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Rate effect on Halden silt

Triaxial testing with different rates of loading

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Preface

This project thesis in geotechnics is written in the course TBA 4510 - Geotechnical specialization project which is part of the MSc Geotechnics and Geohazards program at NTNU. The project is carried out during the autumn semester of 2019, and is executed in cooperation with NGI-Norwegian Geotechnical Institute. Before this project could get started, I had to learn my way around the labs and how the triaxial apparatus worked. I had to start from scratch and learn all the practical parts of running a triaxial test by experimenting with dummy samples over a few weeks with help from the geotechnical staff, in addition to how to process the data. This impacted the available time to write the report.

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Acknowledgment

I would like to thank Professor Jean-Sebastien L'Heureux at NTNU for overseeing this project. I would also like to thank Dr. Ana Priscilla Paniagua Lopez at NGI for being a great supervisor and for helping me with all my questions. A special thanks to Karl Ivar Volden Kvisvik for being pacient when he showed me how to use the lab equipment in the early stages of this project.

S.B.M.

Summary and Conclusions

This project describes the methods and results from running triaxial tests with different loading rates on a silt material from Halden, Norway. The test site in Halden have been investigated for several years, and has been well characterized by other testing methods. By comparing the obtained results during this project with older results, an evaluation of the impact the loading rate have on shear strength is determined. This project mainly explains the triaxial testing procedure, the results from the tests and an evaluation of the undrained shear strength of the material. The sample from Halden has been stored cold in a fridge for over two years, and had to be trimmed down to proper dimensions before testing could occur. A higher undrained shear strength is observed when the samples are loaded with a higher rate. These values seemed to be slightly too high for use as deign values, and should be neglected. The samples sheared at a lower rate seems to coincide well with the previous results from the test site. The undrained shear strength is estimated to be around 100 kPa at around 15.25m where the sample is taken from.

Contents

Chapter 1

Introduction

In Halden, Norway there is a permanent geotechnical test site which is used for silt measurements in situ and sample collecting. These test sites are meant to provide valuable information for public authorities, industries and research organizations. The Halden test site is located in the southeast of Norway, close to the Swedish boarder and approximately 120km south of Oslo seen in Figure 1.1. There has been performed several different in situ tests on this site (CPTU, SCPT, RCPTU, SDMT and other tests). Samples has also been collected using various samplers. In this project, the block sample HALB04 collected at 15.25m depth will be investigated in the lab. Triaxial tests will be performed to investigate the effect of load applied at different rates. The reason to carry out this project is that the silt is a genuinely difficult material to evaluate, especially for very low plasticity to non-plastic silt. In addition to this, there is no permanent framework to evaluate the sample quality. The samples of intermediate soils of high quality is often troublesome to obtain. Furthermore, there is quite little information regarding the topic of selecting the fitting engineering properties for practical use.

1.1 Background

1.1.1 Halden test site

As of 2011, the test site in Halden has been used for different geotechnical soil testing. The site contains layers of sand, clayey silt and clay. In this report, only the silt is to be investigated. The test site is located in the western part of the city Halden. As of now, the site is a public park owned by the municipality located close to a residential area. The total area of the site is about 6000 m^2 and the topography is mainly flat. As seen in Figure 1.1 there is adequate vegetation in the area. Right next to the site to the north and west, a ridge ascends up about 15 meters. On the other, to the east, another ridge rises up about 8 meters. This will lead the precipitation down towards the test site and influence the ground conditions to a certain amount.

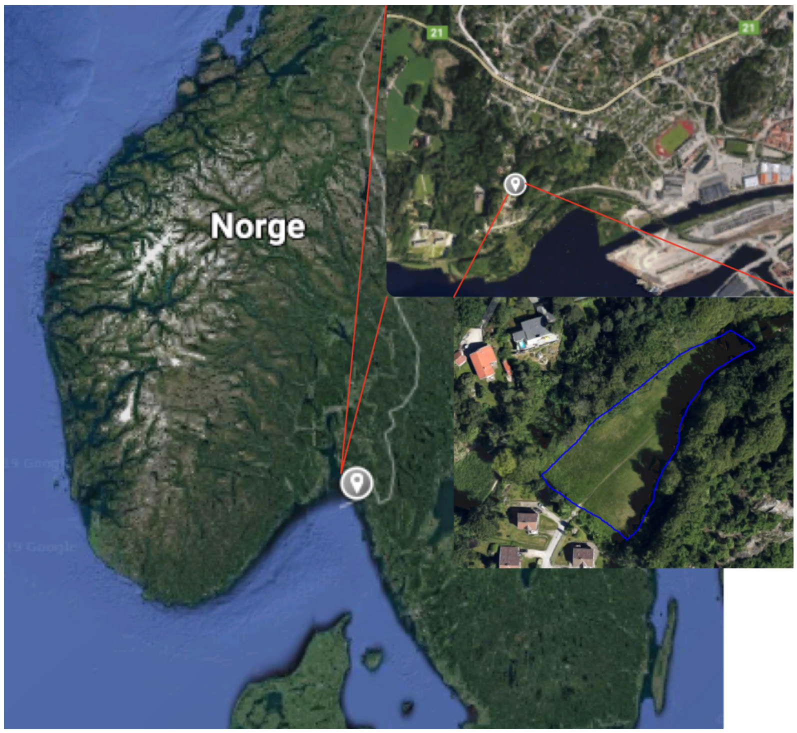

Figure 1.1: Location of the Halden test site in Norway

1.1.2 Problem Formulation

This project aims to investigate the effect of different loading rates on the silt material obtained by block sampling in Halden, Norway in a triaxial test. The rates used in this project is set to 1.5% and 15% Berre (1982). The rate is found by choosing a percentage which according to ISO (2018) is within acceptable range, and dividing this percentage by 60 minutes. The results from using 1.5% and 15% is shown in Table 1.1 below. 15% is a rather extreme value, and will shear the sample in a short amount of time. The reason for choosing such a high value is to determine if a rate of this magnitude will influence the resulting undrained shear strength.

Rate	Velocity [mm/min]
1.5%	0.025
15%	0.25

Table 1.1: Different rates used in the laboratory

The sample is being tested with a CIUc-test, which is an Isotropic Consolidated undrained test. This means that the sample is consolidated with the axial stress σ_1 is equal to the radial stress σ_3, which is a very common test method for silts.

1.1.3 Literature review

This project is mainly an addition to the results from the journal article published by AIMS Geosciences, named *The Halden research site: geotechnical characterization of a post glacial silt* Blaker et al. (2019). This report explains the characterization of the test site, sampling methods and contains results from several testing methods from the site. The block sample tested in this project is retrieved from the same site, and will be compared to the results from the report.

Furthermore, preparing silt for triaxial testing without significant disturbance is difficult as described by Fleming and Duncan (1990);Høeg et al. (2000). Disturbance of the sample will influence the measured shear strength and obscure the past consolidation pressure in consolidation tests Brandon et al. (2006). Sample quality should always be evaluated when advanced tests is conducted in the laboratory. If the tests are performed on poor quality samples, it could affect the engineering soil parameters which could lead to unsafe geotechnical design Blaker et al. (2019).

The testing conducted in this report follows standards and guidelines commonly used for laboratory testing. The Norwegian standard NS-EN ISO 17892-9:2018 ISO (2018) is the main document securing the correct way to test the silt samples in the triaxial apparatus. Further, the article published by NGI Berre (1982), *Triaxial Testing at the Norwegian Geotechnical Institute* is used in addition to the standard to compliment the testing procedures. The tests in this project will be performed under these conditions, since the journal article published by AIMS Geosciences is based on the procedures from the NGI article in addition to the standard.

1.2 Objectives

The main objectives of this project are:

1. To conduct a proper literature study for a better understanding of silts
2. Run triaxial tests in the lab on the retrieved samples
3. Interpret the results and compare with other tests from the area

1.3 Limitations

Due to the rather short amount of time this report has to be constructed in, only a few samples will be tested. Originally it was planned to run nine tests, with three different loading rates. This is limited to four tests with two loading rates. The desired number of tests would have made a better basis for comparison.
The collected sample has been stored cold in the fridge for quite some time. This could influence the water content in the sample and affect the testing results. This will most likely be seen when the tests is complete and the results are compared with other data.

1.4 Approach

The main tasks in this project is shown in the list below:

1. Learn how the triaxial apparatus works
2. Create test samples from the block
3. Running triaxial tests on the obtained samples
4. Interpret and compare results

Chapter 2

Method

In this chapter, the methods used in the laboratory is explained.

2.1 The block sample

The block sample was collected using a Sherbrooke block sampler with Φ250 mm. The block was taken from 15.15-15.5 meter below the surface and has been stored in a fridge after transportation to Trondheim, Norway. The block has to be cut in different parts to be able to tested. Since the triaxial apparatus used in this project requires a final sample height of 10 cm, the block is split in half. By cutting the block in half, ten samples can be cut out of the block for testing. First the sample was taken out of the container, and the plastic film was removed. The first observation is that the outside of the block seemed quite dry. The material was easy to fracture simply by touching it. The state of the block sample can be observed in Figure 2.1. The crust at the top and the sides were completely dry. Shell fragments could be seen when the top of the block were examined further.

First, the block were trimmed by 3 cm at the top. A circle of about 2 cm around the edges was rather dry. The block was in good condition apart from the dry edge. Furthermore, there was observed a small black circle with some organic material. There was also detected that the block contained a substantially amount of shells. One of the shells in the top was quite big compared to most of the other inspected shells. When the block was trimmed the shells got stuck in the steel wire, which made the process somewhat difficult. The larger shell made quite the hole in the block and disturbed the sample a bit.

Figure 2.1: The block sample used in the tests

From Figure 2.2 it is possible to witness the V-shaped mark were the shell was placed. The dark organic material can also be seen.

Further, the block sample was split in half for a total height of 12 cm. The bottom half of the block were put back in the fridge for storage. The other half was first cut in half circles. One piece were cut out from the half circle and put in the soil sample trimming device. The other parts were concealed with plastic wrapping and the placed back in the fridge. During the testing period, samples were taken out of the fridge only when needed. This was done to secure that the samples was not dried out between test preparations.

Figure 2.2: The block sample after trimming at the top

2.2 Trimming the samples from the block

The triaxial apparatus requires a certain geometry of the samples. The main goal is to trim the sample as circular as possible. To be able to accomplish this, the samples were put in a soil sample trimming device. The device was adjusted to a diameter of 54 mm which is one of the preferred sample diameters for several different institutions in Norway Vegdirektoratet (2014). The sample piece is first roughly trimmed at the edges to get rid of most of the unnecessary parts. Then the sample is placed on to the trimming apparatus and secured by lowering the top plate down on to the sample. The top plate is screwed tight so the sample can not move in any directions when the cutting is performed.

For cutting of the sample, the same steel wire is used. The steel wire is dragged along the adjusted steel plates in the apparatus which is there to make sure the sample us cut equal each time. When the sample is cut in one direction, the sample is turned simply by spinning it as both the top- and bottom plate can be rotated. The process continues until the sample have achieved satisfactory shape. The results from cutting and trimming of the sample can be seen in Figure 2.3 and Figure 2.4 below.

Figure 2.3: Piece cut out from the block

Figure 2.4: Sample after trimming on the sides

Further, the sample is placed in a steel casing which is 10 cm long. The top and the bottom of the sample is trimmed simply by dragging the steel wire carefully along the edges of the steel casing. It is always kept track of which side of the sample which was facing upwards in-situ. The sample is then built in to the triaxial apparatus in the same direction as it had in-situ. After the trimming of the sample is completed, a visual inspection of the sample was conducted. This is done to make sure that the sample is not disturbed in any way.

2.3 Preparing the triaxial apparatus

Before the sample is placed into the triaxial apparatus, some preparations were made. First, the pressure systems which regulate the cell- and back pressures is filled with de-aired water. Then the "fast empty" function on the pressure systems is used to clean out the drainage tubes in the top cap and the bottom pedestal, in case there is some of residue from previous tests. It is also important to make sure that the O-ring in the pedestal and the pedestal itself is clean, to prevent any leakage. Furthermore, the porous discs is cleaned and saturated in a container with de-aired water. Filter paper is cut out in 54 mm circular shapes and saturated, and the "drainage paper" used around the side of the sample is saturated as well. Prior to each test, all the testing equipment was given a visual inspection to make sure there was no damages to the system and preparation equipment.

2.4 Building the sample into the triaxial apparatus

The sample is trimmed down to the required size and shape. The next step is to build in the sample into the triaxial apparatus. This is executed as described in NS-EN ISO 17892-9:2018 ISO (2018), to make sure that the procedure is done equally each time. The steps relevant to this report regarding sample mounting is listed below:

1. Applied grease to the top cap and the pedestal to make sure the rubber membrane is simple to remove after the test is completed.

2. The rubber membrane was fitted onto the membrane stretcher with the four O-rings, before the membrane stretcher was connected to an air compressor.

3. Filter paper was placed on the top and bottom of the sample, in addition to the filter paper on the sides.

4. The pedestal was filled with a water film using the pressure device, before the porous disc was slided onto the pedestal to keep air out of the system.

5. The sample is placed on the pedestal in the in-situ direction.

6. The air compressor is turned on, and the membrane stretcher is slided over the sample using a steel rod which is screwed into the pedestal. When the membrane stretcher is covering the sample and locked in position, the membrane is pulled down onto the pedestal, followed by the O-rings.

7. The porous disc is then placed on top of the sample, followed by the top cap. The membrane is pulled onto the top cap followed by the last two O-rings.

8. The membrane stretcher is then dismantled and the sample is ready to be covered by the triaxial cell.

The result from the building into the apparatus can be observed in Figure 2.5 below:

Figure 2.5: The sample prepared for testing

This process is carried out with care to make sure the sample is not disturbed during installment. A new rubber membrane was used in every test to make sure each sample were tested in the same conditions.

2.5 Final preparations of the triaxial apparatus

After the triaxial cell is mounted and fastened properly, and the piston is lowered to a point were it does not have contact with the top cap, the filling of water in to the cell is performed. When the water level reaches the midpoint on the sample, the pressures is set to zero on the pressure devices to make sure this is the reference point. The pore pressure is set to zero as well. When the pressures is zero, the filling of the cell is continued. When the water reaches the top, the air valves is tightened one by one until all the air is out of the cell.

The next step is to get rid of all the air in the system (tubes). First the cell pressure is increased to 10 kPa. Then the valves for the top cap and the pedestal is opened separately, and water flows through the tubes using gravity. When the air bubbles can not be observed after a short period of time, the air is out of the system. Now the sample is ready to get saturated.

2.6 Saturation of sample

Effective stress triaxial tests (CU) requires that the sample is saturated for testing Gawen (2017).This is done to get reliable pore pressure measurements due to no air in the specimen. The option "Saturation ramp" in the computer program is now chosen to make sure that the sample get completely saturated. The saturation is checked with a following "B-check". The B-value is calculated based on the following formula in ISO (2018):

$$B = \frac{\Delta U}{\Delta \sigma'_c} \tag{2.1}$$

Where:

$$\Delta U = \text{Change in pore pressure}$$

$$\Delta \sigma_3' = \text{Change in confining pressure}$$

To be able to start running the consolidation phase, a B-check is conducted. The B-value should be 0.95 ISO (2018) or greater within a given time frame during the B-check. The saturation ramps usually requires a few tests to be able to reach the appropriate B-value. The saturation ramps was in this project increased with intervals of 50 kPa. Both the cell- and back pressure has to be increased by the same value. The cell pressure was always kept 10 kPa higher than the back pressure. During all four conducted tests, the B-value was satisfied when the cell- and back pressures exceeded around 250 kPa and 240 kPa respectively.

2.7 Consolidation of sample

After the required B-value is obtained, the consolidation phase was initiated. To be able to run consolidation, the mean effective in-situ stress must be determined. This was already determined in the NGTS project.

The mean effective stress was read out from Figure 6 in Blaker et al. (2019) to be ~ 170 kPa. This value is then the difference between the back pressure and the cell pressure in the consolidation phase. The duration of the consolidation phase was a minimum of 24 hours to ensure that the samples was given enough time to return to its natural state. Furthermore, the tests was performed isotropically meaning the stresses inn all directions are the same ($\sigma_1 = \sigma_3$).
Since this test is carried out as an effective stress test the sample will be consolidated to an effective pressure. In this test, the pore pressure will be replaced by the back pressure to be able to define the effective stresses. Once the mean effective in-situ stress is applied, excess pore pressure will develop in the sample. During the consolidation phase, the excess pore pressure will dissipate out of the sample and decrease its volume. This process is complete when the change in volume is less than 0.1% of the sample volume per hour and 95% of the excess pore pressure have dissipated ISO (2018). At this point the pore pressure is similar or equal to the back

pressure, and is used to calculate the effective stress conditions in the sample Gawen (2017).

2.8 Shearing of sample

When the requirements for the consolidation phase were met, the shear phase was initiated. In the shear phase the axial stress σ_1 is gradually increased while the confining pressure σ_3 remains constant. The increase in axial stress is achieved by moving the piston into the triaxial cell with a constant rate. This process continues until failure occur. When the sample reaches failure, the maximum shear stress the sample can take is determined. The test will proceed until 15% strain is reached according to ISO (2018). Figure 2.6 below illustrates a successful shear test. The failure line is clearly visible through the rubber membrane.

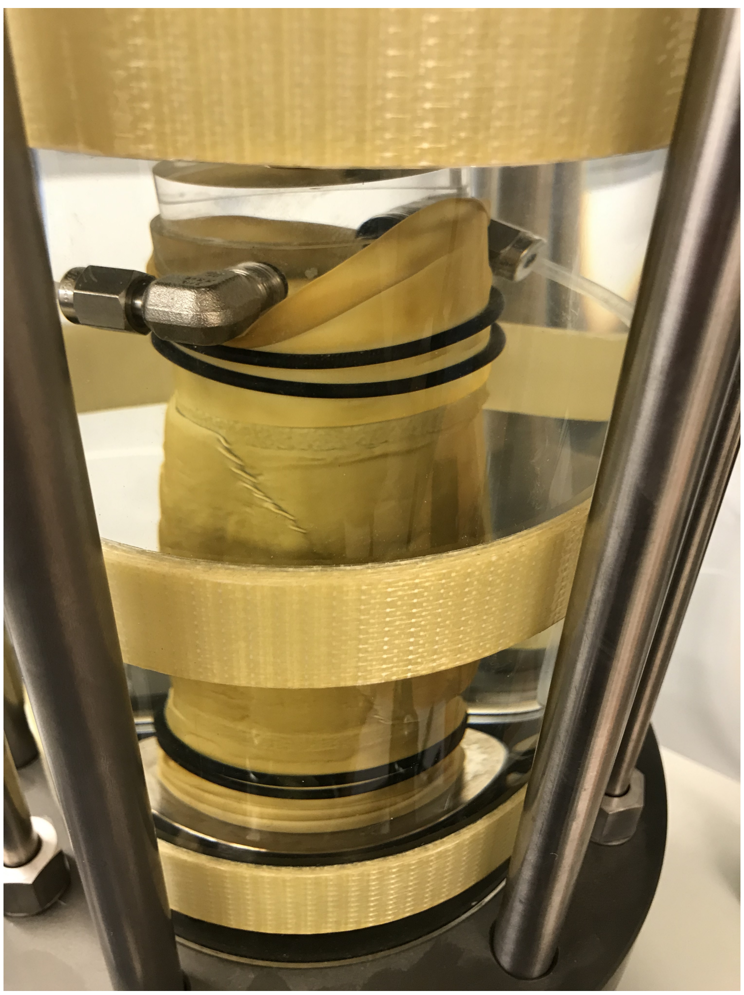

Figure 2.6: The sample after complete shearing

The loading rate is determined before the initiation of the shear test. The chosen velocities used in this project is described in Table 1.1 in chapter 1.1.2. The shear test was performed undrained, meaning no water is allowed to drain out of the sample. The volume of the sample will remain constant during testing. However, the geometry of the sample will change.

From the shear test, the parameters ϕ (friction angle), c' (cohesion) and S_u (undrained shear strength) can be established. These parameters are important regarding geotechnical engineering, hence it is crucial to estimate as accurate as possible.

Chapter 3

Results

3.1 Water content

The water content is found by weighing the material before and after drying. The material used in these measurements were collected from various points in the trimmed block. Immediately after the sample is retrieved, the sample is placed in a bowl, weighed and put in an oven at 105° for 24 hours. The samples is weighed again after drying. Then Equation 3.1 found in Sandven et al. (2015) is used to calculate the water content:

$$w = \frac{m - m_s}{m_s} * 100\% \tag{3.1}$$

Where:

$$w = \text{water content [\%]}$$

$$m = \text{Mass of wet sample minus weight of bowl [g]}$$

$$m_s = \text{Mass of dry sample minus weight of bowl [g]}$$

Three samples were collected for water content measurements in total from various points in the top half of the block sample. The water content found in this test along with the previously found water contents from the surface and down to is presented in Table 3.1 below:

Depth [m]	Water content [%]
2-4	30-35
4-8	27-32
8-12	24-32
12-15	19-28
Obtained values from the sample	
15.25	19.5-22.5

Table 3.1: Water contents with depth in the same borehole the sample in this project is retrieved from.

3.2 Undrained shear strength

The undrained shear strength is one of the most critical parameters in geotechnical engineering to estimate correctly. Relevant plots is conducted by using Microsoft Excel, and the shear strength can be determined.

The tests clearly shows a strong dilative behavior after the initial contraction during shearing. It can be challenging to determine the undrained shear strength for dilating silts since the test results does not provide a peak shear strength. The report written by Blaker et al. (2019) suggests three different methods for determination of the undrained shear strength, which will be used in this report. By doing this, it is possible to compare results and investigate if the shear rate will influence the results. Brandon et al. (2006) describes the methods and is explained below:

(a) $S_u = q_f$ at the maximum pore pressure u_{max}

(b) $S_u = q_f$ at the point where Skempton's pore pressure parameter A=0 (A=$(\Delta u - \Delta\sigma_3)/(\Delta\sigma_1 - \Delta\sigma_3)$)

(c) $S_u = q_f$ at a limiting axial strain $\varepsilon_f = 4\%$

Method (a) is the most conservative, as the shear stress at this point is not fully mobilized and lays below the failure line determined in the p'q-plot. Method (b) and (c) gives much higher values for the shear strength, and method (c) in particular gives a wider spread in the results. Thereby a combination of the methods (a) and (b) is used to interpret the results. The Figures below displays the relevant obtained plots used to interpret the undrained shear strength.

Method (a) is describes further in this section. Figure 3.1 shows strain plotted versus ΔU. By reading the graph where the highest pore pressure is obtained, the corresponding deviatoric stress is found in Figure 3.2.The undrained shear strength is found by dividing the deviatoric stress by 2. The deviatoric stress is found using Equation 3.2:

$$q = \sigma_1 - \sigma_3 \tag{3.2}$$

The results from previous tests and the tests performed in this project is listed in Table 3.2 and Table 3.3 below:

Depth [m]	S$_u$[kPa]
5	35
8.4	45
11.5	48
12.5	59
13.6	63
14.5	72

Table 3.2: Shear strength with depth using method (a) from previous tests

The results performed in this project at 15.25m is listed below:

Sample	Rate [%]	S_u
S1A	1.5	94.5
S1B	1.5	80
S2A	15	126
S2B	15	96

Table 3.3: S_u using method (a)

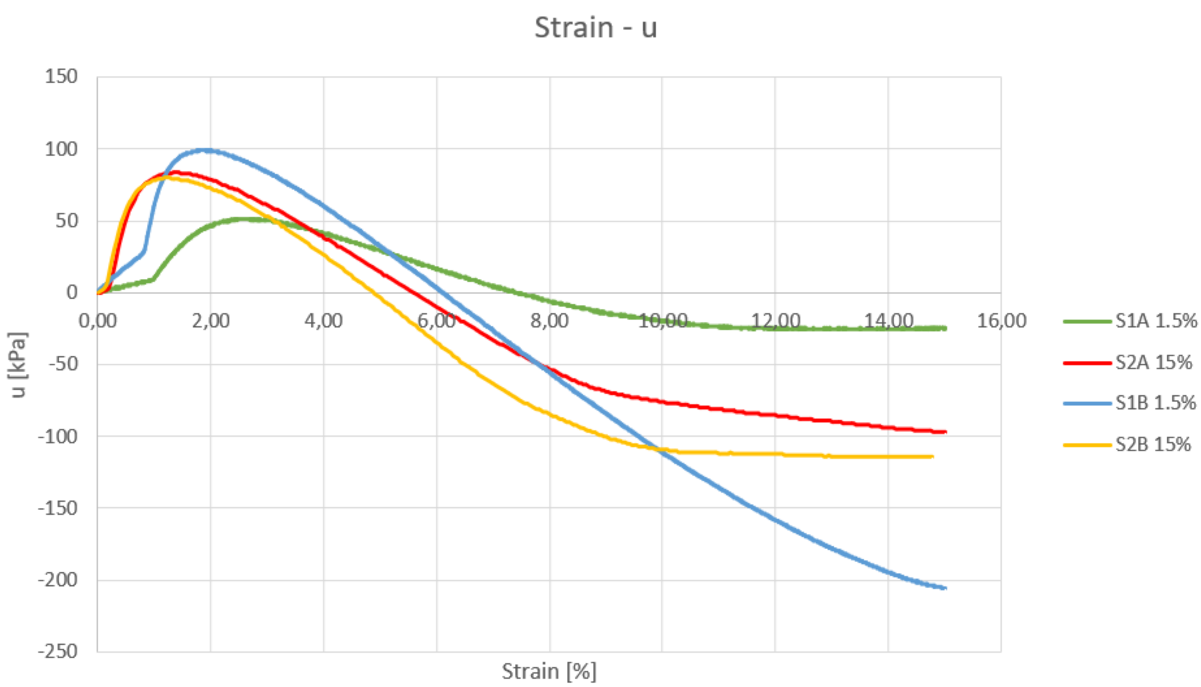

Figure 3.1: Plot showing Strain versus the change in pore pressure

Method (c) is performed by using Figure 3.2. The undrained shear strength should normally be read at 5% strain as in Blaker et al. (2019), but three of the tests did not reach 5%. This lead to the decision of using 4% instead. The values from the previous tests is collected from Figure 26. (c) in Blaker et al. (2019) The results from using method (c) from previous tests is found in Table and results from this project is found in Table below:

Depth [m]	$S_u[kPa]$
5	54
8.4	62
11.5	71
12.5	98
13.6	131
14.5	177

Table 3.4: S_u with depth using method (c) from previous tests

The results performed in this project at 15.25m is listed below:

Sample	Rate [%]	S_u
S1A	1.5	114
S1B	1.5	156
S2A	15	234
S2B	15	211.5

Table 3.5: S_u using method (c)

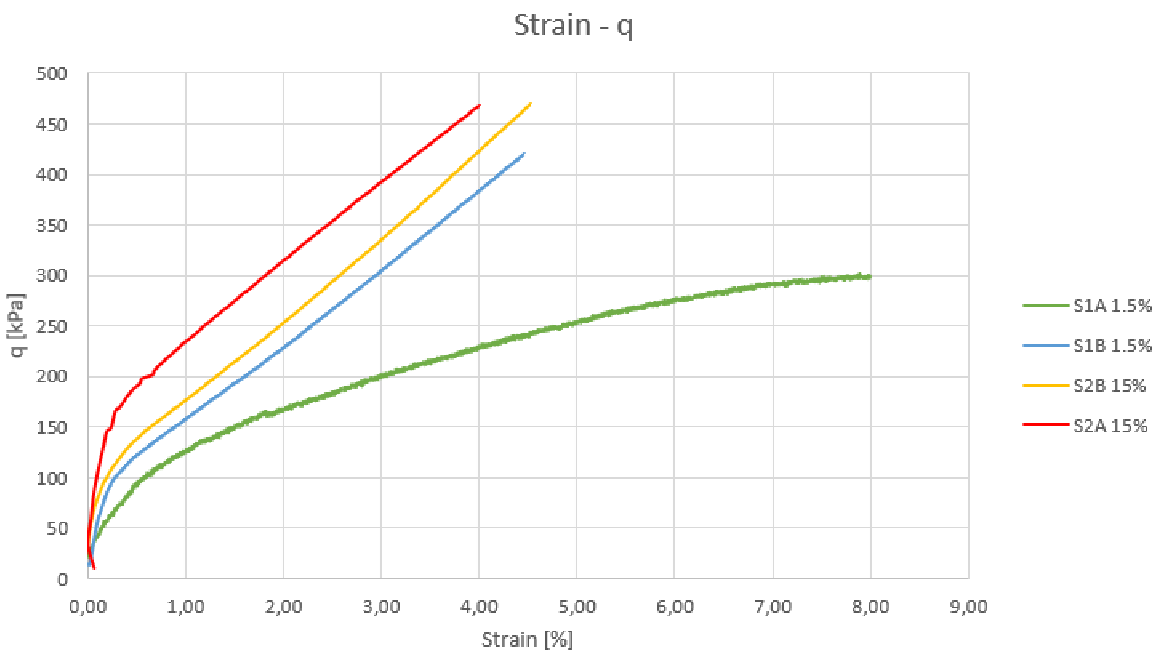

Figure 3.2: Plot showing strain versus the deviatoric stress

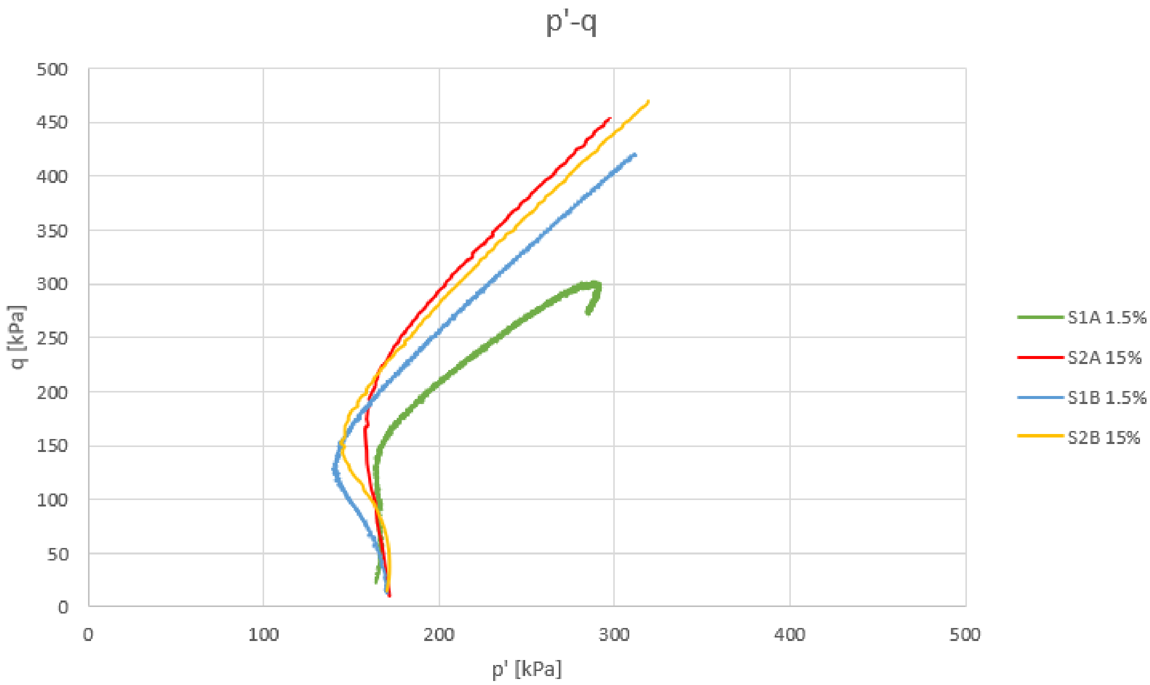

Figure 3.3: Plot showing the effective mean stress versus the deviatoric stress

Method (c) is found using the S-t plot. The point where A=0 is located using Equation 3.3 below:

$$A = \frac{\Delta U}{\Delta \sigma_3} = 0 \tag{3.3}$$

The deviatoric stress is read out at this point and divided by 2. Results from previous tests is found in Table 3.6 below:

Depth [m]	$S_u[kPa]$
5	58
8.4	70
11.5	82
12.5	94
13.6	103
14.5	111

Table 3.6: S_u with depth using method (b) from previous tests

The results performed in this project at 15.25m is listed below:

Sample	Rate [%]	S_u
S1A	1.5	130
S1B	1.5	208
S2A	15	225
S2B	15	210

Table 3.7: S_u using method (b)

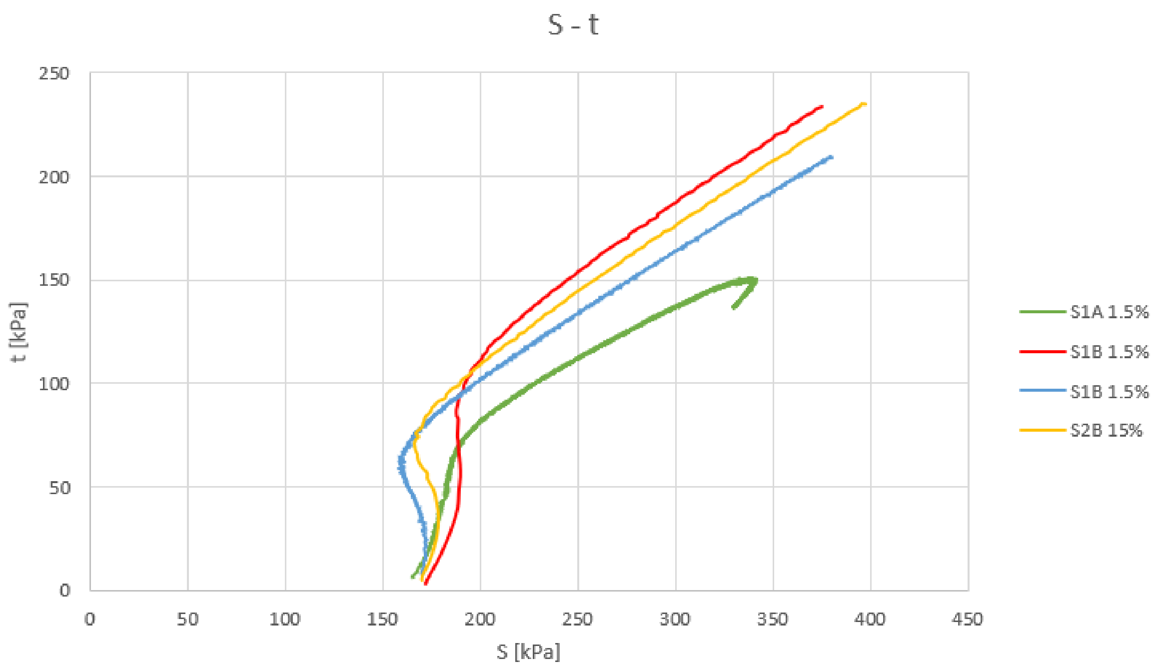

Figure 3.4: Plot showing S, center of the Mohr circle and t, radius of the Mohr circle

3.3 Friction angle

The friction angle is obtained using both S-t and p'-q plots. Equations for the different parameters is collected from Nordal (2019) listed below:

$$p' = \frac{\sigma_1' + 2 * \sigma_3'}{3} \tag{3.4}$$

$$q = \sigma_1 - \sigma_3 \tag{3.5}$$

$$S = \frac{\sigma_1 + \sigma_3}{2} \tag{3.6}$$

$$t = \frac{\sigma_1 - \sigma_3}{2} \tag{3.7}$$

The friction angle is found by estimating the different inclinations of the failure lines for each test. The different plots have different methods of finding these. By using the p'-q plot, the friction angle have to be estimated by finding the inclination M. M is based upon the following equation since $\sigma_2 = \sigma_3$ during constant radial pressure:

$$M = \frac{6 * \sin\rho}{3 - \sin\rho} \tag{3.8}$$

However, since the failure line is known, the M-value will be used to back-calculate the friction angle. By using the following method, the friction angle is estimated:

$$\text{Friction angle } \rho = \tan^{-1}(\frac{y}{x}) \tag{3.9}$$

$$M = \tan\rho \tag{3.10}$$

$$\phi = \sin^{-1}(\frac{3 * M}{6 + M}) \tag{3.11}$$

Where x and y is the change in length and height of the failure line respectively.

The friction angle is also estimated from the S-t plot. The inclination of the failure line is in this case found using the following equation:

$$\phi = \sin^{-1}(\frac{y}{x}) \tag{3.12}$$

Both methods/calculations should yield the same friction angle. When both plots gives the same friction angle, it is assumed that the calculations is performed correctly. The excpected value for Norwegian silts is 32-35 degrees Long et al. (2010). Previous tests at the Halden site has indicated a friction angle of 36 degrees Blaker et al. (2019). The values obtained in this project is found in Table 3.8:

Depth [m]	ϕ [degrees]
5	36
8	39.5
11.5	36
12.5	35.5
13.6	36
14.5	36.5

Table 3.8: ϕ with depth from previous tests

The friction angles found in this project at 15.25m is presented in Table 3.9:

Sample	ϕ (p'-q)	ϕ (S-t)
S1A	27.3	27.3
S1B	33.6	33.6
S2A	37.9	37.9
S2B	36.5	36.5

Table 3.9: S_u using method (b)

Chapter 4

Discussion

4.1 Water content

One can observe a good match by comparing the obtained results with the results described in Figure 7. (b) in Blaker et al. (2019) shown in Table 3.1. Even though the block sample have been stored in a fridge over a longer period of time, the sample has managed to stay in good shape. The obtained values is in the range where one can expect them to be.

4.2 Interpretation of the undrained shear strength

Using method (a): The results indicates that a rate of 1.5% leads to a good match with what is to be expected with this method. By comparing the obtained values with Table 3.2, one can observe a reasonably good match. By investigating Figure 26. (a) in Blaker et al. (2019), an observation of a high increase in the S_u value occurs around 15m. However, by inspecting the values from the samples sheared at 15%, the S_u increases significantly. Further, the values are more scattered. A higher value for sample 2B was expected. This could indicate that one of the samples is somewhat disturbed, or the triaxial apparatus did not work properly. This method is rather conservative, and the values should be used together with an additional method to get a more suited S_u at 15.25m.

Using method (b): The results shown in Table 3.7 indicates a somewhat expected S_u. By using this method, the S_u is interpreted fairly close to the point where the failure occurs. By combining this method with method (a), a reasonably S_u value could be determined. By inspecting Figure 3.4, one can observe a strange behavior for sample 1B. The sample was expected to have a lower value as sample 1A. Something might have gone wrong during the test, or the triaxial apparatus could have made a mistake. However, sample 1A have a very good match with Figure 26. (b) in Blaker et al. (2019). Further, the samples sheared at 15% gives a higher value which is expected. They have a small variation, which could indicate some disturbance in the samples or a mistake made by the triaxial apparatus. The results would be too radical to use in design values.

Using method (c) The results shown in Table 3.5 does not match very well with the expected values. The values for the samples sheared at 1.5% is lower than the typical values. Further, the results have a rather wide spread and is not as reliable as for the other two methods. The values is most likely lower than the expected, because the results from Blaker et al. (2019) are interpreted with 5% strain instead of 4%. Furthermore, the samples sheared at 15% results in a higher S_u again using this method. The results are higher than expected, even though the S_u is interpreted at 4%. Overall, this method should not be used to decide the S_u in this case, as the results varies too much and can not be trusted to some degree.

Overall results observed in the plots: By investigating Figure 3.1, a strange behavior in sample 1B is displayed. The peak value is higher than the values for the samples sheared at 15%, which should not be the case. This might be due to some disturbance in the sample, a measuring error in the equipment or a personal mistake when running the test. This behavior can further be seen in Figure 3.2, where the blue line (1B) is almost as high as the samples sheared at 15%. Further, the Figures 3.3 and 3.4 indicates that sample 1B is resulting in a higher S_u.

4.3 Interpreting the friction angle

The friction angle is found by plotting the failure lines in Figure 3.3 and 3.4. The results from doing this can be seen in 3.9. The friction angle for sample 1A is slightly lower than what is expected. Again the reason for this could be disturbance in the sample or some error with the measurements. Sample 1B shows a better fit with what is to be expected. The two samples sheared at 15% gives a slightly higher friction angle, but is still in the range of Norwegian silts.

Chapter 5

Summary and Recommendations for Further Work

5.1 Summary and Conclusions

The main object of this project was to learn how the triaxial apparatus work, and to investigate the impact loading rates have on silt material. By preparing samples as explained in Chapter 2 and program the equipment, triaxial tests were performed on a silt from Norway. By comparing the obtained results with the results presented in Blaker et al. (2019), an estimation of the undrained shear strength is concluded.

The water content was found to be 19.5 – 22.5% at 15.25m depth. This coincides very well with the previous obtained value. Even though the sample has been stored for over 2 years, the water content has stayed unchanged. The edge of the sample seen in Figure 2.2 shows that the sample had dried to some extent, but the water content measured in various points in the middle of the sample turned out to be unchanged.

Three method's for estimating the undrained shear strength was used. Since method (c) lead to scattered results, the first two methods is used with care. Further, the values obtained by using a loading rate of 15% is estimated to be to high for practical use. The shear strength was determined to be higher by more rapid loading and the results from these tests is estimated to be too radical.

The shear strength should be determined by looking closer at the results from the samples sheared at 1.5%. By doing this, an S_u of ~ 100 kPa seems reasonable at 15.25m depth. This value may be a bit conservative, but determination of shear strength in silts is a delicate matter and should be performed diligently.

5.2 Recommendations for Further Work

For further work more tests should be conducted for a better basis and understanding of the interpreted results. At least one or more additional tests for each chosen rate, as well as three or more tests on an additional rate. The last rate should be 0.15%, or 0.0025 mm/min. This will lead to a better understanding of the impact the loading rate have on the material. There would be interesting to investigate if the S_u get an even lower value than the results in this project, by choosing a loading rate which is significantly lower.

Also, even more training in using a triaxial apparatus would be favorable, to make sure the tests is run correctly. The available time for conducting this project, including laboratory work and writing this report was rather short. The triaxial apparatus is a complex device to learn, and more time should be designated to learn this process properly to eliminate mistakes that could have been made.

Appendix A

Acronyms

CPTU, SCPT, RCPT Cone Penetration Test

SDMT Seismic flat dilatometer

CRS Constant Rate of Strain

CIUC-test Consolidated Isotropic Undrained Compression test

$\mathbf{S}_u$ Undrained shear strength

u Pore pressure

ϕ Friction angle

ε Strain

σ', σ Effective stress, total stress

Appendix B

Obtained plots from tests

B.1 Sample 1A

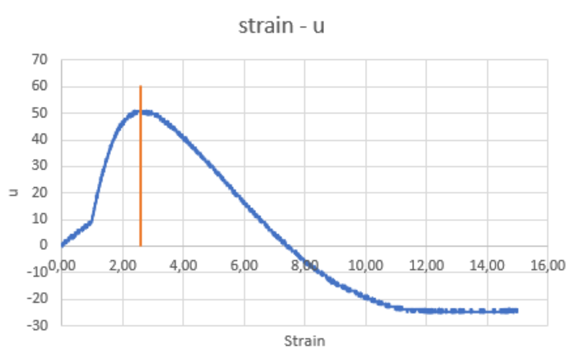

Figure B.1

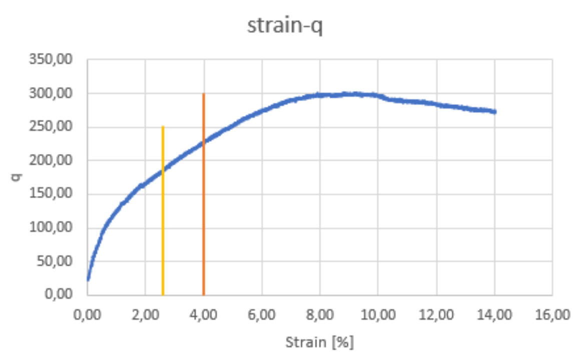

Figure B.2

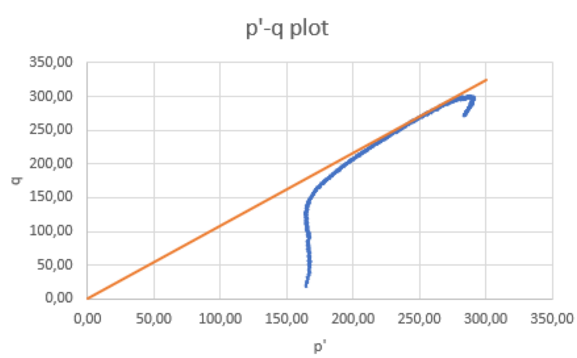

Figure B.3

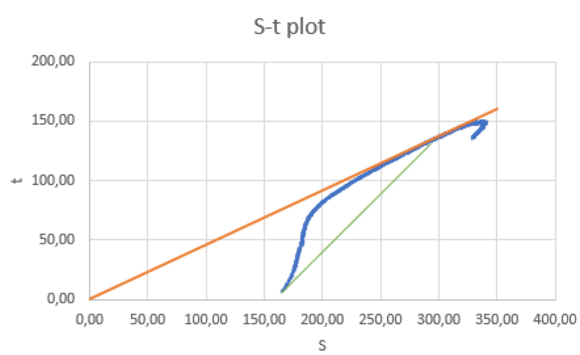

Figure B.4

B.2 Sample 1B

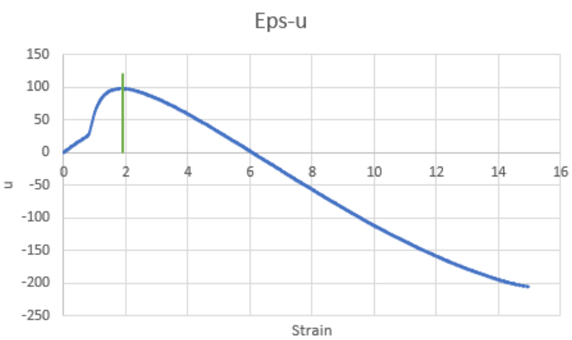

Figure B.5

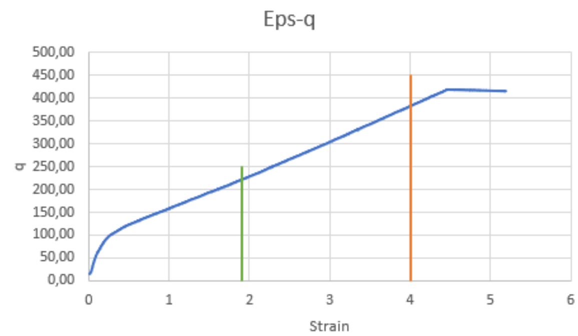

Figure B.6

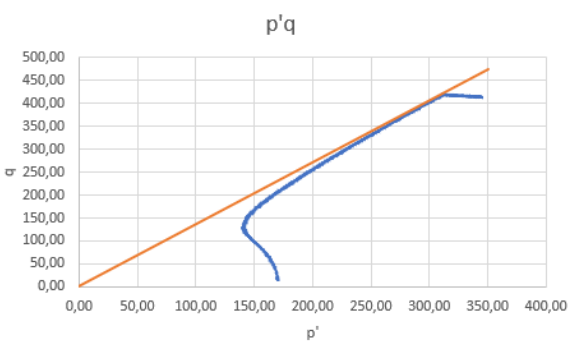

Figure B.7

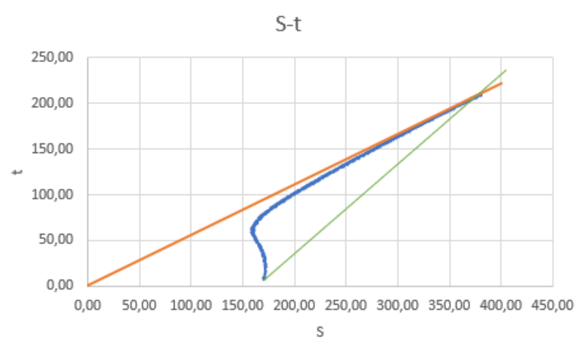

Figure B.8

B.3 Sample 2A

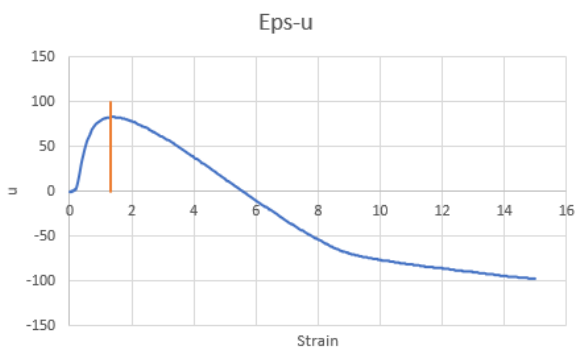

Figure B.9

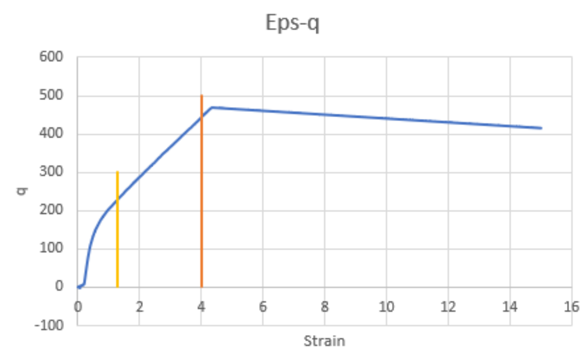

Figure B.10

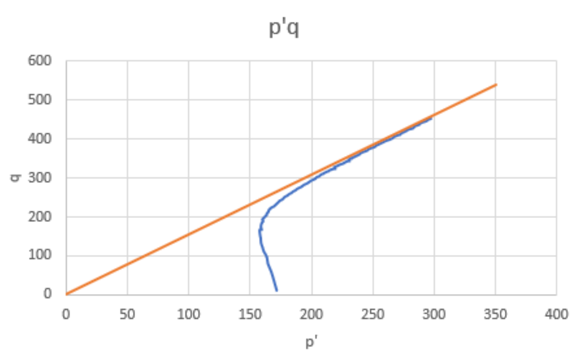

Figure B.11

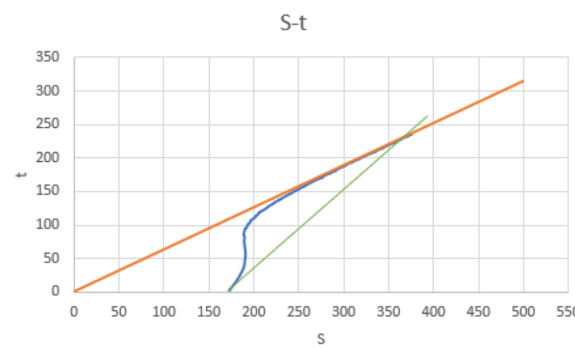

Figure B.12

B.4 Sample 2B

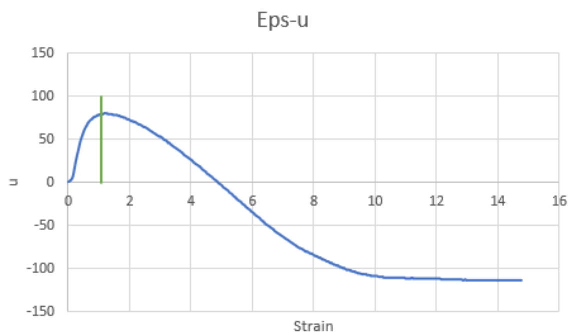

Figure B.13

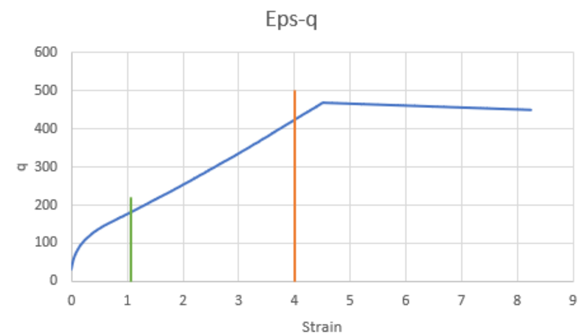

Figure B.14

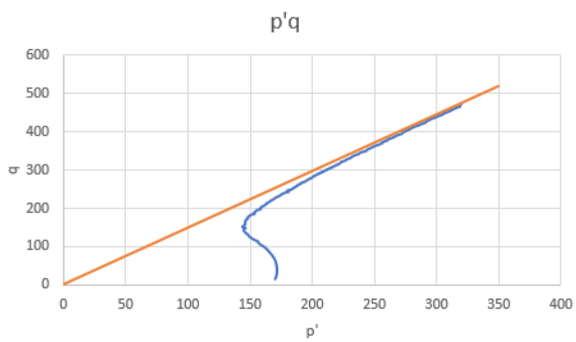

Figure B.15

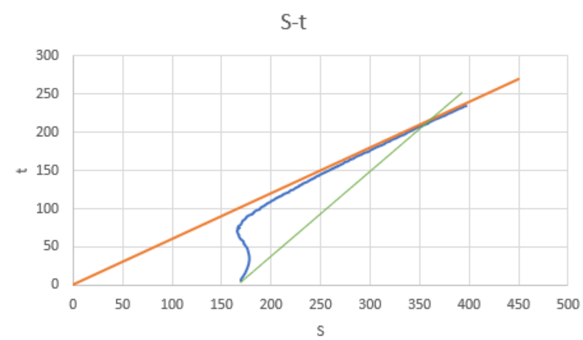

Figure B.16

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