................................................... 75
6.3 CRSC oedometer tests .................................................. 77
6.4 CAUC triaxial shear tests .............................................. 82

7 Conclusion ................................................................. 93
7.1 Summary and conclusion .............................................. 93
7.2 Further work ............................................................. 95

Appendices ................................................................. 99
A Index tests ............................................................... 101
B Oedometer tests ......................................................... 105
C Triaxial tests ............................................................. 165
List of Figures

2.1 Results on $s_u$ and $p'_c$, presented by Lunne, Gue, Perkins and Selvig (2012) .................................................. 8
2.2 Results on $s_u$ and $p'_c$, presented by Gue, Lunne and Perkins (2015) .............................................................. 10

3.1 Sherbrooke block sampling versus 54mm piston sampling (Lunne, Berre, Andersen, Strandvik & Sjursen, 2006) ................. 14

4.1 The mini-block sampler used for this work, presented by Emdal, Gylland, Amundsen, Kåsin and Long (2016) .................. 20
4.2 Mini-block samples wrapped and encased for transportation and storage ........................................................................ 21
4.3 Difference in sample diameter and traces of stones were a common sight ...................................................................... 23
4.4 Subdivision and storage of MBS slice and specimens ......................................................................................... 25
4.5 Scheme of subdivision of mini-block samples used in this work ........................................................................ 26
4.6 Schematic of subdivision of quarter slices and triaxial test specimens ................................................................. 28
4.7 Water content equipment ................................................................................................................................. 33
4.8 Extracting representative samples for testing $w_0$ from MBS slices ................................................................. 33
4.9 Schematic of relevant consistency/Atterberg limits ......................................................................................... 34
4.10 Liquid limit equipment ........................................................................................................................................ 35
4.11 The Casagrande device used to determine percussion liquid limits ................................................................... 36
4.12 Plastic limit equipment ........................................................................................................................................ 37
4.13 Spreading the clay either on a glass plate or a ceramic tile for drying ...................................................................... 37
4.14 Cone test equipment ............................................................................................................................................ 38
4.15 Determining shear strengths of undisturbed and remoulded samples ...................................................................... 39
4.16 Most equipment for preparation and testing of CRSC oedometer specimens. ........................................ 40
4.17 Unfastened oedometer base for better control of porous filter placement. ........................................ 43
4.18 Evaluating $p'_c$ for CRSC_3 from MBS_1 using lin. and log. $\sigma'_v - \varepsilon_a$ plots. ............................... 44
4.19 Evaluating $p'_c$ for CRSC_3 from MBS_1 using $\sigma'_v$, $\varepsilon_a$ and $M$. ........................................ 45
4.20 Determining $M_{OC}$ from a line through $p'_0$ and $p'_c$ in a $\sigma'_v - \varepsilon_a$ plot. ............................. 46
4.21 Determining $m$ and $p'_r$ from a line following NC behaviour in a $\sigma'_v - M$ plot. ............................... 47
4.22 Triaxial shear test equipment as used in testing of Lilleby clay. ....................................................... 50
4.23 Quarter pieces of triaxial MBS slices during subdivision and storage. .............................................. 52
4.24 Most equipment for preparation and mounting of CAUC specimens. .............................................. 53
4.25 Mounting of a CAUC test specimen onto the triaxial test base. ....................................................... 54
4.26 Figurative explanations of procedures used during CAUC triaxial testing. ....................................... 55
4.27 Determining attraction intersection and slope of the failure line. ..................................................... 58
5.1 Determined $p'_c$ values from all CRSC tests of Lilleby clay. ............................................................... 64
5.2 $\sigma'_v - \varepsilon_a$ plot of all CRSC tests from both depths in MBS_2. ....................................................... 66
5.3 Determined $s_u$ values from all CAUC tests of Lilleby clay. .............................................................. 68
5.4 NTNU plot for all triaxial shear tests performed. ..................................................................................... 69
6.1 Examples of stones and silt and sand layers in the Lilleby clay. ......................................................... 74
6.2 There is substantial difference in clay composition for different depths. ............................................. 75
6.3 $\sigma'_v - \varepsilon_a$ plots showing the CRSC tests from both depths in MBS_1. ........................................ 79
6.4 Some challenges encountered during CRSC oedometer compression testing. .................................. 80
6.5 Diagram showing showing different CAUC consolidation behaviours for MBS_4. .......................... 84
6.6 Periodic “ticks” are seen for both test specimens CAUC_9 and 10. .................................................... 85
6.7 NTNU-plot and stress-strain plots for CAUC tests from MBS_3. ....................................................... 86
6.8 Challenges with MBS_3 due to it’s bend and narrow diameter. .......................................................... 87
6.9 Stress paths of all CAUC test specimens from MBS_2 ....................................................................... 88
6.10 Significant difference in development of $u$ for CAUC_5. ................................................................. 89
6.11 Different failure modes for the three CAUC specimens from MBS_2. 90
6.12 CAUC_9 and 10 indicating negative values of $a$ for observed failure lines. ................................. 91
List of Tables

3.1 Plasticity for typical Norwegian clays (Norsk Geoteknisk Forening, 2011) ................................................................. 12
3.2 Sensitivity for typical Norwegian clays (Norsk Geoteknisk Forening, 2011) ................................................................. 13
3.3 Evaluation of sample quality based on $\varepsilon_V$ (Andresen & Kolstad, 1979) ................................................................. 16
3.4 Evaluation of sample quality based on $\Delta e/e_0$ (Lunne, Berre & Strandvik, 1997) ................................................................. 17

4.1 Detailed information on sampling and storage of the mini-block samples used ................................................................. 24
4.2 Planned laboratory program for the different block samples in this thesis ................................................................. 29
4.3 Overview of storage and testing temperatures of all test types performed ................................................................. 30
4.4 Overview of temperature and humidity during testing of mini-block samples ................................................................. 32

5.1 Laboratory program for the different mini-block samples ................................................................. 59
5.2 Results from Atterberg limit tests ................................................................. 62
5.3 Results from fall cone tests ................................................................. 63
5.4 Results from CRSC oedometer tests ................................................................. 67
5.5 Results from CAUC triaxial shear tests ................................................................. 71
<table>
<thead>
<tr>
<th>Table 1</th>
<th>Description of Variable Definitions</th>
<th>Page 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2</td>
<td>Analysis of Historical Data</td>
<td>Page 2</td>
</tr>
<tr>
<td>Table 3</td>
<td>Comparison of Results</td>
<td>Page 3</td>
</tr>
<tr>
<td>Table 4</td>
<td>Summary of Findings</td>
<td>Page 4</td>
</tr>
</tbody>
</table>
# List of Symbols

## Roman letters

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>Attraction</td>
</tr>
<tr>
<td>$A_0$</td>
<td>Initial specimen area</td>
</tr>
<tr>
<td>$A_a$</td>
<td>Specimen area during/after consolidation</td>
</tr>
<tr>
<td>$A_s$</td>
<td>Specimen area during/after shear</td>
</tr>
<tr>
<td>$c_v$</td>
<td>Coefficient of consolidation</td>
</tr>
<tr>
<td>$e$</td>
<td>Void ratio</td>
</tr>
<tr>
<td>$e_0$</td>
<td>Initial void ratio</td>
</tr>
<tr>
<td>$H$</td>
<td>Specimen height</td>
</tr>
<tr>
<td>$H_0$</td>
<td>Initial specimen height</td>
</tr>
<tr>
<td>$H_{e0}$</td>
<td>Specimen height at $\sigma_{e0}' = p_{0}'$</td>
</tr>
<tr>
<td>$i$</td>
<td>Pore water gradient</td>
</tr>
<tr>
<td>$I_L$</td>
<td>Liquidity index</td>
</tr>
<tr>
<td>$I_P$</td>
<td>Plasticity index</td>
</tr>
<tr>
<td>$K_0'$</td>
<td>At rest coefficient for effective stresses</td>
</tr>
<tr>
<td>$K_n$</td>
<td>Coefficient compensating for $w_n \neq w_L$</td>
</tr>
<tr>
<td>$M$</td>
<td>Tangent modulus/ oedometer modulus</td>
</tr>
<tr>
<td>$m$</td>
<td>Modulus number</td>
</tr>
<tr>
<td>$m_d$</td>
<td>Mass of dry specimen</td>
</tr>
<tr>
<td>$M_{OC}$</td>
<td>Average tangent modulus/ oedometer modulus between $p_{0}'$ and $p_{c}'$</td>
</tr>
<tr>
<td>$m_s$</td>
<td>Mass of wet specimen</td>
</tr>
<tr>
<td>$M_{e0}$</td>
<td>Tangent modulus/ oedometer modulus at $\sigma_{e0}' = p_{0}'$</td>
</tr>
<tr>
<td>$m_w$</td>
<td>Mass of free water</td>
</tr>
<tr>
<td>$p'$</td>
<td>Effective mean stress</td>
</tr>
<tr>
<td>$p_{0}'$</td>
<td>Initial effective overburden pressure/stress ($p_{0}' = \sigma_{e0}'$ )</td>
</tr>
<tr>
<td>$p_{c}'$</td>
<td>Effective preconsolidation pressure/stress</td>
</tr>
<tr>
<td>$p_{r}'$</td>
<td>Effective reference pressure/stress</td>
</tr>
</tbody>
</table>
Deviatoric stress

Slope of failure line in a $\sigma'_r$ vs. $0.5(\sigma'_a - \sigma'_r)$ plot

Remoulded shear strength/stress

Sensitivity

Remoulded shear strength/stress

Temperature, in °C

Pore water pressure

Pore water pressure at base

Specimen volume

Initial specimen volume

Water content

Initial/natural water content

Water content at liquid limit after $n$ drops

Liquid limit

Plasticity limit

Depth below surface terrain

Greek letters

Unit weight of soil

Adjusted unit weight of soil

Effective unit weight of soil

Unit weight of solids

Unit weight of water

Implies change in a parameter

Vertical deformation

Strain

Axial strain

Strain at failure ($\tau_{max}$).

Volumetric strain

Pore pressure ratio

Density

Density of solid particles

Total stress

Total vertical stress

Effective vertical stress

Maximum effective principal stress

Minimum effective principal stress

Axial effective confining stress
$\sigma'_{r,c}$  Radial effective confining stress
$\sigma'_{v0}$  Initial vertical effective stress
$\tau$  Shear stress
$\tau_{max}$  Maximum shear stress
$\phi$  Friction angle

**Abbreviations**

*MBS*  Mini-Block Sample(s)
*CAUC*  “Consolidated Anisotropic, Undrained Compression”
*CRSC*  “Constant Rate of Strain, Compression”
*LVDT*  Linear Variable Differential Transformer
*NC*  Normally Consolidated
*OC*  Over Consolidated
*OCR*  Overconsolidation Ratio
Chapter 1

Introduction

During sampling, transportation, storage, and laboratory testing of soil specimens, the soil material is often subjected to significant variations in temperature. Soils from a few meters depth and below often hold mean annual ground temperatures of 6-7°C. Temperatures in standard geotechnical laboratories, on the other hand, are often near room a temperature of 21°C. This results in a difference in temperature of approximately 15°C from extraction to testing.

Due to the often limited capacity at geotechnical laboratories, clay specimens are often stored for periods ranging from several days to a few months. Some recent reports and guidance papers mention storage temperature as an element causing significant effects seen from storage durations on test results (L’Heureux & Kim, 2014), and recommend keeping a storage temperature matching in situ conditions (Norsk Geoteknisk Forening, 2013). As of yet, there are no standardized corrections or recommendations made towards testing temperature.

Already in the 1960’s, studies on the importance of testing temperature were conducted, and while its effects on test results were acknowledged even then, appropriate measures remain to be seen in geotechnical engineering practice. Recent studies in association with the Norwegian Geotechnical Institute (NGI) have worked to increase the understanding of the effects of both storage and testing temperature, finding significantly higher values for soil parameters when testing in temperatures closer to the in situ temperatures (Perkins & Sjursen, 2009; Lunne, Gue, Perkins & Selvig, 2012; Gue, Lunne & Perkins, 2015).

Leroueil and Marques (1996) collated large amounts of research data on tem-
perature effects published between the 1960’s and 1990’s. This resulted in a prospective factor of 10% increase in undrained soil strength and preconsolidation pressure for around 10 °C decrease in temperature. This is supported by results found by Perkins and Sjursen (2009), Lunne et al. (2012) and Gue et al. (2015) when mainly studying offshore clays. They conclude that more data will be needed to establish a correctional factor for general use.

The aim of this master thesis is to supplement this research by studying the effect of temperature on a clay sampled from the Lilleby site, using the mini-block sampler developed by the Geotechnical Division at NTNU. Parallel constant rate of strain compression tests and undrained triaxial shear tests are run for two different testing temperatures, storage lengths, and storage temperatures. Some index tests are also performed for both storage durations, and storage and testing temperatures.

Results for engineering soil properties such as preconsolidation pressures ($p'_c$) and undrained shear strengths ($s_u$) are evaluated, with the intent of revealing trends towards increased $s_u$ and $p'_c$ for test temperatures close to in situ temperatures, as well as for shorter storage durations. While the main focus has been on gathering more data, apparent trends are discussed along with issues encountered that might affect the results found. The findings are summarized, and some recommendations towards further work are made.

1.1 Problem Formulation

This report will present results from a laboratory test study on the effect of temperature from different storage and testing temperatures. Parallel tests of selected index tests, CRSC oedometer tests and CAUC triaxial shear tests are performed to evaluate the effect of temperature on laboratory measured soil properties including preconsolidation pressure ($p'_c$) and undrained shear strength ($s_u$). The low permeable, cohesive soil material that will be tested is a clay from a construction site at Lilleby, sampled using a mini-block sampler developed at NTNU.

Objectives

- Perform parallel fall cone, CRSC and CAUC shear tests on clay from the Lilleby site to determine engineering parameters including $p'_c$ and $s_u$
Run tests on multiple samples handled differently, in a climate room at NTNU, in order to:

1. Identify effects of testing temperatures on measured values, by performing tests on similar clay specimens with the climate room’s temperature set close to 6°C and 21°C.
2. Identify effects seen from storage temperatures, by testing samples stored at approximately 6°C and 21°C.
3. Identify differences measured for samples either stored approximately 170 days or freshly sampled.

- Evaluate plasticity of the clay, mapping water content and Atterberg limits for all samples.
- Evaluate sensitivity of the clay, mapping undrained and remoulded shear strengths for all samples.
- Discuss results while comparing against other recent studies on the same subject.

1.2 Outline

The main part of this thesis is outlined as follows:

Chapter 2 - Background presents some background on the effects of temperature, based on state of the art studies on the subject. And Chapter 3 - Sample quality presents information on soil classification and sample quality, also mentioning important factors affecting sample disturbance.

All test procedures and equipment are described in Chapter 4 - Methodology, while Chapter 5 - Test results presents the laboratory test results and notable trends.

Finally Chapter 6 - Discussion discusses the effects seen and compares the results against similar previous studies, before a summary, concluding remarks, and recommendations for further work follow in Chapter 7 - Conclusion.
Chapter 2

Background

Already in the 1940-1960’s the effect of temperature on engineering properties and behaviour was discussed and debated. The discussion on temperature and heat effects was especially active during the 1960s, culminating in an international conference on the subject and a *Highway Research Board Special Report* in 1969, organized by J.K. Mitchell and his committee. The work done by Mitchell and others have been important in later studies on temperature effects on laboratory tested engineering soil properties. After 1969, though, many studies did in large part focus on temperature cycles elevated above 20°C. Later studies done by NGI, among others, then go “back” to assessing temperature gradients between *in situ* and laboratory testing temperatures.

An extensive literature survey on several of the studies published since the 1960s was conducted by the author during the fall of 2016, in association with the Project Work building up to this master thesis. The backbone of that work was some of J. K. Mitchell’s introductory work on the effects of temperature during the 1960s, including Mitchell (1964) and Campanella and Mitchell (1968), as well as his latest issue of the book *Fundamentals of Soil Behaviour* (Mitchell & Soga, 2005). Important and pertinent studies including Leroueil and Marques (1996), Perkins and Sjursen (2009), Lunne et al. (2012) and Gue et al. (2015) were chosen and focused on during the concluding parts of the project work.

This chapter will give a quick presentation and summary of the most relevant studies selected during the literature survey conducted. The main focus will be on the parts describing the effects of temperature from Campanella and Mitchell
(1968) and in Mitchell and Soga (2005). Trends drawn and theories from the extensive research by Leroueil and Marques (1996) will also receive focus, together with some results and conclusions from the studies by Perkins and Sjursen (2009), Lunne et al. (2012) and Gue et al. (2015) mainly at NGI.

2.1 State of the art

J.K. Mitchell early hypothesized that an increase in temperature above normal for a soil specimen, would lead to a decrease in measured shear resistance if all other factors were held constant. This was based on his postulations on interparticle contacts and these particles’ resistance to relative displacements (Mitchell, 1964). Testing his hypothesis by running both drained and undrained triaxial compression tests on remoulded San Fransisco Bay mud between 4.7 °C and 31.4 °C provided results that led to the presentation of two major effects of temperature on soil (Campanella & Mitchell, 1968).

The first major effect mentioned by Campanella and Mitchell (1968) is the effect temperature variations have on more or less reversible thermal expansion and contraction of solid particles and pore water. The second effect is a physico-chemical structural modification between particles. This latter effect is an irreversible effect initiated by an increase above normal temperatures for a particular soil. An increase in thermal energy will cause a partial collapse of the soil structure due to reduced shear forces at interparticle contacts. Both these effects are explained in detail in both Campanella and Mitchell (1968) and Mitchell and Soga (2005) and will not be further explained here.

It is nevertheless recognized that, especially due to the latter effect, samples planned to be tested at temperatures close to in situ temperatures should not be subjected to higher temperatures, in order to ensure the values determined for laboratory tested engineering properties are as precise as possible. All temperatures applied to an extracted soil sample after sampling is thus of importance. Temperatures during transportation, storage and opening of samples should be as close to in situ temperatures as possible in order to achieve as representative values as possible when testing in cold temperatures.

Leroueil and Marques (1996) did extensive work on gathering information and examining the importance of strain rate and temperature effects in geotechnical engineering. Several papers and articles published over the years were skimmed before drawing lines and conclusions on the effects discussed. It was recognized
by Leroueil and Marques (1996) that viscous effects on undrained shear strength ($s_u$) and preconsolidation pressures ($p_c'$) of clays are important, and that an approximate change of 10% can be expected for both $s_u$ and $p_c'$ for a temperature change of about 12°C.

**Recent studies on the effect of temperature**

Regarding more recent studies on the temperature effect, Perkins and Sjursen (2009) start off with an extensive study of previous work published on the effect of temperature on soil properties, before presenting their study on the effect of cold temperature on properties of the unfrozen offshore Troll clay. They performed both CAUC triaxial shear tests and CRSC oedometer tests. All samples were stored for one to two weeks at 10-20°C before being moved to a humidity room at 7°C. Prior to testing, all samples were tempered in room temperature and tested with different temperature schemes. Perkins and Sjursen (2009) report a clear tendency of increased undrained shear strengths and preconsolidation pressures for decreases in testing temperatures. The specimens tested close to 0°C showed between 8 and 12% higher values of $s_u$ than the clay tested in room temperature. Average increase in $p_c'$ for colder testing temperatures was calculated to be about 30%. They also found a trend with decreasing values for the coefficient of consolidation $c_v$ with decreasing test temperatures. Lunne et al. (2012) estimated the decrease shown in $c_v$ from Perkins and Sjursen (2009) to be about 34%.

Lunne et al. (2012), in a joint industry research project (JIP) with Montana State University (MSU), did a study on temperature effects on laboratory measured strength for eight different soft clays. Both CAUC triaxial shear tests and CRSC oedometer tests on multiple test specimens from the eight different clays were performed. Both reconstituted clay and clay from various consulting projects both offshore and onshore were tested. The reconstituted clays had a very controlled temperature environment, while the clays used from various consulting jobs had less controlled environments. All clays had a testing program which included two to four different temperature scenarios each. The various alternate temperature scenarios used by Lunne et al. (2012) are briefly summarized below.

- stored and tested at low temperature (0.5°C, 5°C and 7°C)
- stored and tested at room temperature (21°C)
2.1. STATE OF THE ART

• stored at room temperature and tested at low temperature
• stored at low temperature and tested at room temperature

Results from tests run on the eight different clay types showed that any effects of change in temperature during the period of storage were small compared to the effect of change in testing temperature. This was mentioned for the results both of undrained shear strengths and preconsolidation pressures. Average increases with colder testing temperatures ranged between $2 - 40\%$ for values of $s_u$ from CAUC triaxial shear tests, and $9 - 38\%$ for values of $p'_c$ from CRSC oedometer tests. The overall average increase in $s_u$ was $25\%$ and $23\%$ for $p'_c$, giving double weight to the well controlled tests part of the JIP. Lunne et al. (2012) also found consistently lower values of $c_v$ with decreasing test temperatures, but no consistent value for this decrease is presented.

![Fig. 2.1: Results on $s_u$ and $p'_c$, presented by Lunne et al. (2012).](image)

Figure 2.1 presents both individual and value ranges for $s_u$ and $p'_c$ from all eight different soft clay types tested. The upper five clays shown with a gray background were the clays that had a highly controlled temperature environment both prior to and during testing. The lower three clays with white backgrounds
were clays from various construction projects that had environments with less controlled temperatures. Ranges are indicated with lines from the lowest to the highest value, while average values are presented with a circle.

The study on temperature effects on laboratory measured strength of soft clays by Gue et al. (2015) makes up the second part of the JIP between NGI and MSU initiated by Lunne et al. (2012). The paper by Gue et al. (2015) present results from series of advanced parallel testing on 15 different soft clays, both remoulded and sampled in connection with various consulting projects. Approximately half of these clays had well controlled temperature environments, whilst the clays from construction projects made up the other half and were not as well controlled. Both CAUC triaxial shear tests and CRSC oedometer tests were performed, using a testing program with temperature scenarios very similar to what was used in Lunne et al. (2012).

- stored and tested at low temperature (-1/0 °C, 0.5 °C, 3.5 °C, 5 °C and 7 °C)
- stored and tested at room temperature (21 °C)
- stored at room temperature and tested at low temperature
- stored at low temperature and tested at room temperature

Included in the test results presented for the CAUC triaxial and CRSC oedometer tests performed on the fifteen various soft clay types, are the results from Lunne et al. (2012). Values of \( s_u \) from CAUC tests ranged between 2 and 42%. The overall average change in \( s_u \) with decreasing test temperatures was 24% when giving double weight to the results from the well controlled tests that were part of the JIP. Values of \( p'_c \) ranged between 8 – 56% with an overall weighed average of 22%. Test results on \( s_u \) and \( p'_c \) are presented in Figure 2.2, in an extended version of the Figure 2.1 presented by Lunne et al. (2012). The same colour and symbol references are applicable here.

From these three studies on temperature effect on laboratory measured strength from soft clays, it is evident that there is a trend showing higher values of both \( s_u \) and \( p'_c \) for tests performed closer to in situ temperatures. Many of the test results presented by Perkins and Sjursen (2009), Lunne et al. (2012) and Gue et al. (2015) are of deep water, offshore, soft clays. These clays have larger temperature gradients from in situ conditions to laboratory conditions. It is therefore important to notice that the clays sampled from the onshore NGI test site Onsøy
in Fredrikstad, Norway, also show very high changes in $s_u$ and $p'_c$ with testing temperature.

Fig. 2.2: Results on $s_u$ and $p'_c$, presented by Gue et al. (2015).
Chapter 3

Sample quality

Clay material is not a homogenized granular system of particles. It is a rather complex structure of microscopically small, plate or needle shaped particles that can have several different particle arrangements. The structure of a clay is significantly affected by the rate and type of flocculation experienced during sedimentation (Mitchell & Soga, 2005). A clay where the outcome is a more open structure is more likely to suffer a partial collapse when affected by external forces. The degree of openness is instrumental in defining several properties of a clay sample, such as sensitivity and void ratio, and then also sample disturbance.

Classification of sampled material in terms of sensitivity and plasticity yields valuable information on the quality of a soil specimen. This chapter will start off by giving a short introduction to relevant classification systems of typical Norwegian clays. Thereafter some relevant sources that can lead to partial collapse of sampled clay will be discussed, before two methods of evaluating sample disturbance are presented. Experience show that caution during several stages of testing clay material is highly preferable to reduce the degree of disturbance and increase the quality of both the sample and the results gathered.

3.1 Material classification

There are several methods and procedures for evaluating sample quality of soil specimens. Basic observation of the specimens while they are opened and handled often yield useful basic information. Traces of the sedimentation history of the
clay is often visible in the layering of the clay. Non-clay material such as straws of grass, shell fragments and grains of sand or even larger stones are also often easily spotted, and could be good indicators of the quality of a specimen.

Index testing easily yields useful information about the quality of a material. In this thesis, data on the natural water content ($w_0$), the liquid limit ($w_L$), and the plastic limit ($w_P$) of each mini-block sample is gathered in order to evaluate the plasticity and the liquidity of the samples. The plasticity of a clay describes its tendency to maintain a shape after being deformed under a finite force. The property is highly affected by mineralogical composition, particle sizes and shapes, and organic substances and additives (Andrade, Al-Qureshi & Hotza, 2011).

The liquidity of a clay, on the other hand, describes its natural moisture condition. The liquidity index is therefore a useful tool in expressing and comparing consistencies of different clays, and is also stated to correlate well with compressibility, strength and sensitivity properties (Mitchell & Soga, 2005). Details on how to find and calculate both the plasticity index ($I_P$) and the liquidity index ($I_L$) is found in Subsection 4.3.2.

Fall cone penetration tests on undisturbed and remoulded clay samples are performed to determine the shear strength of both phases. From the ratio of these strengths one can evaluate the sensitivity ($S_t$) of a clay. The degree of sensitivity reflects the response of a soils shear strength to disturbance, and is an important tool in classifying a clay sample. A high $S_t$ value indicates that the clay is highly sensitive to structural damage. Details on how to perform a fall cone test, and determine the shear strengths and the sensitivity of a soil test, is presented in Subsection 4.3.3.

Table 3.1: Plasticity for typical Norwegian clays (Norsk Geoteknisk Forening, 2011).

<table>
<thead>
<tr>
<th>Classification of material</th>
<th>Classification of plasticity</th>
<th>Plasticity index $I_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less plastic</td>
<td>Low plasticity</td>
<td>$&lt; 10%$</td>
</tr>
<tr>
<td>Medium plastic</td>
<td>Medium plasticity</td>
<td>$10 - 20%$</td>
</tr>
<tr>
<td>Highly plastic</td>
<td>High plasticity</td>
<td>$&gt; 20%$</td>
</tr>
</tbody>
</table>

Norsk Geoteknisk Forening (2011) presents classification systems for both plasticity and sensitivity of typical Norwegian clays in a revised version of a 1982 issue. These are recreated in tables 3.1 and 3.2, ranging both the material and the properties from low to high.
Table 3.2: Sensitivity for typical Norwegian clays (Norsk Geoteknisk Forening, 2011).

<table>
<thead>
<tr>
<th>Classification of material</th>
<th>Classification of sensitivity</th>
<th>Sensitivity $S_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less sensitive</td>
<td>Low sensitivity</td>
<td>$&lt; 8$</td>
</tr>
<tr>
<td>Medium sensitive</td>
<td>Medium sensitivity</td>
<td>$8 – 30$</td>
</tr>
<tr>
<td>Highly sensitive</td>
<td>High sensitivity</td>
<td>$&gt; 30$</td>
</tr>
</tbody>
</table>

### 3.2 Sources of disturbance

The type of equipment and procedure used during extraction has a large influence on the quality of a sample. In addition, the handling of the sample during transport and storage, as well as during opening, trimming and testing, is of significant importance. Disturbances resulting from the extraction of soil samples have been subject to extensive research for decades. Several studies on the matter have contributed heavily to the type of procedures used in sampling, handling and testing samples today (L’Heureux & Kim, 2014).

Experience from sampling and testing of undisturbed clay shows that using a mechanically carving block sampler like the one developed at the Sherbrooke University by Lefebvre and Poulin (1979) results in a far better sample quality than most other current sampling methods (Lunne, Berre & Strandvik, 1997; Lunne, Berre, Andersen, Strandvik & Sjursen, 2006; Amundsen, 2012; L’Heureux & Kim, 2014). Figure 3.1 shows the results from one of these studies, where Lunne et al. (2006) did tests on Daneviksgate and Onsøy clays that were sampled by both a Sherbrooke block sampler and a NGI 54mm piston sampler.

It is critical to have the best possible sample quality when performing tests on soil strength. Measured mechanical properties do in large part depend on the intactness of the soil structure. The importance of sample quality is of even greater importance when studying the effect of change in temperature. To be able to see the effect of temperature, and give greater confidence in the results, it is important that all other influencing factors are reduced as much as possible. Because it is unlikely that all other sources of disturbance can be removed, as they are difficult to separate and distinguish, the best effort possible is to take any necessary precautions and handle the soil specimens with utmost care and caution (L’Heureux & Kim, 2014).

A mini-block sampler developed by the Geotechnical Division of NTNU has been used in the extraction of clay samples for this master thesis. This sampler
Fig. 3.1: Sherbrooke block sampling versus 54 mm piston sampling (Lunne et al., 2006).

has been documented to yield results very similar to those of the traditional Sherbrooke block sampler (Emdal, Gylland, Amundsen, Kåsin & Long, 2016). After extraction, care is taken to inflict as little disturbance on the samples as possible during packaging, transportation and storage. Both block samplers, as well as the later handling of the extracted samples, are presented in Section 4.1.

The extracted mini-block samples (MBS) were all opened, trimmed, prepared and tested by the same operator to further reduce the risk of sample disturbance. The various testing procedures were practiced during several weeks of repeated fail-testing and mending of laboratory test equipment. This has helped provide the operator with necessary knowledge of critical steps and sensitive elements,
enabling her to perform the tests with the gentle care and attention needed.

3.2.1 Effect of storage time

Sampled clay specimens are seldom tested immediately after extraction. The often limited capacity at geotechnical laboratories results in clay sample storage periods ranging from a few days to several months. The effects of storage time have seen extensive research since the late 1940s. The recently published report by L’Heureux and Kim (2014), prepared for the governmental research project Naturfare, Infrastruktur, Flom og Skred (NIFS), collates much of that research. The literature review presented in the report concludes on several mechanisms that have profound effect on measured test results:

- Migration of pore fluids and associated changes in stress distributions
- Drying and moisture loss
- Chemical effects and pH changes
- Temperature and humidity changes

For this work, the most relevant conclusion drawn by L’Heureux and Kim (2014) is the fact that measured values of peak shear stress, preconsolidation stress, remoulded shear stress and thus also the sensitivity of a clay, are all reduced during storage. The effects of storage time on measured mechanical properties of clays are significant even during the first couple of weeks. The impact of the mechanisms listed above can easily be affected by other factors, such as the procedure and equipment used during sampling and transportation, the clay sensitivity, and the temperature and humidity at which the samples are stored. The use of high quality block samples, for instance, has been proved to reduce the impact of effects of storage time. This is also the case with the use of lowly sensitive clay rather than highly sensitive clay (L’Heureux & Kim, 2014).

3.3 Sample disturbance

Sample quality has long been evaluated by checking the volumetric change of a triaxial shear test specimen during consolidation. The complex structural arrangements of clay particles is partially collapsed when exposed to disturbance.
This leads to a larger amount of pore water being expelled from the sample during the consolidation process, indicating a larger volumetric change in the clay specimen. With this in mind, Andresen and Kolstad (1979) introduced a classification of sample disturbance based on volumetric strain, recreated in Table 3.3.

Table 3.3: Evaluation of sample quality based on $\varepsilon_V$ (Andresen & Kolstad, 1979).

<table>
<thead>
<tr>
<th>Volume change $\varepsilon_V$</th>
<th>Sample quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1%</td>
<td>Very good to excellent</td>
</tr>
<tr>
<td>1-2%</td>
<td>Good</td>
</tr>
<tr>
<td>2-4%</td>
<td>Fair</td>
</tr>
<tr>
<td>4-10%</td>
<td>Poor</td>
</tr>
<tr>
<td>&gt; 10%</td>
<td>Very poor</td>
</tr>
</tbody>
</table>

Volumetric strain is calculated by dividing the amount of expelled pore water ($\Delta V$) by the initial sample volume ($V_0$), see Equation 3.1. This allows the correctness of laboratory test results to be more accurately evaluated. A triaxial test specimen of lesser quality will expel more water during consolidation, and undergo more compaction than one of better quality. Disturbance of samples will also appear in plotted results of laboratory tests. Stress paths of disturbed samples will not exhibit the peaking behavior seen in Figure 3.1.

$$\varepsilon_V = \frac{\Delta V}{V_0} \quad [-] \quad (3.1)$$

Lunne et al. (1997) proposed updated criteria for evaluating sample disturbance of triaxial test specimens. Recreated in Table 3.4, the new criteria is based on the change in void ratio ($\Delta e$) divided by the initial void ratio ($e_0$), equal to the relative change of the pore volume. This means that the pore volume is now considered relative to the initial pore volume, rather than to the initial total volume, as seen in Equation 3.1. The updated criteria is recommended based on the assumption that a change in pore volume will be more detrimental to the particle arrangement for a lower initial pore volume (Lunne et al., 1997). Table 3.4 is a reproduction of the criterion proposed by Lunne et al. (1997).

No pycnometer tests or alternative ways of finding the density of solid particles ($\rho_s$) of the clay are performed. A typical density value for Norwegian clays, $\rho_s$ of 2.73 g/cm³, is therefore used to calculate the initial void ratio using Equation 3.2.
Table 3.4: Evaluation of sample quality based on $\Delta e/e_0$ (Lunne et al., 1997).

<table>
<thead>
<tr>
<th>OCR $p'_c/p'_0$</th>
<th>$\Delta e/e_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>&lt; 0.04</td>
</tr>
<tr>
<td></td>
<td>0.04-0.07</td>
</tr>
<tr>
<td></td>
<td>0.07-0.14</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.14</td>
</tr>
<tr>
<td>2-4</td>
<td>&lt; 0.03</td>
</tr>
<tr>
<td></td>
<td>0.03-0.05</td>
</tr>
<tr>
<td></td>
<td>0.05-0.10</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.10</td>
</tr>
</tbody>
</table>

and the degree of saturation ($S_r$), presented in Equation 3.3 describing the ratio between the volume of water to the total available pore volume.

$$e_0 = \frac{V_p}{V_s} = \frac{w \cdot \gamma_s}{\gamma_w \cdot S_r} = \frac{\gamma_s (1 + w)}{\gamma} - 1 \quad [-] \quad (3.2)$$

$$S_r = \frac{V_w}{V_p} = \frac{w \cdot \gamma}{\gamma_w (1 + w + \frac{\gamma}{\gamma_s})} \quad [-] \quad (3.3)$$

The change in void ratio is derived based on the assumption that since water and solids are nearly incompressible, hence any change in total volume during compression is a result of change in the pore volume. The void ratio $e$ is defined as pore volume $V_p$ divided by volume of solids $V_s$ (Equation 3.2). When the initial void ratio $e_0$ changes by $\Delta e$ to a new value $e_1$, the resulting change in volumetric strain $\varepsilon_V$ is given by Equation 3.4.

$$\Delta \varepsilon_V = \frac{\Delta e}{1 + e_0} \quad [-] \quad (3.4)$$

When considering infinitesimal changes in volumetric strain from $e_0$ to $e_1$ one can integrate Equation 3.4 over this interval, giving the logarithmic Equation 3.5. Solving for $\Delta e$ yields the exponential expression (3.6).

$$\Delta \varepsilon_V = ln(1 + e_1) - ln(1 + e_0) = ln \left( \frac{1 + e_0 + \Delta e}{1 + e_0} \right) \quad [-] \quad (3.5)$$

$$\Delta e = (exp(\Delta \varepsilon_V) - 1) \cdot (1 + e_0) \quad [-] \quad (3.6)$$

The expression for $e_0$ in (3.2) and $\Delta e$ in (3.6) will give the most correct value for $\Delta e/e_0$ and is therefore used to evaluate sample quality for both CAUC triaxial shear tests and CRSC oedometer tests. For CAUC tests the sample quality is assessed based on the amount of water expelled after the consolidation.
3.3. SAMPLE DISTURBANCE

The CRSC oedometer test specimens are evaluated based on the deformation registered from start until estimated \( p'_0 = \sigma'_v \) is reached. This results in \( \Delta \varepsilon_V = \varepsilon_{a,v0} = \Delta H_{v0}/H_0 \) and Equation 3.8.

\[
\frac{\Delta e}{e_0} = \frac{\exp(\varepsilon_{a,v0}) - 1}{e_0} \cdot (1 + e_0) \quad [-] \quad (3.7)
\]

\[
\frac{\Delta e}{e_0} = \frac{\exp(\varepsilon_{a,v0}) - 1}{e_0} \cdot (1 + e_0) \quad [-] \quad (3.8)
\]
Chapter 4

Methodology

In order to provide high quality results it is important that all steps of each testing procedure, as well as the approach used to extract test specimens, are performed as consistently as possible. This chapter presents the procedures as they were followed, including the sets of equipment used. The following section first outlines how the mini-block samples were extracted and handled after storage. Section 4.2 then describes how the samples were opened and divided into test specimens.

Finally a larger section details the laboratory testing program, including the specification of and reasoning behind the storage and temperature schemes used. The following subsections then mention the standard on which their procedures are based, outlining any significant deviations, and list the equipment used. CRSC oedometer tests and CAUC triaxial shear tests are described in more detail, as their procedures are significantly more intricate, including how their results are gathered.

4.1 Sampling and storage

A mini-block sampler that mechanically carves out samples with a maximum size of $\phi 160mm \times 300mm$ has been used. Developed at the Geotechnical Division of NTNU, it is in essence a scaled down version of the Sherbrooke University block sampler first introduced by Lefebvre and Poulin (1979) (Emdal et al., 2016). Figure 4.1a, a technical drawing of the mini-block sampler, illustrates the vertical and radial dimensions of the metal frame of the sampler (Emdal et al., 2016).
The main difference between the NTNU mini-block sampler and the Sherbrooke block sampler is in the sample size. The mini-block sampler carves out smaller blocks, having its outer diameter reduced from 410mm to 230mm (Emdal et al., 2016). This reduction in size makes it possible to install on an ordinary geotechnical drill rig, leading to easier and safer sampling conditions, less time spent and also lower cost than using a traditional Sherbrooke block sampler (Emdal et al., 2016). A few small modifications have also been made to the metal frame of the mini-block sampler, allowing for better load transfer and cutting technique. See Emdal et al. (2016) for a more thorough discussion.

Emdal et al. (2016) state that the operating principles of the mini-block sampler are in large part based on those of the a Sherbrooke block sampler. A hole of the desired diameter and depth is pre-drilled using an auger. A casing is then installed to stabilize the hole and prevent surface debris from entering, before a flat-bottomed auger is used to flatten and clean the bottom of the borehole, after which the casing is filled with water. Inside the water-filled casing the mini-block sampler uses three circumferentially placed water jets to carve out a cylindrically shaped clay sample.

When a maximum height of 300mm is reached, a drop weight is released onto
the metal frame, activating three cutters at the bottom. These are held back by torque springs (visible in Figure 4.1a) during the carving of the annulus, and will cut the bottom of the sample when triggered by the drop weight. The bottom cutters also provide support for the base of the block sample when retracting it to terrain surface (Emdal et al., 2016).

After the newly carved MBS reaches the surface, surplus soil material around the clay sample is cleaned away. The sample is then placed on a custom made base and immediately wrapped in several layers of plastic foil, as seen in Figure 4.2b. By quickly wrapping the sample, with a minimal amount of air trapped on the inside, the initial loss of moisture is drastically reduced. This contrasts the traditional procedures with a Sherbrooke block sampler, where the sample is also wrapped in tin foil and covered in wax. These are procedures that have been abandoned based on hypotheses of unwanted effects on mechanical properties derived from laboratory testing of block samples (Emdal et al., 2016).

![Image](a) PVC tube and styrofoam balls  
(b) Plastic foil and duct tape

Fig. 4.2: Mini-block samples wrapped and encased for transportation and storage.

The wrapped MBS is then encased in a φ187mm wide polyvinyl chloride (PVC) tube fastened to the base the sample rests on. The gap between the block sample and the tube is then filled with styrofoam balls to stabilize the sample (Emdal et al., 2016). An example of this is shown in Figure 4.2a. In accordance with the Norsk Geoteknisk Forening (2013) guidance on soil sampling, samples
are transported using a shock protected and insulated box to further reduce the risk of significant sample disturbance.

Norsk Geoteknisk Forening (2013) recommends that soil samples are stored in a cold storage room, holding an approximate mean in situ temperature of 7°C and a relatively high humidity. According to multiple sources, including Sandven et al. (2014) on NTNU field- and laboratory testing methods, the cold storage room available at NTNU maintains an average temperature of 5°C. This cold storage room has been used to store most of the MBS used in this work. The exception is the MBS stored for 159 days at room temperature. This sample was placed in a room holding approximately 21°C ± 2°C. Since there are no detailed recordings of either temperature or humidity in either storage rooms, no references to storage temperatures should be considered to have an accuracy higher than 1°C. Both long and short term storage temperatures and testing temperatures are detailed in Section 4.3.

### 4.1.1 Mini-block samples from Lilleby

For this work a number of mini-block samples were sampled, packed and transported in the manners described above. All samples were extracted from a single borehole at a construction site at Lilleby in Trondheim, Norway. The Lilleby site has historically been the location of a smelter, Lilleby Smelteverk, and the brickwork Nidaros Teglverk, before that (EiendomsMegler 1, n.d.). A high overconsolidation ratio (OCR) is therefore expected. Both geological maps and previous testing of the soil material indicate several meters of non-sensitive marine clay at the site. In order to ensure a consistent temperature of around 6°C throughout the year, all samples were taken from a depth of at least 6m. The mini-block sample extracted closest to surface terrain is sampled from 6.30-6-60m depth.

Six mini-block samples were extracted in total, four in mid October 2016 and two in late April and mid May. Two of the four MBS from October 2016 have been used for testing, holding two in reserve. Before these were successfully sampled, a few earlier attempts failed due to a combination of problems such as relatively large amounts of non-clay material. The cutting process in a non-sensitive clay, such as the one at the Lilleby site, requires the use of more time and thus water during the carving process. High amounts of silt and gravel in the clay sampled additionally makes the retrieval of good quality samples challenging (Emdal et al., 2016).
None of the sampled MBS used in this work had their potential maximum diameter of 160mm, due to damage caused by silt and gravel bodies carving the annulus together with the water from the sampler jets. Figures 4.3a and 4.3b show that the sampled diameter was neither the maximum diameter of φ160mm nor was it consistent over the sampled height. The average diameter of the two long term stored MBS was about φ150mm, while the two freshly sampled MBS had an even narrower diameter of approximately φ140 – 145mm. Additionally, Figure 4.3b shows some white spots on the surface of the sample. This is mold that grew on MBS_1 while it was stored in room temperature. Figure 4.3b shows a vertical cut through MBS_4 that contained an even higher amount of small to medium sized stones than the general case of the tested mini-block samples.

There were parts of clay in the mini-block samples that had few to no traces of sand or stones of any size, but large parts of the clay sampled contained turbulent layers of silt and sand, and stones ranging from about 1 – 2mm in diameter to 20 – 30mm in diameter. Some examples of the largest stones found during the testing of clay from Lilleby are presented in Figure 6.1a in Chapter 6 - Discussion. Challenges regarding the heterogeneity of the Lilleby clay, and some of the impacts this had on testing, are also discussed further in Chapter 6.

The two long-term stored MBS that are used in this work were sampled the 18th and 19th of October. The two freshly sampled mini-block samples were extracted the 28th of April and 11th of May. More detailed information about
the four mini-block samples extracted and tested in this work, including sample depth, storage length and temperature during storage, is presented in Table 4.1 in Section 4.2 on the opening and dividing of mini-block samples.

## 4.2 Opening of mini-block samples

The four mini-block samples used in this master thesis are chronologically named. Of note, MBS_1 is from a larger depth than MBS_2, since a choice was made to start testing on the MBS with the least favourable storage conditions. MBS_1 was stored for 159 days in temperatures close to 21°C prior to opening, while MBS_2 was stored for 170 days in the cold room storage, which held about 5°C. Detailed information about sample depth, storage length and storage temperatures for all four MBS is presented in Table 4.1.

Table 4.1: Detailed information on sampling and storage of the mini-block samples used.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Depth [m]</th>
<th>Date [dd.mm.yy]</th>
<th>Storage Length [days]</th>
<th>Storage Temp. [°C]</th>
<th>Opening Date [dd.mm.yy]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS_1</td>
<td>6.6-6.9</td>
<td>19.10.16</td>
<td>159</td>
<td>21</td>
<td>27.03.17</td>
</tr>
<tr>
<td>MBS_2</td>
<td>6.3-6.6</td>
<td>18.10.16</td>
<td>170</td>
<td>5</td>
<td>06.04.17</td>
</tr>
<tr>
<td>MBS_3</td>
<td>7.8-8.15</td>
<td>28.04.17</td>
<td>1</td>
<td>5</td>
<td>29.04.17</td>
</tr>
<tr>
<td>MBS_4</td>
<td>8.2-8.5</td>
<td>11.05.17</td>
<td>2</td>
<td>5</td>
<td>13.05.17</td>
</tr>
</tbody>
</table>

Although there were significant variations in sample height and diameter between mini-block samples, and sometimes also in the diameter over their height, all four of the samples underwent the approximately same scheme of subdivision into what are termed MBS slices or MBS layers in this text. These MBS slices are horizontal layers of clay separated using a wire saw and a trimming device built specifically for MBS extracted using the mini-block sampler. This procedure is roughly illustrated in Figure 4.4a, where the top cap of MBS_1 is being sliced off.

The trimming device used to horizontally divide mini-block samples into MBS slices was always placed in a room holding the same temperature as that for which the first tests would be run. For the long-term stored mini-block samples, these were the same temperatures as the storage temperatures. Beginning with MBS_1, it was stored in room temperatures, opened in room temperatures and tested first.
in room temperatures. The temperature in the climate room was then set to cold temperatures for the second half of the tests, leading into MBS_2 being opened and tested at cold temperatures. This way the MBS_2 specimens tested in cold temperature were never exposed to warmer temperatures, a procedure deemed particularly important due to the temperature effects mentioned in Chapter 2.

This objective was harder to accomplish when working on the freshly sampled MBS. They could both have been opened in cold temperatures, and tested in these temperatures first, but an important factor that needed to be taken into account regarding these specimens, is the loss of laboratory measured strength in just a few days after sampling (L’Heureux & Kim, 2014). Therefore it was decided to extract one MBS, open it as soon as possible at one temperature and first test it at this temperature. The climate room’s temperature would then be changed to the other temperature to run the second half of the tests, and then extract another MBS and open and test first at this temperature. The specimens tested cold from MBS_3 were thus stored in cold temperatures for one day, opened in room temperatures and stored in cold temperatures again until tested cold. See Table 4.3 in Section 4.3 for more information on storage and testing temperatures.

![Fig. 4.4: Subdivision and storage of MBS slice and specimens.](image)

The procedure of opening and subdividing the mini-block samples was always completed in one day. The samples were all opened using a small and sharp cutting knife, starting at the top of the sample. Only the first couple of centimeters were uncovered at first, to limit the loss of water from the sample’s surface as much as possible. The gradual uncovering of more and more clay was done in
parallel to subdividing the MBS into slices, following the schematic presented in Figure 4.5. If more than the needed height of a MBS slice was uncovered for observation, as seen in Figure 4.3a in the previous section, the sample was quickly covered in plastic film again, as soon as observations were done. This covering procedure was also used in between subdivision of the MBS. When opening mini-block samples in room temperature aluminum foil was used as well, to reduce the effect the room’s temperature had on the temperature held by the remaining part of the MBS.

![Diagram of subdivision of mini-block samples](image)

*Fig. 4.5: Scheme of subdivision of mini-block samples used in this work.*

All MBS slices that were cut off of the MBS were also subdivided into either halves or quarter pieces of the original circular slice depending on what tests they were intended for. Certain tests were performed during the subdivision of
the MBS, but always after the other half or quarter pieces from that same slice were wrapped and put away for intermediate storage. The pieces intended for intermediate storage were gently covered, as airtight as possible, with several layers of plastic film to limit reduction in water content. Some damp paper was added in between layers of plastic film to maintain a high humidity around the samples throughout intermediate storage. Figure 4.4b presents a photograph of the pieces prepared for intermediate storage from MBS_3, placed on a table in the cold storage room.

Figure 4.5 shows a to scale version of a typical mini-block sample used in this thesis. The height was approximately 300mm for all MBS, and the diameter was about 150mm. The MBS slices used for extraction of specific test specimens are indicated with dashed lines with heights that are to scale with the approximate heights used. Specimens for checking water content were extracted fairly regularly over the height of each MBS, including representative samples from the top cap and bottom part, so that the whole height of the MBS would be used. Representative samples were unfortunately not extracted from the bottom part of MBS_1 due to a misunderstanding.

The two more central slices used for extracting representative samples for checking water content, were also used for testing both undrained and remoulded strength using fall cone tests, and finding the water content at the plastic and liquid consistency limits. These limits are also referred to as Atterberg limits throughout this work. Because the “same” clay is used for several types of tests from these MBS slices, the height of the slices were always about 3cm high. Fall cone tests performed at the same temperature as opening temperature, were always performed immediately after having sliced the layer off and put the other half piece away for intermediate storage. Tests on Atterberg limits were typically performed when permitted by the schedule during the next couple of days.

Oedometer test specimens were extracted from two 4 – 5cm high MBS slices. Each of these slices were divided into quarter pieces, yielding one test specimen each. The triaxial tests specimens were always extracted from the middle part of the mini-block samples. An 11 – 12cm high layer was sliced off the MBS and then divided into quarter pieces, just as for the oedometer slices. A to scale diagram of a horizontally cut MBS slice for extracting CAUC test specimens is presented in Figure 4.6. In this figure the circles indicate the φ54mm large triaxial test specimens. It is then clear that the quarter slices were large enough when the MBS had a diameter of 150mm or more, but mini-block samples with a narrower
width and/or a bent nature would constitute a considerable challenge.

\begin{center}
\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{Fig_4.6}
\caption{Schematic of subdivision of quarter slices and triaxial test specimens.}
\label{fig:4.6}
\end{figure}
\end{center}

\section{Labotory testing}

Already mentioned are some different test types, with additional information about their height and width requirements among other things. This section will present and explain the different testing procedures and what the main purposes of performing the tests are.

As can be seen in Figure 4.5, water content has been found from several depths. This includes both natural water content \( w_0 \) and water content at the plastic \( w_P \) and liquid \( w_L \) consistency limits/Atterberg limits. These properties are used to help better evaluate and classify the Lilleby clay, and to see any effect of either storage or test temperature. Various engineering properties have been determined from fall cone tests, CRSC oedometer tests and CAUC triaxial shear tests. The main focus has been on determining undrained shear strengths \( s_u \) from fall cone tests and CAUC triaxial tests, and preconsolidation pressures \( p_c' \) from CRSC oedometer tests. The effects of both storage and test temperature on these parameters constitute the backbone of this master thesis.

Table 4.2 presents the planned laboratory program, including the number of tests run of each type for each mini-block sample. Eight specimens for testing
Table 4.2: Planned laboratory program for the different block samples in this thesis.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample depth</th>
<th>Water content &amp; Atterberg limits (CRSC)</th>
<th>Oedom. tests (CRSC)</th>
<th>Triaxial tests (CAUC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS_1</td>
<td>6.6-6.9m</td>
<td>8</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>MBS_2</td>
<td>6.3-6.6m</td>
<td>8</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>MBS_3</td>
<td>7.8-8.15m</td>
<td>8</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>MBS_4</td>
<td>8.2-8.5m</td>
<td>8</td>
<td>4</td>
<td>8</td>
</tr>
</tbody>
</table>

Water content, four specimens for first testing shear strengths by fall cone and afterwards determining Atterberg limits, eight oedometer test specimens, and four triaxial test specimens from each MBS.

Procedures on determining natural water content are presented in Subsection 4.3.1, while the procedures on determining the Atterberg limits, as well as both plasticity and liquidity indices, are presented in Subsection 4.3.2. How to find both undrained and remoulded shear strength using fall cone tests, in addition to determining the sensitivity of the clay, is presented in Subsection 4.3.3. Lastly, comprehensive sections on equipment, procedures and determinations of all desired test parameters are presented for both CRSC oedometer test and CAUC triaxial shear tests in sections 4.3.4 and 4.3.5 respectively.

Temperature scheme

As mentioned in Section 4.2 on opening and subdivision of mini-block samples, a strict and carefully planned temperature scheme was followed. This included temperatures during long-term storage, opening, intermediate storage and testing of Lilleby clay specimens. The different temperatures decided upon are presented in Table 4.3, and a brief justification follows below. Table 4.3 presents a detailed overview of the different storage and testing temperatures. All test types except water content is listed twice, because all other tests were conducted both close to 6 °C and 21 °C.

Both long-term stored mini-block samples were opened and first tested at the same temperature they were stored at. The freshly sampled mini-block samples were always stored intermediately at 5 °C, but were opened at different temperatures, and thus also first tested at different temperatures. The reason for this is explained thoroughly in Section 4.2.

In Table 4.3 only one temperature is listed under Storage temp. for water con-
4.3. LABORATORY TESTING  

Table 4.3: Overview of storage and testing temperatures of all test types performed.

<table>
<thead>
<tr>
<th>MBS ID</th>
<th>Type of test</th>
<th>Storage temp. [°C]</th>
<th>Test temp. [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS_1</td>
<td>Water content</td>
<td>21</td>
<td>21</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>21</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>21</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>21</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>21</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>21</td>
<td>21.7</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>21</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBS_2</td>
<td>Water content</td>
<td>5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>6.0</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>21.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBS_3</td>
<td>Water content</td>
<td>5</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>21.3</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MBS_4</td>
<td>Water content</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Fall cone</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Atterberg</td>
<td>5</td>
<td>21.1</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Oedometer</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>5.9</td>
</tr>
<tr>
<td></td>
<td>Triaxial</td>
<td>5</td>
<td>21.1</td>
</tr>
</tbody>
</table>

This is because tests on water content were conducted during the opening of the mini-block sample, never requiring any intermediate storage. The same is the case for the fall cone test specimens that were conducted during MBS opening.
All other specimens, including those for the fall cone tests performed after temperature change in the climate room, are listed with two different storage temperatures. The latter is always that of the intermediate storage, being either stored in the cold storage room holding 5 °C or in the climate room holding the same temperature as the current testing temperature.

The fall cone test specimens performed at the other temperature were always placed in cold storage. The same procedure has been followed for all CRSC oedometer and CAUC triaxial tests performed at the other temperatures. The intermediate storage temperature listed for the test specimens from MBS_2, tested in room temperatures, was mostly around 5 °C, but each specimen was taken out of cold storage 24 hour prior to testing, to temperate in room temperature before testing. This was done so that all specimens would experience the same degree of elevated temperatures prior to testing. See Chapter 2 on the second temperature effect proposed by Campanella and Mitchell (1968).

The temperature for intermediate storage listed for the first Atterberg tests, CRSC tests and CAUC tests is always the same as the testing temperature. This is because all these specimens were stored in the climate room prior to testing. The second Atterberg limit tests are also listed having the intermediate storage temperature as the testing temperature. Because the Atterberg limits were found using the same clay previously tested using fall cone equipment, the remoulded clay was covered in plastic film and stored in the climate room after fall cone tests were finished.

A thermometer logging both temperature and humidity every tenth minute was used in the climate room during laboratory testing. The mean value of the temperature measured during each testing period, either in cold temperature or room temperature, is listed as testing temperature in Table 4.3. Nearly all testing temperatures are presented with an accuracy of 0.1 °C. The water content tests from MBS_1 were not conducted in the climate room. The first mini-block sample was opened in the geotechnical laboratory in room temperatures, with help from faculty staff on the opening procedure. All tests on water content from MBS_1 were thus tested in the laboratory, with a test temperature of 21 °C.

Table 4.4 presents the same mean testing temperatures as listed in Table 4.3. Also listed in Table 4.4 are the minimum and maximum values of the testing temperatures measured, together with the standard deviation of the testing temperature. As mentioned, the thermometer also measured humidity, and the measured minimum and maximum values together with the mean value and standard
deviation for each testing period are also listed in Table 4.4.

Table 4.4: Overview of temperature and humidity during testing of mini-block samples.

<table>
<thead>
<tr>
<th>MBS ID</th>
<th>Date range</th>
<th>Temperature [°C]</th>
<th>Humidity [%RH]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>MBS_1</td>
<td>27.03-01.04.17</td>
<td>20.8</td>
<td>22.4</td>
</tr>
<tr>
<td></td>
<td>02.04-06.04.17</td>
<td>4.8</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>06.04-10.04.17</td>
<td>5</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>11.04-15.04.17</td>
<td>19.8</td>
<td>21.9</td>
</tr>
<tr>
<td>MBS_2</td>
<td>27.04-03.05.17</td>
<td>20.4</td>
<td>22.6</td>
</tr>
<tr>
<td></td>
<td>04.05-08.05.17</td>
<td>5.1</td>
<td>7.8</td>
</tr>
<tr>
<td></td>
<td>13.05-17.05.17</td>
<td>4.9</td>
<td>7.8</td>
</tr>
<tr>
<td>MBS_4</td>
<td>18.05-21.05.17</td>
<td>20.2</td>
<td>22.2</td>
</tr>
</tbody>
</table>

4.3.1 Water content testing

The natural water content \( w_0 \) for a soil sample is defined as the ratio of the mass of free water \( m_w \) to the mass of dry solids \( m_d \), as is shown in Equation 4.1 below. The ratio is often given as a percentage.

\[
 w_0 = \frac{m_w}{m_d} \cdot 100\% = \frac{m_s - m_d}{m_d} \cdot 100\% \quad [\%] \quad (4.1)
\]

The water content was determined in accordance to NS-EN ISO 17892-1, by selecting representative samples as soon as practicable and weighing them to estimate the mass of the wet sample \( m_s \). After the samples had been dried, they were weighed to estimate the mass of dry solids \( m_d \). The difference between wet mass \( m_s \) and dry mass \( m_d \) is the mass of free water \( m_w \), and the water content can be determined using Equation 4.1.

For this thesis two representative samples from four layers throughout the height of each mini-block sample were gathered. These samples were cut out and weighed as soon as it was practicable during the opening and subdivision of the MBS. As indicated in Figure 4.5 in Section 4.2, these samples were extracted from the bottom of the top cap, from another MBS slice approx. 2 – 5cm below the top, yet another MBS slice approx. 21 – 24cm from the top, and lastly from the upper part of the bottom layer. Two photographs showing how and where these samples were gathered, from a top cap and an MBS slice, are presented in Figure 4.8.
Equipment used:

- Cutting knife
- Ceramic specimen cups
- Balance accurate to 0.01g
- Drying oven at 110 ± 5 °C

Fig. 4.7: Water content equipment.

(a) From the bottom of the top cap  (b) From a slice of the mini-block sample

Fig. 4.8: Extracting representative samples for testing \( w_0 \) from MBS slices.

All trimmed oedometer and triaxial test specimens were weighed before and after testing to check the natural water content as well. All values of water content, both from specific water content tests and from CRSC and CAUC tests, are plotted with sample depth and presented on the left hand side of the layout in Appendix A - Index tests.

4.3.2 Atterberg limits

There is a relation between the water content of a clay and its consistency, making the clay liquid with high water contents and dry and crumbly with low water contents. The transitions from one state to another are called consistency or
Atterberg limits, and are used extensively for identification, description, and classification of cohesive soils. They are also often used as a basis for assessing mechanical properties of these soils (Mitchell & Soga, 2005). The consistency limits are determined by manipulation of remoulded soil samples, and methods for determining them are standardized in NS 8001-8004. Terminology and symbols used for the limits are standardized in NS 8000.

Increasing water content \( w \)

- Liquid limit \( w_L \)
- Plastic limit \( w_P \)
- Plasticity index \( I_P \)

**Fig. 4.9: Schematic of relevant consistency/Atterberg limits.**

In this thesis the purpose of finding the Atterberg limits is to determine the plasticity of the clay specimens, and thereby finding the (percussion) liquid limits \( w_L \) and the plastic limits \( w_P \). Figure 4.9 shows a schematic illustrating the relationship between the plasticity index \( I_P \) and the consistency/Atterberg limits \( w_P \) and \( w_L \) in fine-grained soils. The schematic is largely based on an illustration in Sandven et al. (2014) but is simplified to show the parameters most in agreement with the scope of this thesis. \( I_P \) is calculated as in Equation 4.2.

\[
I_P = (w_L - w_P) \cdot 100\% \quad [\%] 
\] (4.2)

The liquidity index \( I_L \) is also a useful parameter determined from water content values, as seen in Equation 4.3. It is evident from Equation 4.3 that the liquidity index normalizes the water content, relative to the range of water content over which a soil is plastic, for a certain clay sample. It is therefore a useful tool.
for expressing and comparing consistencies of different clays, and is also stated to correlate well with compressibility, strength and sensitivity properties (Mitchell & Soga, 2005).

\[ I_L = \frac{w_0 - w_P}{w_L - w_P} \quad [\text{[-]}] \quad (4.3) \]

All values for the Atterberg limits determined, and the plasticity and liquidity indices related to the specific Atterberg limits are presented in Table 5.2 in Section 5.2 - Atterberg limit results. All consistency limits are additionally visualized together with values of water contents from their specific depth presented on the left hand side of the layout in Appendix A.

**Percussion liquid limit testing**

Subsequent studies of the liquid limit of fine-grained soils indicate that this consistency limit corresponds to shearing resistances in the range 1.7 – 2.0kPa, and with a pore water suction of approximately 6kPa. The method used to find the liquid limit, whether by using a Casagrande device or a fall cone device, is a kind of dynamic shear test (Mitchell & Soga, 2005).

**Equipment used:**

- Casagrande liquid limit device
- Grooving tool
- Steel cup and spatula
- Bottle with distilled water
- Ceramic specimen cups
- Balance accurate to 0.01g
- Drying oven at 110 ± 5°C

![Fig. 4.10: Liquid limit equipment.](image)

The water content at the liquid limits is determined according to NS 8001, using a Casagrande device and finding the percussion liquid limits. The device used is presented in Figure 4.11a. Distilled water was carefully added to the remoulded samples previously used in cone penetration tests. After the added water
was mixed into the clay samples, they were continually tested in the Casagrande device until they yielded satisfying results. According to NS 8001, $w_L$ for a clay is found when a furrow drawn through the clay collapses, with 1.3cm of contact, after 25 drops. An example of such a furrow with a collapse of approximately 1.3cm is presented in Figure 4.11b.

For the tests performed in this work, the liquid limit was determined using the Single Point method for either 24, 25, or 26 drops. Representative samples were extracted, weighed, dried, and then weighed again, yielding a water content $w_n$. For a specimen collapsing after $n = 25$ drops, the value of $w_n$ is equal to $w_L$. For specimens collapsing after 24 or 26 drops, Equation 4.4 may be used together with a coefficient $K_n$, with values 0.995 for $n = 24$ and 1.005 for $n = 26$.

$$w_L = K_n \cdot w_n \cdot 100\% \quad [\%]$$

(a) The Casagrande device used (b) Approx. 1.3cm collapse of furrow

Fig. 4.11: The Casagrande device used to determine percussion liquid limits.

**Plastic limit testing**

The plastic limit represents the lowest water content a remoulded cohesive soil can have and still be plastic. The amount of water is thus sufficiently low to allow for movement between particles while maintaining a molded shape. Undrained shear strengths at the plastic limit has been found to range between 100 and 300kPa, with an average value of approximately 170kPa (Mitchell & Soga, 2005).
Equipment used:

- Glass plate
- Unglaced ceramic tile
- Spatula
- Ceramic specimen cups
- Balance accurate to 0.01g
- Drying oven at 110 ± 5°C

![Fig. 4.12: Plastic limit equipment.](image)

(a) Glass plate at room temperatures  
(b) Ceramic tile at cold temperatures

*Fig. 4.13: Spreading the clay either on a glass plate or a ceramic tile for drying.*

The plastic limit was determined according to NS 8003, by reusing the remoulded clay recently tested for the percussion liquid limit. The clay was immediately spread over either a glass plate when testing in room temperatures, or over an unglaced ceramic tile with a rough surface in cold temperatures. This procedure is illustrated in Figure 4.13, and was developed to more effectively dry the clay without use of any heat dryers. Using heat dryers would heat the clay, thus reducing the value of executing this test at both temperatures. The most effective way of reducing sufficient water content proved to be by first gently rolling small samples of clay on the ceramic tile, before continuing the procedure on the glass plate. All clay samples were rolled repeatedly by use of bare hands on the glass plate shown in Figures Figure 4.13.
4.3.3 Fall cone testing

The fall cone test is a fairly easy and quick method of determining undrained shear strength \( (s_u) \) of a cohesive soil. The method is a penetration test performed by dropping metal cones with specific weight and opening angle into a test specimen. This gives a quick and almost non-destructive indication of soil strength. By also determining the remoulded shear strength \( (s_r) \) one can calculate the sensitivity \( (S_t) \) of the clay. The sensitivity of an undisturbed structure is the ratio between the undisturbed and fully remoulded strength, see Equation 4.5. \( S_t \) is an important and useful tool for classification and evaluation of clay samples and their quality. Typical values of sensitivity for Norwegian clays are listed in Table 3.2 in Chapter 3 - Sample quality.

\[
S_t = \frac{s_u}{s_r} \quad [-]
\]  

The method of determining shear strengths by fall cone tests is standardized in NS 8015, and all cone penetration tests were performed according to that standard. As mentioned in Subsection 4.3.1, the half slice of the mini-block sample used to extract water content samples was reused to determine the undrained shear strength of the soil. Figure 4.15a shows one step from this procedure, where the central part of the half MBS slice is tested. Undisturbed clay samples were tested once, while remoulded clay samples were tested twice. The procedure of remoulding the material and testing it a second time is a recommendation from NS 8015, and was used mainly to assert that the first mean value was representative.

**Equipment used:**
- Cone test apparatus
- 60g cone with 60° angle
- 100g cone with 30° angle
- Steel cup and spatula
- Sheet with strength values

For all fall cone tests on both undisturbed and remoulded clay samples, five
cone penetration measurements were made. Averages over five corresponding strength values were then calculated from the five penetrations, and are presented as the \( s_u \) and \( s_r \) of the specific test sample. The decision to take the average over five values, rather than the minimum of three values proposed by NS 8015, was made due to the anisotropy of the clay samples tested. Only the first, and most representative \( s_r \) value, was used in calculations of \( S_t \).

(a) Undrained shear strength, \( s_u \)  
(b) Remoulded shear strength, \( s_r \)

Fig. 4.15: Determining shear strengths of undisturbed and remoulded samples.

All results from the fall cone tests are presented with values of \( s_u \) from the CAUC triaxial tests, by depth, with a colour indicator for testing temperature, on the right hand side of the layout in Appendix A - Index tests.

### 4.3.4 CRSC oedometer testing

An oedometer test is a type of confined one-dimensional compression test, used to evaluate the compressibility and deformability of a soil specimen. No lateral strain is permitted during the compression of the test specimen, made possible by containing the specimen within an oedometer ring. The oedometer ring is a rigid and stiff steel ring that prevents the sample from changing form radially. Lateral deformation is possible due to drainage of pore water during the execution of the compression test, either only at the top, or both at the top and the bottom, of the oedometer test specimen. Load is typically added either incrementally or by constant rate of strain (CRS).

For this work all oedometer tests were generally performed according to standard NS 8018, describing procedures for control of equipment, and preparation and
testing of soil specimens using a continuously loaded oedometer test apparatus. Sandbaekken, Berre and Lacasse (1986) has also been consulted. The testing purpose has been to estimate a preconsolidation stress ($p'_c$) in each clay specimen, and to see if the measured $p'_c$-values varies with storage and/or testing temperatures. From this soil property the over consolidation ratio (OCR) of each specimen is found, as well as some parameters also related to the estimated in situ overburden pressure ($p'_0$). These include the coefficient of consolidation ($c_v$) and tangent modulus ($M_{OC}$). The procedures used to determine these parameters are presented in the following section.

![Fig. 4.16: Most equipment for preparation and testing of CRSC oedometer specimens.](image)

### Equipment

The CRSC oedometer apparatus used at NTNU allows for one way drainage at the top of the test specimen, with pore water pressure measurements made at the bottom. No back pressure is used for oedometer testing, meaning that test specimens are being tested without being 100% water saturated. Norwegian clays are nevertheless assumed to be fully saturated, and the lack of back pressure is thus not considered to have significant impact on the test results. The oedometer ring used has a diameter of 50mm and a height of 20mm, yielding test specimens of the same height and with a surface area of 20cm². Only water saturated filters are in use at NTNU, partially because their porous stone material make them unsuited as dry filters. This is a deviation from NS 8018 and Sandbaekken et al. (1986), who recommend the use of dry filters.
All of the equipment used to prepare and test oedometer specimens for this work is listed below, most of which is also shown in Figure 4.16. The same equipment, including porous filter stones and the oedometer ring, has been used for all oedometer tests. The equipment has been thoroughly cleaned between execution of each test, including de-airing of the porous filter stones to approximately 30 ± 2 mbar in distilled water.

Equipment used:

- Oedometer ring of φ50mm
- Two trimming equipment pieces
- Silicon oil
- Plastic base with aluminum foil
- Wire saw
- Balance accurate to 0.01g
- Two porous filter stones
- UV washing machine
- Vacuum desiccator
- Vacuum pump
- Exicator fat
- Distilled and de-aired water
- Water bottle and syringe
- CRSC oedometer test apparatus
- Oedometer base and two screws
- Hex key
- Rubber O-ring
- Guiding ring
- Clamp ring and three screws
- Top cap and metal ball
- Ceramic specimen cups
- Drying oven at 110 ± 5°C

On the procedure

As detailed in Section 4.2, each MBS layer used for oedometer testing was divided into four quarter pieces yielding one test specimen each. The quarter slices were all gently packed airtight using several layers of plastic wrapping, with some damp paper added in between layers to maintain a high humidity around the sample. Most quarter slices were stored cold, at approximately 6 °C, though the ones from MBS_1 were stored in room temperature. MBS_1 was also stored in room temperature prior to opening.

The natural water content and unit weight was calculated for each oedometer test specimen in order to evaluate sample quality. After the specimen was trimmed, the volume inside the oedometer ring and the weight of the specimen immediately after trimming was used to calculate the unit weight (γ) using Equation 4.6. The value of γ was used to calculate in situ effective overburden
pressure \( p'_0 \), the same as the in situ effective vertical stress \( \sigma'_v \), for each test specimen. Most important is the calculation of \( \gamma \) for the first specimen from each mini-block sample, as this specimen determines the unit weight used to calculate the consolidation pressure for all CAUC triaxial test specimens from the same MBS.

\[
\gamma = \frac{m_s}{V_0} \cdot g \approx \frac{m_s}{40 \text{cm}^3} \cdot 9.81 \frac{\text{m}}{\text{s}^2} \left[ \frac{\text{kN}}{\text{m}^3} \right] (4.6)
\]

Due to the heterogeneous nature of the Lilleby clay, some patch work was needed on the surfaces of some of the CRSC oedometer test specimens during trimming. When stones were encountered on what would have been the bottom surface of a specimen, the first solution attempted was always to push the oedometer ring further down into the quarter slice of soil. After the surface at the bottom of the sample had been trimmed as evenly as possible, work on trimming the other surface started. This did not always go well, and in these cases patch work was needed to a greater or lesser extent. Parts of the clay that was trimmed off the test specimen was used to carefully patch the holes where stones had been, and then trimmed down to a smooth and even end surface.

To ensure that the top porous stone filter was accurately positioned, Arnfinn Emdal had recommended unfastening the oedometer base prior to mounting of the clay specimens (see Figure 4.17). Unfortunately, this conflicted with the software’s instruction of zeroing the pore water pressure prior to installing the bottom stone filter. Fastening the oedometer base then resulted in a decrease in measured pore water pressure from an initial value of around 1 to 2 kPa, to a range of \(-2\) to \(-13\) kPa afterwards. This offset appeared to persist for the duration of the test, and in the evaluation and presentation of measured pore water pressures this offset has therefore been compensated for.

The NS 8018 maximum strain rate of 0.75%/h, or 150 \( \mu \)m/h, for 20 mm high test specimens, was used for all tests. This strain rate falls within the 0.5 to 1.0%/h range suggested by Sandbaekken et al. (1986). A strain rate between 0.5 to 1.0%/h normally ensures that the pore pressure ratio \( \lambda = u_b/p' \), the ratio between measured pore water pressure at the base \( u_b \) and applied pressure \( p' \), is kept within a desired range (Sandbaekken et al., 1986). The erroneously decreased pore water pressure mentioned above makes it difficult to verify the value of \( \lambda \) reported by the software, but presumably it remained within the desired range.
Gathering results

The natural water content \( (w_0) \) and the unit weight of the soil \( (\gamma) \) were determined for each CRSC test specimen. Both these values were used for calculations associated with laboratory test data gathered from the compression test itself. The software for all CRSC oedometer tests yielded raw data of time \( (t) \) in seconds, deformation \( (\delta) \) in micrometers, and total vertical stress \( (\sigma_v) \) and pore water pressure \( (u_b) \) in kilopascals. To evaluate and present the laboratory data, some corrections and calculations were needed. Mean vertical stress over the 20mm height of the clay specimen has been calculated using the measured total vertical stress \( (\sigma_v) \) and pore water pressure at the base of the sample \( (u_b) \), see Equation 4.7. The mean stress was calculated using the reset value of the initial measured pore water pressure mentioned above.

\[
\sigma'_v = \sigma'_m = \sigma_v - \frac{2}{3} u_b \quad [\text{kPa}] 
\]  

Calculations of axial strain \( (\varepsilon_a) \) were based on the measured deformation \( (\delta) \) and the initial height \( (H_0) \), as recommended in NS 8018. NS 8018 allows for use of the current height \( (H) \) in calculations as well, but this height is not recommended as it only has practical meaning for very large values of strain. In this work \( \varepsilon_a \) was thus calculated as presented in Equation 4.8.
To select an appropriate value for the preconsolidation pressure, the key point is to find when the soil transitions from overconsolidated (OC) to normally consolidated (NC) behavior. In several different diagrams, this transition will be accompanied by a change in the curvature of their plots. An example of this can be seen in Figure 4.19.

The value of $p'_c$ was chosen mainly from plotting $\sigma'_v$ versus $\varepsilon_a$ both linearly and logarithmically, and finding the stress value best suiting the bending of the line in both plots. Tangential lines were drawn form both sides approaching this point, and the stress value of their intersection determines $p'_c$. This is illustrated in Figure 4.18, where $p'_c$ for oedometer test CRSC_3 from mini-block sample MBS_1 is estimated to 295kPa.

The $p'_c$ value determined using linear and logarithmic $\sigma'_v - \varepsilon_a$ plots was then cross examined against the behaviour of $\sigma'_v$ plotted with $M$, where $M$ is the tangent modulus derived from the change in $\sigma'_v$ by the change in $\varepsilon_a$ (see Equation 4.9). The tangent modulus is also often called the oedometer modulus, and these two names will be used interchangeably. Aligning a $\sigma'_v - \varepsilon_a$ plot over the $\sigma'_v - M$ plot, a line can be drawn through both plots, representing the value of $p'_c$. If this value is in agreement with the OC and NC behaviour visible in the

$$
\varepsilon_a = \frac{\Delta H}{H_0} \cdot 100\% \quad [\%]
$$

(4.8)
4.3. LABORATORY TESTING

\[ \sigma'_v = \sigma_v - \frac{2}{3}u_k \text{ [kPa]} \]

\[ \varepsilon_a = \frac{\Delta M}{p_0} \% \]

\[ M = \frac{d\sigma'_v}{d\varepsilon_a} \approx \frac{\Delta\sigma'_v}{\Delta\varepsilon_a} \text{ [MPa]} \quad (4.9) \]

As part of processing the laboratory test data from the CRSC oedometer tests, several other common parameters were calculated as well. This includes the oedometer modulus \((M_{OC})\) indicating the OC behaviour between initial \textit{in situ} overburden pressure \(p'_0 = \sigma'_{v0}\) and \(p'_c\), and a modulus number \((m)\) representing the NC behaviour of the clay. \(M_{OC}\) was derived from the tangent of the \(\sigma'_v - \varepsilon_a\) plot between \(p'_0\) and \(p'_c\), as seen in Figure 4.20. The change in axial strain over this segment was assumed to be nearly constant, which gave an average \(M_{OC}\) from the inverse of the slope. In addition, a value \(M_{o0}\) was found for \(p'_0 = \sigma'_{v0}\).

The modulus number was determined from the slope of the linear regression

\[ \sigma'_v - M \text{ plot, this strengthens the validity of the chosen } p'_c \text{ value. The procedure is illustrated in Figure 4.19.} \]

\[ M = \frac{d\sigma'_v}{d\varepsilon_a} \approx \frac{\Delta\sigma'_v}{\Delta\varepsilon_a} \text{ [MPa]} \quad (4.9) \]
4.3. LABORATORY TESTING

\[ \sigma'_v = \sigma_v - \frac{2}{3} u_b \text{ [kPa]} \]

Fig. 4.20: Determining \( M_{OC} \) from a line through \( p'_0 \) and \( p'_c \) in a \( \sigma'_v - \varepsilon_a \) plot.

The dashed line in Figure 4.21 shows estimated \( m \) following the NC behaviour of the soil specimen CRSC_3 from MBS_1. As the dashed line does not cross the horizontal axis close to the origin, a reference pressure (\( p'_r \)) is provided for the stress value of the intersection. The light dotted line gives an indication of the slope needed to intersect the origin.

The coefficient of consolidation (\( c_v \)) has also been evaluated in this work. The coefficient is used to describe the rate at which a clay undergoes consolidation or compaction under an increase in pressure, and was calculated using Equation 4.10. The current height \( H \) of the specimen was used to derive \( c_v \), and was found by \( H = H_0 (1 - \varepsilon) \) as recommended by NS 8018. A single value of \( c_v \) was found for \( p'_0 = \sigma'_v \) as this was the most interesting and relevant value.

\[
c_v = \frac{d\sigma'_v}{dt} \cdot \frac{H^2}{2u_b} \approx \frac{\Delta \sigma}{\Delta t} \cdot \frac{[H_0(1-\varepsilon)]^2}{2u_b} \left[ \frac{m^2}{yr} \right] \tag{4.10}
\]

Four diagrams are used to present the results of the CRSC oedometer tests in Appendix B: a \( \sigma'_v - \varepsilon_a \) plot, a \( \sigma'_v - u_b \) plot, a \( \sigma'_v - M \) plot and a \( \sigma'_v - c_v \) plot. All of these are aligned along the same horizontal axis of \( \sigma'_v \) ranging from...
0 to 1000 kPa. For the last three to be readable, the source data needed to be smoothed before presentation, allowing general trends to be discerned. For $u_b$ a running average of 100 was used, while $M$ and $c_v$ have a running average of 200 applied to them.

All the parameters discussed above, $p'_c$, $M_{v0}$, $M_{OC}$, $m$, $p'_v$, and $c_v$, are presented for each oedometer test specimen in Table 5.4 in Chapter 5 - Test results Section 5.4, and in Appendix B - Oedometer tests on their corresponding data sheets (except $M_{v0}$).

### 4.3.5 CAUC triaxial shear testing

Geotechnical testing of soil specimens has over the years yielded a gradual realization that soil samples should be subjected and tested, as closely as possible, to the stress situation they are naturally subjected to in situ. Several test types, including the triaxial shear test, have therefore been developed. The development of both new equipment and procedures allows for any combination of vertical and horizontal stresses to be applied, making it a test that can simulate the in situ stress situation fairly well before determining the strength of the soil specimen (Berre, 1982). A triaxial test can be executed in several ways, with either isotropic or anisotropic consolidation, with static or cyclic loading, and
with compression or extension shearing, run either for a drained or an undrained situation.

For this work only anisotropically consolidated, undrained static compression (CAUC) triaxial shear tests have been used. Procedures for preparation and testing of CAUC triaxial specimens were largely performed as recommended in the standard ISO/TS 17892-9, on geotechnical investigation and testing using consolidated triaxial compression tests on water-saturated soil. Berre (1982) on triaxial testing at NGI has also been consulted. All test specimens were trimmed to a cylindrical shape with φ54mm diameter and 100mm height, using the trimming equipment presented in Figure 4.24a.

The testing purpose for this work has been to determine the maximum shear stress \( (\tau_{\text{max}}) \) in each clay specimen of Lilleby clay, and see if the maximum stress value changes with either storage and/or testing temperatures. For cohesive and low permeable soils as the Lilleby clay, tested using a CAUC procedure, the maximum shear stress property can also be called the undrained shear strength \( (s_u) \). \( \tau_{\text{max}} \) and \( s_u \) are referred to and used interchangeably. The strain at failure \( (\varepsilon_f) \), in other words the strain at which \( \tau_{\text{max}} \) is reached, has also been determined and evaluated for all test specimens, in addition to the parameters attraction \( (a) \) and friction angle \( (\phi) \). The processes used to find all of these are explained in the following section.

**Equipment**

There are two types of triaxial apparatuses in common use at the Geotechnical Division of NTNU. For this master thesis the apparatus type with a loading cell placed outside the triaxial cell, and with the possibility of using back pressure has been used. One of these apparatuses were already stationed down in the climate room, but did unfortunately need extensive work on troubleshooting, checking and changing of parts before it was in sufficiently good condition to run tests with.

All pieces of equipment used to prepare and test triaxial test specimens are listed below. This list of equipment includes most pieces that are not part of the triaxial apparatus itself, but also some that are considered a part of the apparatus but also important enough for independent mention. The test apparatus, with burette, block valve, regulators, tubes, air valve etc. is presented from several angles, and with different main foci, in Figure 4.22. The photos do in large part
present the apparatus as it was during the testing of Lilleby clay, after about two months of troubleshooting and changing of parts.

Equipment used:

- Crib with exact 100mm length
- Trimming equipment ($\phi 54 \text{mm}$)
- Silicon oil
- Aluminum foil
- Wire saw
- Balance accurate to 0.01g
- Two porous filter stones
- UV washing machine
- Vacuum desiccator
- Distilled and de-aired water
- Water bottles and syringes
- Triaxial test apparatus
- Burette
- Air trap device with cup
- Valve block and tubes
- Isolated tank with water
- One long rubber membrane
- Two rubber membrane strips
- Talcum/baby powder
- Exicater fat
- Four rubber O-rings
- Filter paper
- Scissor and plastic tape
- Cylindrical metal casing
- Metal fastening rod
- Vacuum pump with tube
- Organic oil
- LVDT
- Load rod with metal ball
- Sandpaper and a lighter
- Ceramic specimen cups
- Drying oven at 110 ± 5°C

Some of the parts that were replaced before official testing started, that can be spotted in Figure 4.22, include the air valve, cell pressure and back pressure regulators, nearly all tubes on the front side of the apparatus and most tubes that are now plastic on the back side. Additionally, the valve block was detached and brought to a workshop to remove something stuck in one of the valves, the burette was taken apart, cleaned and dried a couple of times, and the step motor under the table was unfastened and fail-tested over a period of time.

Throughout triaxial shear testing of the Lilleby clay, only one rubber membrane and the filter papers was replaced. All other equipment, including tubes, porous stone filters and O-rings, was used for all test specimens tested. A few times one of the tubes broke off close to its valve because it became brittle and sensitive to touch in cold temperatures. This never required replacement of the
tube during testing, only mending and refastening using a scissor, sandpaper and a lighter.

An LVTD was also added to the test equipment midways into the testing period, due to an unfortunate event with test specimen CAUC_8 further discussed in Section 6.4. With the introduction of the LVTD the software used for CAUC testing was changed, but this is not deemed to have any impact on test results. All equipment was thoroughly cleaned between test runs, including de-airng of the porous filters to $30 \pm 2\text{mbar}$ in distilled water.

**Consolidation stresses**

Prior to doing any form of physical work on the Lilleby clay, some work to determine the confining consolidation stresses, both radially ($\sigma_{r,c}'$) and axially ($\sigma_{a,c}'$) was required. This included gathering information on the level and type of pressure from the ground water at Lilleby, the density or unit weight of the Lilleby clay, and the at rest effective coefficient ($K_0'$) used to find $\sigma_{r,c}'$.

For previous work done at the Lilleby site, piezometers measuring ground water level and pore water pressures have been utilized. Results from measurements gathered using this equipment indicate a pore water overpressure due to upward ground water flow at the site. A constant flow gradient ($i$) of 0.18 from surface terrain to rock surface has been calculated from these results. Using Equation 4.11, an expression for the adjusted unit weight of the soil material ($\bar{\gamma}$) could then be derived using $i$ equal to 0.18, the unit weight of water ($\gamma_w$).
presumed to be 10kN/m³ and \( \gamma' \) as the effective unit weight.

\[
\bar{\gamma} = \gamma' - i \cdot \gamma_w \quad \left[ \frac{kN}{m^3} \right]
\]  
(4.11)

The expression presented in Equation 4.12 could then be used to calculate the \textit{in situ} effective vertical pressure (\( \sigma_{v0}' \)) with the unit weight of the soil (\( \gamma \)) and the depth below surface terrain (\( z \)) as input parameters. The value determined for (\( \sigma_{v0}' \)) from each sample depth, is then equal to the effective axial confining pressure (\( \sigma_{a,c}' \)) that a test sample from that depth should be consolidated to.

\[
\sigma_{v0}' = \sigma_{a,c}' = (\gamma - 11.8) \cdot z \quad [kPa]
\]  
(4.12)

To find the effective radial confining pressure (\( \sigma_{r,c}' \)), knowledge about the effective at rest coefficient (\( K_0' \)) was needed. There are no known measurements or tests performed to determine \( K_0' \) for the Lilleby clay, but due to historical events mentioned in Subsection 4.1.1 a high value of OCR was expected. After consulting with some members of the faculty staff at NTNU an educated guess of \( K_0' = 0.7 \) was decided upon. Equation 4.13 could then be used to calculate values of \( \sigma_{r,c}' \) from each sample depth.

\[
\sigma_{b0}' = \sigma_{r,c}' = K_0' \cdot \sigma_{v0}' \quad [kPa]
\]  
(4.13)

Unfortunately, due to a minor flaw in the derivation of the expression for calculating \( \sigma_{v0}' \), the expression in Equation 4.14 was used instead. This error was not discovered until after all triaxial tests were performed, having lead to erroneous calculations of \( \sigma_{a,c}' \), also leading to inaccurate values for \( \sigma_{r,c}' \). This is handled and discussed further in Chapter 6 - Discussion.

\[
\sigma_{v0}' = (\gamma - 8.2) \cdot z \quad [kPa]
\]  
(4.14)

As mentioned under Procedure in Subsection 4.3.4, the values for the unit weight (\( \gamma \)) used in calculations of the confining consolidation stresses are always predetermined from the first CRSC oedometer test performed for each mini-block sample. It was decided to use CRSC specimens because the volume of these specimens is confined within the rigid steel oedometer ring, with a given height and diameter. This well defined volume is therefore considered to result in the most representative values of \( \gamma \) achievable when no standardized tests were done to find this parameter. The decision to use a different value of \( \gamma \) for each MBS
was based on knowledge of the heterogeneous nature of the Lilleby clay material. Having a representative value of $\gamma$ is desirable, and therefore it was decided to determine one from each MBS.

**On the procedure**

As mentioned in Section 4.2, the middle section of each mini-block sample was always used for triaxial testing. MBS slices of about 12cm height were sliced into four quarter pieces that yielded one test specimen each (see Figure 4.23a). One quarter slice was always used immediately, whilst the other three pieces were gently packed airtight using several layers of plastic film. The pieces were then carefully placed inside large beaker glasses with a diameter of approximately 15cm, before some damp paper was placed inside to maintain a high humidity around the sample. The beaker glasses were finally sealed tight with plastic film and some tape, before being stored at the desired temperatures. An example of a beaker glass with a quarter clay piece sealed inside is presented in Figure 4.23b.

![Quarter pieces of triaxial MBS slices during subdivision and storage.](image)

Soil samples were always trimmed immediately before mounting and start of testing. Quite a lot of preparation work for the triaxial apparatus was therefore done prior to retrieval and trimming of the specimens. Preparations like these include applying exicator fat on top cap and base of the apparatus to better seal against water transfer, checking rubber membrane for cracks by submerging it into water when filled with air and assembling and preparing the rest of the mounting equipment presented in Figure 4.24b.
4.3. LABORATORY TESTING

The two small strips of membrane presented in Figure 4.24b were used to minimize the chance that either of the porous stone filters placed on each side of the triaxial test specimen would harm and ruin the rubber membrane surrounding the clay test specimen. One small membrane strip was therefore placed over the intersections between clay, porous stone filter and either the base or top caps. This procedure is seen in Figure 4.24 showing parts of the mounting process used for each test specimen. The upper porous stone filter is seen on top of the clay specimen in Figure 4.25a, whilst the bottom stone filter is already protected covered by a membrane strip. The bottom strip was always placed on the base prior to placement of the test specimen on the base.

Although it is recommended in both ISO/TS 17892-9 and Berre (1982) that dry porous filters are used to minimize the risk the material swelling, fully saturated filters were used in all triaxial tests in this work. This may have lead to the ends of each test specimen swelling some before consolidation starts, but would then again not cause drying of the specimens ends or incorrect amounts of expelled water to be measured during consolidation. The porous stone filters used at NTNU use a material unsuited for dry filters, and hence can not be used properly when dry.

Because fully saturated stone filters have been used in this work instead of dry filters, among other things, the procedures used during consolidation and shearing of triaxial test specimens deviated substantially from what is described and recommended both in ISO/TS 17982-9 and Berre (1982). This section presents
the most important and relevant elements of the procedures used for this thesis.

After mounting of a specimen has been finished, roughly as presented in Figure 4.25, the triaxial cell was filled with water before a layer of about 10mm of organic oil was sucked down on top of the water. The triaxial cell was then sealed tight by the placement of a load rod (see Figure 4.26a). A confining cell pressure of $\sim 10$ kPa was then applied in order to be able to flush the filters. Air bubbles that got stuck in the valve block and the intersections between tubes and valves were removed by carefully flicking and tapping the tubes, especially the top drainage tube between the valve block and the air trap. This is the tube previously mentioned to break off when flicked and tapped in cold temperatures.

When the stone filters were sufficiently flushed and little to no amount of air bubbles were seen throughout the system of tubes and valves, consolidation of the test specimens was started. Because it is recommended in NS/TS 17982-9 to adjust/apply cell pressures of $\sigma_{r,c}'$ and $\sigma_{v,c}'$ in small increments to avoid particles coming out from the specimen, increments of 5kPa every 30 minutes were used by recommendation from Helene A. Amundsen. After having reached the desired values of $\sigma_{r,c}'$ and $\sigma_{v,c}'$, the consolidated specimens were left for 10-15 hours, typically over night, to stabilize.

Starting in the morning the following day, the filters were again flushed to make sure that any unwanted air from around the test specimen would be removed. The same procedure as described for the previous filter flushing was used,
with the addition of a syringe with de-aired and distilled water connected to the valve block. This syringe was used to more efficiently remove all air bubbles, especially those stuck in the tubes and in the valve block, by pressing water through the desired parts of the system in a controlled manner. A photograph showing the block valve and how the syringe is connected to the system is presented in Figure 4.26b. Back-pressure was applied when the system was deemed sufficiently flushed.

A back-pressure of about 250kPa was applied to all test specimens prior to shearing, typically by carefully increasing both back pressure and cell pressure by 50kPa every 10-15 minutes in parallel. The value of 250kPa was decided on because Berre (1982) recommends about 200kPa and Helene A. Amundsen recommended using 250kPa. Both NS/TS 17982-9 and Berre (1982) recommend performing a B-test to ensure that the test specimen is sufficiently saturated. A B-value of at least 0.95 reached after performing a B-test and using Equation 4.15 is recommended for static shear tests.

\[
B = \frac{\Delta u}{\Delta \sigma} \quad [\text{--}] \quad (4.15)
\]

B-tests were performed on several of the clay specimens during the troubleshooting period before official testing on Lilleby clay. The use of 250kPa was satisfactory on several occasions, but for some there were unfavourable changes observed in stresses and applied force after performing the B-tests. This was finally re-
solved to be caused by a string of code written into the software, making the stepping motor account for loss in applied force with increasing cell pressure. Thus, when increasing cell pressure to perform a B-test, the stepping motor compensated by adding more force, which was irreversible when the added cell pressure for the test was removed afterwards. For this reason, no B-tests were performed during the triaxial testing of Lilleby clay.

**Gathering results**

Natural water content \( (w_0) \) and unit weight \( (\gamma) \) is determined for all CAUC test specimens. These values are later used in calculations also including elements from the shear test data itself. Even though two different types of software scripts/programs are used during CAUC triaxial shear testing, the same type of data is logged. Both programs yield raw data on time \( (t) \) in seconds, vertical deformation \( (\delta) \) in millimeters, load in Newton, differential, cell and back pressures in kilo pascals and expelled pore water in cubic centimeters. In order to evaluate and present the measured laboratory data, some corrections and calculations are needed.

In order to get as correct values of \( \sigma_{a,c}' \) and \( \sigma_{r,c}' \), being practically the same as the maximum and minimum principal stresses \( \sigma_1' \) and \( \sigma_3' \) respectively, a correction must be made to the initial value for surface area \( (A_0) \). Corrections of \( A_0 \) are made both during consolidation of the specimen, and during the shearing of the specimen. During consolidation the test specimens are subjected to small volumetric reductions. Using known values for initial surface area \( (A_0) \), initial sample volume \( (V_0) \) and change in specimen volume \( (\Delta V) \), equal to the amount of expelled pore water, one can determine a step-wise change in surface area both during and after the consolidation phase of the test using Equation 4.16.

\[
A_n = A_0 \cdot \frac{\left(1 - \frac{\Delta V}{V_0}\right) \left(1 - \frac{\Delta V}{3V_0}\right)}{\left(1 - \frac{\Delta V}{3V_0}\right)} \quad [m^2]
\]

The area correction for expelled water just mentioned is the most important correction done for triaxial tests run at NTNU. There are several other corrections, including corrections for elastic membranes and filter paper strips, both mentioned in NS/TS 17892-9, Berre (1982) and lecture notes and compendiums from NTNU. The only other correction made to the measured test data in this work, is another area correction practised and recommended at NTNU. This area
correction considers the increase in cross-sectional area caused by the increase in shear strain during the shearing of a test. The area correction also takes the typical barrel shaped failure mode into account Sandven et al. (2014). The corrected area both during and after the shear phase can hence be derived using Equation 4.17 with the corrected area after consolidation \( A_a \) and measured axial strain values \( \varepsilon_a \) as input parameters.

\[
A_s = \frac{A_a}{(1 - \varepsilon_a)} \quad [m^2]
\]

After having made corrections to the surface area of the test specimen, accurate values for \( \sigma_{a,c}' \) are calculated. The \( \sigma_{a,c}' \approx \sigma_{1}' \) together with \( \sigma_{r,c}' \approx \sigma_{3}' \) is then used to derive the shear strengths \( (\tau) \) using Equation 4.18, deviatoric stresses \( (q) \) using Equation 4.19 and effective mean stresses \( (p') \) using Equation 4.20, and the fact that \( \sigma_2' = 2 \cdot \sigma_{r,c}' \) in a CAUC triaxial shear test.

\[
\tau = \frac{\sigma_{1}' - \sigma_{3}'}{2} \approx \frac{\sigma_{a,c}' - \sigma_{r,c}'}{2} \quad [kPa]
\]

\[
q = \sigma_{1}' - \sigma_{3}' \approx \sigma_{a,c}' - \sigma_{r,c}' \quad [kPa]
\]

\[
p' = \frac{\sigma_{1}' + 2 \cdot \sigma_{3}'}{3} \approx \frac{\sigma_{a,c}' + 2 \cdot \sigma_{r,c}'}{3} \quad [kPa]
\]

These stresses are all used in the plotting of three different diagrams from the shear phase of the test, for each specimen tested. One of these is a stress-strain diagram plotting \( \varepsilon_a \) vs. \( \tau = 0.5(\sigma_{a,c}' - \sigma_{r,c}') \). This diagram is used, among other things, in determining correct values of the maximum shear stress equal to the undrained shear strength, and the corresponding failure strain \( (\varepsilon_f) \). Another diagram presented is the NTNU plot where \( \sigma_{r,c}' \) is plotted against \( \tau \). This diagram is used when evaluating the behaviour of the stress path of a test specimen, as well as to select values for attraction and friction angle. The last of the three diagrams presented is the \( p'-q \) plot where effective mean stress \( (p') \) is plotted versus deviatoric stress \( (q) \). This latter plot is mainly used in the evaluation of the stress path, as it is theoretically supposed to have a vertically developing stress path until the failure line is reached for CAUC triaxial shear tests.

As mentioned, the undrained shear strength for all triaxially sheared test specimens, is found as the maximum value of shear stress for each test. The failure strain is found as the \( \varepsilon_a \) value for that \( \tau_{max} \) value. Finding the attraction
(a) and the friction angle (φ), on the other hand, is a bit more work. An elongated line from the estimated failure line in an NTNU-plot is drawn down to where it intersects the horizontal axis. The negative value of $\sigma_{r,c}'$ at the intersection point is estimated to be the positive value of $a$. Friction angle (φ) can be derived from the slope of the failure line ($S_f$) using Equation 4.21. Figure 4.27 illustrates the procedure of determining $a$ and $S_f$ from an NTNU plot.

\[
\sin(\phi) \frac{S_f}{S_f + 1} \quad [-]
\]  

Fig. 4.27: Determining attraction intersection and slope of the failure line.
Chapter 5

Test results

This chapter presents the results obtained from all laboratory tests performed in this work. All results will be presented by depth in a table associated to the type of test performed. Additionally, mechanical properties are presented either by line graphs or scatter plots by depth. Individual test results will not be presented here, but are available on data sheets in the appendices. Appendix A presents index test results using a common layout, Appendix B contains CRSC oedometer data sheets, and Appendix C include CAUC triaxial data sheets. Keeping these accessible while following this chapter might be useful.

Table 5.1: Laboratory program for the different mini-block samples.

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Sample depth</th>
<th>Water cont. &amp; Atterb. limits</th>
<th>Falling cone test</th>
<th>Oedom. test (CRSC)</th>
<th>Triaxial test (CAUC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS_1</td>
<td>6.6-6.9m</td>
<td>4</td>
<td>4</td>
<td>7</td>
<td>4</td>
</tr>
<tr>
<td>MBS_2</td>
<td>6.3-6.6m</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>MBS_3</td>
<td>7.8-8.15m</td>
<td>4</td>
<td>4</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>MBS_4</td>
<td>8.2-8.5m</td>
<td>4</td>
<td>4</td>
<td>8</td>
<td>4</td>
</tr>
</tbody>
</table>

The laboratory program performed on the four MBS is presented in Table 5.1, showing the types and extent of tests performed on each sample. A total of 16 Atterberg limit tests, 16 falling cone tests, 29 CRSC oedometer tests and 15 CAUC triaxial shear tests have been performed, which excludes the 3 CRSC and 1 CAUC tests that were discarded due to rock bodies ruining the test specimen. Additionally, several water content samples were extracted over the MBS height.
5.1. Water content results

A thorough indication of the natural water content \((w_0)\), over the height of all mini-block samples, has been gathered using the procedures from Subsection 4.3.1. Eight representative samples were gathered as soon as practicable from MBS_2, MBS_3 and MBS_4, whilst only six were extracted from MBS_1, lacking its two bottom specimens. A total average \(w_0\) of 29.65% is concluded from these 30 test specimens, with values ranging from a minimum value of 26.33% and a maximum value of 36.27%.

When including all additional tests on natural water content from CRSC and CAUC test specimens, there is a total of 74 \(w_0\) values gathered. Each MBS yields 17 to 20 values, with little variation in average \(w_0\) for each MBS. All these additional values fall in the existing range defined above. The mean natural water content is 29.98% \(\approx\) 30%. A scatter plot of all 74 \(w_0\) values by depth is presented on the left hand side of the layout in Appendix A.

Little effect of storage temperature and/or freshness of the mini-block samples are seen in the scatter plot. Considering only the specific samples gathered for checking the water content, there is an average value of 29.28% for the shallowest
mini-block sample, MBS_2, stored for 170 days in cold temperatures. For MBS_1, which was stored for 159 days in room temperature, the average is 28.48. There is a larger difference between the two fresh samples, where MBS_3 stored for 1 day in cold temperatures yields a mean $w_0$ of 28.01%, and MBS_4 stored for 3 days in cold temperatures yields 32.53%.

5.2 Atterberg limit results

Both the plastic and liquid consistency limits of the Lilleby clay have been determined using the procedures presented in Subsection 4.3.2. A total of 16 plastic limits and 16 liquid limits were found, 8 of each in room temperature and in situ temperature. All determined values of $w_P$ and $w_L$ are presented, along with the average of the two measured water contents from the same MBS layer, by depth in Table 5.2. The corresponding plasticity and liquidity indices are also presented in this table.

The average value of $w_P$ tested at cold temperatures is 19.80% and at room temperature 19.31%, while the cold average of $w_L$ is 33.85% and the room temperature average 32.79%. Both the average values and the single values presented in Table 5.2 show a small but clear tendency of higher values of both $w_P$ and $w_L$ for testing temperatures close to in situ temperature. The average increase in $w_L$, for single values from the same depth, is 1.06%, whilst the average increase in $w_P$ is 0.49%. The effect of temperature on the consistency limits of MBS_1, the mini-block sample stored in room temperature for 159 days, is far less evident than on the other mini-block samples.

The plasticity index ($I_P$) of the Lilleby clay range from 11.78 to 17.09% with an average of 13.76%. The cold temperature average of $I_P$ is 14.04 whilst the room temperature average is 13.48. All different values of $I_P$, either tested in cold or room temperatures, fits well within the classification range of a medium plastic clay, see Table 3.1 in Section 3.1. The liquidity index $I_L$ ranges from 0.63 to 0.95, never exceeding the value of 1.0. The fact that $I_L < 1$, and the fact that all values of natural water content lies below the water content at the corresponding liquid limit ($w_0 < w_L$), is another clear indicator that the Lilleby clay is not of high plasticity.

All values of the Atterberg limits $w_P$ and $w_L$ are plotted by depth, with a colour indicating test temperature, in the left hand plot on the layout in Appendix A. It is clear from this graphical presentation that the $w_P$ limits of each
depth agree well with each other, while there is a greater spread between $w_L$ values from the same depth tested at different temperatures.

### 5.3 Fall cone test results

A total of 16 fall cone tests have been performed on the Lilleby clay, both on undisturbed and remoulded clay samples, using the procedures presented in Subsection 4.3.3. Eight tests determining both $s_u$ and $s_r$ were performed in room temperature, the other eight in cold temperature. Tests determining $s_r$ were performed twice, but only the first and most representative value is used to calculate the sensitivity. All values of $s_u$, $s_r$ and $S_t$ are presented in Table 5.3.

The cold temperature average of $s_u$ is 49.65kPa while the room temperature average of 46.27kPa. There is a clear indication of the undrained shear strength increasing with colder test temperatures, as this is seen for all test depths except one. The same tendency is evident for the first remoulded shear strength ($s_{r1}$). The average increase in $s_u$ for a given depth is 3.39kPa, or 7.14% with a range from $-8.43\%$ to $22.28\%$. Only one out of eight being a negative value. There

### Table 5.2: Results from Atterberg limit tests.

<table>
<thead>
<tr>
<th>MBS ID</th>
<th>Depth [m]</th>
<th>Test date [dd.mm.yy]</th>
<th>Test temp. [°C]</th>
<th>Water contents $w_0$ [%]</th>
<th>$w_P$ [%]</th>
<th>$w_L$ [%]</th>
<th>Indices $I_P$ [%]</th>
<th>$I_L$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MBS_2</td>
<td>6.33</td>
<td>07.04.17</td>
<td>6.0</td>
<td>31.15</td>
<td>20.46</td>
<td>34.23</td>
<td>13.77</td>
<td>0.78</td>
</tr>
<tr>
<td></td>
<td>6.33</td>
<td>12.04.17</td>
<td>21.2</td>
<td>31.15</td>
<td>19.41</td>
<td>32.92</td>
<td>13.51</td>
<td>0.87</td>
</tr>
<tr>
<td></td>
<td>6.52</td>
<td>07.04.17</td>
<td>6.0</td>
<td>28.23</td>
<td>19.45</td>
<td>33.49</td>
<td>14.04</td>
<td>0.63</td>
</tr>
<tr>
<td></td>
<td>6.52</td>
<td>12.04.17</td>
<td>21.2</td>
<td>28.23</td>
<td>19.05</td>
<td>32.33</td>
<td>13.28</td>
<td>0.69</td>
</tr>
<tr>
<td>MBS_1</td>
<td>6.63</td>
<td>29.03.17</td>
<td>21.7</td>
<td>28.51</td>
<td>19.59</td>
<td>32.01</td>
<td>12.41</td>
<td>0.72</td>
</tr>
<tr>
<td></td>
<td>6.63</td>
<td>03.04.17</td>
<td>21.7</td>
<td>28.51</td>
<td>19.64</td>
<td>32.57</td>
<td>12.94</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>6.82</td>
<td>30.03.17</td>
<td>21.7</td>
<td>28.76</td>
<td>19.26</td>
<td>33.05</td>
<td>13.79</td>
<td>0.69</td>
</tr>
<tr>
<td></td>
<td>6.82</td>
<td>05.04.17</td>
<td>21.7</td>
<td>28.76</td>
<td>20.14</td>
<td>32.35</td>
<td>12.20</td>
<td>0.71</td>
</tr>
<tr>
<td>MBS_3</td>
<td>7.84</td>
<td>01.05.17</td>
<td>21.3</td>
<td>27.12</td>
<td>18.26</td>
<td>30.04</td>
<td>11.78</td>
<td>0.75</td>
</tr>
<tr>
<td></td>
<td>7.84</td>
<td>05.05.17</td>
<td>21.3</td>
<td>27.12</td>
<td>18.65</td>
<td>31.54</td>
<td>12.89</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>8.04</td>
<td>01.05.17</td>
<td>21.3</td>
<td>28.97</td>
<td>18.96</td>
<td>32.71</td>
<td>13.75</td>
<td>0.73</td>
</tr>
<tr>
<td></td>
<td>8.04</td>
<td>06.05.17</td>
<td>21.3</td>
<td>28.97</td>
<td>19.13</td>
<td>33.94</td>
<td>14.82</td>
<td>0.66</td>
</tr>
<tr>
<td>MBS_4</td>
<td>8.22</td>
<td>15.05.17</td>
<td>21.3</td>
<td>36.24</td>
<td>21.26</td>
<td>38.35</td>
<td>17.09</td>
<td>0.88</td>
</tr>
<tr>
<td></td>
<td>8.22</td>
<td>20.05.17</td>
<td>21.3</td>
<td>36.24</td>
<td>20.78</td>
<td>37.07</td>
<td>16.29</td>
<td>0.95</td>
</tr>
<tr>
<td></td>
<td>8.40</td>
<td>16.05.17</td>
<td>5.9</td>
<td>31.24</td>
<td>19.70</td>
<td>34.29</td>
<td>14.59</td>
<td>0.79</td>
</tr>
<tr>
<td></td>
<td>8.40</td>
<td>21.05.17</td>
<td>5.9</td>
<td>31.24</td>
<td>19.19</td>
<td>32.19</td>
<td>13.00</td>
<td>0.93</td>
</tr>
</tbody>
</table>
CHAPTER 5. TEST RESULTS  

5.3. FALL CONE TEST RESULTS

Table 5.3: Results from fall cone tests.

<table>
<thead>
<tr>
<th>MBS ID</th>
<th>Depth [m]</th>
<th>Test date [dd.mm.yy]</th>
<th>Test temp. [°C]</th>
<th>Strength [kPa]</th>
<th>Sensitivity [−]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$s_u$</td>
<td>$s_{r,1}$</td>
</tr>
<tr>
<td>MBS_2</td>
<td>6.33</td>
<td>06.04.17</td>
<td>6.0</td>
<td>55.20</td>
<td>8.22</td>
</tr>
<tr>
<td></td>
<td>6.33</td>
<td>11.04.17</td>
<td>21.2</td>
<td>48.66</td>
<td>7.55</td>
</tr>
<tr>
<td></td>
<td>6.52</td>
<td>06.04.17</td>
<td>6.0</td>
<td>42.65</td>
<td>8.44</td>
</tr>
<tr>
<td></td>
<td>6.52</td>
<td>11.04.17</td>
<td>21.2</td>
<td>46.48</td>
<td>10.02</td>
</tr>
<tr>
<td>MBS_1</td>
<td>6.63</td>
<td>27.03.17</td>
<td>21.7</td>
<td>57.56</td>
<td>8.32</td>
</tr>
<tr>
<td></td>
<td>6.63</td>
<td>02.04.17</td>
<td>5.9</td>
<td>61.62</td>
<td>12.96</td>
</tr>
<tr>
<td></td>
<td>6.82</td>
<td>27.03.17</td>
<td>21.7</td>
<td>49.26</td>
<td>6.75</td>
</tr>
<tr>
<td></td>
<td>6.82</td>
<td>02.04.17</td>
<td>5.9</td>
<td>60.24</td>
<td>10.94</td>
</tr>
<tr>
<td>MBS_3</td>
<td>7.84</td>
<td>29.04.17</td>
<td>21.3</td>
<td>39.70</td>
<td>7.96</td>
</tr>
<tr>
<td></td>
<td>7.84</td>
<td>04.05.17</td>
<td>5.9</td>
<td>45.30</td>
<td>11.38</td>
</tr>
<tr>
<td></td>
<td>8.04</td>
<td>29.04.17</td>
<td>21.3</td>
<td>50.22</td>
<td>11.38</td>
</tr>
<tr>
<td></td>
<td>8.04</td>
<td>04.05.17</td>
<td>5.9</td>
<td>52.28</td>
<td>11.70</td>
</tr>
<tr>
<td>MBS_4</td>
<td>8.22</td>
<td>13.05.17</td>
<td>5.9</td>
<td>40.50</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>8.22</td>
<td>18.05.17</td>
<td>21.1</td>
<td>39.92</td>
<td>4.78</td>
</tr>
<tr>
<td></td>
<td>8.40</td>
<td>13.05.17</td>
<td>5.9</td>
<td>39.52</td>
<td>6.38</td>
</tr>
<tr>
<td></td>
<td>8.40</td>
<td>18.05.17</td>
<td>21.1</td>
<td>38.34</td>
<td>6.14</td>
</tr>
</tbody>
</table>

is also an average increase in $s_{r,1}$ of 1.54 kPa/20.57%, and an average increase in $s_{r,2}$ of 0.78 kPa/11.21%.

From Table 5.3 no tendency towards increasing undrained shear strength by depth can be seen, in fact the mini-block sample displaying the best mean $s_u$ from the fall cone tests is MBS_1 at 57.17 kPa. This MBS was sampled between 6.6 and 6.9 m depth and has been stored nearly 160 days in room temperature before opening. The two freshly sampled MBS from 7.8 to 8.15 m and 8.2 to 8.5 m depth show the lowest average $s_u$ values, MBS_3 with 46.88 kPa and MBS_4 with 39.57 kPa.

The sensitivity is determined to lie between 3.98 and 8.47, with an average of 5.89. The average value of $S_t$ tested in cold temperatures is 5.61, which is a bit lower than the average $S_t = 6.16$ for testing temperatures around room temperature. Looking at the different $S_t$ values from each depth, there is an average decrease in sensitivity of 0.55 with colder testing temperatures. Using the sensitivity classification by Norsk Geoteknisk Forening (2011) presented in Table 3.2 in Section 3.1, only two out of sixteen values of $S_t$ are higher than 8.0, where $S_t = 8.0$ defines the transition between a less sensitive to a medium sensitive clay. The Lilleby clay is therefore with fair certainty of low sensitivity,
5.4 CRSC oedometer test results

Out of the total 32 CRSC oedometer tests planned, 29 were successfully prepared and executed, following the procedures presented in Subsection 4.3.4. Only three of these test specimens do not show any signs of preconsolidation stress, all from MBS_1 at a depth of approximately 6.68m. Overall 26 of the test specimens can provide data on $p'_c$ and the other parameters of interest. Procedures on how $p'_c$ and some of the other parameters were found are presented in Subsection 4.3.4. Results are listed by depth and temperature in Table 5.4.

![Fig. 5.1: Determined $p'_c$ values from all CRSC tests of Lilleby clay.](image)

Looking at the presented values of $p'_c$, either in Table 5.4 or the scatter plot in Figure 5.1, there is a clear tendency of higher values of $p'_c$ with colder testing temperatures. Values of $p'_c$ range between 170 and 315kPa with an overall average of 263.85kPa. The mean $p'_c$ for cold run tests is 272.14kPa, and around 250.00kPa.
CHAPTER 5. TEST RESULTS 5.4. CRSC OEDOMETER TEST RESULTS

for those run in room temperature. When comparing the average results at each depth by temperature, there is an average increase in \( p'_c \) of 21.07kPa for those performed in cold temperatures. This increase approximates an 8.61\% increase in \( p'_c \), with a range of 0kPa and 21.05\%.

Contrary to what one might expect, there is no clear indication of an increase in \( p'_c \) by depth or sample freshness. In fact, both of the two mini-block samples freshly extracted from below 7.5m depth show lower values of \( p'_c \) than the two that were stored for a longer time, and taken from a shallower depth. The average \( p'_c \) determined from the shallowest mini-block sample, MBS_2 stored for 170 days in cold temperature, is 274kPa. The mini-block sample MBS_1, extracted just below MBS_2 and stored 159 days in room temperature, include both the highest average \( p'_c \) value of all MBS, but also the only tests not yielding any \( p'_c \) values at all. The average \( p'_c \) of MBS_2 is 299kPa. The two freshly sampled mini-block samples both yield lower averages, MBS_3 an average \( p'_c \) of 233kPa and MBS_4 an average of 259kPa.

As indicated in Figure 5.1, mini-block sample MBS_2 from 6.3 – 6.6m depth (stored 170 days in cold temperatures) show the most distinct difference in testing temperature. The stress-strain curves of all CRSC tests performed, at both depths, are presented as combined plots in Figure 5.2. The specimens from the depth of 6.37m are presented above the specimens from 6.55m depth below.

The analysis of other CRSC test parameters \( M_{OC} \), \( m \), \( p'_r \) and \( c_v \) is interesting as well. The effect of testing temperature on the modulus number (\( m \)) is seemingly non existent, with an average of 24.50 in cold testing temperatures and 24.56 in room temperatures. Looking at tests from the same depths, there are both increases and decreases of \( m \) for colder testing temperatures. Results for the tangent modulus (\( M_{OC} \)) between \( p'_0 \) and \( p'_c \) show a cold average of 10.12MPa and a room temperature average of 9.57MPa. For \( M_{OC} \), however, there is a slight tendency towards higher values for colder test temperatures, with an average increase by depth of 0.51MPa, equal to 6.39\%.

The reference pressure shows a clear tendency to increase with colder testing temperatures. In cold temperatures \( p'_r \) has an average value of 151.25kPa, falling to 139.29kPa for room temperature. When considering only those specimens giving an indication of \( p'_c \) and comparing the results for each depth, all but one (CRSC_15 at 6.55m) show distinct increases in \( p'_r \) for cold test temperature. These increases average on 21.88kPa, or 19.01\%. Results for the specimens from depth 6.55m in MBS_2 show the opposite tendency, with cold \( p'_r \) being 10.0kPa.
lower than the room temperature value.

Values on the coefficient of consolidation \(c_v\) (single value chosen for \(p_0')\) have a wide spread, ranging from 5.85m²/yr to 31.95m²/yr with an overall mean value of 13.34m²/yr. The average of \(c_v\) from testing close to in situ temperatures is 16.41m²/yr, while the average value for testing in room temperatures is 10.22m²/yr. Looking again at tests performed at different temperatures from the same depth, there is a general trend of increasing values of \(c_v\) with decreasing test temperatures, even though both increases and decreases are seen. The values do, however, show large differences, even for tests performed at the same temperature on specimens from the same depth. This is evident from table 5.4.

Full results from each of the 29 performed CRSC oedometer tests are presented in designated data sheets presented in Appendix B.
### Table 5.4: Results from CRSC oedometer tests.

<table>
<thead>
<tr>
<th>CRSC ID</th>
<th>Depth [m]</th>
<th>Test date [dd.mm.yy]</th>
<th>Test temp. [°C]</th>
<th>Index properties</th>
<th>Deformation parameters</th>
<th>OCR</th>
<th>c&lt;sub&gt;u&lt;/sub&gt;, e&lt;sub&gt;o&lt;/sub&gt;</th>
<th>Δe/ε&lt;sub&gt;o&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRSC 9</td>
<td>6.37</td>
<td>06.04.17</td>
<td>6.0</td>
<td>19.56</td>
<td>30.24</td>
<td>49.42</td>
<td>0.78</td>
<td>6.16</td>
</tr>
<tr>
<td>CRSC 10</td>
<td>6.37</td>
<td>07.04.17</td>
<td>6.0</td>
<td>19.57</td>
<td>29.93</td>
<td>49.51</td>
<td>0.78</td>
<td>6.40</td>
</tr>
<tr>
<td>CRSC 13</td>
<td>6.37</td>
<td>11.04.17</td>
<td>21.2</td>
<td>19.48</td>
<td>30.07</td>
<td>48.67</td>
<td>0.79</td>
<td>5.84</td>
</tr>
<tr>
<td>CRSC 14</td>
<td>6.37</td>
<td>12.04.17</td>
<td>21.2</td>
<td>19.46</td>
<td>30.12</td>
<td>48.79</td>
<td>0.79</td>
<td>5.81</td>
</tr>
<tr>
<td>CRSC 11</td>
<td>6.55</td>
<td>08.04.17</td>
<td>6.0</td>
<td>19.79</td>
<td>28.45</td>
<td>52.35</td>
<td>0.74</td>
<td>7.06</td>
</tr>
<tr>
<td>CRSC 12</td>
<td>6.55</td>
<td>09.04.17</td>
<td>6.0</td>
<td>19.70</td>
<td>29.17</td>
<td>51.73</td>
<td>0.76</td>
<td>7.39</td>
</tr>
<tr>
<td>CRSC 15</td>
<td>6.55</td>
<td>13.04.17</td>
<td>21.2</td>
<td>19.58</td>
<td>29.65</td>
<td>50.97</td>
<td>0.77</td>
<td>7.51</td>
</tr>
<tr>
<td>CRSC 16</td>
<td>6.55</td>
<td>14.04.17</td>
<td>21.2</td>
<td>19.64</td>
<td>29.23</td>
<td>51.37</td>
<td>0.76</td>
<td>6.92</td>
</tr>
<tr>
<td>CRSC 1</td>
<td>6.68</td>
<td>27.03.17</td>
<td>21.7</td>
<td>19.79</td>
<td>28.36</td>
<td>53.36</td>
<td>0.74</td>
<td>N/A</td>
</tr>
<tr>
<td>CRSC 5</td>
<td>6.68</td>
<td>02.04.17</td>
<td>5.9</td>
<td>19.64</td>
<td>29.12</td>
<td>52.39</td>
<td>0.76</td>
<td>N/A</td>
</tr>
<tr>
<td>CRSC 6</td>
<td>6.68</td>
<td>03.04.17</td>
<td>5.9</td>
<td>19.84</td>
<td>28.15</td>
<td>53.74</td>
<td>0.73</td>
<td>N/A</td>
</tr>
<tr>
<td>CRSC 3</td>
<td>6.85</td>
<td>28.03.17</td>
<td>21.7</td>
<td>19.74</td>
<td>28.58</td>
<td>54.42</td>
<td>0.74</td>
<td>8.08</td>
</tr>
<tr>
<td>CRSC 4</td>
<td>6.85</td>
<td>29.03.17</td>
<td>21.7</td>
<td>19.29</td>
<td>30.13</td>
<td>51.31</td>
<td>0.83</td>
<td>6.99</td>
</tr>
<tr>
<td>CRSC 7</td>
<td>6.85</td>
<td>04.04.17</td>
<td>5.9</td>
<td>19.51</td>
<td>30.85</td>
<td>52.82</td>
<td>0.80</td>
<td>7.23</td>
</tr>
<tr>
<td>CRSC 8</td>
<td>6.85</td>
<td>05.04.17</td>
<td>5.9</td>
<td>19.30</td>
<td>32.47</td>
<td>51.36</td>
<td>0.84</td>
<td>6.74</td>
</tr>
<tr>
<td>CRSC 18</td>
<td>7.88</td>
<td>29.04.17</td>
<td>21.3</td>
<td>19.97</td>
<td>26.91</td>
<td>64.33</td>
<td>0.70</td>
<td>7.74</td>
</tr>
<tr>
<td>CRSC 21</td>
<td>7.88</td>
<td>04.05.17</td>
<td>5.9</td>
<td>19.76</td>
<td>26.62</td>
<td>62.65</td>
<td>0.74</td>
<td>7.59</td>
</tr>
<tr>
<td>CRSC 22</td>
<td>7.88</td>
<td>05.05.17</td>
<td>5.9</td>
<td>20.03</td>
<td>26.86</td>
<td>64.82</td>
<td>0.70</td>
<td>8.07</td>
</tr>
<tr>
<td>CRSC 19</td>
<td>8.08</td>
<td>30.04.17</td>
<td>21.3</td>
<td>19.17</td>
<td>32.60</td>
<td>59.51</td>
<td>0.85</td>
<td>4.45</td>
</tr>
<tr>
<td>CRSC 20</td>
<td>8.08</td>
<td>01.05.17</td>
<td>5.9</td>
<td>19.12</td>
<td>33.41</td>
<td>59.12</td>
<td>0.87</td>
<td>4.73</td>
</tr>
<tr>
<td>CRSC 24</td>
<td>8.08</td>
<td>06.05.17</td>
<td>5.9</td>
<td>19.16</td>
<td>32.47</td>
<td>59.41</td>
<td>0.85</td>
<td>5.41</td>
</tr>
<tr>
<td>CRSC 25</td>
<td>8.26</td>
<td>13.05.17</td>
<td>5.9</td>
<td>19.18</td>
<td>32.99</td>
<td>60.96</td>
<td>0.86</td>
<td>7.52</td>
</tr>
<tr>
<td>CRSC 26</td>
<td>8.26</td>
<td>14.05.17</td>
<td>5.9</td>
<td>19.06</td>
<td>33.37</td>
<td>59.93</td>
<td>0.87</td>
<td>7.24</td>
</tr>
<tr>
<td>CRSC 29</td>
<td>8.26</td>
<td>18.05.17</td>
<td>21.1</td>
<td>19.40</td>
<td>30.97</td>
<td>62.72</td>
<td>0.81</td>
<td>7.21</td>
</tr>
<tr>
<td>CRSC 30</td>
<td>8.26</td>
<td>19.05.17</td>
<td>21.1</td>
<td>19.16</td>
<td>32.78</td>
<td>62.76</td>
<td>0.86</td>
<td>6.98</td>
</tr>
<tr>
<td>CRSC 27</td>
<td>8.43</td>
<td>15.05.17</td>
<td>5.9</td>
<td>19.29</td>
<td>31.60</td>
<td>63.14</td>
<td>0.83</td>
<td>6.91</td>
</tr>
<tr>
<td>CRSC 28</td>
<td>8.43</td>
<td>16.05.17</td>
<td>5.9</td>
<td>19.33</td>
<td>31.40</td>
<td>63.47</td>
<td>0.82</td>
<td>5.56</td>
</tr>
<tr>
<td>CRSC 31</td>
<td>8.43</td>
<td>20.05.17</td>
<td>21.1</td>
<td>19.42</td>
<td>30.74</td>
<td>64.20</td>
<td>0.80</td>
<td>7.74</td>
</tr>
<tr>
<td>CRSC 32</td>
<td>8.43</td>
<td>21.05.17</td>
<td>21.1</td>
<td>19.30</td>
<td>31.59</td>
<td>63.18</td>
<td>0.83</td>
<td>6.55</td>
</tr>
</tbody>
</table>

CRSC 9 CRSC 10 CRSC 13 CRSC 14 CRSC 11 CRSC 12 CRSC 15 CRSC 16 CRSC 1 CRSC 5 CRSC 6 CRSC 3 CRSC 4 CRSC 7 CRSC 8 CRSC 18 CRSC 21 CRSC 22 CRSC 19 CRSC 20 CRSC 24 CRSC 25 CRSC 26 CRSC 29 CRSC 30 CRSC 27 CRSC 28 CRSC 31 CRSC 32
5.5 CAUC triaxial test results

Out of 16 planned CAUC triaxial tests, 15 of the specimens were prepared and tested. The preparation, mounting and testing procedures from Subsection 4.3.5 were followed as closely as possible to provide the most identical environments possible for the tests. In spite of this, some exceptions and deviations have occurred during the process, and some artifacts have appeared in the results. A maximum shear stress ($\tau_{\text{max}}$), equal to the undrained shear strength ($s_u$), has nevertheless been found for the 15 CAUC test specimens. Results for $s_u$, failure strain ($\varepsilon_f$), attraction intersection ($a$), and friction angle ($\phi$) are presented in Table 5.5.

Results of $s_u$ from the Lilleby clay have an overall average value of 68.39kPa, ranging from 55.32kPa to 81.93kPa. The average is 70.10kPa for cold testing temperatures and 66.44kPa for room temperature testing. There is evidence of higher strength for colder temperatures, as three out of four mini-block samples show this clearly. MBS_3 on the other hand, shows the exact opposite result: higher values of $s_u$ when testing in room temperatures than for cold temperatures.

![Graph showing $\tau_{\text{max}} = s_u$ values from all CAUC tests of Lilleby clay.]

The average change in $s_u$ for a given depth across all mini-block samples is an increase of 3.68kPa for cold temperatures, a 6.20% relative increase. If the results
from MBS_3 are discarded, this grows to 6.72kPa, or 10.80%. Values of average change in $s_u$ by depth for CAUC triaxial testing range from $-7.61\%$ to 16.02% with cold test temperatures, with only one out of four values being negative. All values of $s_u$ are graphically presented by depth, with colour indication for testing temperature, in Figure 5.3.

It can be seen in both Table 5.5 and Figure 5.3 that on average $s_u$ has little increase by depth and/or sample freshness. The average strength values of the stored mini-block samples are 72.01kPa for MBS_2 at 6.45m depth, and 61.46kPa for MBS_1 at 6.74m depth. There is a clear increase in $s_u$ for colder storing temperatures, but the spread in the results is quite large compared to the results from the freshly sampled mini-block samples. MBS_3 shows an average strength value of 68.58kPa from 7.96m depth, and MBS_4 shows an average $s_u$ of 72.43kPa from 8.33m depth, both with much less spread in the values.

There does not seem to be any noticeable effect of testing temperature on the strain at failure ($\varepsilon_f$), the strain value at maximum shear stress. In general there is an average of 0.91% for cold testing temperatures and 0.87% for room temperature testing, while comparing results from the same depths shows both increases and decreases with colder testing temperatures.

![NTNU Plot](image)

*Fig. 5.4: NTNU plot for all triaxial shear tests performed.*
The effect of temperature on the attraction and friction angle is a bit difficult to assess as nearly all CAUC test specimens failed with visible shear bands, and not the barreling failure mode one might expect. Even so, values for attraction and friction angle have been derived as presented in Subsection 4.3.5, and are presented in Table 5.5. On average $a$ increases from 6.57kPa when tested at room temperature to 8.75kPa in cold temperatures. In contrast to the other samples, with average increases from warm to cold temperatures of around 6.5kPa, MBS_4 show a decreased attraction by about 7.5kPa for the cold temperature.

Where the cold tested specimens exhibit an average friction angle of 32.59°, the room temperature ones have an average of 33.24°. Mirroring the behavior of $a$, $\phi$ at each depth shows a small decrease for cold tested specimens, ranging from 1.60 to 3.29°, while MBS_4 has an increase of around 4.25°.

All results from each of the 15 CAUC triaxial shear tests performed are presented in designated data sheets presented in Appendix C. Figure 5.4 presents the results from all CAUC triaxial shear tests in an NTNU plot. From this figure the trend of higher values of both $s_u$ and $a$ with colder testing temperatures is observable.
Table 5.5: Results from CAUC triaxial shear tests.

<table>
<thead>
<tr>
<th>CAUC ID</th>
<th>Depth [m]</th>
<th>Test date [dd.mm.yy]</th>
<th>Test temp. [°C]</th>
<th>Index properties</th>
<th>Consolidation properties</th>
<th>Shear test results</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$\gamma$ [kN/m$^3$]</td>
<td>$w_0$ [%]</td>
<td>$e_0$ [-]</td>
</tr>
<tr>
<td>CAUC 5</td>
<td>6.45</td>
<td>06.04.17 6.0</td>
<td></td>
<td>19.95</td>
<td>29.38</td>
<td>0.74</td>
</tr>
<tr>
<td>CAUC 6</td>
<td>6.45</td>
<td>08.04.17 6.0</td>
<td></td>
<td>20.11</td>
<td>29.37</td>
<td>0.72</td>
</tr>
<tr>
<td>CAUC 8</td>
<td>6.45</td>
<td>12.04.17 21.2</td>
<td></td>
<td>19.76</td>
<td>29.41</td>
<td>0.75</td>
</tr>
<tr>
<td>CAUC 9</td>
<td>6.74</td>
<td>27.03.17 21.7</td>
<td></td>
<td>20.42</td>
<td>28.52</td>
<td>0.69</td>
</tr>
<tr>
<td>CAUC 2</td>
<td>6.74</td>
<td>30.03.17 21.7</td>
<td></td>
<td>20.39</td>
<td>28.19</td>
<td>0.68</td>
</tr>
<tr>
<td>CAUC 3</td>
<td>6.74</td>
<td>02.04.17 5.9</td>
<td></td>
<td>20.10</td>
<td>29.31</td>
<td>0.72</td>
</tr>
<tr>
<td>CAUC 4</td>
<td>6.74</td>
<td>04.04.17 5.9</td>
<td></td>
<td>20.34</td>
<td>29.17</td>
<td>0.70</td>
</tr>
<tr>
<td>CAUC 9</td>
<td>7.96</td>
<td>29.04.17 21.3</td>
<td></td>
<td>20.00</td>
<td>30.02</td>
<td>0.74</td>
</tr>
<tr>
<td>CAUC 10</td>
<td>7.96</td>
<td>01.05.17 21.3</td>
<td></td>
<td>20.18</td>
<td>29.40</td>
<td>0.72</td>
</tr>
<tr>
<td>CAUC 11</td>
<td>7.96</td>
<td>04.05.17 5.9</td>
<td></td>
<td>19.94</td>
<td>29.33</td>
<td>0.74</td>
</tr>
<tr>
<td>CAUC 12</td>
<td>7.96</td>
<td>06.05.17 5.9</td>
<td></td>
<td>19.95</td>
<td>29.49</td>
<td>0.74</td>
</tr>
<tr>
<td>CAUC 13</td>
<td>8.33</td>
<td>13.05.17 5.9</td>
<td></td>
<td>19.66</td>
<td>30.91</td>
<td>0.78</td>
</tr>
<tr>
<td>CAUC 14</td>
<td>8.33</td>
<td>15.05.17 5.9</td>
<td></td>
<td>19.60</td>
<td>31.44</td>
<td>0.80</td>
</tr>
<tr>
<td>CAUC 15</td>
<td>8.33</td>
<td>18.05.17 21.1</td>
<td></td>
<td>19.72</td>
<td>31.43</td>
<td>0.79</td>
</tr>
<tr>
<td>CAUC 16</td>
<td>8.33</td>
<td>20.05.17 21.1</td>
<td></td>
<td>19.66</td>
<td>30.91</td>
<td>0.78</td>
</tr>
</tbody>
</table>
Chapter 6

Discussion

This chapter will discuss the values and tendencies of the results presented in Chapter 5, from the index tests, CRSC oedometer tests and CAUC triaxial shear tests performed in this master thesis. Both the effect of storage temperature and testing temperature, as well as the effect of storage length, are handled, but because the effect of storage temperature and sample freshness seems to be less evident for the Lilleby clay, these effects are weighted less. The main focus will therefore be on the effect of testing temperature, and deviations from apparent trends, on results for the soil parameters $p'_c$ from CRSC tests, and $s_u$ from fall cone tests and CAUC tests.

Some artifacts and irregularities will be mentioned and are discussed to some extent. This work does not focus on challenges and problems encountered with possible fault in the laboratory equipment. Deviations in laboratory data or behaviour believed to be caused by laboratory equipment will thus be mentioned but not discussed in extent or troubleshooting for explanations or answers anymore than what was done previous to, or during, official testing of the Lilleby clay.

6.1 Heterogeneity of Lilleby clay

As was mentioned in Section 4.1 on the sampling of the clay at Lilleby, this clay is not a homogeneous and isotropic material. Several challenges due to this heterogeneity was encountered throughout dividing, trimming, mounting and testing the Lilleby clay. Turbulent layers of silt and sand were found in
6.1. HETEROGENEITY OF LILLEBY CLAY

some parts of the clay, and stones ranging from only a couple of millimetres in
diameter to about 25mm were sporadically encountered. Some of these layers
and stones resulted in a good deal of problems and challenges when testing the
clay, and some test specimens even had to be discarded. Figure 6.1a shows some
of the largest stones encountered during the laboratory testing, and Figure 6.1b
present a CRSC test specimen that had to be discarded due to a vertical layer of
sand that cracked open during trimming of the specimen.

![Some large stones encountered](image1.png)  ![Failed CRSC specimen due to sand](image2.png)

Fig. 6.1: Examples of stones and silt and sand layers in the Lilleby clay.

There are some possible explanations for how and why the Lilleby clay has
such distinct levels of anisotropy, but they will in large parts be mostly guesswork
and speculation based on the geological history of the Lilleby site. The Lilleby site
is situated fairly close to the coast of the Trondheimsfjord, approximately 1.5km
from the coastline both west- and eastbound, and 2km northbound. Today’s
coastal areas in Sør-Trøndelag became free from continental glaciers about 12
500 years ago. The glacier then retreated quickly by large amounts of glacier
calving south- and eastwards from today’s Trondheim, but with several retarda-
tions during its retreat (Reite, Sveian & Erichsen, 1999).

Calving processes like this, bringing larger material further out into the fjord
and ocean than the streams and currents normally would allow for, could be the
reason why such a high amount of stones of various sizes are encountered in the
clay material. The turbulent sedimentation layers also incorporating layers and
pockets of silt and sand, could be a result of slides, happening either off shore
or close to shore, during the many years of isostatic uplift of Trondheim and
surrounding areas during the last 9000 years (Reite et al., 1999).

The large variations in anisotropy of the clay encountered both between mini-block samples and between layers/slices of one mini-block sample nevertheless cause an uncertainty that can not be disregarded when evaluating, discussing and concluding on test results from Lilleby clay samples. It makes comparison of strength and other parameters difficult between block samples, making the results from specimens extracted from the same depth in a mini-block sample, tested on different temperatures, the most relevant values to compare and draw conclusions from.

6.2 Index tests

Water contents \( w_0 \), \( w_P \) and \( w_L \)

The 74 different values of water content from all four mini-block samples show a range from 26.33\% to 36.27\%, with almost 10\% difference. The same range and difference is the case for the 30 specific water content specimens. A difference of nearly 10\% between minimum and maximum value of \( w_0 \) is significant, but then there are only two values of \( w_0 \) above 33.5\%, both values above 36\% from the same MBS slice at 8.22m depth. Values of \( w_0 \) lower than 27\% are also rare, with only four values, all of which are results from the freshly sampled MBS_3.

(a) Clay, silt and sand in MBS_3  
(b) Clean and smooth clay from MBS_4

Fig. 6.2: There is substantial difference in clay composition for different depths.

The deviations in \( w_0 \) from the typical values ranging from 28 to 31\% are most
likely a result of the turbulent sedimentation layers of the Lilleby clay. The low values encountered throughout mini-block sample MBS_3 could be due to high amount of turbulent layers and pockets of sand and silt that characterized this MBS. The failed CRSC test specimen presented in Figure 6.1b was from MBS_3, and another example of turbulent layers including silt and sand is presented in Figure 6.2a. Layers and pockets of coarser and more permeable material like this drain the clay more efficiently than it would have done by itself.

The clay from 8.22m depth in MBS_4, showing very high values of natural water content, was a layer showing above normal homogeneity for the Lilleby clay. The extraction of water content specimens from this layer was highly non-typical. A photo is presented in Figure 6.2b showing how fat and clean this slice was compared to the slice from MBS_3 presented in Figure 6.2a. There are no signs of turbulent sedimentation layers of either clay or coarser material here, thus resulting in better maintenance of the natural water content. Because of this, MBS_4 might be most representative of the two freshly sampled MBS, at least with regard to water contents.

Values of water content determined at the plastic and liquid consistency limits from the sampled Lilleby clay show the exact same tendencies as discussed for the natural water content. Mini-block sample MBS_4 result in the highest measured values (avg. \( w_P = 20.23\% \) and avg. \( w_L = 35.48\% \)), and MBS_3 result in the lowest measured values (avg. \( w_P = 18.75\% \) and avg. \( w_L = 32.06\% \)). The difference between MBS_1 (avg. \( w_P = 19.66\% \) and avg. \( w_L = 32.29\% \)) and MBS_2 (avg. \( w_P = 19.59\% \) and avg. \( w_L = 33.24\% \)) are not significant, and neither are the differences between these two long-term stored MBS compared to the freshly sampled MBS_3. The tendencies are fairly evident from both Table 5.2 presented in Chapter 5, and the left hand plot of the layout in Appendix A - Index tests.

\( s_u \) from fall cone tests

From the results presented in Section 5.3 a tendency can be seen towards higher strength values for colder testing temperatures. This tendency is seen for undrained shear strength values from all tests run, except for the test performed on a slice from MBS_2 at 6.52m depth. The fall cone test performed on the sample from 6.52m depth, in cold temperatures just after it was sliced off of MBS_2, showed 42.56kPa, about 12kPa lower strength, than the sample sliced and tested
from the shallower depth of 6.33m earlier that same day. The two fall cone tests performed on the other halves of the MBS slices, after four days of storage in cold temperatures and one day in room temperature, all showed higher results of $s_u$ than 42.56kPa.

Visual observations of the specimens from 6.33m and 6.52m depth gave no indication of specific differences when tested. Evaluation of the water contents from the different depths does not shed any further light on the opposite temperature effect encountered at this depth. The Atterberg limits from both depths are very similar, as are the values of the natural water content. The tests were done using all of the same equipment, thoroughly cleaned between tests. There are, in other words, no trivial explanation for why the undrained shear strength is 3.92kPa lower for colder testing temperatures than room temperatures.

Comparing results of undrained shear strengths between mini-block samples show a relatively large spread. There is about 28kPa difference in $s_u$ between the minimum value of 38.34kPa and the maximum of 61.62kPa. MBS_1 was stored for 159 days in room temperatures before being opened and tested, but nevertheless show the highest values of $s_u$ encountered. The lowest values are encountered in the freshly sampled MBS_4. The reason why the mini-block sample that has the worst storage conditions show the best results, while one of the MBS stored only for a few days show the worst results, is hard to explain when testing has been done with the same equipment and without any apparent inconsistencies.

6.3 CRSC oedometer tests

When assessing sample quality, all CRSC oedometer tests show values of $\Delta e/e_0$ ranging from 0.047 to 0.102. Using the evaluation criterion from Lunne et al. (1997), presented in Table 3.4, these values indicate sample quality ranging from good to fair quality, to very poor quality. The average value of $\Delta e/e_0$ for all 29 CRSC specimens tested is 0.072, indicating that several test specimens fall into the sample quality characterization of poor quality. Only one specimen, CRSC_30, falls into the category of very poor quality.

This evaluation of sample quality for Lilleby clay specimens is made by comparing the calculated values of $\Delta e/e_0$ to the values listed for OCR ranging between 2-4 in Table 3.4. Values of OCR for the Lilleby clay range from 2.9 to 6.0, with an average of 4.7 indicating that most values are above 4. The criterion by Lunne et al. (1997) might therefore not be sufficient to characterize the
sample quality of the specimens. There is also a relatively large spread in the calculated $\Delta e/e_0$ values, where some seem to be reasonable based on test results, while others are not.

As mentioned in Section 5.4 on CRSC oedometer results, there is a tendency of increasing $p'_c$ with decreasing testing temperatures. Samples from all but one depth have an average increase when evaluating values of samples tested at different temperatures from the same depth. Average increase with colder testing temperatures by depth range between 0.0% and 21.05% with an average of 8.61%. These values fit well with the values both Lunne et al. (2012) and Gue et al. (2015) found from similar tests run at NGI and MSU. They also agree with the expectation of approximately 10% change in strength values per 12 °C change in temperature proposed by Leroueil and Marques (1996).

Samples from 6.55m depth in MBS_2 show zero effect of different testing temperature on the measured values of $p'_{c}$, in large parts due to CRSC_11 yielding a much lower value of $p'_{c}$ than all the other three. There are no clear indications from either the clay material itself or the testing procedure practised on why this sample should yield 40kPa lower value of $p'_{c}$ than CRSC_12 from the same depth, tested at the same temperature and with the same equipment. CRSC_11 does in fact yield the best sample quality evaluation of them all, second best of the whole mini-block sample.

The difference in measured $p'_{c}$ for CRSC_11 and CRSC_12 is not a singular occurrence. Some other pairs of test specimens that are from the same depth and are tested at the same temperature also produce relatively large differences in measured preconsolidation pressure. CRSC_26 and CRSC_25 both show the exact same values respectively, and thus have the same difference in $p'_{c}$ observed for CRSC_11 and 12. CRSC_19 and CRSC_20 show a difference of 30kPa. Both cases show better sample quality evaluation for the test specimen yielding the highest value of $p'_{c}$, possibly explaining the differences observed here. The sedimentation process of the clay could also have caused different microscopical structural arrangements, hard to observe and assess, that can have an impact on the results.

Determination of preconsolidation stress is difficult for the upper layer in MBS_1. Three tests were performed on the material at 6.68m depth, presented in the upper $\sigma'_{v} - \varepsilon_{a}$ diagram in Figure 6.3, showing no indication of $p'_{c}$. Some difficulties were encountered, both with trimming and mounting test specimens from this depth. The clay showed irregularities in its composition during trimming,
and for one test specimen this resulted in a small gap between the oedometer ring and the test specimen. This gap caused water to transfer from below the base of the specimen up to the top during mounting, as seen in Figure 6.4a. Another problem was encountered when the clamp ring (no: klemring) got stuck on the oedometer ring. This caused the oedometer ring to slide along the trimmed test specimen, CRSC_1, which resulted in disturbance of the clay in the interface between clay and metal.

Neither of these problems should be significant enough to remove all traces of \(p'_c\), especially not for the last oedometer test CRSC_6 from the same depth. CRSC_6 was both trimmed and mounted carefully and without any inconsistencies in the testing procedure. CRSC_6 is, however, the test specimen showing highest degree of sample disturbance, with a \(\varepsilon_V\) value of 0.099 almost defining it as a very poor quality specimen. CRSC_1 and CRSC_5 have \(\varepsilon_V\) values of 0.060
and 0.068, showing some of the best sample quality results of all specimens tested.

Test specimens CRSC_3 and CRSC_4 from 6.85m depth were both tested in between CRSC_1 and CRSC_5, and both show very clear indications of their preconsolidation stresses, thus reducing the likelihood that the operator or equipment are at fault. All CRSC test specimens from the mini-block samples, MBS_2 sampled above MBS_1, and MBS_3 and MBS_4 sampled below, all show clear indications of \( p'_c \). In other words, the lack of \( p'_c \) only encountered for this one depth might just be a result of encountering a thin layer of disturbed clay. A slide could possibly have caused the grain structure to break down in such a layer before sedimentation of more clay material continued later on.

![Fig. 6.4: Some challenges encountered during CRSC oedometer compression testing.](image)

(a) Gap between clay specimen and ring  (b) Shifting of guiding ring due to O-ring

When presenting values on the coefficient of consolidation in Section 5.4, a wide spread in values was mentioned, both across the different mini-block samples, but also for specimens from the same depth under the same test conditions. A minimum value of 5.85m\(^2\)/yr was observed for the fresh MBS_4, while the maximum value was observed from the other freshly sampled MBS, at 31.95m\(^2\)/yr. Still, 14 out of 29 values fall in the range of 10 – 14m\(^2\)/yr, and show a trend towards higher values for testing temperatures closer to in situ conditions. This observation is the opposite of what both Perkins and Sjursen (2009) and Lunne et al. (2012) found, as mentioned in Chapter 2 - Background. Further investigation into this might be needed.

Comparing and assessing the effect of storage temperature on the stored mini-block samples MBS_1 and MBS_2 has proven troublesome since one out of four depths show no indication of \( p'_c \). Because MBS_1, stored for 159 days in room
temperature, yields very high results of $p'_c$ from the one depth that provides a value, the strength results from this mini-block sample are considerably higher than for MBS_2. Strength values from both testing temperatures range from 275 to 315kPa for MBS_1, whilst only from 230 to 305kPa for MBS_2. MBS_2 was stored for 170 days in $\sim 6^\circ C$. These results are not as expected, but they do in fact agree with the findings made by Lunne et al. (2012) on the effects of storage temperatures (see Chapter 2).

That the poorest results observed for both individual and average values of $p'_c$ are found in the two fresh mini-block samples, stored for only a few days before testing, is incomprehensible. Their sample quality is not good, with specimens generally determined to be of poor quality, but this is not exceptional for these MBS. Average values of $\Delta e/e_0$ for both MBS_3 and 4 are approximately the same as for MBS_1 and 2. MBS_3 shows both the lowest individual and average values of $p'_c$, yet has the best average value of $\Delta e/e_0 = 0.066$ compared to the rest. It is hard to present any justifiable explanation for this, other than there possibly being a substantially different soil material at these depths.

Looking back at Figure 6.3, specifically at the lower plot from 6.85m depth, there is another somewhat strange behaviour that can be seen. Relatively large changes in $\varepsilon_a$ are observed for minor changes in $\sigma'_v$. This behaviour is applicable for approximately 18 of the 29 performed CRSC tests, with an increase in $\varepsilon_a$ of about 2 – 3% during the initial 10 – 15kPa change in $\sigma'_v$. Appendix B shows this behaviour more clearly.

One possibility is that the trimmed clay specimen does not fill the oedometer ring properly, exaggerated in Figure 6.4a, which would lead to a “false” deformation, where the specimen deforms to fill the ring before true compression occurs. Gaps between the specimen and the ring were seldom observed, but even small gaps might have an effect. This raises the question of whether values of $\Delta e/e_0$ assessing sample quality for CRSC specimens are correct, and that the sample quality might be considerably better than indicated.

For the 18 tests showing the distinct increase in $\varepsilon_a$ for minor changes in $\sigma'_v$, the actual sample quality of the specimen could very well be better than presented both previously in this chapter and in Table 5.4. Occurrences of this sharp immediate increase of $\varepsilon_a$ correlate very well with specimens that have high values for $\Delta e/e_0$. Less emphasis is therefore placed with the oedometer specimens’ sample quality.

During laboratory testing, using the CRSC oedometer apparatus in temper-
atures close to the *in situ* temperature of clays, some general irregularities were encountered. For several specimens mounted and tested at cold temperatures, it seemed as though the rubber O-ring that is used to seal the base to the guiding ring was less prone to being compressed when the clamp ring was tightened with its three screws. Instead of being compressed properly, like it usually is during room temperature testing, the O-ring seemed to curl, shifting on the placement of the guiding ring. A photograph of the event is presented in Figure 6.4b (the water seen in the photograph is from the mounting of the sample).

Trying to gently move the guiding ring, or shift it back down to its normal position, seemed impossible after it was mounted. It was immobile, and pinned in this position throughout the compression test. There were no indications of leakages during the tests, and no obvious effect of these events appears in the test results. Nevertheless, it is mentioned here because it happened more than once, always in cold temperatures, and may have caused problems or impacts that have not yet been recognized.

6.4 CAUC triaxial shear tests

Sample quality for CAUC triaxial test specimens is evaluated using both the $\Delta V/V_0$ criterion proposed by Andresen and Kolstad (1979) and the criterion using $\Delta e/e_0$ proposed by Lunne et al. (1997). Both criteria are presented in Chapter 3 on sample quality. Unfortunately, because the consolidation stresses were calculated erroneously prior to testing, all CAUC test specimens were consolidated to a higher value, both radially and axially, than they should have been.

Axially, the difference in $\sigma_{a,c}^\prime$ from what was used and what should have been used ranges between 23kPa and 30kPa. The difference in $\sigma_{r,c}^\prime$ range between 16kPa and 21kPa. This probably caused more water to be expelled during consolidation than there would have been for correctly calculated values, likely resulting in an indicated sample quality worse than might actually be the case. That said, the effective at rest coefficient ($K_0'$) of 0.7 is only an estimate, which also introduces some uncertainty for the anisotropic consolidation stresses.

Values of $\varepsilon_V = \Delta V/V_0$ range from 1.50% to 4.00% with an average of 2.3%, though only two values are higher than 3.00%. Both of the two last CAUC specimens tested expelled about 9mL = 9cm$^3$ of pore water, resulting in values of $\varepsilon_V$ close to 4%. All other tests expelled between 3.45mL and 6.24mL during con-
solidation, and among these only specimens tested in room temperature expelled more than 5.06 mL of pore water. Using the criterion presented in Table 3.3, eight of the specimens yield $\varepsilon_V$ values characterizing them as good quality specimens, while the remaining seven specimens including CAUC_15 and 16 are of fair quality.

Calculated values of the ratio $\Delta e/e_0$ using Equation 3.7 range from 0.036 to 0.093, with an average value of 0.055. The trend in values of $\Delta e/e_0$ is the same as that described for $\varepsilon_a$ above, showing values far higher for CAUC_15 and CAUC_16 than for all other CAUC test specimens. With knowledge of the Lilleby clay having a high value of OCR, and using the sample quality criterion presented in Table 3.4, eight of the test specimens tested evaluate to good to fair quality, while the remaining seven are of poor quality.

The amounts of expelled pore water mentioned above might be correct. Knowing the amount of leakages encountered and presumed mended during the troubleshooting period of this thesis, the clear trend of room temperature consolidation not stabilizing properly (which can be seen in the consolidation curves in Appendix C) could also be due to an undiscovered leakage only observable in room temperature. The consolidation graphs of CAUC tests from MBS_4 at 8.33 m depth are presented in Figure 6.5, showing CAUC_15 and CAUC_16 with dashed lines.

Also visible in Figure 6.5 is the typical fluctuation behaviour occurring for several of the CAUC test specimens during consolidation. The fluctuation seems very regular in Figure 6.5, but looking at some of the other consolidation plots in Appendix C it is clear that several types of both fluctuating and non-fluctuation consolidation curves occur throughout CAUC testing of the Lilleby clay. These fluctuations were subject to extensive troubleshooting, with assistance from members of the faculty and other students, but all attempts at finding a cause were unsuccessful.

It should be noted that the exaggerated fluctuation in the consolidation curve for the CAUC_1 specimen during load application, presented in the first data sheet in Appendix C, is not of the same type as the one mentioned above. The type of fluctuation seen here was another irregularity subject to quite a lot of troubleshooting, but this was resolved during testing of CAUC_1. Due to the isolated nature of the NTNU climate room, mobile phones will tend to increase their signal strength in an effort to connect to the mobile network. This interferes with the burette’s sensitive equipment when held in close proximity.

This could count in favor of a hypothesis that some part or parts of the burette
6.4. CAUC TRIAXIAL SHEAR TESTS

Fig. 6.5: Diagram showing showing different CAUC consolidation behaviours for MBS_4.

might be the source of the first type of fluctuation as well. An argument against this, however, is that analysis of the shear tests of for example CAUC_9 and 10 reveals another pattern of noise. At this point the connection to the burette has been closed, yet as can be seen in Figure 6.6 there are still regular ticks along the otherwise smooth curves.

As mentioned in Section 5.5 on triaxial test results, there is a trend of increasing values of $s_u$ with testing temperatures closer to in situ temperatures compared to tests run in room temperatures. Three out of four mini-block samples show an increase in $s_u$, ranging from averages of 2.42kPa to 9.12kPa by depth, whilst MBS_3 shows the opposite tendency with an average decrease of 5.42kPa. These values for $s_u$ are seen as the maximum values in both line graphs presented for MBS_3 in Figure 6.7, clearly showing higher values for room temperature tests.

Also evident in Figure 6.7 are the relatively non-typical behaviours of CAUC_11 and 12 seen in the lower stress-strain plot. These test specimens show the least protruding peaks of all 16 CAUC test specimens, a behaviour typically observed for disturbed test specimens. The mini-block sample that these specimens were extracted from was very bent and narrow, see Figure 6.8a, causing quite a bit of trouble during cutting and dividing of the triaxial test layer of MBS_3. For
the two test specimens CAUC_11 and 12 this resulted in trimmed test specimens that were a few millimeters short of filling the whole volume it ought to have. This lacking volume is shown for CAUC_11 in Figure 6.8b.

According to the indicated sample quality of CAUC_11 and 12, they should be in no worse condition than the other two specimens from the same depth, tested at room temperature. All four of the specimens yield values of $\varepsilon_V$ ranging from $1.73 - 2.61\%$ and values of $\Delta e/e_0$ ranging from $0.041 - 0.063$. One possible explanation for why this mini-block sample shows results for temperature effect on measured strength contrary to what is expected and seen for the rest of the mini-block samples, is the lack of volume and surface area at the sample base.

Another possible cause is that the treatment of this mini-block sample did not adhere to the advice given in Chapter 2, based on the second effect proposed by Campanella and Mitchell (1968) and Mitchell and Soga (2005). Contrary to this
6.4. CAUC TRIAXIAL SHEAR TESTS

![Graph showing Cauc triaxial shear tests results](image)

Fig. 6.7: NTNU-plot and stress-strain plots for CAUC tests from MBS_3.

advice, the cold tested specimens from MBS_3 were subjected to higher temperatures than the in situ temperatures during opening and subdivision. Because of this, the structure of the soil might have been subjected to a partial collapse due to the irreversible decrease in interparticle bond strength.

When the results of $s_u$ from mini-block sample MBS_3 are included, the changes in undrained shear strength with colder testing temperatures for a certain depth range between $-8.43\%$ to $22.28\%$ with an average of $6.20\%$. If MBS_3 is left out of the comparison of the strength parameter, $s_u$ ranges between $3.40\%$ to $16.02\%$ with an average value of $10.80\%$. These values are in agreement with
CHAPTER 6. DISCUSSION

6.4. CAUC TRIAXIAL SHEAR TESTS

(a) MBS_3 before opening and testing  (b) CAUC_11 not filling the whole volume

Fig. 6.8: Challenges with MBS_3 due to it’s bend and narrow diameter.

the findings both Lunne et al. (2012) and Gue et al. (2015) made during their extensive testing by similar procedures. The results also fit reasonably well, at least if MBS_3 is disregarded, with the expectation presented by Leroueil and Marques (1996) of finding 10% change in strength per 12 °C change in temperature.

For the triaxial tests there is also a apparent trend of higher strength values for colder storage temperatures. When comparing strength values determined from the two long-term stored mini-block samples, MBS_2 stored for 170 days close to in situ temperatures show better average values of strength than MBS_1, stored 159 days in room temperatures. MBS_2 from the shallowest depth show values of $s_u$ ranging between 66.27 – 81.93kPa with an average of 72.01kPa, while MBS_1 sampled just below MBS_2 show values of $s_u$ ranging between 55.32 – 68.48kPa with an average of 61.46kPa.

The average values of $s_u$ determined from test specimens from the two freshly sampled MBS, MBS_3 and MBS_4, are very similar to the values just presented for MBS_2 and MBS_1. MBS_3, being the shallowest sample of the two, have $s_u$ ranging between 65.61 – 71.64kPa with an average value of 68.58kPa, while MBS_4 show a range of 70.66 – 74.81kPa with an average of 72.43kPa. It is hard to make any assumptions about what effects are seen and not, when comparing values from all four MBS. There are too many irregularities seen in the test results to present any explanations or typical trends. This is especially regarding MBS_3, showing irregularities already discussed, and MBS_2 with three quite different stress paths presented in the NTNU plot in Figure 6.9.

When testing CAUC test specimens from MBS_2, the two first CAUC spe-
imens tested at 6.0 °C showed very different behaviours and results. CAUC_5 yields a $s_u$ value of 81.93 kPa, by far the highest value of all CAUC test specimens, while CAUC_6 yield a $s_u$ value of 67.83 kPa. CAUC_7 had to be discarded due to a large stone of about 25mm in diameter that surfaced during the trimming of the specimen, leaving only one specimen (CAUC_8) for room temperature testing. Unfortunately, during shearing of CAUC_8 something connected to the stepping motor running the shear test went wrong. This problem seems to have happened after having reached both the maximum shear stress ($\tau_{\text{max}}$) and the failure line.

The problem visible for the stress path of CAUC_8 in Figure 6.9, or at least a very similar problem, was encountered during the period of troubleshooting prior to the start of actual testing of Lilleby clay as well. What was first thought to be a problem with the step motor itself, is instead likely a problem with the connection between the computer and the step motor, occurring due to the regular expansion and contraction of the cables’ connectors as the climate room changing temperature between $\sim 6$ °C and $\sim 21$ °C.

CAUC_5, the test specimen yielding the highest value for $s_u$ of all the CAUC specimens, also showed quite an unusual dilating behaviour compared to all the other specimens. CAUC_5 dilated substantially before falling down onto the

![Fig. 6.9: Stress paths of all CAUC test specimens from MBS_2](image_url)
failure line, and then contracting along this line for the remainder of the test. CAUC_6 from the same depth, and tested at the same temperature, showed nowhere near the same degree of dilatant behaviour. All CAUC triaxial tests performed do in fact show some degree of dilatant behaviour due to their OC nature. Over consolidated clays with values of $OCR > 2.5$ are often compacted so densely that a volume increase will occur when they are subjected to external compression forces. For triaxial compression tests run undrained, this dilatancy phenomenon results, instead, in a reduction of pore water pressure after having reached a certain amount of stress (Hattab & Hicher, 2004).

Typical dilatant and contractant behaviours of the Lilleby clay are presented for the test specimens CAUC_5 and 6 in a plot of axial strain versus pore water pressure ($u$) in Figure 6.10. The behaviour observed for CAUC_6 is very similar to all other CAUC tests performed. CAUC_5, on the other hand, dilated to the point where a negative pore water pressure of $-18.76\, kPa$ was measured, and never crossed back over to positive pore water pressure levels. It is also evident how CAUC_5 clearly differs from all other CAUC tests performed when observing the stress paths from all CAUC tests presented in Figure 5.4 in Section 5.5.

![Fig. 6.10: Significant difference in development of $u$ for CAUC_5.](image)

No observations were made of abnormalities in either the clay material of the
specimen or testing procedure that could explain the significant deviations that CAUC_5 has compared to all the other triaxial test results. In the evaluation of sample quality of CAUC_5, the specimen actually yields the best values of both $\varepsilon_V$ and $\Delta e/e_0$ of all CAUC test specimens, with respective values of 1.50% and 0.036. The failure mode of the test specimen CAUC_5 also differs from nearly all the other specimens, showing a more typical barrel shaped failure mode, presented in Figure 6.11a. This may be an indication that the specimen CAUC_5 might actually be the one most representative of the Lilleby clay.

During shear testing of triaxial specimens, a change in surface area will occur with increasing vertical force. Contrary to the more common barrel shaped failure mode, an evident shear band is seen in nearly all failure modes of CAUC specimens tested in this work. Photos of the failure modes are in the designated data sheets in Appendix C. The failure modes of the three specimens from MBS_2, all showing different modes, are also presented in Figure 6.11. Figure 6.11a shows the typical barrel shape mode observed for CAUC_5, while Figure 6.11b shows CAUC_6 being the only specimen with a failure mode showing two shear bands forming an X. Most of the CAUC specimens failed along a single shear band, like the one seen for CAUC_8 in Figure 6.11c.

Because failure for most of the CAUC test specimens is not barrel shaped, the change in surface area during shearing of the specimen is not that significant. The area correction done using Equation 4.17 presented in Subsection 4.3.5 is
therefore used somewhat inaccurately. The use of this area correction when most failure modes do not have a barrel shape, probably leads to incorrect values being determined and presented for strength parameters and plot values, causing an additional uncertainty of the determined values, and trends linked to the effects of temperature.

Both the attraction intersection and the friction angle slope are determined by evaluation of the failure line observed for the stress paths of each CAUC test specimen. Naturally, the determined values of $a$ and $\phi$ are affected by the use of area correction, especially since the area correction used has a gradually larger impact as the values of axial strain increase (see Equation 4.17). The use of area correction is, however, probably not the only cause of inaccurate values for $a$ and $\phi$. Because most of the specimens fail along distinct shear bands, the failure line observed from the CAUC stress paths may not be the “correct” failure line for the Lilleby clay.

$$\tau = \frac{1}{2}(\sigma_{a,c}' - \sigma_{r,c}') \text{ [kPa]}$$

**Fig. 6.12:** CAUC_9 and 10 indicating negative values of $a$ for observed failure lines.
Determination of attraction values for the Lilleby clay, two CAUC test specimens, CAUC_9 and 10 indicates an intersection with the horizontal axis for positive stress values. This is presented in Figure 6.12 where CAUC_9 and CAUC_10 are plotted in an NTNU plot for determination of $a$. A dashed line indicating the failure line observed for CAUC_9, which is showing the highest $a$ value of the two of them, falls on a value of $-2\text{kPa}$. A stress path has been plotted for CAUC_9, without application of the area correction of $A_s$, but this did not yield a positive value of $a$. It is therefore likely that the failure line observed is an incorrect one, and determined values of attraction for CAUC_9 and 10 are therefore set to a value of zero, as negative values of attraction are extremely rare.
Chapter 7

Conclusion

This chapter will first present a brief summary of the tests done and results gathered from the laboratory work of this thesis. Results for \( p'_c \) and \( s_u \) are evaluated, and considered in light of effects of test and storage temperatures. These results are then compared to previous studies used as reference for this thesis. Some conclusion are drawn, before recommendations for further work are put forward.

7.1 Summary and conclusion

Four mini-block samples (MBS) have been extracted using the NTNU mini-block sampler at the constructional site of Lilleby. These four MBS have been subject to strict temperature controlled environments during storage, opening, dividing and testing of them. All four were subdivided into MBS slices. A total of 30 water content specimens were extracted and tested, as well as 16 tests were done to determine the water content of the plastic and liquid consistency limits. 16 fall cone tests and 15 CAUC triaxial shear tests have been performed mainly to estimate values of undrained shear strength \( (s_u) \), while 29 CRSC oedometer tests contribute to estimate preconsolidation pressures \( (p'_c) \). Other test parameters from all tests mentioned have also been checked for temperature effect with different testing and storing temperatures.

Laboratory test results reveal clear traces of testing temperature affecting several engineering properties. Most importantly, there are tendencies of measuring
higher values of both preconsolidation pressure ($p'_c$) and undrained shear strength ($s_u$) with testing temperatures closer to the annual in situ ground temperature. Average changes in $p'_c$ with testing temperature for each depth range between the values of 0% to 21%. This results in an average increase in $p'_c$ of 21kPa equal to 9% compared to room temperature testing. The three test specimens that yielded no indication of $p'_c$ are excluded, see Section 5.4.

Evaluation of undrained shear strength on test specimens from the same depth range between −8% to 22% for colder testing temperatures during fall cone testing, with only one out of eight being a negative value. The overall average increase of $s_u$ from fall cone testing closer to in situ temperatures is about 4kPa equal to 7%. For CAUC triaxial shear testing, increases of $s_u$ ranged between −8% and 16%, with an overall average increase of 4kPa equal to 6% for colder testing temperatures. When excluding results from mini-block sample MBS_3 (see Section 6.4), the increases of $s_u$ range between 3% and 16%, with an overall average of 6.72kPa or 11%.

Previous studies that have been focused on, Lunne et al. (2012) and Gue et al. (2015) in particular, show both larger ranges in increasing values of $p'_c$ and $s_u$, and higher values of overall averages. Both studies were more comprehensive than this work, but were executed in a manner fairly similar to what was done in this thesis. More details on their studies are briefly presented in Chapter 2 - Background.

Lunne et al. (2012) found average increases in $p'_c$ to range between 9 – 38%, with an overall average increase of 23% for CRSC oedometer tests performed closer to in situ temperatures. Average increases of $s_u$ were found to range between 2 – 40%, with an overall average of 25%. Gue et al. (2015), continuing on the work presented by Lunne et al. (2012), found average increases in $p'_c$ to range between 8 and 56%, with an overall average of 22%. Increases in $s_u$ ranged between 2 – 42%, with an average value of 24%.

Even though both Lunne et al. (2012) and Gue et al. (2015) are mainly focused on testing deep water offshore soft clays, the studies show very good results on tests sampled at the NGI test site at Onsøy in Fredrikstad, Norway as well. The laboratory test results and apparent trends on the effect of testing temperature presented in this report thus clearly agrees with the previous studies done, but are less pronounced than the results from Lunne et al. (2012) and Gue et al. (2015).

The effect of storage temperature is not as clearly seen as might be expected.
For some of the parameters, apparent changes are observed, but the sample size is too limited to make any conclusions with fair certainty. For many of the cases where apparent tendencies were observed between MBS_1 (stored 159 days in room temperature) and MBS_2 (stored 170 days in cold temperature) there are larger differences between MBS_3 and MBS_4, that were both freshly sampled and only stored a couple of days before opening and testing. The clearer trend on effect of testing temperature than the effect of storage temperature, agrees with what Lunne et al. (2012) found on the same matter.

Throughout testing of the four mini-block samples, some of the highest values and best test results on both $p'c$ and $su$, were indeed found from mini-block sample MBS_1, considered to have the least favourable storage conditions. On the other hand, MBS_3 and MBS_4, with the best storage conditions, still yielded some of the poorest results. The combination of these factors indicate that neither storage length nor the temperature affecting the mini-block samples during storage seem to cause significant differences for either $p'c$ and $su$.

With limited effects seen from storage temperatures, and relatively small changes for testing temperatures, the variation stemming from the clay itself seem to dwarf those of the temperature effects. The objectives of this work have, nevertheless, largely been fulfilled, providing additional data towards investigations into the effect of temperature on laboratory measured soil parameters. Hopefully, this could contribute towards the development of an applicable correctional factor for testing temperatures.

### 7.2 Further work

The sample size for this master thesis might be too small to be able to assess both the effect of storage and test temperature, especially when using a clay as heterogeneous as the Lilleby clay. Focus should possibly be on either storage or testing temperature. Increasing the sample size for one effect, will allow for more accurate comparison. More in depth studies are preferable, as test specimens should be site-specific and tests should be performed using strict temperature schemes for both storage and test temperatures.

Several apparent trends observed for effects of testing temperature on different soil properties are presented in Chapter 5 - Test results. Some of these are further discusses in Chapter 6 - Discussion, but have no obvious conclusions at this point. Further studies on possible temperature effects on parameters
including attraction from CAUC triaxial shear tests, coefficient of consolidation from CRSC oedometer tests, and water contents \( w_P \) and \( w_L \) at the consistency limits, are recommended. For \( c_v \) in particular, the observations made contradict those presented by Perkins and Sjursen (2009) and Lunne et al. (2012).

Fall cone tests and tests to determine Atterberg limits are standardized tests using tables and procedures for determination of soil parameters developed for room temperature laboratory testing. The values found using these tables for laboratory testing close to \textit{in situ} temperatures, might not be accurate. Further studies on parallel fall cone tests and Atterberg limit tests in room and \textit{in situ} temperatures could focus on the correctness of the procedures for low temperature testing.

Experience from this work has shown that the recommendations by Gue et al. (2015) are of particular importance when studying effects of temperature. Clay specimens should be site specific, and similar in both depth and classification properties. Relatively strict temperature schemes should be followed through both storage and test procedures, and a test programme of several CAUC and CRSC tests among others should be performed on significant soil layers. Based on further evaluations from parallel tests at room and cold temperatures, correctional factors for testing temperature may then be developed (Lunne et al., 2012).
Bibliography


Appendices

The appendices present interpreted data from all laboratory tests performed, and is subdivided into index tests in Appendix A, CRSC oedometer tests in Appendix B and CAUC triaxial tests in Appendix C.

Appendix A presents one page with a typical layout on index test results, plotting water content, unit weight and shear strengths by depth. Appendix B includes single page data sheets on the 29 CRSC oedometer tests performed, while Appendix C includes similar single page data sheets for the 15 CAUC triaxial shear tests. All data sheets are presented in chronological order with a table on important information and results, two photographs and four charts for each test specimen.
Appendix A

Index tests

Appendix A - Index tests presents the index test results using a common layout. Values determined from all specimens for natural water content ($w_0$), plastic limit ($w_P$), liquid limit ($w_L$), unit weight ($\gamma$), and undrained shear strength ($s_u$) and remoulded shear strength ($s_r$) from fall cone tests, are included. No distinction is made between natural water content found for representative specimens and the natural water content determined for CRSC and CAUC tests. They are presented together on the left hand side of the layout. No standardized tests of $\gamma$ has been performed, but all values determined for CRSC and CAUC specimens are presented in the middle diagram on the layout. Values of $s_u$ determined from CAUC triaxial shear tests are included in the right hand diagram on strengths.
Index test results for all MBS_1 through MBS_4
Appendix B

Oedometer tests

Appendix B - *Oedometer tests* include 29 data sheets, one for each of the CRSC oedometer tests performed. They are presented in chronological order, with several of the parameters from Table 5.4 and two photos showing the top and bottom of nearly all trimmed specimens. Below them are four characteristic diagrams on the behaviour of axial strain ($\varepsilon_a$), pore water pressure ($u_b$), tangent modulus/Oedometer modulus ($M$) and coefficient of consolidation ($c_v$) for increased values of vertical effective stress ($\sigma'_v$).
Oedometer specimen CRSC_1 from MBS_1

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Lilleby</td>
</tr>
<tr>
<td>Depth</td>
<td>6.68m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>19.10.2016</td>
</tr>
<tr>
<td>Opening date</td>
<td>27.03.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>27.03.2017</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>20°C</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>21.7°C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150µm/h</td>
</tr>
<tr>
<td>Opening date</td>
<td>27.03.2017</td>
</tr>
<tr>
<td>p′_c</td>
<td>N/A</td>
</tr>
<tr>
<td>OCR</td>
<td>N/A</td>
</tr>
<tr>
<td>Δe/ε₀</td>
<td>0.060</td>
</tr>
<tr>
<td>cᵥ</td>
<td>11.3m²/year</td>
</tr>
<tr>
<td>γ</td>
<td>19.79kN/m³</td>
</tr>
<tr>
<td>w₀</td>
<td>28.36%</td>
</tr>
<tr>
<td>σᵥ₀</td>
<td>53.36 kPa</td>
</tr>
<tr>
<td>σ′_v</td>
<td>53.36 kPa</td>
</tr>
<tr>
<td>M</td>
<td>dσ′_v/dε_a [MPa]</td>
</tr>
<tr>
<td>ε_a</td>
<td>2.5H/H₀ [%]</td>
</tr>
<tr>
<td>u_a</td>
<td>[kPa]</td>
</tr>
<tr>
<td>σ′_v</td>
<td>σ_v - ½u_b [kPa]</td>
</tr>
<tr>
<td>cᵥ</td>
<td>m²/yr</td>
</tr>
</tbody>
</table>
Oedometer specimen CRSC_3 from MBS_1

Site: Lilleby \[ \gamma = 19.74 \text{kN/m}^3 \]

Depth: 6.85m \[ w_0 = 28.58\% \]

Sampling date: 19.10.2016 \[ \sigma_{v0} = 54.42 \text{kPa} \]

Opening date: 27.03.2017 \[ p_r = 295 \text{kPa} \]

Testing date: 28.03.2017 \[ OCR = 5.4 \]

Storage temp.: 20 °C \[ M_{OC} = 11.5 \text{MPa} \]

Testing temp.: 21.7 °C \[ m = 25.7 \]

Strain rate: 150 µm/h \[ p_r' = 170 \text{kPa} \]

\( \frac{\Delta e}{e_0} = 0.082 \)

\( c_v = 13.2 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_4 from MBS_1

Site: Lilleby \( \gamma = 19.29\text{kN/m}^3 \)
Depth: 6.85m \( \omega_0 = 32.03\% \)
Sampling date: 19.10.2016 \( \sigma_{\omega 0} = 51.27\text{kPa} \)
Opening date: 27.03.2017 \( p'_c = 275\text{kPa} \)
Testing date: 29.03.2017 \( OCR = 5.4 \)
Storage temp.: 20 °C \( MOC = 10.7\text{MPa} \)
Testing temp.: 21.7 °C \( m = 24.2 \)
Strain rate: 150µm/h \( p'_r = 175\text{kPa} \)
\( \Delta \varepsilon / \varepsilon_0 = 0.081 \)
\( c_v = 12.2\text{m}^2/\text{yr} \)

\[ \epsilon_a = \frac{\Delta H}{H_0} \% \]

\[ u_b \text{[kPa]} \]

\[ M = \frac{\Delta e}{\Delta \sigma_e} \text{[MPa]} \]

\[ c_v \text{[m}^2/\text{year}] \]

\[ \sigma'_v = \sigma_v - \frac{5}{3}u_b \text{[kPa]} \]
Oedometer specimen CRSC_5 from MBS_1

<table>
<thead>
<tr>
<th>Site</th>
<th>Lilleby</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth</td>
<td>6.68m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>19.10.2016</td>
</tr>
<tr>
<td>Opening date</td>
<td>27.03.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>02.04.2017</td>
</tr>
<tr>
<td>Storage temp.:</td>
<td>20 °C</td>
</tr>
<tr>
<td>Testing temp.:</td>
<td>5.9 °C</td>
</tr>
<tr>
<td>Strain rate:</td>
<td>150µm/h</td>
</tr>
<tr>
<td>Δε/ε₀</td>
<td>0.068</td>
</tr>
<tr>
<td>cᵥ</td>
<td>11.6m²/yr</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>γ</th>
<th>19.64kN/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>w₀</td>
<td>29.12%</td>
</tr>
<tr>
<td>σ'₀</td>
<td>52.39kPa</td>
</tr>
<tr>
<td>p'ᵢ</td>
<td>N/A</td>
</tr>
<tr>
<td>OCR</td>
<td>N/A</td>
</tr>
<tr>
<td>m</td>
<td>25.0</td>
</tr>
<tr>
<td>p'ᵣ</td>
<td>0kPa</td>
</tr>
</tbody>
</table>

![Graphs and charts]

\[ ε_a = \frac{ΔH}{H₀} [%]\]

\[ u_b [kPa]\]

\[ M = \frac{Δε_a}{ε_a} [MPa]\]

\[ cᵥ [m²/year]\]

\[ σ' = σ_v - \frac{2}{3}u_b [kPa]\]
Oedometer specimen CRSC_6 from MBS_1

Site: Lilleby  \( \gamma = 19.84 \text{kN/m}^3 \)
Depth: 6.68m  \( \omega_0 = 28.15\% \)
Sampling date: 19.10.2016  \( \sigma_{\omega_0} = 53.74 \text{kPa} \)
Opening date: 27.03.2017  \( p'_c = \text{N/A} \)
Testing date: 03.04.2017  \( OCR = \text{N/A} \)
Storage temp.: 20 °C  \( M_{OC} = \text{N/A} \)
Testing temp.: 5.9 °C  \( m = 25.0 \)
Strain rate: 150μm/h  \( p'_r = 0 \text{kPa} \)
\( \Delta e/e_0 = 0.099 \quad c_v = 11.0 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_7 from MBS_1

Site: Lilleby  \( \gamma = 19.51\text{kN/m}^3 \)
Depth: 6.85m  \( w_0 = 30.85\% \)
Sampling date: 19.10.2016  \( \sigma'_{w0} = 52.82\text{kPa} \)
Opening date: 27.03.2017  \( p'_c = 315\text{kPa} \)
Testing date: 04.04.2017  \( OCR = 6.0 \)
Storage temp.: 20°C  \( MOC = 11.4\text{MPa} \)
Testing temp.: 5.9°C  \( m = 24.1 \)
Strain rate: 150μm/h  \( p'_r = 190\text{kPa} \)
\( \Delta e/e_0 = 0.071 \)  \( c_v = 28.0\text{m}^2/\text{yr} \)
Oedometer specimen CRSC_8 from MBS_1

- Site: Lilleby
- Depth: 6.85m
- Sampling date: 19.10.2016
- Opening date: 27.03.2017
- Testing date: 05.04.2017
- Storage temp.: 20 °C
- Testing temp.: 5.9 °C

Sample Details:
- \( \gamma = 19.30 \text{kN/m}^3 \)
- \( \varepsilon_0 = 32.47\% \)
- \( \sigma'_{v0} = 51.36 \text{kPa} \)
- \( p'_c = 310 \text{kPa} \)
- \( OCR = 6.0 \)
- \( MOC = 11.4 \text{MPa} \)
- \( m = 23.8 \)
- Strain rate: 150 \( \mu \text{m/h} \)
- \( p'_r = 200 \text{kPa} \)
- \( \Delta e/\varepsilon_0 = 0.074 \)
- \( c_v = 19.5 \text{m}^2/\text{yr} \)

Graphs:
- \( \varepsilon_a = \frac{\Delta H}{H_0} \) [ε_a [%]]
- \( u_a [\text{kPa}] \)
- \( M = \frac{\Delta e}{\varepsilon_0} [\text{MPa}] \)
- \( c_v [\text{m}^2/\text{year}] \)

Equations:
- \( \sigma'_v = \sigma_v - \frac{2}{3} u_b [\text{kPa}] \)
Oedometer specimen CRSC_9 from MBS_2

Site: Lilleby \( \gamma = 19.56 \text{kN/m}^3 \)
Depth: 6.37m \( \mathcal{w}_0 = 30.24\% \)
Sampling date: 18.10.2016 \( \sigma_{w0} = 49.42 \text{kPa} \)
Opening date: 06.04.2017 \( p'_r = 290 \text{kPa} \)
Testing date: 06.04.2017 \( OCR = 5.9 \)
Storage temp.: 5 °C \( MOC = 9.8 \text{MPa} \)
Testing temp.: 6.0 °C \( m = 24.4 \)
Strain rate: 150\( \mu \text{m/h} \) \( p'_c = 180 \text{kPa} \)
\( \Delta e/e_0 \) = 0.074 \( c_v = 16.4 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC\_10 from MBS\_2

Site: Lilleby \quad \gamma = 19.57\text{kN/m}^3
Depth: 6.37m \quad \omega_0 = 29.93\%
Sampling date: 18.10.2016 \quad \sigma_{\omega_0} = 49.51\text{kPa}
Opening date: 06.04.2017 \quad p'_c = 285\text{kPa}
Testing date: 07.04.2017 \quad OCR = 5.8
Storage temp.: 5\degree\text{C} \quad MOC = 9.6\text{MPa}
Testing temp.: 6.0\degree\text{C} \quad m = 24.2
Strain rate: 150\mu\text{m/h} \quad p'_c = 180\text{kPa}
$\Delta e/e_0 = 0.083 \quad c_v = 16.5\text{m}^2/\text{yr}$
Oedometer specimen CRSC_11 from MBS_2

Site: Lilleby  
Depth: 6.55m  
$\gamma = 19.79 \text{kN/m}^3$  
Sampling date: 18.10.2016  
$\sigma_{\nu0} = 52.35 \text{kPa}$  
Opening date: 06.04.2017  
$p^r = 265 \text{kPa}$  
Testing date: 08.04.2017  
$OCR = 5.1$  
Storage temp.: 5 °C  
$\sigma_{\nu} = 10.9 \text{MPa}$  
Testing temp.: 6.0 °C  
$m = 27.8$  
Strain rate: 150µm/h  
$p^r = 165 \text{kPa}$  
$\Delta e/\epsilon_0 = 0.049$  
$cv = 15.3 \text{m}^2/\text{yr}$

\[
\sigma'_{\nu} = \sigma_{\nu} - \frac{\gamma}{2} u_b \quad \text{[kPa]}
\]
Oedometer specimen CRSC_12 from MBS_2

Site: Lilleby  \( \gamma = 19.70 \text{kN/m}^3 \)
Depth: 6.55 m  \( w_0 = 29.19\% \)
Sampling date: 18.10.2016  \( \sigma_{v0} = 51.73 \text{kPa} \)
Opening date: 06.04.2017  \( p'_c = 305 \text{kPa} \)
Testing date: 09.04.2017  \( OCR = 5.9 \)
Storage temp.: 5 °C  \( M_{OC} = 11.6 \text{MPa} \)
Testing temp.: 6.0 °C  \( m = 25.2 \)
Strain rate: 150 \( \mu \text{m/h} \)  \( p'_r = 185 \text{kPa} \)
\( \Delta \varepsilon/\varepsilon_0 = 0.069 \)  \( c_v = 13.6 \text{m}^2/\text{yr} \)

\( \varepsilon_a = \frac{\Delta H}{H_0} \%
\)

\( u_b \) [kPa]

\( M = \frac{\Delta \varepsilon}{\Delta \sigma_v} \) [kPa]

\( c_v \) [m²/year]
Oedometer specimen CRSC_13 from MBS_2

Site: Lilleby  \( \gamma = 19.44 \text{kN/m}^3 \)
Depth: 6.37m  \( w_0 = 30.07\% \)
Sampling date: 18.10.2016  \( \sigma'_{v0} = 48.67 \text{kPa} \)
Opening date: 06.04.2017  \( p'_c = 230 \text{kPa} \)
Testing date: 11.04.2017  \( OCR = 4.7 \)
Storage temp.: 5 °C  \( MOC = 8.6 \text{MPa} \)
Testing temp.: 21.2 °C  \( m = 24.1 \)
Strain rate: 150\(\mu \text{m/h} \)
\( \Delta e/e_0 = 0.047 \)
\( c_v = 14.3 \text{m}^2/\text{year} \)
Oedometer specimen CRSC_14 from MBS_2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Lilleby</td>
</tr>
<tr>
<td>Depth</td>
<td>6.37m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>18.10.2016</td>
</tr>
<tr>
<td>Opening date</td>
<td>06.04.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>12.04.2017</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>21.2 °C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150µm/h</td>
</tr>
<tr>
<td>Opening date</td>
<td>06.04.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>12.04.2017</td>
</tr>
<tr>
<td>OCR</td>
<td>5.0</td>
</tr>
<tr>
<td>MOC</td>
<td>8.9MPa</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>21.2 °C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150µm/h</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>Depth</td>
<td>6.37m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>18.10.2016</td>
</tr>
<tr>
<td>Opening date</td>
<td>06.04.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>12.04.2017</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>21.2 °C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150µm/h</td>
</tr>
</tbody>
</table>

\[
\sigma_v' = \sigma_v - \frac{2}{3} u_b \ [\text{kPa}]
\]

\[
\frac{\Delta e}{e_0} = 0.081
\]

\[
c_v = 6.7m^2/yr
\]
Oedometer specimen CRSC_15 from MBS_2

Site: Lilleby  $\gamma = 19.58\text{kN}/\text{m}^3$
Depth: 6.55m  $w_0 = 29.64\%$
Sampling date: 18.10.2016  $\sigma_v' = 50.97\text{kPa}$
Opening date: 06.04.2017  $p_r' = 280\text{kPa}$
Testing date: 13.04.2017  $OCR = 5.5$
Storage temp.: 5 °C  $\sigma_{oc} = 11.8\text{MPa}$
Testing temp.: 21.2 °C  $m = 25.8$
Strain rate: 150µm/h  $p_r' = 185\text{kPa}$
$\Delta e/e_0 = 0.075$  $c_v = 8.0\text{m}^2/\text{yr}$

$\varepsilon_a = \frac{H}{H_0}$

$u_b [\text{kPa}]$

$M = \frac{\sigma_v'}{\varepsilon_a} [\text{MPa}]$

$c_v [\text{m}^2/\text{year}]$

$\sigma_v' = \sigma_v - \frac{2}{3}u_b [\text{kPa}]$
Oedometer specimen CRSC_16 from MBS_2

Site: Lilleby  \( \gamma = 19.64 \text{kN/m}^3 \)
Depth: 6.55m  \( w_0 = 29.23\% \)
Sampling date: 18.10.2016  \( \sigma'_{v0} = 51.37 \text{kPa} \)
Opening date: 06.04.2017  \( p'_c = 290 \text{kPa} \)
Testing date: 14.04.2017  \( OCR = 5.6 \)
Storage temp.: 5 °C  \( MOC = 11.8 \text{MPa} \)
Testing temp.: 21.2 °C  \( m = 25.8 \)
Strain rate: 150µm/h  \( p'_r = 185 \text{kPa} \)
\( \Delta e/e_0 = 0.070 \)
\( c_v = 10.8 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_18 from MBS_3

Site: Lilleby \( \gamma = 19.97 \text{kN/m}^3 \)
Depth: 7.88m \( w_0 = 26.91\% \)
Sampling date: 28.04.2017 \( \sigma'_{w_0} = 64.33 \text{kPa} \)
Opening date: 29.04.2017 \( p'_s = 265 \text{kPa} \)
Testing date: 29.04.2017 \( OCR = 4.1 \)
Storage temp.: 65 °C \( M_{OC} = 10.1 \text{MPa} \)
Testing temp.: 21.3 °C \( m = 25.6 \)
Strain rate: 150 µm/h \( p'_c = 120 \text{kPa} \)
\( \Delta e/e_0 = 0.088 \) \( c_v = 10.9 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_19 from MBS_3

Site: Lilleby
Depth: 8.08m
Sampling date: 28.04.2017
Opening date: 29.04.2017
Testing date: 30.04.2017
Storage temp.: 5 °C
Testing temp.: 21.3 °C
Strain rate: 150 µm/h

γ = 19.17kN/m³
w₀ = 32.60%
σ'₀ = 59.51kPa
p'ᵣ = 170kPa
OCR = 2.9
MOC = 5.7MPa
M = dσ'v/dεa [MPa]
ε = ∆H/H₀ [%]
uₐ [kPa]
cᵥ [m²/year]

Δe/ε₀ = 0.096 cᵥ = 7.1m²/yr
Oedometer specimen CRSC_20 from MBS_3

Site: Lilleby  \( \gamma = 19.12 \text{kN/m}^3 \)
Depth: 8.08m  \( w_0 = 33.41\% \)
Sampling date: 28.04.2017  \( \sigma'_{v0} = 59.11 \text{kPa} \)
Opening date: 29.04.2017  \( p'_c = 200 \text{kPa} \)
Testing date: 01.05.2017  \( OCR = 3.4 \)
Storage temp.: 5 °C  \( MOC = 6.0 \text{MPa} \)
Testing temp.: 21.3 °C  \( \dot{m} = 23.3 \)
Strain rate: 150\( \mu \text{m/h} \)  \( p'_r = 110 \text{kPa} \)
\( \Delta \varepsilon/\varepsilon_0 = 0.055 \)  \( c_v = 10.3 \text{m}^2/\text{yr} \)

\[
\frac{\Delta H}{H_0} = \frac{\varepsilon_a}{\varepsilon_0} \%
\]

\[
u_b \text{ [kPa]}
\]

\[
M = \frac{\Delta \varepsilon}{\sigma'_v} \text{ [MPa]}
\]

\[
c_v \text{ [m}^2/\text{year]}
\]

\[
\sigma'_v = \sigma_v - \frac{2}{3} u_b \text{ [kPa]}
\]
Oedometer specimen CRSC_21 from MBS_3

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Lilleby</td>
</tr>
<tr>
<td>Depth</td>
<td>7.88 m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>28.04.2017</td>
</tr>
<tr>
<td>Opening date</td>
<td>29.04.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>04.05.2017</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>5.9 °C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150 µm/h</td>
</tr>
<tr>
<td>Δε/ε₀</td>
<td>0.049</td>
</tr>
<tr>
<td>γ</td>
<td>19.76 kN/m³</td>
</tr>
<tr>
<td>ω₀</td>
<td>28.62%</td>
</tr>
<tr>
<td>σ'₀</td>
<td>62.65 kPa</td>
</tr>
<tr>
<td>p'ᵣ</td>
<td>280 kPa</td>
</tr>
<tr>
<td>OCR</td>
<td>4.5</td>
</tr>
<tr>
<td>MOCR</td>
<td>10.6 MPa</td>
</tr>
<tr>
<td>m</td>
<td>24.4</td>
</tr>
<tr>
<td>p'ᵣ</td>
<td>160 kPa</td>
</tr>
<tr>
<td>cᵥ</td>
<td>20.5 m²/yr</td>
</tr>
</tbody>
</table>

![Graphs showing various parameters](image-url)
Oedometer specimen CRSC_22 from MBS_3

Site: Lilleby \( \gamma = 20.03 \text{kN/m}^3 \)

Depth: 7.88 m \( w_0 = 26.86\% \)

Sampling date: 28.04.2017 \( \sigma'_{w0} = 64.82 \text{kPa} \)

Opening date: 29.04.2017 \( p'_c = 285 \text{kPa} \)

Testing date: 05.05.2017 \( OCR = 4.4 \)

Storage temp.: 5 °C \( M_{OC} = 11.9 \text{MPa} \)

Testing temp.: 5.9 °C \( m = 25.8 \)

Strain rate: 150 \( \mu \text{m/h} \) \( p'_r = 160 \text{kPa} \)

\( \Delta e/e_0 = 0.051 \) \( c_v = 32.0 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_24 from MBS_3

<table>
<thead>
<tr>
<th>Site:</th>
<th>Lilleby</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth:</td>
<td>8.08m</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>$19.16\text{kN/m}^3$</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>32.47%</td>
</tr>
<tr>
<td>Sampling date:</td>
<td>28.04.2017</td>
</tr>
<tr>
<td>Opening date:</td>
<td>29.04.2017</td>
</tr>
<tr>
<td>Testing date:</td>
<td>06.05.2017</td>
</tr>
<tr>
<td>OCR$^*$</td>
<td>3.4</td>
</tr>
<tr>
<td>$\sigma'_{v0}$</td>
<td>59.41kPa</td>
</tr>
<tr>
<td>$p'_c$</td>
<td>200kPa</td>
</tr>
<tr>
<td>Storage temp.:</td>
<td>5 °C</td>
</tr>
<tr>
<td>$\sigma'_v$</td>
<td>59.41kPa</td>
</tr>
<tr>
<td>$m$</td>
<td>23.8</td>
</tr>
<tr>
<td>Strain rate:</td>
<td>150µm/h</td>
</tr>
<tr>
<td>$\Delta e/e_0$</td>
<td>0.056</td>
</tr>
<tr>
<td>$c_v$</td>
<td>18.8m$^2$/yr</td>
</tr>
</tbody>
</table>

---

**Graphs:**

1. $\varepsilon_a = \frac{\Delta H}{H_0} [\%]$ vs. $\sigma'_v - \frac{2}{3} \mu_b [\text{kPa}]$
2. $u_s [\text{kPa}]$ vs. $\sigma'_v - \frac{2}{3} \mu_b [\text{kPa}]$
3. $\frac{\sigma'_v}{\mu_b} [\text{MPa}]$ vs. $\sigma'_v - \frac{2}{3} \mu_b [\text{kPa}]$
4. $c_v [\text{m}^2/\text{year}]$ vs. $\sigma'_v - \frac{2}{3} \mu_b [\text{kPa}]$
Oedometer specimen CRSC_25 from MBS_4

Site: Lilleby  \( \gamma = 19.18 \text{kN/m}^3 \)
Depth: 8.26m  \( w_0 = 32.99\% \)
Sampling date: 11.05.2017  \( \sigma_{\nu 0} = 60.96 \text{kPa} \)
Opening date: 13.05.2017  \( p'_i = 305 \text{kPa} \)
Testing date: 13.05.2017  \( OCR = 5.0 \)
Storage temp.: 5 °C  \( MOC = 11.2 \text{MPa} \)
Testing temp.: 5.9 °C  \( m = 24.4 \)
Strain rate: 150 µm/h  \( p'_r = 200 \text{kPa} \)
\( \Delta \varepsilon / \varepsilon_0 = 0.068 \)  \( c_v = 12.5 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_26 from MBS_4

<table>
<thead>
<tr>
<th>Site:</th>
<th>Lilleby</th>
<th>( \gamma ) = 19.06kN/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth:</td>
<td>8.26m</td>
<td>( w_0 ) = 33.37%</td>
</tr>
<tr>
<td>Sampling date:</td>
<td>11.05.2017</td>
<td>( \sigma_{vo} ) = 59.93kPa</td>
</tr>
<tr>
<td>Opening date:</td>
<td>13.05.2017</td>
<td>( p'_c ) = 265kPa</td>
</tr>
<tr>
<td>Testing date:</td>
<td>14.05.2017</td>
<td>OCR = 4.4</td>
</tr>
<tr>
<td>Storage temp.:</td>
<td>5 (^\circ)C</td>
<td>( M_{OC} ) = 9.8MPa</td>
</tr>
<tr>
<td>Testing temp.:</td>
<td>5.9 (^\circ)C</td>
<td>( m ) = 23.8</td>
</tr>
<tr>
<td>Strain rate:</td>
<td>150(\mu)m/h</td>
<td>( p'_r ) = 180kPa</td>
</tr>
<tr>
<td>( \Delta e/e_0 )</td>
<td>= 0.092</td>
<td>( c_v ) = 12.0m(^2)/yr</td>
</tr>
</tbody>
</table>

\[ \sigma'_v = \sigma_v - \frac{2}{3}u_b \text{ [kPa]} \]
Oedometer specimen CRSC_27 from MBS_4

Site: Lilleby
Depth: 8.43m
Sampling date: 11.05.2017
Opening date: 13.05.2017
Testing date: 15.05.2017
Storage temp.: 5 °C
Testing temp.: 5.9 °C
Strain rate: 150 µm/h

\[ \Delta e/e_0 = 0.081 \]
\[ c_v = 9.4 \text{ m}^2 / \text{yr} \]

\[ \varepsilon_a = \frac{\Delta H}{H_0} \% \]
\[ u_b \text{ [kPa]} \]

\[ M = \frac{d\sigma'_v}{d\varepsilon_a} \text{ [MPa]} \]

\[ \sigma'_v = \sigma_v - \frac{2}{3} u_b \text{ [kPa]} \]
Oedometer specimen CRSC_28 from MBS_4

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Lilleby</td>
</tr>
<tr>
<td>Depth</td>
<td>8.43m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>11.05.2017</td>
</tr>
<tr>
<td>Opening date</td>
<td>13.05.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>16.05.2017</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>5.9 °C</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150 µm/h</td>
</tr>
<tr>
<td>∆e/ε₀</td>
<td>0.062</td>
</tr>
<tr>
<td>Parameter $\gamma$</td>
<td>19.33kN/m³</td>
</tr>
<tr>
<td>$\omega_0$</td>
<td>31.40%</td>
</tr>
<tr>
<td>$\sigma_\text{v,0}'$</td>
<td>63.47 kPa</td>
</tr>
<tr>
<td>$p_\text{r}'$</td>
<td>255 kPa</td>
</tr>
<tr>
<td>OCR</td>
<td>4.0</td>
</tr>
<tr>
<td>$M_{OC}$</td>
<td>10.3 MPa</td>
</tr>
<tr>
<td>$m$</td>
<td>23.3</td>
</tr>
<tr>
<td>$c_v$</td>
<td>6.9 m²/year</td>
</tr>
</tbody>
</table>

![Graphs showing various parameters over time](image-url)
Oedometer specimen CRSC_29 from MBS_4

Site: Lilleby  \( \gamma = 19.40 \text{kN/m}^3 \)

Depth: 8.26m  \( w_0 = 30.97\% \)

Sampling date: 11.05.2017  \( \sigma'_{w_0} = 62.72 \text{kPa} \)

Opening date: 13.05.2017  \( p'_C = 260 \text{kPa} \)

Testing date: 18.05.2017  \( OCR = 4.1 \)

Storage temp.: 5 °C  \( MOC = 10.3 \text{MPa} \)

Testing temp.: 21.1 °C  \( \dot{m} = 23.8 \)

Strain rate: 150 \( \mu \text{m/h} \)  \( p'_r = 160 \text{kPa} \)

\( \Delta e/e_0 = 0.089 \)  \( c_v = 5.9 \text{m}^2/\text{yr} \)
Oedometer specimen CRSC_30 from MBS_4

Site: Lilleby
Depth: 8.26m
Sampling date: 11.05.2017
Opening date: 13.05.2017
Testing date: 19.05.2017
Storage temp.: 5 °C
Testing temp.: 21.1 °C
Strain rate: 150 µm/h
Δε/ε₀ = 0.102

γ = 19.16kN/m³
ω₀ = 32.78%
σ'₀ = 60.76kPa
p’₀ = 250kPa
OCR = 4.1
MOC = 9.5MPa
p’c = 250kPa

- εa = ∆H/H₀ [%]
- uₐ [kPa]
- M = dε’/dσ’ [MPa]
- cᵥ [m²/year]

σ’ = σᵥ - 2/3 uₐ [kPa]
### Oedometer specimen CRSC_31 from MBS_4

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>Lilleby</td>
</tr>
<tr>
<td>Depth</td>
<td>8.43m</td>
</tr>
<tr>
<td>Sampling date</td>
<td>11.05.2017</td>
</tr>
<tr>
<td>Opening date</td>
<td>13.05.2017</td>
</tr>
<tr>
<td>Testing date</td>
<td>20.05.2017</td>
</tr>
<tr>
<td>γ</td>
<td>19.42kN/m³</td>
</tr>
<tr>
<td>( \omega_0 )</td>
<td>30.74%</td>
</tr>
<tr>
<td>( \sigma'_v )</td>
<td>64.20kPa</td>
</tr>
<tr>
<td>( \rho'_c )</td>
<td>255kPa</td>
</tr>
<tr>
<td>OCR</td>
<td>4.0</td>
</tr>
<tr>
<td>Storage temp.</td>
<td>5 °C</td>
</tr>
<tr>
<td>( M_{OC} )</td>
<td>10.3MPa</td>
</tr>
<tr>
<td>Testing temp.</td>
<td>21.1 °C</td>
</tr>
<tr>
<td>( m )</td>
<td>24.4</td>
</tr>
<tr>
<td>Strain rate</td>
<td>150 ( \mu )m/h</td>
</tr>
<tr>
<td>( p'_c )</td>
<td>160kPa</td>
</tr>
<tr>
<td>( \frac{\Delta e}{e_0} )</td>
<td>0.047</td>
</tr>
<tr>
<td>( c_v )</td>
<td>13.6m²/yr</td>
</tr>
</tbody>
</table>

![Graphs of e/a vs. H/H₀, u_b vs. kPa, M vs. MPa, c_v vs. m²/year]
Oedometer specimen CRSC_32 from MBS_4

Site: Lilleby \( \gamma = 19.30 \text{kN/m}^3 \)
Depth: 8.43m \( w_0 = 31.59\% \)
Sampling date: 11.05.2017 \( \sigma_{\nu 0} = 63.18 \text{kPa} \)
Opening date: 13.05.2017 \( p'_c = 235 \text{kPa} \)
Testing date: 21.05.2017 \( OCR = 3.7 \)
Storage temp.: 5 °C \( MOC = 9.3 \text{MPa} \)
Testing temp.: 21.1 °C \( m = 24.0 \)
Strain rate: 150μm/h \( p'_r = 145 \text{kPa} \)
\( \Delta e/e_0 = 0.060 \) \( c_v = 11.1 \text{m}^2/\text{yr} \)
Appendix C

Triaxial tests

Appendix C - Triaxial tests include data sheets for the 15 CAUC triaxial shear tests performed. They are also presented in chronological order, with a table of parameters from Table 5.5, two photos showing the test specimens before and after testing, and four characteristic diagrams.

One diagram plots values of expelled pore water ($\Delta V$) for a change in square root of time ($\sqrt{t}$), showing the consolidation behaviour of the soil. A second chart presents the stress-strain relationship during shearing, plotting shear stress ($\tau$) versus axial strain ($\varepsilon_a$). The last two charts are different presentations of the stress path of a specimen, presented either in an NTNU plot with shear stress ($\tau$) plotted for radial effective confinement stress ($\sigma_{r,c}'$), or in a $p$-$q$ plot with deviator stress ($q$) plotted for effective mean stress ($p'$).
Triaxial specimen CAUC_1 from MBS_1

Site: Lilleby
Depth: 6.74m
Sampling date: 19.10.2016
Opening date: 27.03.2017
Testing date: 27.03.2017
Storage temp.: 20°C
Testing temp.: 21.7°C
Strain rate: 0.75mm/h

\[ \sigma'_{a,c} = 78.12 \text{kPa} \]
\[ \sigma'_{r,c} = 54.68 \text{kPa} \]
\[ w_0 = 28.52\% \]
\[ \gamma = 20.42 \text{kN/m}^3 \]
\[ \Delta V = 4.27 \text{cm}^3 \]
\[ \varepsilon_{vo} = 1.86\% \]
\[ \Delta \varepsilon/\varepsilon_0 = 0.046 \]
\[ \tau_{max} = s_a = 58.48 \text{kPa} \]
\[ \varepsilon_f = 1.03\% \]
\[ a = 5\text{kPa} \]
\[ \phi = 34.3^\circ \]
Triaxial specimen CAUC_2 from MBS_1

Site: Lilleby
Depth: 6.74m
Sampling date: 19.10.2016
Opening date: 27.03.2017
Testing date: 30.03.2017
Storage temp.: 20 °C
Testing temp.: 21.7 °C
Strain rate: 0.75mm/h

\[ \begin{align*}
\sigma'_{a,c} &= 78.12 \text{kPa} \\
\sigma'_{r,c} &= 54.68 \text{kPa} \\
w_0 &= 28.19\% \\
\gamma &= 20.39 \text{kN/m}^3 \\
\Delta V &= 6.35 \text{cm}^3 \\
\varepsilon_{v} &= 2.77\% \\
\Delta\varepsilon/\varepsilon_0 &= 0.069 \\
\tau_{\text{max}} = s_u &= 55.32 \text{kPa} \\
\varepsilon_f &= 1.06\% \\
a &= 4 \text{kPa} \\
\phi &= 34.1^\circ
\end{align*} \]

\[ \begin{align*}
\tau &= \frac{1}{2} (\sigma'_{a,c} - \sigma'_{r,c}) \\
p' &= \frac{1}{2} (\sigma'_{a,c} + 2 \sigma'_{r,c})
\end{align*} \]
Triaxial specimen CAUC_3 from MBS_1

Site: Lilleby
Depth: 6.74m
Sampling date: 19.10.2016
Opening date: 27.03.2017
Testing date: 02.04.2017
Storage temp.: 20 °C
Testing temp.: 5.9 °C
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma'_{c,a} &= 78.12 \text{kPa} \\
\sigma'_{c,r} &= 54.68 \text{kPa} \\
w_0 &= 29.31\% \\
\gamma &= 20.10 \text{kN/m}^3 \\
\Delta V &= 4.44 \text{cm}^3 \\
\varepsilon_\gamma &= 1.94\% \\
\Delta \varepsilon / \varepsilon_0 &= 0.047 \\
\tau_{\text{max}} &= s_u = 63.55 \text{kPa} \\
\varepsilon_f &= 0.85\% \\
\alpha &= 11 \text{kPa} \\
\phi &= 31.6^\circ
\end{align*}
\]
Triaxial specimen CAUC_4 from MBS_1

Site: Lilleby  
Depth: 6.74m  
Sampling date: 19.10.2016  
Opening date: 27.03.2017  
Storage temp.: 20 °C  
Testing temp.: 5.9 °C  
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma_{a,c}' &= 78.12 \text{kPa} \\
\sigma_{r,c}' &= 54.68 \text{kPa} \\
w &= 29.17\% \\
\gamma &= 20.34 \text{kN/m}^3 \\
\Delta V &= 4.49 \text{cm}^3 \\
\varepsilon_{uv} &= 1.96\% \\
\Delta \varepsilon / \varepsilon_0 &= 0.048 \\
\tau_{\text{max}} &= \sigma_a = 68.48 \text{kPa} \\
\varepsilon_f &= 0.79\% \\
a &= 8 \text{kPa} \\
\phi &= 33.6^\circ
\end{align*}
\]
Triaxial specimen CAUC_5 from MBS_2

Site: Lilleby  
Depth: 6.45m  
Sampling date: 18.10.2016  
Opening date: 06.04.2017  
Testing date: 06.04.2017  
Storage temp.: 5 °C  
Testing temp.: 6.0 °C  
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma'_{a,c} &= 73.27 \text{kPa} \\
\sigma'_{r,c} &= 51.29 \text{kPa} \\
w_0 &= 29.38\% \\
\gamma &= 19.95 \text{kN/m}^3 \\
\Delta V &= 3.45 \text{cm}^3 \\
\epsilon_v &= 1.50\% \\
\Delta \epsilon/\epsilon_0 &= 0.036 \\
\tau_{\text{max}} &= s_u = 81.93 \text{kPa} \\
\epsilon_f &= 0.91\% \\
\sigma_a &= 10 \text{kPa} \\
\phi &= 28.6°
\end{align*}
\]
Triaxial specimen CAUC_6 from MBS_2

Site: Lilleby
Depth: 6.45m
Sampling date: 18.10.2016
Opening date: 06.04.2017
Testing date: 08.04.2017
Storage temp.: 5 °C
Testing temp.: 6.0 °C
Strain rate: 0.75mm/h

\[ \sigma'_{a,c} = 73.27 \text{kPa} \]
\[ \sigma'_{r,c} = 51.29 \text{kPa} \]
\[ w_0 = 29.37\% \]
\[ \gamma = 20.11 \text{kN/m}^3 \]
\[ \Delta V = 3.85 \text{cm}^3 \]
\[ \varepsilon_{\nu} = 1.68\% \]
\[ \Delta\varepsilon/\varepsilon_0 = 0.040 \]
\[ \tau_{max} = s_u = 67.83 \text{kPa} \]
\[ \varepsilon_f = 0.77\% \]
\[ a = 11 \text{kPa} \]
\[ \phi = 31.6^\circ \]

\[
\tau = \frac{1}{2}(\sigma'_{a,c} - \sigma'_{r,c}) \quad [\text{kPa}]
\]

\[
p' = \frac{1}{3}(\sigma'_{a,c} + 2\sigma'_{r,c}) \quad [\text{kPa}]
\]
Triaxial specimen CAUC_8 from MBS_2

Site: Lilleby
Depth: 6.45m
Sampling date: 18.10.2016
Opening date: 06.04.2017
Testing date: 12.04.2017
Storage temp.: 5 °C
Testing temp.: 21.2 °C
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma'_{a,c} & = 73.27 \text{kPa} \\
\sigma'_{r,c} & = 51.29 \text{kPa} \\
\gamma & = 29.41\% \\
\Delta V & = 19.76 \text{kN/m}^3 \\
\varepsilon_\text{p} & = 6.24 \text{cm}^3 \\
\Delta \varepsilon/\varepsilon_0 & = 2.73\% \\
\tau_{\text{max}} = s_u & = 66.27 \text{kPa} \\
\varepsilon_f & = 0.82\% \\
a & = 4 \text{kPa} \\
\phi & = 33.4^\circ \\
\end{align*}
\]

\[
\begin{align*}
p' & = \frac{1}{3} (\sigma'_{a,c} + 2 \sigma'_{r,c}) \\
q & = \sigma'_{a,c} - \sigma'_{r,c} \\
\tau & = \frac{1}{2} (\sigma'_{a,c} - \sigma'_{r,c}) \\
\end{align*}
\]
Triaxial specimen CAUC_9 from MBS_3

Site: Lilleby
Depth: 7.96m
Sampling date: 28.04.2017
Opening date: 29.04.2017
Testing date: 29.04.2017
Storage temp.: 5 °C
Testing temp.: 21.3 °C
Strain rate: 0.75mm/h

$\sigma'_{a,c} = 93.67$ kPa
$\sigma'_{r,c} = 65.58$ kPa
$w_0 = 30.02\%$
$\gamma = 20.00$kN/m$^3$
$\Delta V = 3.95$ cm$^3$
$\varepsilon_v = 1.73\%$
$\Delta \varepsilon/\varepsilon_0 = 0.041$
$\tau_{max} = s_u = 71.64$kPa
$\varepsilon_f = 0.79\%$
$a = 0$kPa
$\phi = 36.4^\circ$

$\tau = \frac{1}{2}(\sigma_{a,c} - \sigma_{r,c})$ [kPa]
$q = \sigma_{r,c} - \sigma_{a,c}$ [kPa]

$p' = \frac{1}{3}(\sigma_{a,c} + 2\sigma_{r,c})$ [kPa]
Triaxial specimen CAUC_10 from MBS_3

Site: Lilleby
Depth: 7.96m
Sampling date: 28.04.2017
Opening date: 29.04.2017
Testing date: 01.05.2017
Storage temp.: 5°C
Testing temp.: 21.3°C
Strain rate: 0.75mm/h

\[ \sigma'_{a,c} = 93.67 \text{kPa} \]
\[ \sigma'_{r,c} = 65.58 \text{kPa} \]
\[ w_0 = 29.40\% \]
\[ \gamma = 20.18 \text{kN/m}^3 \]
\[ \Delta V = 5.97 \text{cm}^3 \]
\[ \varepsilon_0 = 2.61\% \]
\[ \Delta\varepsilon/\varepsilon_0 = 0.063 \]
\[ \tau_{\text{max}} = s_u = 70.94 \text{kPa} \]
\[ \varepsilon_f = 0.77\% \]
\[ a = 0 \text{kPa} \]
\[ \phi = 36.4^\circ \]
Triaxial specimen CAUC_11 from MBS_3

Site: Lilleby
Depth: 7.96m
Sampling date: 28.04.2017
Opening date: 29.04.2017
Testing date: 04.05.2017
Storage temp.: 5°C
Testing temp.: 5.9°C
Strain rate: 0.75mm/h

\[ \sigma'_{a,c} = 93.67 \text{kPa} \]
\[ \sigma'_{r,c} = 65.58 \text{kPa} \]
\[ w_0 = 29.33\% \]
\[ \gamma = 19.94 \text{kN/m}^3 \]
\[ \Delta V = 5.06 \text{cm}^3 \]
\[ \varepsilon_a = 2.21\% \]
\[ \Delta \varepsilon / \varepsilon_0 = 0.053 \]
\[ \tau_{max} = s_u = 66.12 \text{kPa} \]
\[ \varepsilon_f = 1.50\% \]
\[ a = 8 \text{kPa} \]
\[ \phi = 33.5^\circ \]

![Graphs and plots related to triaxial testing results.](image)
Triaxial specimen CAUC_12 from MBS_3

Site: Lilleby
Depth: 7.96m
Sampling date: 28.04.2017
Opening date: 29.04.2017
Testing date: 06.05.2017
Storage temp.: 5 °C
Testing temp.: 5.9 °C
Strain rate: 0.75mm/h

\[ \sigma'_{a,c} = 93.67 \text{kPa} \]
\[ \sigma'_{r,c} = 65.58 \text{kPa} \]
\[ w_0 = 29.49\% \]
\[ \gamma = 19.95 \text{kN/m}^3 \]
\[ \Delta V = 4.95 \text{cm}^3 \]
\[ \varepsilon_v = 2.16\% \]
\[ \Delta \varepsilon/\varepsilon_0 = 0.051 \]
\[ \tau_{max} = s_u = 65.61 \text{kPa} \]
\[ \varepsilon_f = 0.88\% \]
\[ a = 4 \text{kPa} \]
\[ \phi = 35.3^\circ \]

\[ p' = \frac{1}{3}(\sigma'_{a,c} + 2\sigma'_{r,c}) \] [kPa]
Triaxial specimen CAUC_13 from MBS_4

Site: Lilleby
Depth: 8.33
Sampling date: 11.05.2017
Opening date: 13.05.2017
Testing date: 13.05.2017
Storage temp.: 5 °C
Testing temp.: 5.9 °C
Strain rate: 0.75mm/h

\[ \sigma'_a,c = 91.46 \text{kPa} \]
\[ \sigma'_r,c = 64.02 \text{kPa} \]
\[ w_0 = 30.91\% \]
\[ \gamma = 19.66 \text{kN/m}^3 \]
\[ \Delta V = 4.33 \text{cm}^3 \]
\[ \varepsilon_a = 1.89\% \]
\[ \Delta \varepsilon / \varepsilon_0 = 0.044 \]
\[ \tau_{\text{max}} = s_u = 74.81 \text{kPa} \]
\[ \varepsilon_f = 0.74\% \]
\[ a = 9 \text{kPa} \]
\[ \phi = 33.7^\circ \]

\[ \tau = \frac{1}{2} (\sigma'_a,c - \sigma'_r,c) \quad [\text{kPa}] \]
\[ q = \sigma'_a,c - \sigma'_r,c \quad [\text{kPa}] \]
\[ p' = \frac{1}{3} (\sigma'_a,c + 2 \sigma'_r,c) \quad [\text{kPa}] \]
Triaxial specimen CAUC_14 from MBS_4

Site: Lilleby
Depth: 8.33m
Sampling date: 11.05.2017
Opening date: 13.05.2017
Testing date: 15.05.2017
Storage temp.: 5 °C
Testing temp.: 5.9 °C
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma'_{a,c} &= 91.46 \text{kPa} \\
\sigma'_{r,c} &= 64.02 \text{kPa} \\
w_0 &= 31.44\% \\
\gamma &= 19.60 \text{kN/m}^3 \\
\Delta V &= 4.10 \text{cm}^3 \\
\varepsilon_v &= 1.79\% \\
\Delta \varepsilon / \varepsilon_0 &= 0.041 \\
\tau_{max} &= s_u = 72.47 \text{kPa} \\
\varepsilon_f &= 0.83\% \\
a &= 9 \text{kPa} \\
\phi &= 32.9^\circ \\
\end{align*}
\]

![Graph 1: ΔV vs. \( \sqrt{T} \)]

![Graph 2: \( \tau \) vs. \( \varepsilon_a \)]

![Graph 3: \( \tau \) vs. \( \sigma'_{r,c} \)]

![Graph 4: \( q \) vs. \( \sigma'_{a,c} - \sigma'_{r,c} \)]
Triaxial specimen CAUC_15 from MBS_4

Site: Lilleby
Depth: 8.33m
Sampling date: 11.05.2017
Opening date: 13.05.2017
Testing date: 18.05.2017
Storage temp.: 5 °C
Testing temp.: 21.1 °C
Strain rate: 0.75mm/h

\[\sigma'_{a,c} = 91.46 \text{kPa}\]
\[\sigma'_{r,c} = 64.02 \text{kPa}\]
\[w_0 = 31.43\%\]
\[\gamma = 19.72 \text{kN/m}^3\]
\[\Delta V = 8.99 \text{cm}^3\]
\[\varepsilon_\phi = 3.93\%\]
\[\Delta \varepsilon/\varepsilon_0 = 0.091\]
\[\tau_{max} = s_u = 71.78 \text{kPa}\]
\[\varepsilon_f = 0.84\%\]
\[a = 17 \text{kPa}\]
\[\phi = 29.1^\circ\]
**Triaxial specimen CAUC_16 from MBS_4**

Site: Lilleby  
Depth: 8.33m  
Sampling date: 11.05.2017  
Opening date: 13.05.2017  
Testing date: 20.05.2017  
Storage temp.: 5°C  
Testing temp.: 21.1°C  
Strain rate: 0.75mm/h

\[
\begin{align*}
\sigma'_{a,c} &= 91.46 \text{kPa} \\
\sigma'_{r,c} &= 64.02 \text{kPa} \\
w_0 &= 30.91\% \\
\gamma &= 19.66 \text{kN/m}^3 \ \\
\Delta V &= 9.17 \text{cm}^3 \\
\varepsilon_v &= 4.00\% \ \\
\Delta \varepsilon / \varepsilon_0 &= 0.093 \ \\
\tau_{\text{max}} = s_u &= 70.66 \text{kPa} \\
\varepsilon_f &= 0.82\% \ \\
a &= 16 \text{kPa} \\
\phi &= 29.0^\circ
\end{align*}
\]