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Thema

The Liquid Limit and The Undrained Shear Strength - Comparison of Different Determination Methods

Declaration of authorship:

“I declare in lieu of an oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred to. The thesis has not been submitted for a degree at any other institution and has not been published yet.”

Leoben, im (Februar, 2018)

(Unterschrift)

(Zahra Motamedi)

Preface, Dedication, Acknowledgement

I would like to thank Prof. Galler for his support during my study. I would also like to thank my supervisor Dr. Gerhard Pittino for his guidance and support in conducting this work. Much of these experiments were conducted at universities of TU-Wien and TU-Graz. I am very grateful to Dr. Stefan Blovsky at the University of TU-Wien for letting me use the laboratory facilities and for his valuable discussion during the work.

I express my warm thanks to Mr. Andreas Hausenberger at the University of TU-Wien and Mrs. Odalys Morales at the University of TU-Graz for their support and helps during my experiments. Without their guidance and valuable help, this thesis would not have been possible.

My sincere appreciation goes to my family. I would like to thank them all, especially my parents for their support. I would also like to thank my brother, Mahdi and my sister Motahareh, for backing me up through my study.

Abstract

This thesis deals with comparative studies for the determination of the liquid limit and the undrained shear strength of various types of soils using different test setups. Two basic methods were used for the evaluation of the liquid limit – the Casagrande percussion method and the fall cone method. Five different types of soil were analyzed for this research. On the other part, the undrained shear strength tests were conducted on four different types of soil specimen using the laboratory vane shear device and fall cone apparatus. These kinds of tests yield values of the undrained shear parameter. Also in the laboratory vane shear test, the influence of the rotation speed and the height of the vane on the undrained shear strength were assessed. Then, further tests were conducted using the penetrometer and torvane alternatively. In order to be able to compare the results of the various shear tests, the soil specimens were produced in the same process with the equal density and water contents. Finally, the correlations with the appropriate test results were made for further interpretation.

Kurzfassung

Die Arbeit befasst sich mit vergleichenden Versuchen zur Bestimmung der Fließgrenze und undrainierte Scherfestigkeit in verschiedenen Böden. Zwei unterschiedliche grundlegende Methoden werden für die Bestimmung der Fließgrenze herangezogen. Die verwendeten Methoden sind die Casagrande Methode und die Fallkegelmethode. Fünf verschiedene Bodentypen wurden für diese Untersuchungen analysiert. Im zweiten Teil werden mittels Laborflügelsonde und Fallkegelversuche vier verschiedene Böden analysiert um die untrainierte Scherfestigkeit zu bestimmen. Aus diesen Untersuchungen resultieren die Parameter für die untrainierte Scherfestigkeit. Die Einflüsse von der Höhe der Sonde und die Rotationsgeschwindidkeit auf die untrainierte Scherfestigkeit wird mit dem Laborflügelversuch ermittelt. Als weitere Methoden wird das Penetrometer und die Taschenflügelsonde verwendet. Um die Vergleichbarkeit der Methoden zu gewährleisten, werden die Bodenproben mit den gleichen Bedingungen, das sind Bodendichte und Wassergehalt, hergestellt. Zur Erklärung der Testergebnisse werden weitere Interpretationen angestellt.

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1 Introduction

In soil mechanics, the strength of the soil is usually described as the shear strength. It takes a central position in the soil properties, because it is decisive for all stability issues such as embankment stability, bearing capacity and earth pressure.

The soil type, geological formation and the rate of loading determine the existence of either a drained or an undrained condition in a soil. When a saturated soil is loaded much quicker than the rate at which the pore water is able to drain out, an undrained condition is developed. Hence, most of the loading is taken by pore water, resulting in an increase in the total stress with increasing the pore water pressure. The undrained shear strength depends on the initial water content of the soil. Actually, it decreases with increasing water content and with increasing liquidity index.

In this study, the undrained shear strength of 4 different soil samples is determined by 4 different methods and the liquid limit is also determined by 2 different methods, which were applied to 5 different soil samples.

In chapter 2 some basic definitions about the soil and two methods for liquid limit determination are explained.

Chapter 3 contains the sieve analysis of the soil samples and in chapter 4 the results of all of the liquid limit experiments are shown.

Chapter 5 deals with theoretical definitions of the shear strength of the soil and some laboratory and field methods for undrained shear strength determination.

Chapter 6 presents the sieve analysis of the shear-strength-tested soil samples.

In chapter 7 all the results of these different methods are gathered. Also, some special tests and some parameters in the laboratory vane shear test are assessed.

All of the gained outcomes are collected in chapter 8 and their conclusions are also discussed.

2 Literature Review and Methodology

2.1 *Introduction*

The basic components of soil are minerals, organic matter, water, and air. Therefore, the soil must be considered as a three-phase system. The solid phase of the soil is known as the soil skeleton, which refers to the relative proportions of particles of various sizes such as sand, silt, and clay [1], [2].
The soil components seem to be clung to each other, but in reality, have spaces in between. These spaces are called pores which are mainly filled with air and water. The water content of the soil is one of the most important soil properties [3]. In general, soils can be placed into two groups namely cohesionless and cohesive groups. The fine cohesive soil can be classified regarding the water content of the pores.
One of the functions of soil mechanics is to find the amount of these three phases to quantify them and to explain their effects with regards to the constructional aspects.

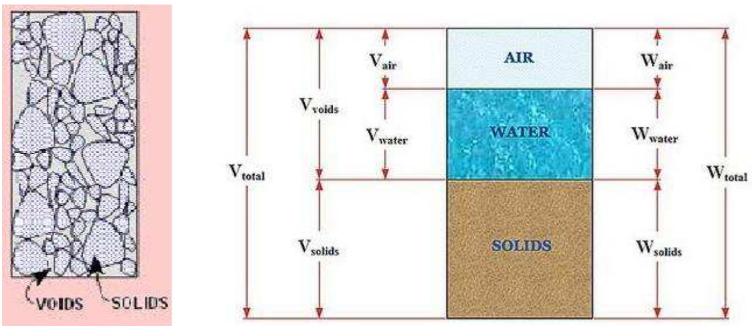


Figure 2-1: Soil as a three-phase system [3], [4], [5]

2.2 *Plasticity and Structure of Soil*

The behavior of the fine cohesive soils depends on many factors, like structure and water content.[4]. With the different water contents, the cohesive soil can appear in various physical states or different consistencies [4]. The different consistencies of the cohesive soil are defined by their water content at critical stages (solid, plastic, liquid) with Atterberg's limits [4]. Attenberg, in his studies, showed that with reducing the water content of the cohesive soil, the physical state of a soil-water mixture changes from a liquid state to a plastic state and finally into a solid state [5]. The liquid limit and the plastic limit are the most important Atterberg's limit to classify the cohesive soils and their behavior.

2.2.1 **Liquid limit**

The liquid limit corresponds to the water content, expressed as a percentage of the mass of oven-dried soil, in which the soil's behavior changes as a liquid or begins to flow [2]. The principle is to find the moisture content with which a soil sample starts to liquefy under a small applied stress. It is determined by means of the standard liquid limit apparatus [6]. The liquid limit is measured via two standard methods which are *Casagrande percussion* and *cone penetration*.

2.2.1.1 Casagrande percussion method, test procedure and analysis

Figure 2-2: Casagrande liquid limit apparatus

At the beginning, the test sample with the maximum grain size of 0.4 mm was mixed with distilled water to obtain a homogenous paste. A portion of the mixed soil was placed in the cup of the apparatus without entrapping air. Subsequently, the soil was divided into two equal parts by drawing the grooving tool from the hinge towards the front in a continuous circular movement. The grooving tool should be moved normal to the surface of the cup [7] ÖNORM B 4411: 2009.
Immediately after finishing the groove the test begins to implement. The cup was lifted and dropped at the rate of two revelations per second until two parts of the soil come into contact with each other for a length of about 13 mm. The number of blows was recorded at which this occurs. Finally, about 10 - 15 g of soil from the cup was taken, weighed and dried to determine its moisture content. The test was repeated with different moisture contents at least four times for blows between 10 and 40 [7].
A semi-logarithmic chart of moisture content as ordinates on the linear scale and the number of blows as abscissae on the logarithmic scale is plotted. The best straight line is drawn between the plotted points. The moisture content corresponding to the abscissa of 25 blows is the liquid limit of that soil.

2.2.1.2 Cone penetration method, test procedure and analysis

The fall cone test is a widely used testing method in which a cone is penetrated into a soil sample by its weight [8]. The Penetration is measured and the moisture content of specimen is determined. Finally, the test is analyzed.

Figure 2-3: Fall cone liquid limit apparatus

The soil sample with maximum grain size of 0.4 mm was mixed with distilled water until the first cone penetration reading is as indicated value in Table 2-1 ÖNORM B 4411: 2009.

Cone penetration requirements	**80 g/ 30°**	**60 g/ 60°**
Initial penetration	About 15 mm	About 7 mm
Penetration rate	15 to 25 mm	7 to 15 mm
Maximum difference between two successive tests	0.5 mm	0.4 mm
W_L determined from penetration of:	20 mm	10 mm

Table 2-1: Cone penetration *requirements*

At first, a clean and dry cup are filled with the help of a palette knife without air entrapping and the surface of the sample shall be stuck off with the help of a spatula. Afterward, the supporting assembly is lowered so that the tip of the cone just touches the surface of the soil and then will be fixed. The cone is in a correct position if a slight movement of the cup just marks the soil surface. ÖNORM B 4411: 2009

Then the cone is released for a period of 5 ± 1 s and the difference between the start and the end positions with the accuracy of 0.1 mm is measured. In this investigation, the cone penetration after 5 s for 6 s, 11 s and 71 s was also observed. It should be noted that during the test procedure any minor vibration must be avoided. The cone is lifted out and cleaned. Finally, about 10 g soil sample from the area, penetrated by the cone, is taken and its moisture content is determined. The test should be repeated at least four times with using the same sample of soil however with different moisture contents [7].

For evaluation, a semi-logarithmic chart of moisture content as ordinate on the linear scale and the cone penetration as abscissae on the logarithmic scale should be plotted and the best-fitted line drawn between the plotted points. The liquid limit corresponds to the moisture content to a cone penetration of 20 mm for 80 g/ 30° cone of 10 mm for 60 g/60° cone.

2.2.2 **Plastic limit**

The plastic limit is known as a transition from the plastic (cohesive) state to semi-solid or semi-rigid state, w_p.[2] The plastic limit is determined by rolling a moisture ball into threads of about 3 mm. The remolding and rolling are repeated until the soil sample starts to crumble into pieces of 10 mm to 12 mm. The measured water content at this point gives the plastic limit [9].

Figure 2-4: Plastic limit test

2.2.3 **Shrinkage limit**

The shrinkage limit is defined as a percentage of moisture content, at which the soil reduces its volume due to capillary forces; and a further reduction in the moisture will not cause any further decrease in the volume of the soil mass [2]. Therefore, loss of water or evaporation of water causes shrinkage in a soil up to a certain level. It should be noted that an increase in the water content will cause an increase in the volume of the soil mass. Actually, the shrinkage limit can be known as passing from the semi-solid to solid state. At this stage, the soil has reached its shrinkage limit beyond which a decrease in the volume does not occur.

2.2.4 **Plasticity-, liquidity- and consistency index**

Plasticity index is defined as a numerical difference between the liquid limit, i.e. W_L, and the plastic limit, i.e. W_p, of soil. The relation is given as [10]:

Equation 2-1: $I_p = W_L - W_p$

The plasticity index indicates the range of the moisture content within which the soil remains in plastic state and exhibits plastic properties.

Plasticity index	Soil description
0	None-plastic
$I_p < 7$	Low plastic
$7 < I_p < 17$	Medium plastic
$I_p > 17$	Highly plastic

Table 2-2: Soil classification related to the plasticity index [10]

Liquidity index of a soil, i.e. I_L, can be defined as a ratio of the difference between the in-situ moisture content of the soil and its plastic limit to its plasticity index. It shows the relative consistency of a cohesive soil in the natural state [11].

Equation 2-2: $L_I = \frac{w - W_p}{W_L - W_p}$

Another index which is widely used is the consistency index and is defined as a ratio of the difference between the liquid limit and the in-situ moisture content of a soil to its plasticity index [10].

Equation 2-3: $Ic = \frac{W_L - w}{W_L - W_p}$

3 Soil samples to Evaluate the Liquid Limit

3.1 *Overview*

In this part, 5 different soil samples were provided. Each of these samples was studied using both the Casagrande percussion method and the fall cone test to determine their liquid limit. All of the samples were sieved to the 0.4 mm maximum grain size (see Table 3-1). However, one of the samples was not sieved to 0.4 mm. Thus, the sample contained a higher degree of sand in comparison to other four samples. The main reason for this is to observe the penetration rate after 5 s at different intervals. The mentioned sample name is sa $\overline{cl}$ $\overline{Si}$. The soil characteristic values were determined in accordance to the corresponding ÖNORM.

	Clay %	**Silt %**	**Sand %**
Label	**< 0.002 mm**	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**
cl ’sa $\overline{Si}$	9.8	73.2	17
sa ’$\overline{cl}$ $\overline{Si}$	43.0	46.5	10.5
cl ’sa $\overline{Si}$	8.5	68.8	22.7
sa ’cl ’ $\overline{Si}$	14.6	75.6	9.8
sa $\overline{cl}$ $\overline{Si}$	34.2	36	29.8

Table 3-1: Results of the sieve analyses for evaluation of the liquid limit.

3.2 ***Sample 1*** $(cl'\ sa\ \overline{Si})$

This sample has a low relation of clay/silt and can be characterized as follows:

Clay %	Silt %	Sand %	relation
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
9.8	73.2	17	0.13

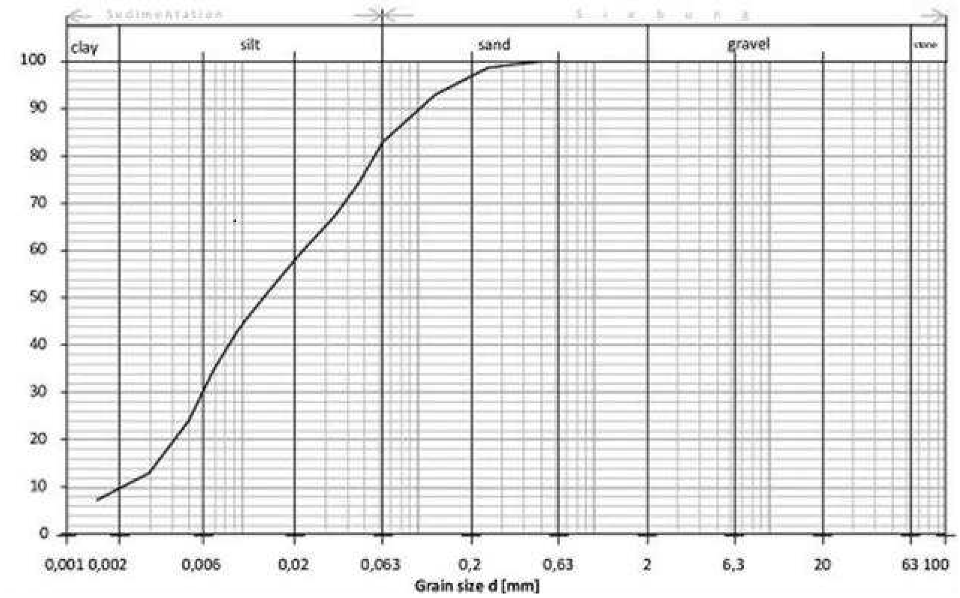


Figure 3-1: Sieve analysis of sample 1

3.3 *Sample 2* ($sa' \, c\bar{l} \, S\bar{i}$)

This sample contained the highest value of clay and can be characterized as follows:

Clay %	Silt %	Sand %	relation
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
43.0	46.5	10.5	0.92

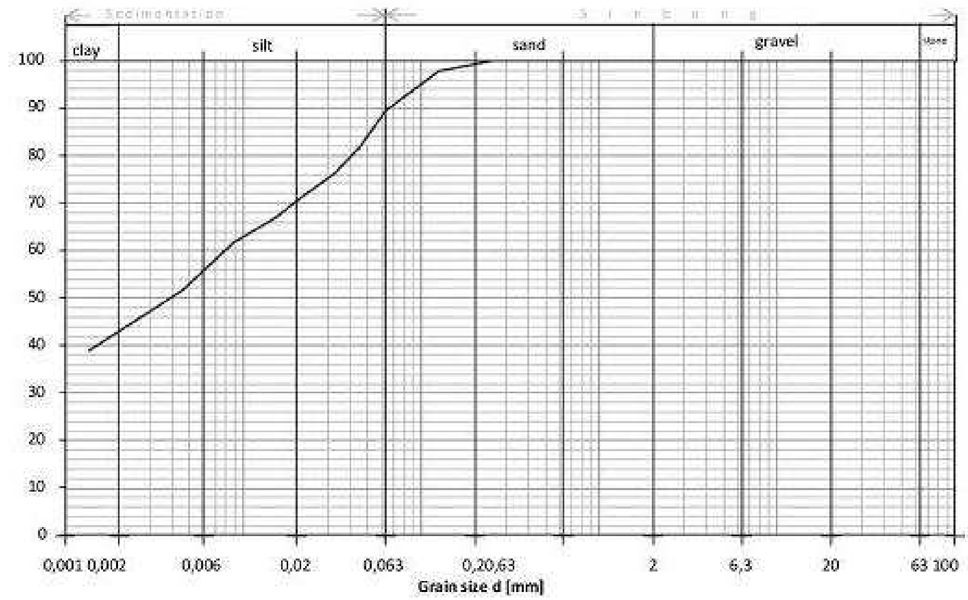


Figure 3-2: Sieve analysis of sample 2

3.4 *Sample 3* ($cl'\ sa\ \bar{Si}$)

This sample has the lowest value of the clay/silt relation and contained the lowest value of clay. It can be characterized as follows:

Clay %	Silt %	Sand %	relation
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
8.5	68.8	22.7	0.12

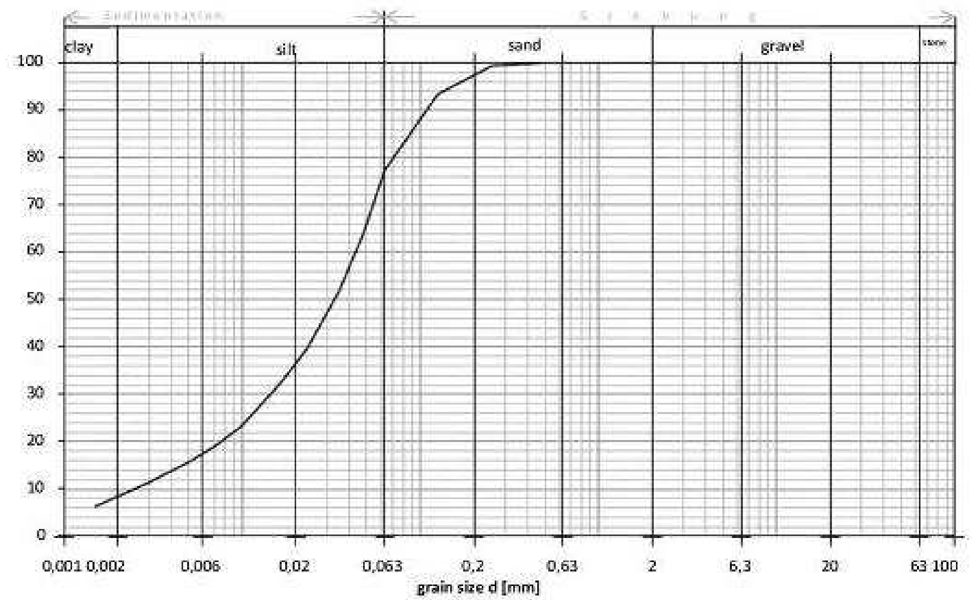


Figure 3-3: Sieve analysis of sample 3

3.5 ***Sample 4*** **(**$sa'\ cl'\ \overline{Si}$**)**

This sample contained the highest value of silt and can be characterized as follows:

Clay %	**Silt %**	**Sand %**	**relation**
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
14.6	75.6	9.8	0.19

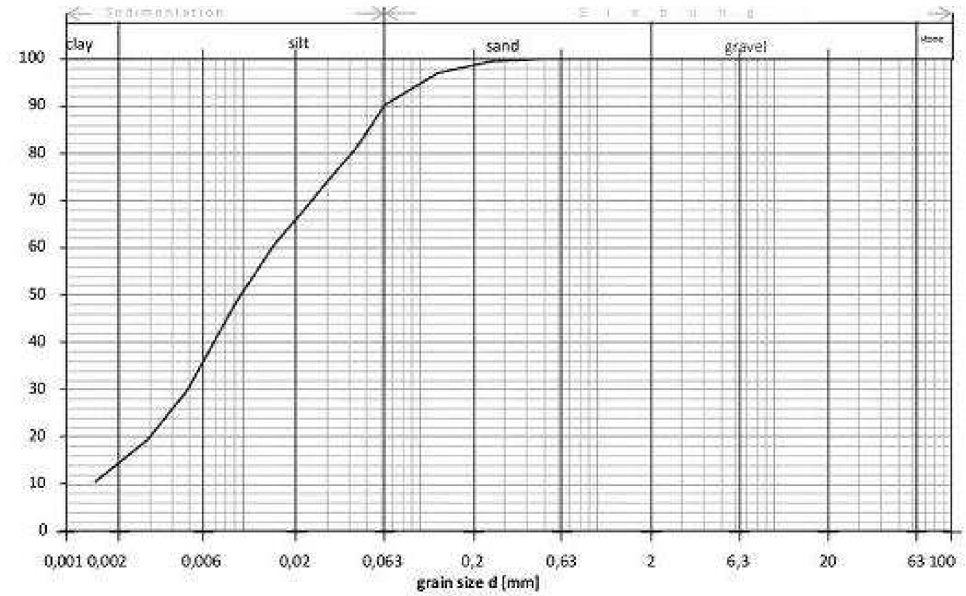


Figure 3-4: Sieve analysis of sample 4

3.6 *Sample 5* ($sa\,\bar{c}l\,S\bar{i}$)

This sample, as can be seen from the table below, contained the highest value of sand and the highest value of the clay/silt relation.

Clay %	**Silt %**	**Sand %**	**relation**
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
34.2	36	29.8	0.95

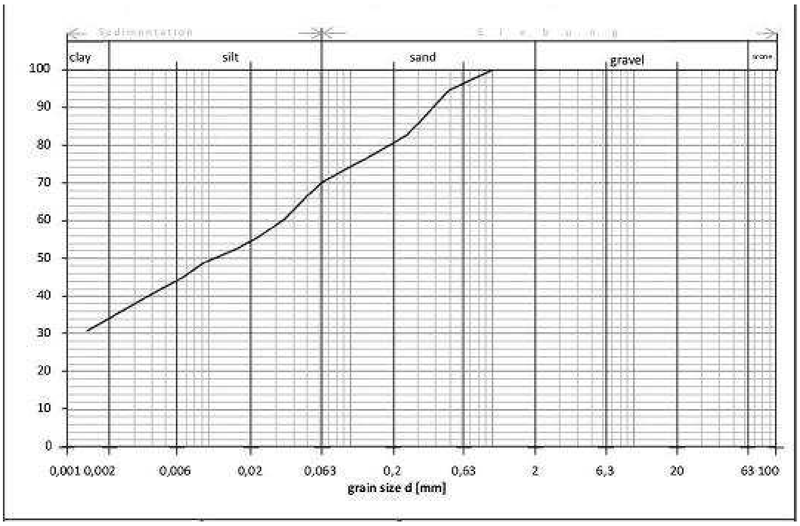


Figure 3-5: Sieve analysis of sample 5

4 Results of the liquid limit evaluation

In this chapter, the results of the samples mentioned in previous chapter were demonstrated in two different parts. The first part includes the results of the liquid limit determination by Casagrande method. At the beginning of each sample, section is a table, which presents the results of every test with different moisture contents and a different number of drops. According to the respective standards, the liquid limit in the Casagrande percussion method is calculated from a semi-logarithmic chart between the moisture content and the number of bowls, which was provided in every first part of the sample results. The liquid limit in this method corresponds to the moisture content of 25 blows, that was calculated in the third table of part one.

Then the second section contains two parts. The first one indicates the results of the liquid limit determination by the fall cone test and the second one shows the observation of the cone penetration after the 5^{th} s, at 6^{th} s, 11^{th} s and 71^{st} s in each sample. This means the cone was released after 5^{th} s for 1 second, 5 seconds and 60 seconds. Here, the penetration of the cone in these intervals was observed. The first table of this part includes the results of every sample with different moisture content and consequently with a different penetration depth of the cone. In light of used cone with an apex angle of 60°, the liquid limit must be calculated from the semi-logarithmic chart between the moisture content and the cone penetration for 10 mm of penetration depth. The other part of this section presents the results of cone penetration observation in one table and two charts. The first chart covers the numbers of every test. In the second chart, as can be seen, the slope of every penetration line of each test is close to zero.

4.1 *Sample 1* $(cl' \, sa \, \overline{Si})$

4.1.1 Casagrande percussion method

Sample No.		**1**	**2**	**3**	**4**	**5**
No. of drops		15	21	22	25	35
Mass of can + moist soil	**g**	10.25	9.18	10.27	10.49	10.22
Mass of can + dry soil	**g**	8.09	7.45	8.31	8.53	8.35
Mass of empty, clean can	**g**	1.08	1.09	1.07	1.08	1.08
Mass of moist soil	**g**	9.17	8.09	9.2	9.41	9.14
Mass of dry soil	**g**	7.01	6.36	7.24	7.45	7.27
Mass of pore water	**g**	2.16	1.73	1.96	1.96	1.87
Water content	**%**	30.81	27.20	27.07	26.31	25.72

Table 4-1: Results of liquid limit determination by Casagrande for sample 1

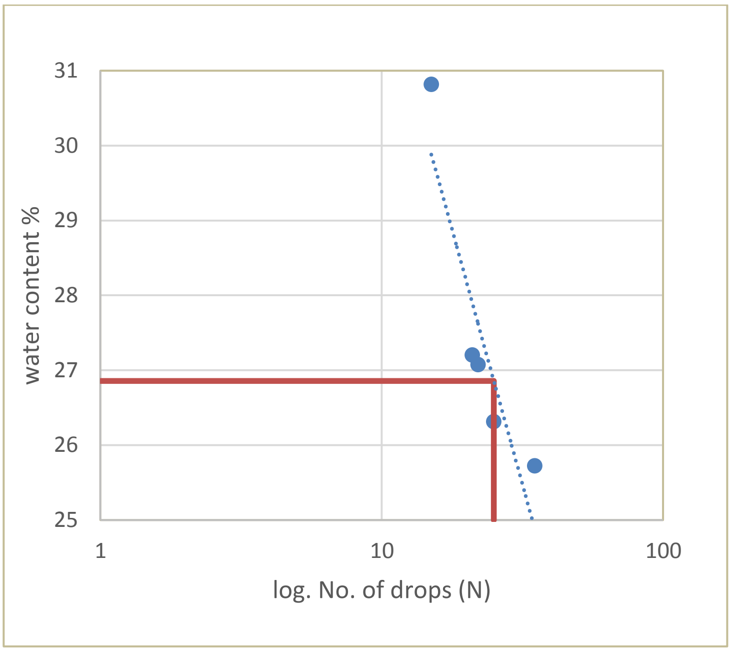


Figure 4-1: Liquid limit determination by Casagrande for sample 1, the red line illustrates 25 blows as the liquid limit of the soil

No. of drops (N)	25
Liquid limit w_L	26.86

4.1.2 Fall cone test

Sample No		1	2	3	4
Mass of can + moist soil	g	19.21	19.58	20.04	19.8
Mass of can +dry soil	g	15.26	15.3	15.4	15.03
Mass of empty, clean. Can	g	2.34	2.33	2.35	2.32
Mass of moist soil	g	16.87	17.25	17.69	17.48
Mass of dry soil	g	12.92	12.97	13.05	12.71
Mass of pore water	g	3.95	4.28	4.64	4.77
Penetration depth in 5 s	mm	8.32	10.81	14.28	16.48
Water content	%	30.57	33	35.56	37.53

Table 4-2: Results of liquid limit determination by fall cone test for sample 1

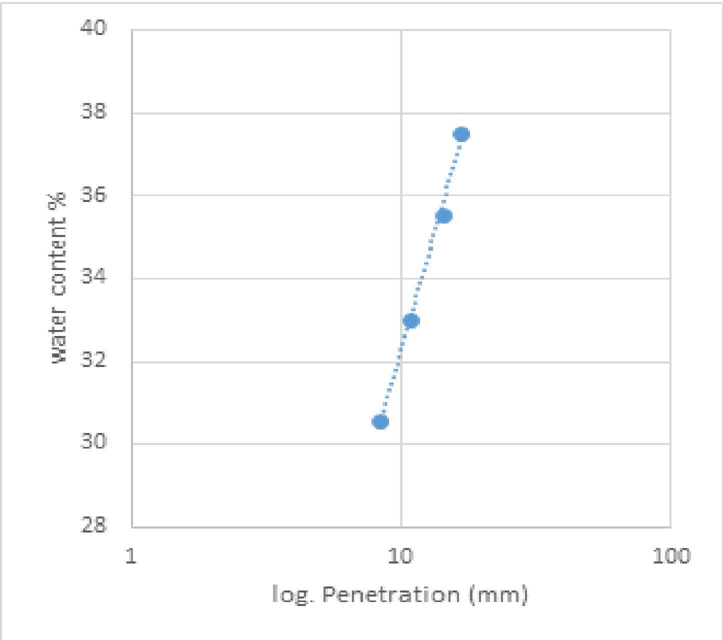


Figure 4-2: Liquid limit determination by fall cone test for sample 1

Penetration depth (mm)	10
Liquid limit W_L	32.30

Observation of cone penetration after 5 seconds:

		1st test	2nd test	3rd test	4th test
Penetration depth in 5 s	**mm**	8.32	10.81	14.28	16.48
Penetration depth in 6 s	**mm**	8.32	10.81	14.35	16.51
Penetration depth in 11 s	**mm**	8.57	10.81	14.35	16.51
Penetration depth in 71 s	**mm**	8.79	11.08	14.45	16.56

Table 4-3: Results of cone penetration observation after 5 s for sample 1

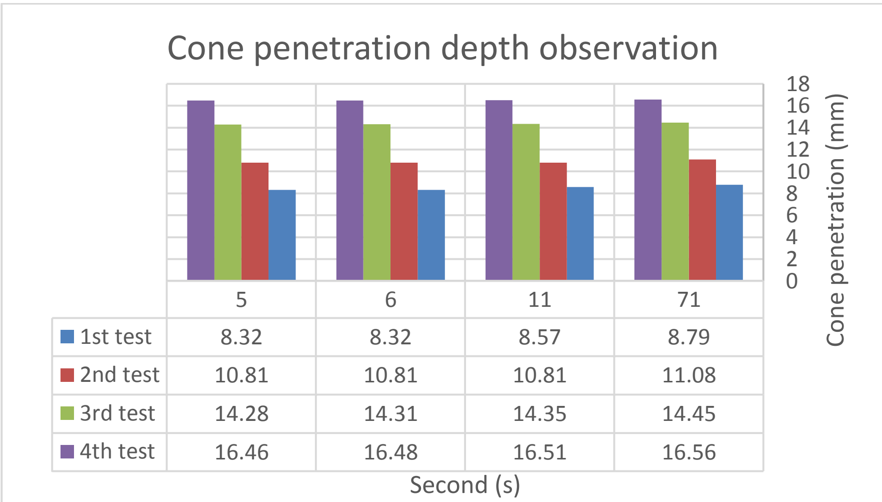


Figure 4-3: Column chart of cone penetration after 5 s for sample 1

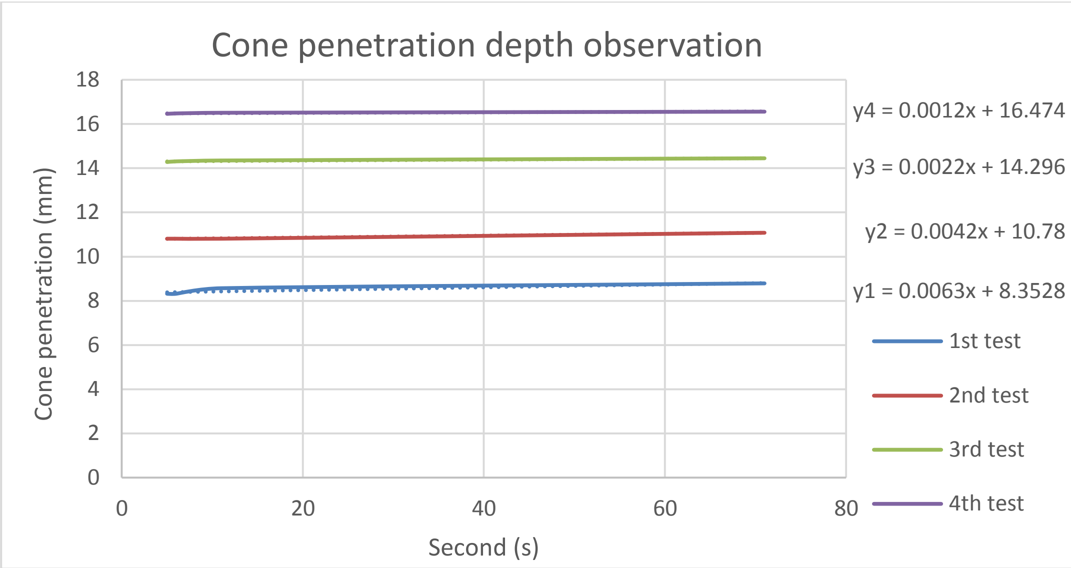


Figure 4-4: Chart of cone penetration observation after 5 s for sample 1

4.2 ***Sample 2 ($sa'\overline{c}l\ S\overline{i}$)***

1.1.1 Casagrande percussion method

Sample No.		**1**	**2**	**3**	**4**	**5**
No. of drops		38	28	22	21	16
Mass of can + moist soil	**g**	7.82	7..30	8.84	9.72	8.92
Mass of can + dry soil	**g**	6.24	5.69	6.86	7.45	6.77
Mass of empty, clean can	**g**	1.09	1.08	1.07	1.07	1.08
Mass of moist soil	**g**	6.73	6.22	7.77	8.65	7.84
Mass of dry soil	**g**	5.15	4.61	5.79	6.38	5.69
Mass of pore water	**g**	1.58	1.61	1.98	2.27	2.15
Water content	**%**	30.77	34.92	34.20	35.58	37.78

Table 4-4: Results of liquid limit determination by Casagrande for sample 2

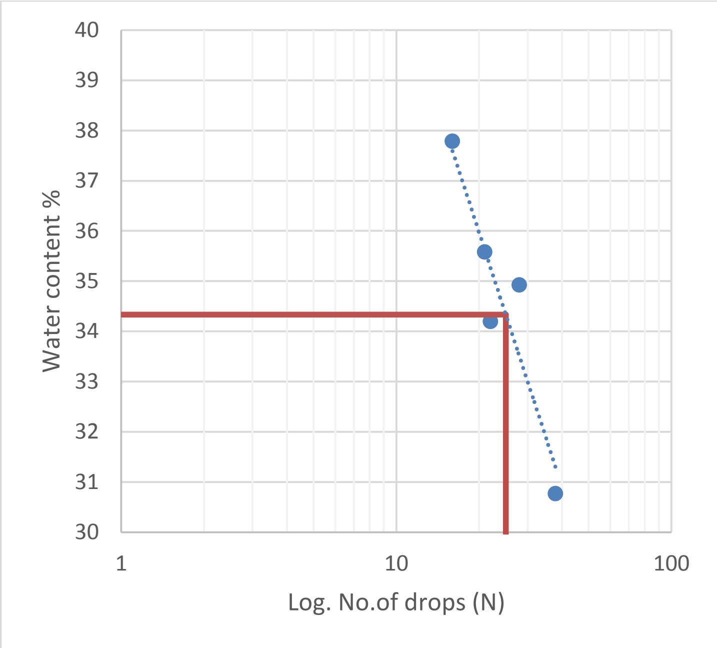


Figure 4-5: Liquid limit determination by Casagrande for sample 2, the red line illustrates 25 blows as the liquid limit of the soil

No. of drops (N)	25
Liquid limit W_L	34.33

4.2.1 Fall cone test

Sample No.		**1**	**2**	**3**	**4**
No. of drops		20.86	20.68	21.68	22.60
Mass of can + moist soil	**g**	16.53	16.09	16.39	16.48
Mass of can + dry soil	**g**	2.32	2.34	2.33	2.33
Mass of empty, clean can	**g**	18.54	18.34	19.35	20..27
Mass of moist soil	**g**	14.21	13.75	14.06	14.15
Mass of dry soil	**g**	4.33	4.59	5.29	6.12
Mass of pore water	**g**	6.41	7.98	9.83	12.83
Water content	**%**	30.47	33.38	37.62	43.25

Table 4-5: Results of liquid limit determination by fall cone test for sample 2

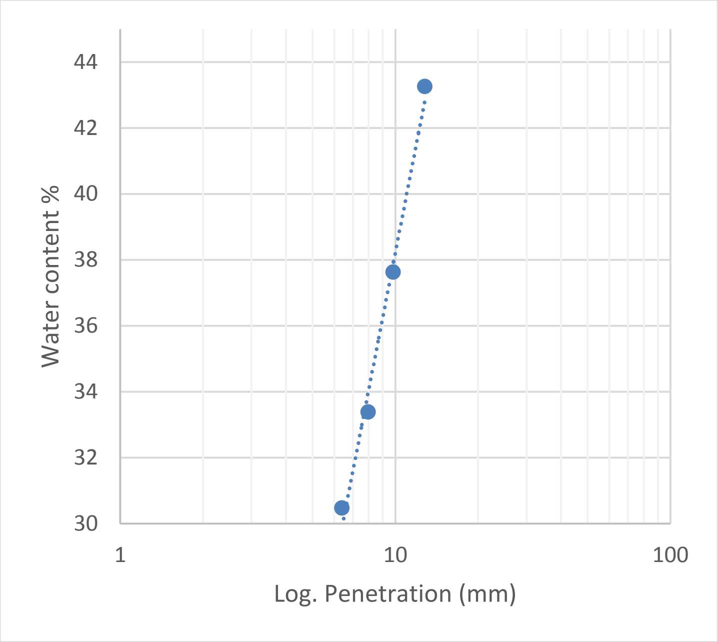


Figure 4-6: Liquid limit determination by fall cone test for sample 2

Penetration depth (mm)	10
Liquid limit W_L	38.23

Observation of cone penetration after 5 s:

		1st test	2nd test	3rd test	4th test
Penetration depth in 5 s	**mm**	6.41	7.98	9.83	12.83
Penetration depth in 6 s	**mm**	6.41	7.98	9.83	12.83
Penetration depth in 11 s	**mm**	6.42	8	9.87	12.86
Penetration depth in 71 s	**mm**	6.46	8.01	9.91	12.89

Table 4-6: Results of cone penetration observation after 5 s for sample 2

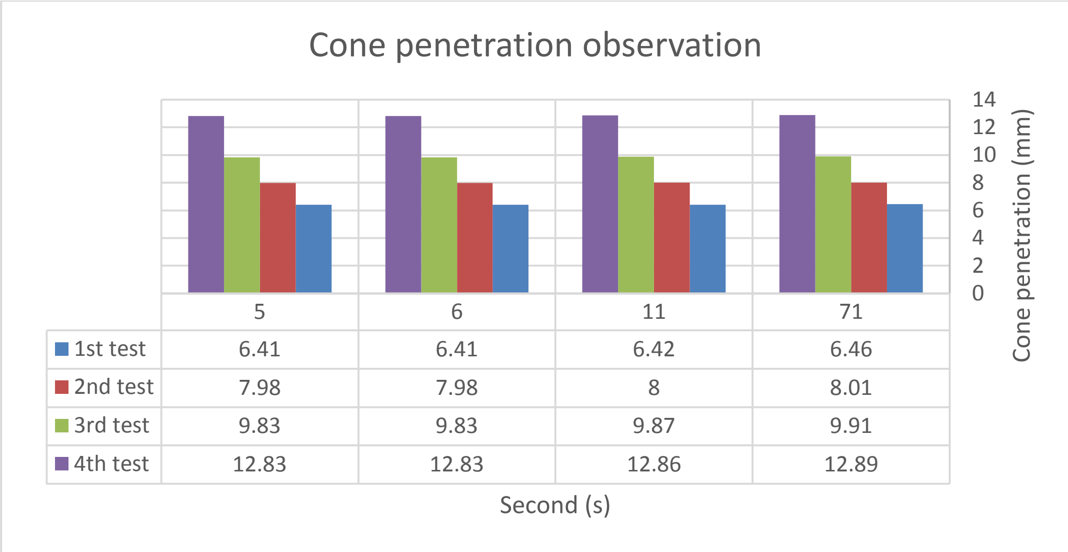


Figure 4-7: Column chart of cone penetration after 5s for sample 2

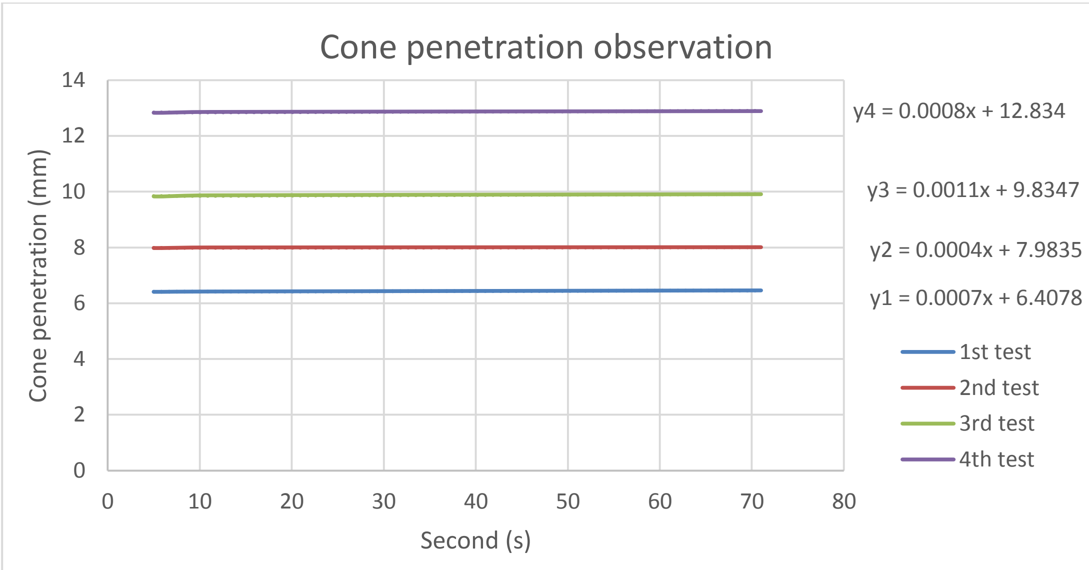


Figure 4-8: Chart of cone penetration observation after 5 s for sample 2

4.3 ***Sample 3 ($cl'sa\ S\bar{i}$)***

4.3.1 **Casagrande percussion method**

Sample No.		**1**	**2**	**3**	**4**	**5**
No. of drops		15	21	22	25	35
Mass of can + moist soil	**g**	10.25	9.18	10.27	10.49	10.22

Mass of can + dry soil	**g**	8.09	7.45	8.31	8.53	8.35
Mass of empty, clean can	**g**	1.08	1.09	1.07	1.08	1.08
Mass of moist soil	**g**	9.17	8.09	9.2	9.41	9.14
Mass of dry soil	**g**	7.01	6.36	7.24	7.45	7.27
Mass of pore water	**g**	2.16	1.73	1.96	1.96	1.87
Water content	**%**	30.81	27.20	27.07	26.31	25.72

Table 4-7: Results of liquid limit determination by Casagrande for sample 3

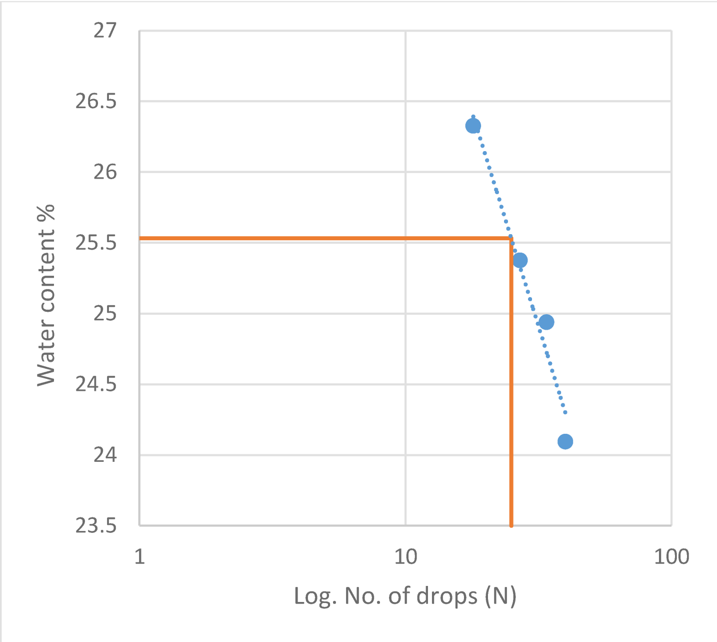


Figure 4-9: Liquid limit determination by Casagrande for sample 3, the red line illustrates 25 blows as the liquid limit of the soil

No. of drops (N)	25
Liquid limit W_L	25.53

4.3.2 **Fall cone test**

Sample No.		**1**	**2**	**3**	**4**	**5**
Mass of can + moist soil	**g**	19.20	20.67	19.96	19.71	21.52

Mass of can +dry soil	**g**	15.74	16.95	16.11	15.85	17.15
Mass of empty, clean can	**g**	2.34	2.33	2.33	2.32	2.33
Mass of moist soil	**g**	16.86	18.34	17.63	17.39	19.19
Mass of dry soil	**g**	13.40	14.62	13.78	13.53	14.82
Mass of pore water	**g**	3.46	3.72	3.85	3.86	4.37
Penetration depth in 5 s	**mm**	8.15	8.72	11.52	12.55	13.43
Water content	**%**	25.82	25.44	27.94	28.53	29.49

Table 4-8: Results of liquid limit determination by fall cone test for sample 3

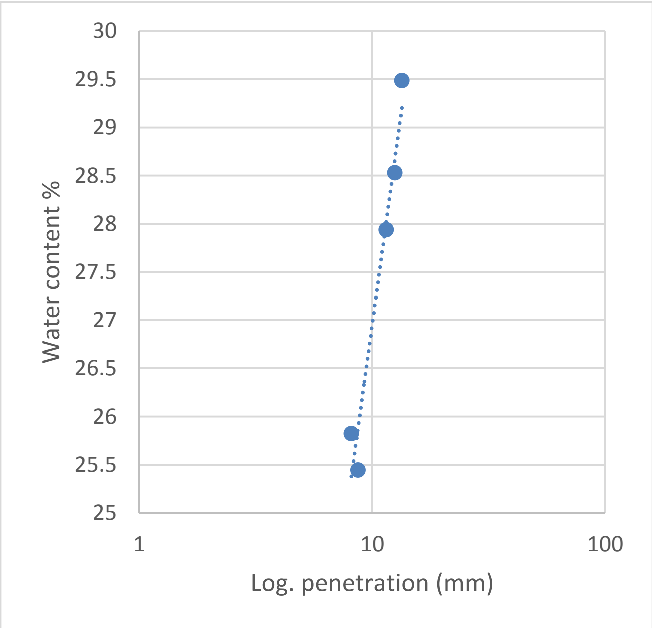


Figure 4-10: Liquid limit determination by fall cone test for sample 3

Penetration depth (mm)	10
Liquid limit W_L	26.95

Observation of cone penetration after 5 s:

		1st test	2nd test	3rd test	4th test	5th test
Penetration depth in 5 s	**mm**	8.15	8.72	11.52	12.55	13.43
Penetration depth in 6 s	**mm**	8.29	8.75	11.57	12.61	13.47
Penetration depth in11s	**mm**	8.47	8.81	11.63	12.66	13.53
Penetration depth in71s	**mm**	8.62	8.89	11.7	12.73	13.6

Table 4-9: Results of cone penetration observation after 5 s for sample 3

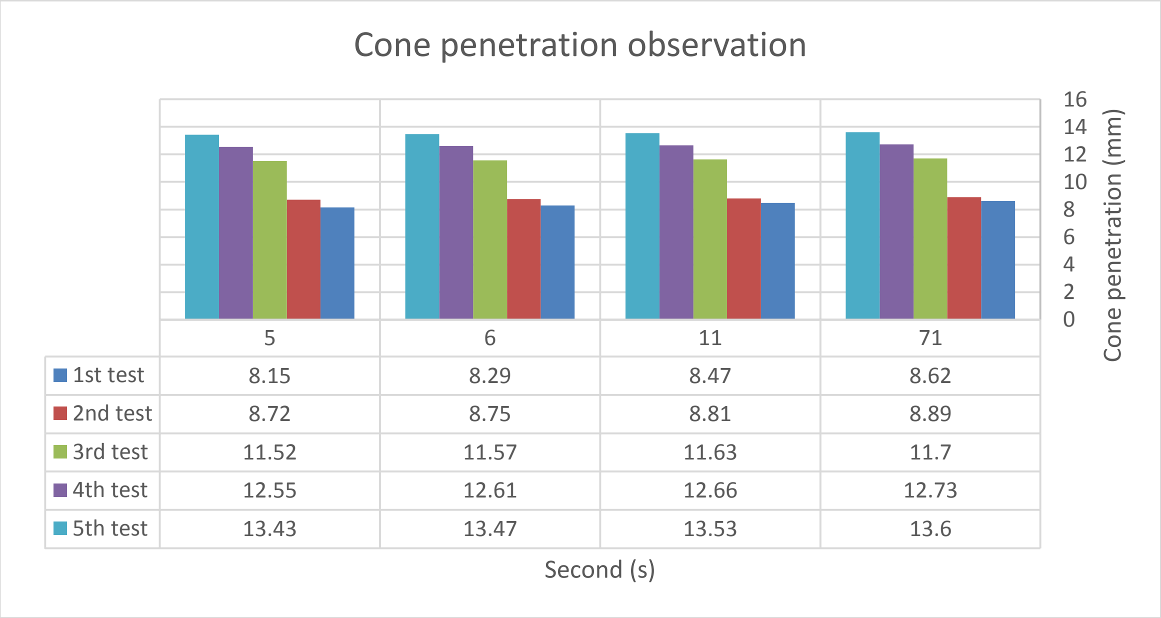


Figure 4-11: Column chart of cone penetration after 5 s for sample 3

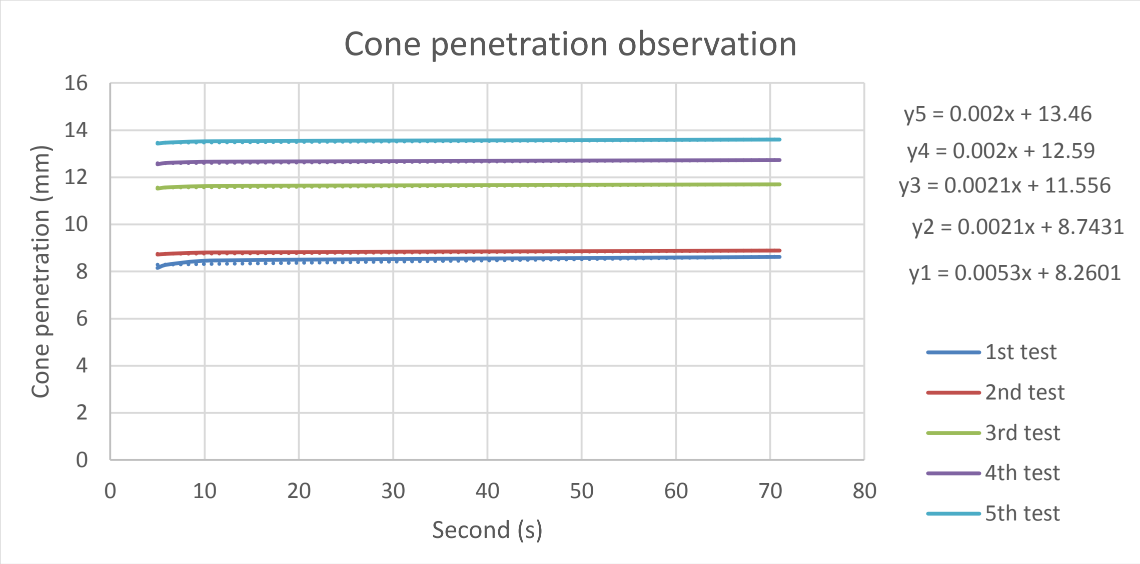


Figure 4-12: Chart of cone penetration observation after 5 s for sample 3

4.4 ***Sample 4 ($sa'cl'\overline{Si}$)***

4.4.1 **Casagrande percussion method**

Sample No.		**1**	**2**	**3**	**4**
No. of drops		17	18	24	32
Mass of can + moist soil	**g**	9.88	9.42	10.21	9.71
Mass of can + dry soil	**g**	7.82	7.48	8.12	7.77
Mass of empty, clean can	**g**	1.07	1.08	1.08	1.07
Mass of moist soil	**g**	8.81	8.34	9.13	8.64
Mass of dry soil	**g**	6.75	6.40	7.04	6.70
Mass of pore water	**g**	2.06	1.94	2.09	1.94
Water content	**%**	30.52	30.31	29.65	28.96

Table 4-10: Results of liquid limit determination by Casagrande for sample 4

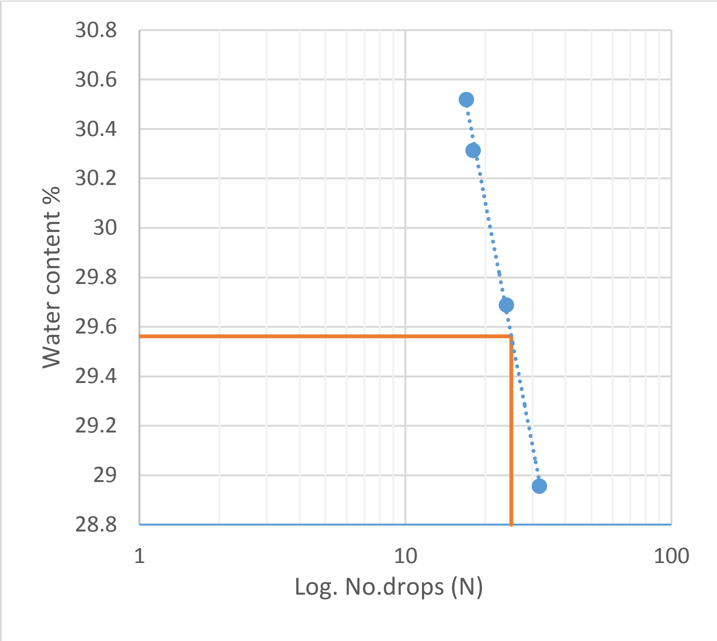


Figure 4-13: Liquid limit determination by Casagrande for sample 4, the red line illustrates 25 blows as the liquid limit of the soil

No. of drops (N)	25
Liquid limit W_L	29.56

4.4.2 **Fall cone test**

Sample No.		**1**	**2**	**3**	**4**
Mass of can + moist soil	**g**	17.74	20.02	18.87	20.61
Mass of can +dry soil	**g**	14.04	15.56	14.41	15.61
Mass of empty, clean can	**g**	2.35	2.34	2.33	2.33
Mass of moist soil	**g**	15.39	17.68	16.54	18.28
Mass of dry soil	**g**	11.69	13.22	12.08	13.28
Mass of pore water	**g**	3.70	4.46	4.46	5.0
Penetration depth in 5 s	**mm**	6.74	8.96	10.75	13.46
Water content	**%**	31.66	33.83	36.96	37.68

Figure 4-14 Results of liquid limit determination by fall cone test for sample 4

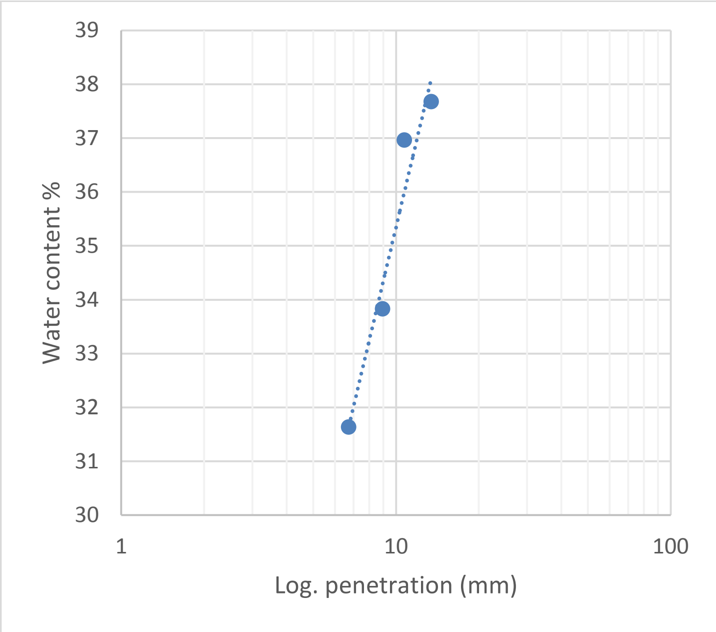


Figure 4-15 Liquid limit determination by fall cone test for sample 4

Penetration depth (mm)	10
Liquid limit W_L	35.34

Observation of cone penetration after 5 s:

		1st test	2nd test	3rd test	4th test
Penetration depth in 5 s	**mm**	6.74	8.96	10.75	-
Penetration depth in 6 s	**mm**	6.76	9.06	10.85	13.49
Penetration depth in 11 s	**mm**	6.86	9.2	10.95	13.56
Penetration depth in 71 s	**mm**	6.99	9.38	13.56	13.63

Table 4-11 Results of cone penetration observation after 5 s for sample 4

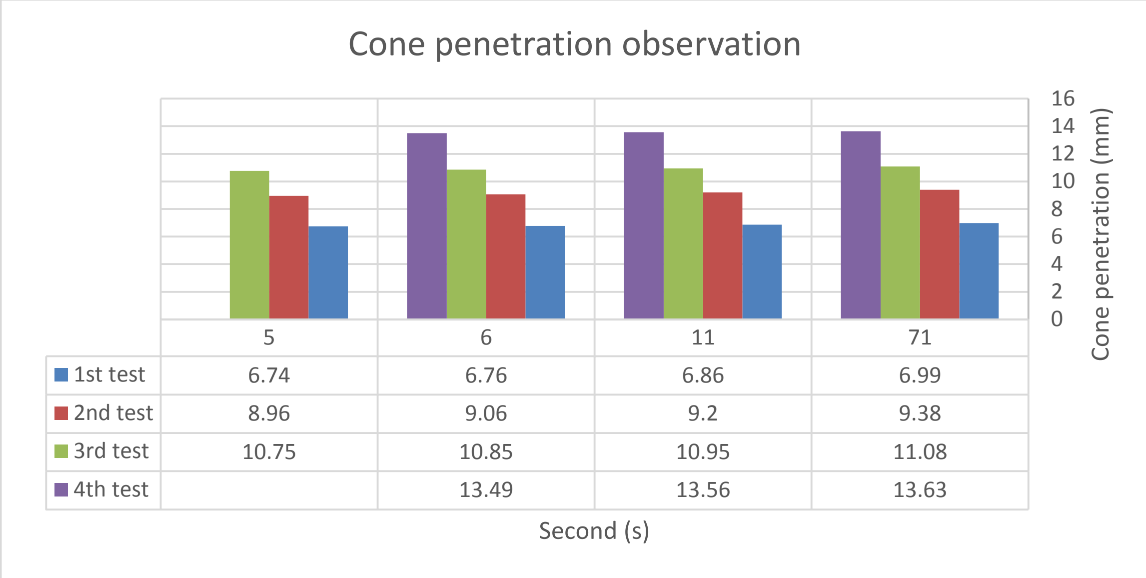


Figure 4-16 Column chart of cone penetration after 5 s for sample 4

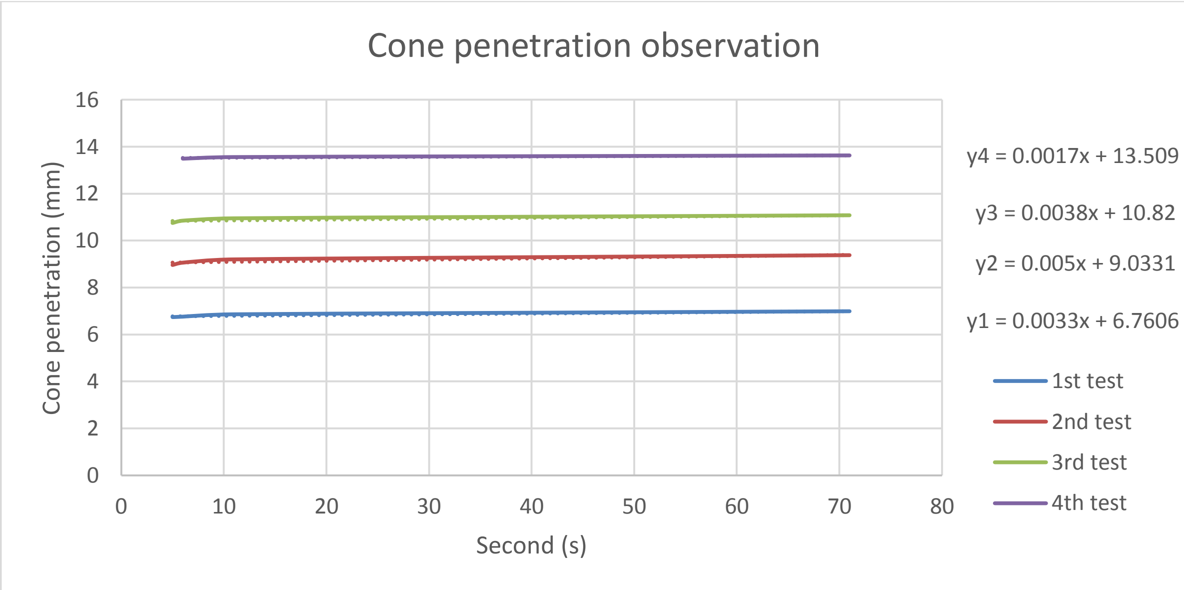


Figure 4-17: Chart of cone penetration observation after 5 s for sample 4

4.5 ***Sample 5*** $(sa\,\bar{c}l\,S\bar{i})$

4.5.1 Casagrande percussion method

Sample No.		**1**	**2**	**3**	**4**
No. of drops		17	19	21	39
Mass of can + moist soil	**g**	11.25	10.46	10.94	10.35
Mass of can + dry soil	**g**	8.86	8.63	8.33	8.38
Mass of empty, clean can	**g**	1.09	1.10	1.08	1.07
Mass of moist soil	**g**	10.16	9.36	9.86	9.28
Mass of dry soil	**g**	7.77	7.53	7.25	7.31
Mass of pore water	**g**	2.39	1.83	2.61	1.97
Water content	**%**	30.76	29.46	30.60	26.95

Table 4-12: Result of liquid limit determination by Casagrande for sample 5

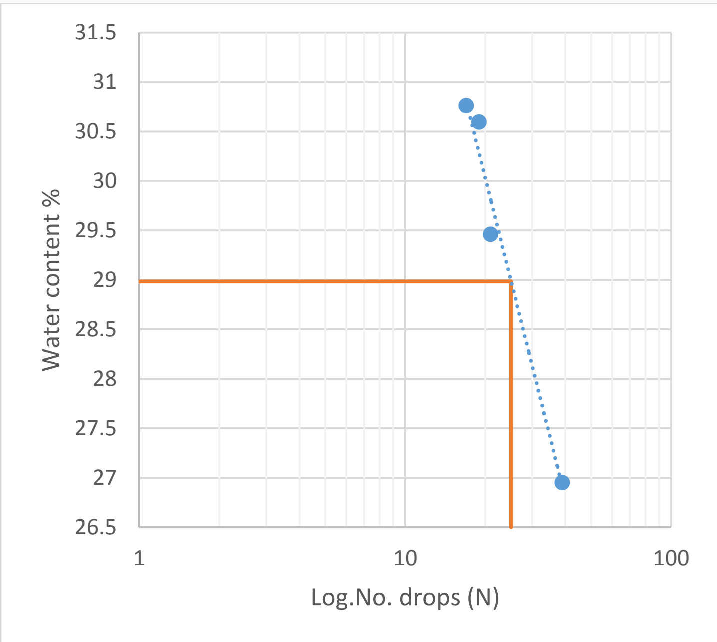


Figure 4-18: Liquid limit determination by Casagrande for sample 5, the red line illustrates 25 blows as the liquid limit of the soil

No. of drops (N)	25
Liquid limit W_L	28.95

4.5.2 Fall cone test

Sample No.		1	2	3	4	5
Mass of can + moist soil	g	20.42	20.36	19.57	20.04	22.10
Mass of can +dry soil	g	16.49	15.32	15.19	15.89	17.6
Mass of empty, clean can	g	2.35	2.33	2.34	2.34	2.35
Mass of moist soil	g	18.07	18.03	17.23	17.70	19.75
Mass of dry soil	g	14.14	12.99	12.85	13.55	15.25
Mass of pore water	g	3.93	5.04	4.38	4.15	4.5
Penetration depth in 5 s	mm	6.99	14.71	11.37	9.06	7.52
Water content	%	27.79	38.80	34.09	30.63	29.51

Table 4-13: Results of liquid limit determination by fall cone test for sample 5

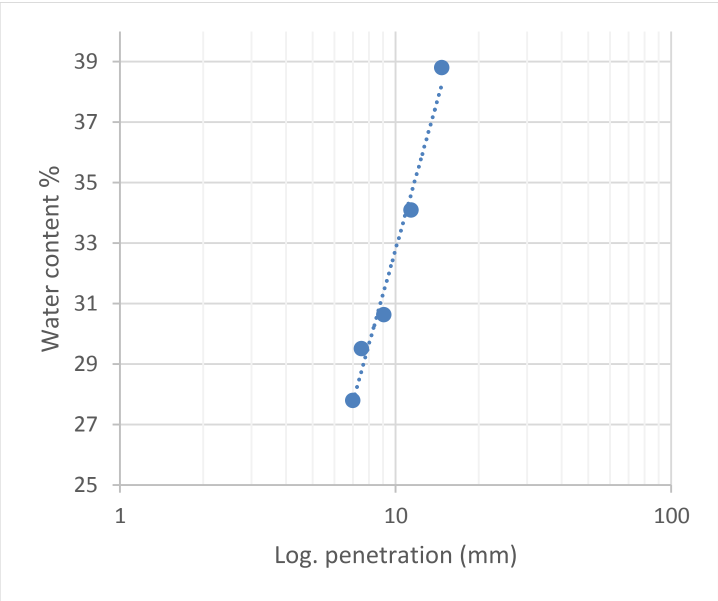


Figure 4-19: Liquid limit determination by fall cone test for sample 5

Penetration depth (mm)	10
Liquid limit W_L	32.81

Observation of cone penetration after 5 s:

		1st test	2nd test	3rd test	4th test	5th test
Penetration depth in 5 s	**mm**	6.99	14.71	11.37	9.06	7.52
Penetration depth in 6 s	**mm**	7.05	14.73	11.46	9.12	7.60
Penetration depth in 11 s	**mm**	7.11	14.78	11.51	9.18	7.65
Penetration depth in 71 s	**mm**	7.16	14.82	11.56	9.23	7.72

Table 4-14: Results of cone penetration observation after 5 s for sample 5

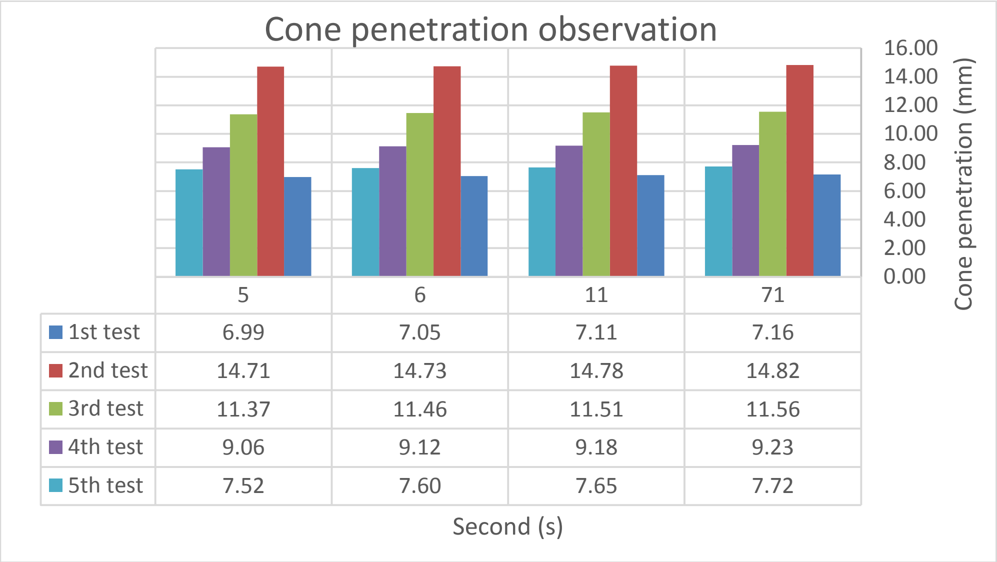


Figure 4-20: Column chart of cone penetration after 5 s for sample 5

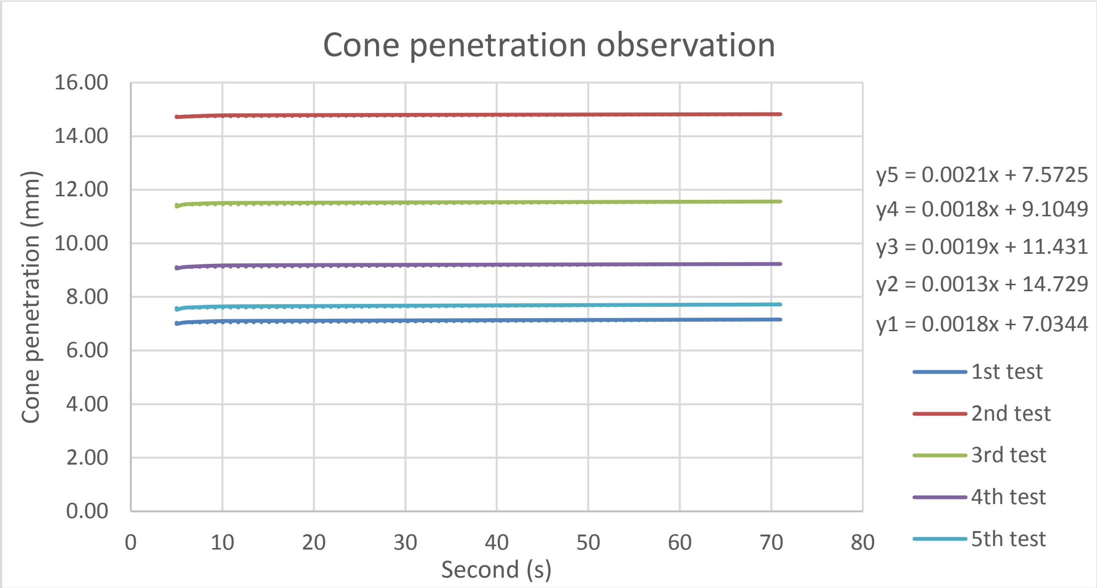


Figure 4-21: Chart of cone penetration observation after 5 s for sample 5

5 Shear strength of soil

Shear strength is a term that describes the resistance of the soil in the shear surface, in which the soil is able to set against the shear stress along the distortion and ultimately sliding failure condition [12]. The shear resistance is derived from the particles friction, the particles interlocking, and the cementation at particles contact.

5.1 *Mohr-Coulomb failure criterion*

The shear strength concept traces back to 1773 when Coulomb proposed the following equation [12]:

Equation 5-1: $\tau_f = c + \sigma \tan\varphi$

where

c = cohesion

φ = angle of internal friction

σ = normal stress on the failure plane

τ_f = shear strength

In this equation the shear strength (τ_f) consists of two components, i.e., cohesive resistance (c) and frictional resistance (φ), that increase proportionally with the normal pressure (σ). Therefore, Coulomb presented the shear stress on the failure plane as a linear function of the normal stress.
Mohr theory (1990) contains that a material fails because of a combination of normal and shear stresses [12]:

Equation 5-2: $\tau = f(\sigma)$

An effective stress concept can be defined as the difference between the total stress and the pore water pressure and can be visualized as the net intergranular stress [13]:

Equation 5-3: $\sigma' = \sigma - u$

σ' = effective stress

σ = total stress

u = pore water pressure

The strength of a saturated soil can be expressed in terms of the effective stress variable as follows:

Equation 5-4: τ_f=c'+ σ'+tanφ'

Thus, the above equation illustrates a linear relationship between shear strength and effective stress. Moreover, it conveys the meaning that the shear strength is based on the total stress and the effective stress.

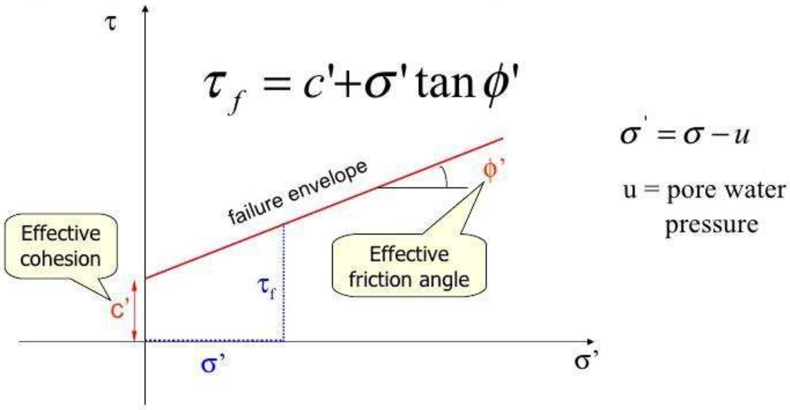


Figure 5-1: Mohr-Coulomb failure criterion, the photo is taken from [14]

According to this Figure 5-1, τ_f corresponds to the maximum shear stress that the soil can take without failure under the normal effective stress of σ'.

5.2 *Drained and Undrained Shear Strength*

The drained condition occurs when there is no change in pore water pressure due to the external loading and the pore water can drain out of the soil easily. It causes volumetric strain in the soil. On the contrary, the undrained condition occurs when the pore water is unable to drain out of the soil. In this condition, the rate of loading is much quicker than the rate at which the pore water is able to drain out of the soil.

The shear strength of a fine-grained soil under the undrained condition is called the undrained shear strength and is denoted by C_u. The undrained shear strength depends only on the initial void ratio or the initial water content of the soil. Therefore, an approximate estimation of C_u can be obtained by knowing the water content of the soil.

5.3 *Laboratory Test for Determination of Undrained Shear Strength*

Studying the laboratory testing should be conducted under certain conditions similar to those encountered in the field to obtain the parameters of constitutive equations which describe the behavior of the soil [15]. There are several empirical methods which are used to determine the undrained shear strength. They are as follows:

- Laboratory vane shear test
- Fall cone test
- Packet penetrometer test
- Torvane test

Among which the *Packet penetrometer* and the *Torvane* tests can measure the undrained shear strength both in the field and in the lab.

5.3.1 **Laboratory vane shear test**

Figure 5-2: Laboratory vane shear test apparatus

One of the methods used by geotechnical engineers to measure the undrained shear strength of a sample of soft to firm cohesive soils, tested under laboratory conditions, is the vane shear test. The vane consists of four rectangular cruciform blades which are mounted at the end of a rod. The vane is forced into the soil and then rotated. The torque is applied to the vane shaft and used to obtain the undrained shear strength of the cohesive soil [16].

5.3.1.1 Sample preparation

All tests for determination of the undrained shear strength were carried out with 4 soil samples, three of which were prepared in an identical manner. The other sample, however, was prepared using the proctor test.
Some plastic bodies, which were essentially made up of typical Westerwald clays and Chamotte of raw materials, i.e. feldspar and chalk, with various grain sizes were provided. Each body is packed in 10 kg bulk and a height of 75 mm with a constant moisture content. A Cylindrical cutter with a diameter of 100 mm was forced into the soil with a constant power to obtain similar undisturbed samples with the same degree of compaction and dimension (D = 100 mm, h = 75 mm).
According to the standard form of the proctor test a cylindrical mold with a nominal capacity of 950 cm^3 and internal diameter of 101.6 mm and height of 116.3 mm is used. Then the sample is compacted by the rammer i.e. the mass of the rammer was 2.49 kg, with 25 blows in 3 equal layers, BS 1377-4:1990 [17].
The 4th sample of the tests was based on the proctor test, however, in a different cylindrical mold with a nominal capacity of 785.34 cm^3 and internal diameter of 100 mm and height of 100 mm. At first, soil was passed through 4.75 mm and discarded granular component retained of sieve. Then the soil was compacted by the identical rammer in 3 equal layers and with 18 blows. Finally, all the samples were loaded under 10 kPa for one hour.

5.3.1.2 Test procedure

Initially, the prepared sample should be fastened to the base of the vane apparatus securely to prevent movement during a test. Furthermore, it must be located under the axis of the vane. Then the vane is inserted steadily into the sample to a minimum depth, i.e. twice the height of the vane blade. Subsequently, the torque is applied to the vane at the rate of 6°/min until the soil has been sheared. After that, the vane is removed steadily to prevent excessive disturbance and the test is repeated at four more additional positions at the same height of the sample. Eventually, the specimen from the level at which the vane test was carried out is taken and its moisture content will be determined, BS 1377-7: 1990 [18].
According to the standard for additional tests, the space between the center of the tests in a 100 mm diameter sampling tube must be kept at least 30 mm by using a 12.7 mm vane.

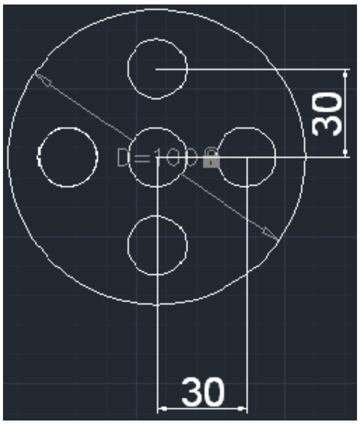


Figure 5-3: Standard space between the center of the tests

In this work, the height of the vane and the rate of rotation were considered as the variables of the tests. Additionally, in this study, some special experiments were also implemented. The first one was a specimen with a division level at 38 mm of the height of the sample. The test was implemented with the application of the standard vane in 12.7×25.4 mm dimension and the rotation rate of 6°/min.

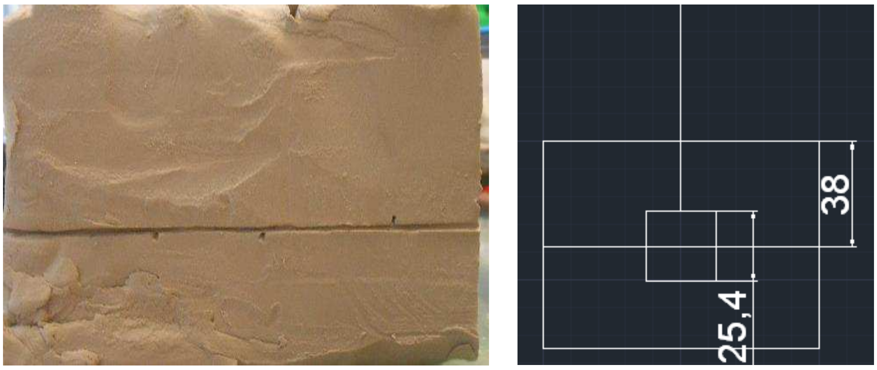


Figure 5-4: The specimen with the division level at the 38 mm of the sample height

The second special test was a specimen with the same height of the used vane (12.7×25.4). In this case, the shear stress was assumed uniform on the vertical sides of the vane.

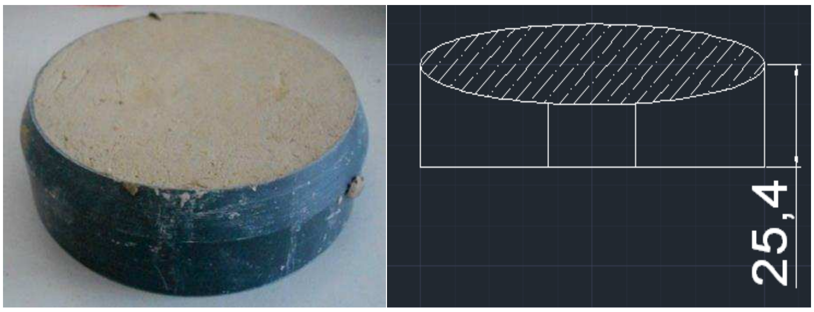


Figure 5-5: The specimen with the equal height of the used vain

The third special experiment was carried out with using the standard vane (12.7×25.4) but it was trodden into the soil for 15 mm of the height of the vane. In this case, the shear stress was distributed around the entered height and the bottom of the vane.

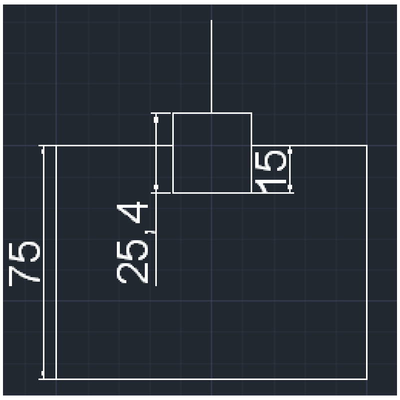


Figure: 5-6: The third special test

5.3.1.3 Analysis and method

The shear strength is determined using three parameters; Torque, vane geometry and the stress distribution. The action of the vane is to rotate a cylindrical portion of the soil into which the vane has penetrated. The diameter of the cylinder is equal to the width of the blade and the height is equal to the length of the blade. In order to simplify, the stress distribution at the end surfaces of the blade is also assumed as a rectangular shape.

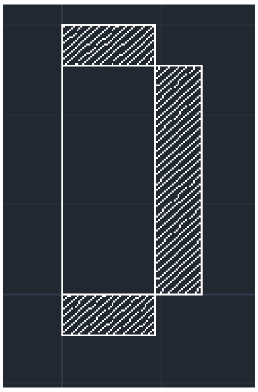


Figure 5-7: Stress distribution around the vane

Torque=force × lever arm

The resisting torque, i.e. T_r, is made up of two components:

T_{r1}: resisting torque provided by the cylindrical surface.

T_{r2}: resisting torque provided by each of the two end areas.

Equation 5-5: $T_r = T_{r_1} + T_{r_2}$

Equation 5-6: $T_{r1} = C_u \times (\pi \times d \times h) \times \frac{d}{2}$ (N.mm)

At the ends, an annular section with radius "r" and width of "dr" is considered.

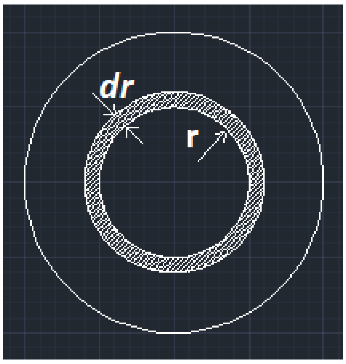


Figure 5-8: The annular section at the ends of vane

$$dT = C_u \times 2 \times \pi \times r \times dr \times r$$

$$\int_0^{\frac{d}{2}} 2 \times \pi \times r^2 \times C_u \times dr$$

Equation 5-7: $T_2 = \frac{\pi \times d^3 \times C_u}{12}$ (N.mm)

Equation 5-8: $T_r = \frac{\pi \times d^2 \times h \times C_u}{2} + 2 \times \frac{\pi \times d^3 \times C_u}{12}$ (N.mm)

Equation 5-9: $C_u = \frac{6\ T_r}{d^2 \times \pi(3h+d)}$ ($N.mm^2$)

For the first explained special test, the shear strength was calculated identically to the normal cases. However, in the second special test the shear stress distribution is assumed merely in the vertical sides of the blade. In the third special test, this was measured around the penetrated length and at the end of the vane [13], [19], [20].

5.3.2 **Fall cone test**

The fall cone test was developed by John Oisson in 1915 in Sweden and was carried out to estimate the undrained shear strength of both the undisturbed and the remolded specimen of a fine-grained cohesive soil [21].

5.3.2.1 Test procedure

Initially, the cone is locked in a position which the tip of the cone touches the specimen surface and a dial gauge should be set at zero. Then the cone is freely dropped. After (5±1) s the cone is locked and the penetration depth is measured by the dial gauge. Later, the cone is removed from the specimen and cleaned carefully and the test is repeated at two more additional positions, ISO/TS 17892-6.
The test's points in the undisturbed specimen should be distributed in a way that the results are unaffected by the other tests and the proximity to the perimeter. No points should be closer to the perimeter than 7 mm, and to the other test points no closer than 14 mm. For the undisturbed sample, at least three tests should be carried out. If any value differs more than 10% from the average, an additional test shall be performed and the most deviating value must be omitted from the calculation of the average[22], ISO/TS 17892-6.

5.3.2.2 Analysis

The undrained shear strength is calculated by the following equation, ISO/TS 17892-6:

Equation 5-10: $C_u = c.g.\frac{m}{i^2}$

where

C_u	undrained shear strength of the undisturbed soil specimen, in kPa.
c	state of the soil and the tip angle constant
c	0.80 for cones with 30° tip;
c	0.27 for cones with 60° tip;
g	acceleration of free fall, in m/s^2
m	mass of the cone, in g
i	cone penetration, in mm

5.3.3 **Torvane test**

The torvane, or pocket vane, shown in Figure 5-9 is a modified form of the vane shear test and operates on a similar principle to the laboratory vane apparatus. It provides a quick and efficient method for determining C_u for the specimens collected from the field during soil exploration. It is widely used for taking on-site measurements of excavations including trenches and test pits.

Figure 5-9: Torvane or packet shear vane, the photo is taken from [23]

5.3.3.1 Test procedure

The shear strength is measured by pushing the torvane into the soil and turning until a maximum reading is achieved and the soil fails. This is calibrated to the reading of the undrained shear strength and can be read directly at the top of the dial. The standard vane is used for measuring the shear strength up to 100 kPa. Additionally, a large vane is suitable for determining the shear strength below 20 kPa with greater sensitivity and a smaller vane is available for the range up to 250 kPa [13].

5.3.4 **Pocket penetrometer**

The pocket penetrometer is usually used for determining the undrained shear strength, C_u, consistency and the approximate unconfined shear strength in the fine grain cohesive soils. Direct-reading scale- in tons/sq ft, or kg/sq cm-corresponds to the equivalent unconfined compressive strength. This device can be used not only in the field but also in the laboratory. The pocket penetrometer specifically determines the penetration resistance of the top layers and of the samples in the field or in the laboratory.

Figure 5-10: Packet penetrometer, the photo is taken from [24]

5.3.4.1 Test procedure

The operator pushes the piston into the soil up to the calibration mark and the pin encounters a force of the soil. The spring is compressed by the force and a slip ring on the scale shows unconfined compressive strength, $q_{u,}$ on the graduated scale.

Due to its small size, several test should be implemented to obtain a statistical determination of q_u [25]. The adapter foot is recommended for extremely low strength cohesive soils. It increases the effective area measured by 16 times through 1 "(25 mm) diameter foot in comparison to the ¼ "(6.35 mm) diameter of the penetrometer piston.

5.3.4.2 Analysis

The undrained shear strength is calculated using the following equation:

Equation 5-11: $$C_u = \frac{q_u}{2} \quad [\frac{kN}{m^2}]$$

6 Soil samples to evaluate the undrained shear strength of soil

6.1 *Overview*

All of the experiments for evaluation of the undrained shear strength were implemented on four soil samples, three of which are the same samples used in chapter 3. The samples are different in sieve analysis results and consequently, various results of the tests are visible, see Table 6-1. The first three samples are plastic soil and the last one is not a plastic soil. The liquid limit, the plastic limit and the plasticity index for every sample were determined and arranged in a table in the relevant part.

	Clay %	**Silt %**	**Sand %**
Label	**< 0.002 mm**	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**
cl si̅ S̅a	26.5	28.3	45.2
sa̿ cl̅ Si̅	34.2	36	29.8
sa ʼcl̅ Si̅	43.0	46.5	10.5
cl ʼsa Si̅	8.5	68.8	22.7

Table 6-1: Results of the sieve analysis

6.2 ***Sample 1 (cl si̅ S̅a)***

As shown in figure 6-1, this sample contains the highest value of sand and consists of the almost equal amount of clay and silt. According to Table 2-2 , this sample is classified as a medium plastic soil but in comparison to other two samples, it has the lowest plastic limit. It can be characterized as follow:

Clay %	**Silt %**	**Sand %**	**relation**
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
26.5	28.3	45.2	0.94

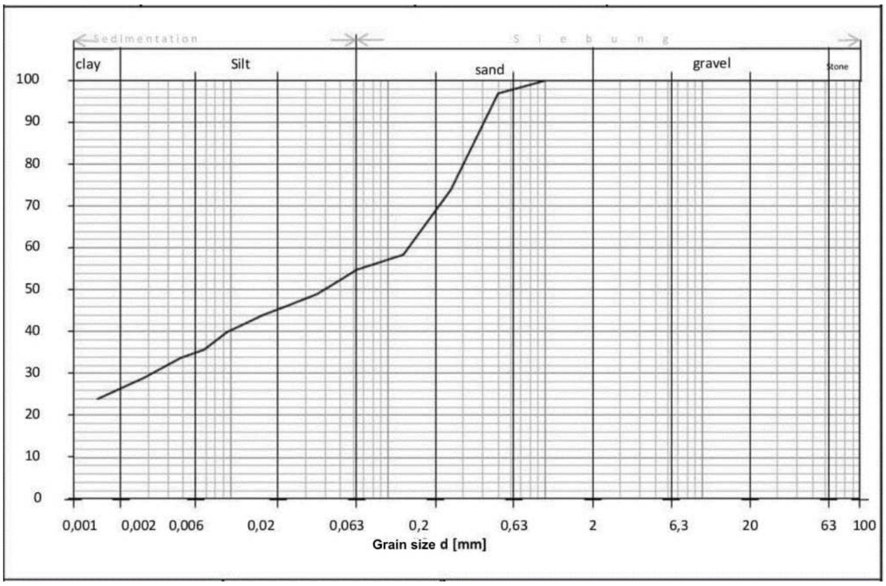


Figure 6-1: Sieve analysis of sample 1

W_L	24.77
W_P	13.08
I_P	11.69

Table 6-2: Liquid limit (Casagrande method), plastic limit and plasticity index of sample 1

6.3 ***Sample 2 (sa$\overline{cl}$ $\overline{Si}$)***

This sample has the highest value of clay/silt relation. In accordance with Table 2-2, this soil sample could be referred to as a medium plastic soil. It can be characterized as follow:

Clay %	Silt %	Sand %	relation
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
34.2	36	29.8	0.95

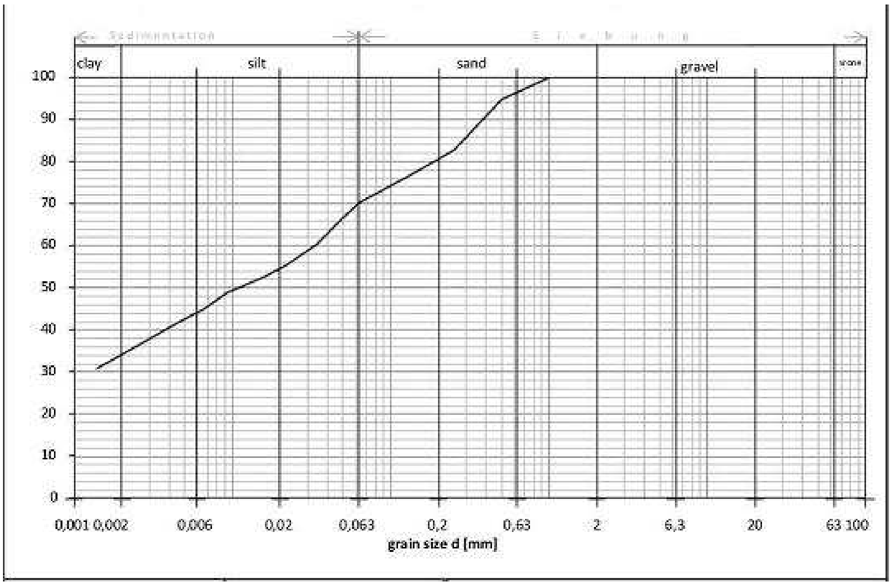


Figure 6-2: Sieve analysis of sample 2

W_L	28.01
W_P	14.72
I_P	13.29

Table 6-3: Liquid limit (Casagrande method), plastic limit and plasticity index of sample 2

6.4 ***Sample 3 (sa' cl̄ Sī)***

This sample contains the lowest amount of the sand and the smallest grain size in comparison to other samples of this chapter. As can be seen in Table 6-4 it is a highly plastic soil since its plasticity index is more than 17. It can be characterized as follow:

Clay %	**Silt %**	**Sand %**	**relation**
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
43.0	46.5	10.5	0.92

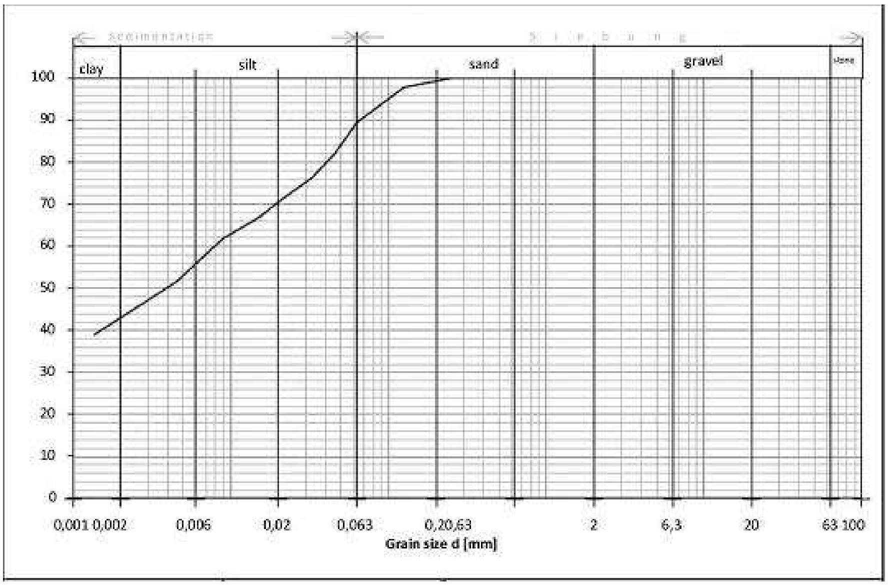


Figure 6-3: Sieve analysis of sample 3

$\boldsymbol{W_L}$	34.33
$\boldsymbol{W_P}$	15.90
$\boldsymbol{I_P}$	18.43

Table 6-4: Liquid limit (Casagrande method), plastic limit and plasticity index of sample 3

6.5 *Sample 4 (cl' sa Si)*

Sample 4 has included the least amount of clay and therefore the lowest value of the clay/silt relation. Hence, we can observe that it could not be classified as a plastic soil. The plastic limit could be measured neither by rolling method nor by linear shrinkage method. This sample can be characterized as follow:

Clay %	**Silt %**	**Sand %**	**relation**
< 0.002 mm	**0.002 - 0.063 mm**	**0.063 - 0.4 mm**	**clay/silt**
8.5	68.8	22.7	0.12

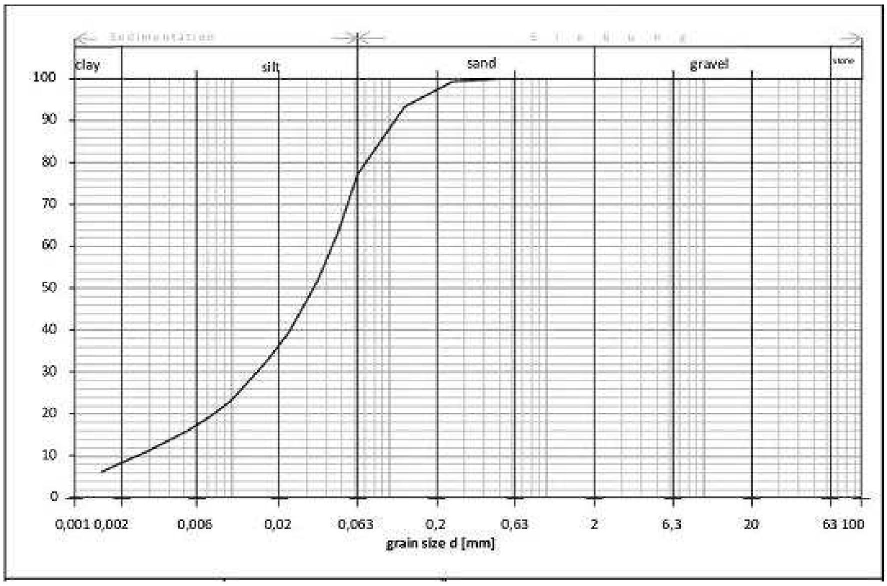


Figure 6-4: Sieve analysis of sample 4

W_L	25.53

Table 6-5: Liquid limit (Casagrande method) of sample 4

7 Results of the Undrained Shear Strength Determination of the Soil Samples

In this chapter, the results of the undrained shear strength assessment are collected. Every sample include four parts. Initially, the first part shows the results of the undrained shear strength evaluation of the soil samples with the help of the laboratory vane shear test. It contains three subsets. The first one demonstrates the trend of the change in the undrained shear strength (C_u) of the soil samples when rotational speed was assumed as a variable. In the second subsets of the first part, C_u is estimated with the change of the height of the vane. In the third subsets, the results of the formerly mentioned special tests are arranged.

In the second part, the undrained shear strength of all of the soil sample was evaluated with the help of the fall cone test. Three tests were implemented on each soil samples to obtain a statistical determination of the C_u. Afterwards, the third part includes the results of the undrained shear strength determination using the soil samples with the torvane test. Finally, the last part illustrates the results of the undrained shear strength evaluation by means of the pocket penetrometer test. In this method, first the unconfined compressive strength q_u was determined and then the C_u was calculated.

7.1 ***Sample 1 (cl si͞ Si͞)***

7.1.1 **Laboratory vane shear test**

7.1.1.1 Rotation speed as a variable

According to the charts, the undrained shear strength rises with an increase in the rotational speed.

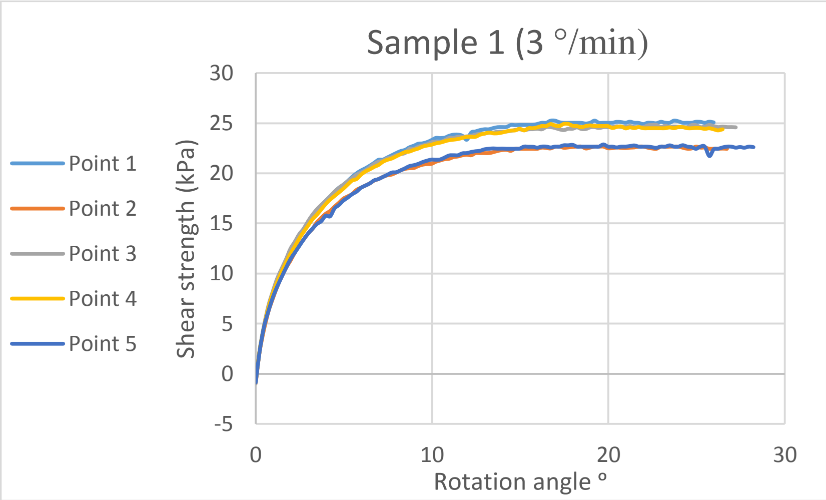


Figure 7-1: Undrained shear strength chart of 3 °/min rotation speed for the soil sample 1

	Point 1	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Average**
Max. shear strength (kPa)	25.25	22.66	24.82	24.93	22.88	24.11
Max. Torque (N.m)	0.19	0.17	0.19	0.19	0.17	0.18
Water content %	16.99					

Table 7-1: Shear strength evaluation results of 3 °/min rotation speed for the soil sample 1

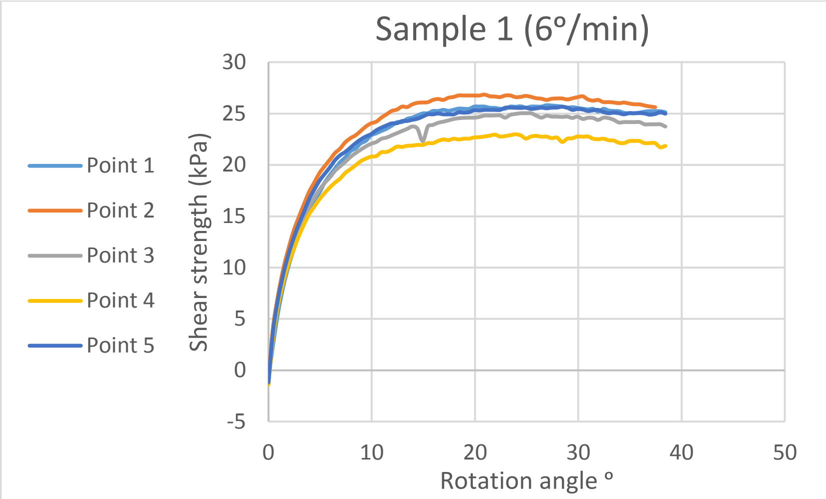


Figure 7-2: Shear strength evaluation chart of 6 °/min rotation speed for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	25.82	26.85	25.04	22.99	25.67	25.27
Max. Torque (N.m)	0.19	0.20	0.19	0.17	0.19	0.19
Water content %	17.13					

Table 7-2: Shear strength evaluation results of 6 °/min rotation speed for the soil sample 1

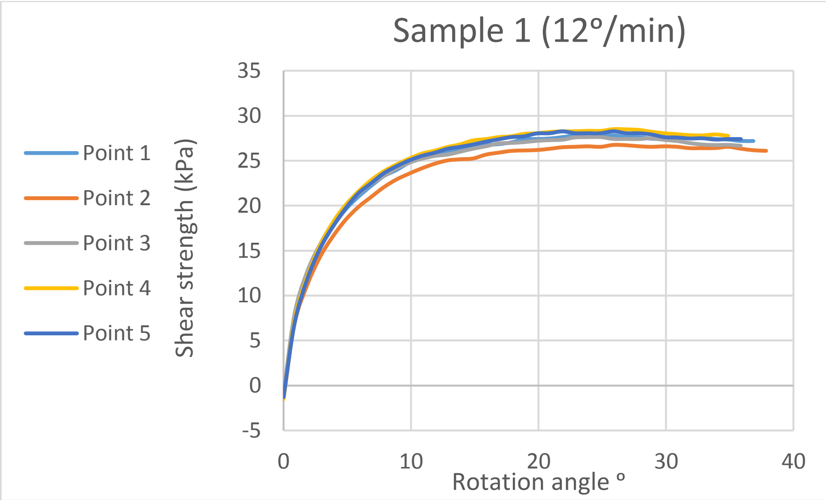


Figure 7-3: Shear strength evaluation chart of 12 °/min rotation speed for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	27.82	26.76	27.63	28.51	28.27	27.80
Max. Torque (N.m)	0.21	0.20	0.21	0.21	0.21	0.21
Water content %	17.14					

Table 7-3: Shear strength evaluation results of 12 °/min rotation speed for the soil sample 1

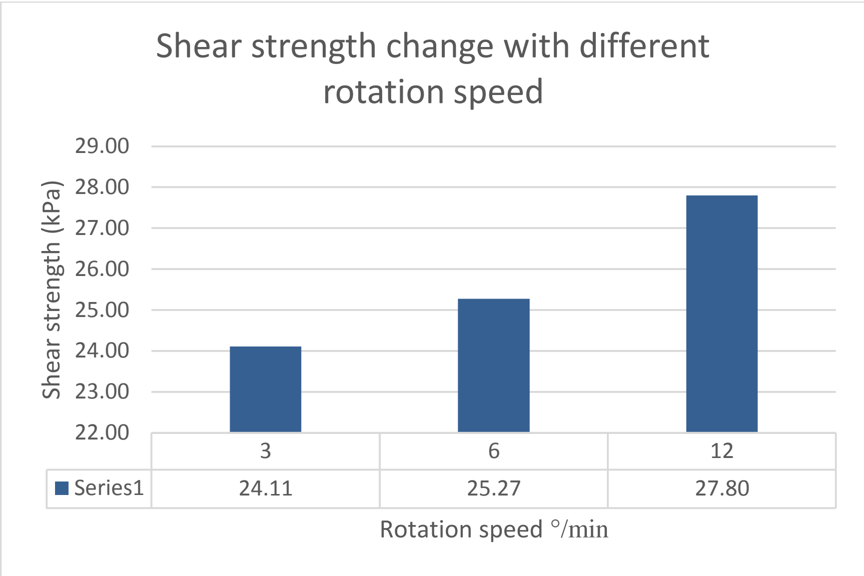


Figure 7-4: Undrained shear strength change chart with different rotation angle for the soil sample1

The height of the vane as a variable:

According to the charts below the undrained shear strength increases with an increase in the height of the vane.

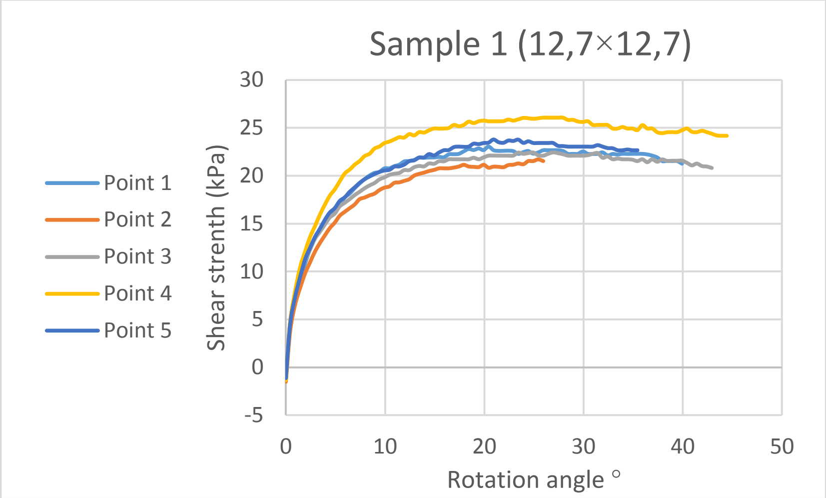


Figure 7-5: Undrained shear strength chart of 12.7×12.7 mm vane for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	23.04	21.71	22.44	26.06	23.78	23.41
Max. Torque (N.m)	0.10	0.09	0.10	0.10	0.10	0.10
Water content %	17.28					

Table 7-4: Shear strength evaluation results of 12.7×12.7 mm vane for the soil sample 1

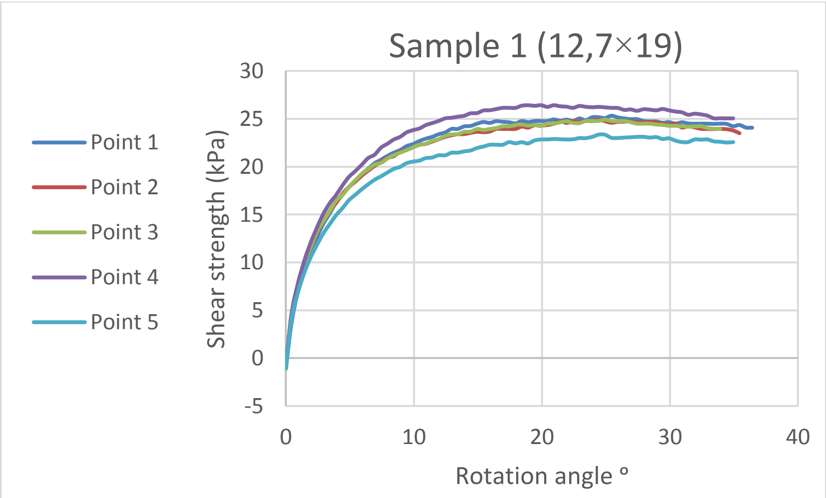


Figure 7-6: Undrained shear strength chart of 12.7×19 mm vane for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	25.33	24.91	24.92	26.43	23.36	24.99
Max. Torque (N.m)	0.15	0.15	0.15	0.16	0.14	0.15
Water content %	17.16					

Table 7-5: Shear strength evaluation results of 12.7×19 mm vane for the soil sample 1

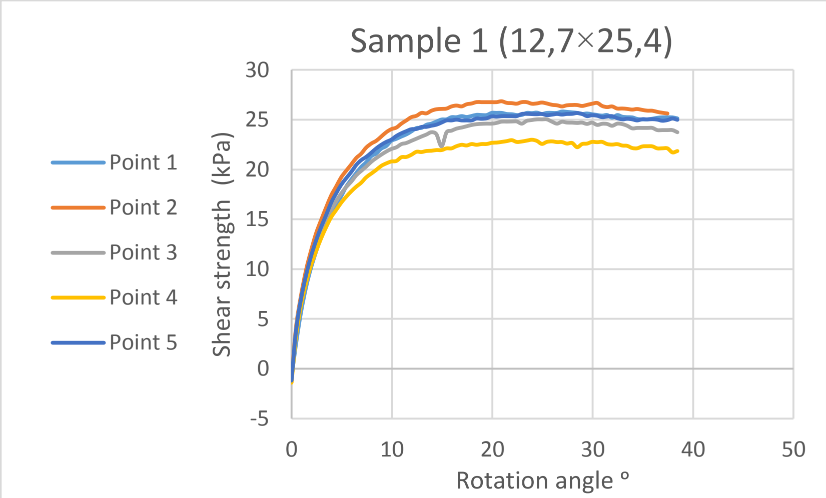


Figure 7-7: Undrained shear strength chart of 12.7×25.4 mm vane for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	25.82	26.85	25.04	22.99	25.67	25.27
Max. Torque (N.m)	0.19	0.20	0.19	0.17	0.19	0.19
Water content %	17.126					

Table 7-6: Shear strength evaluation results of 12.7×25.4 mm vane for the soil sample 1

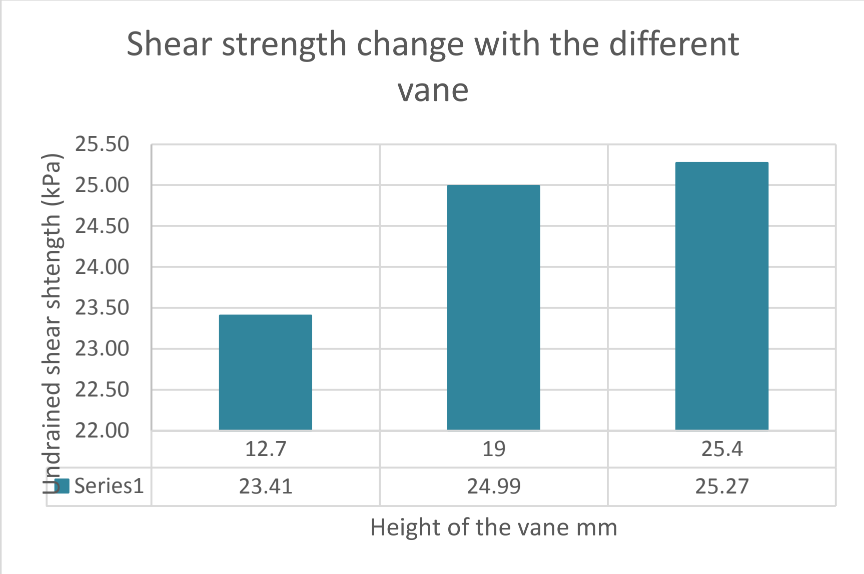


Figure 7-8: Undrained shear strength change chart with the different vane for the soil sample 1

Special experiments:

- **The specimen with a division level at 38 mm**

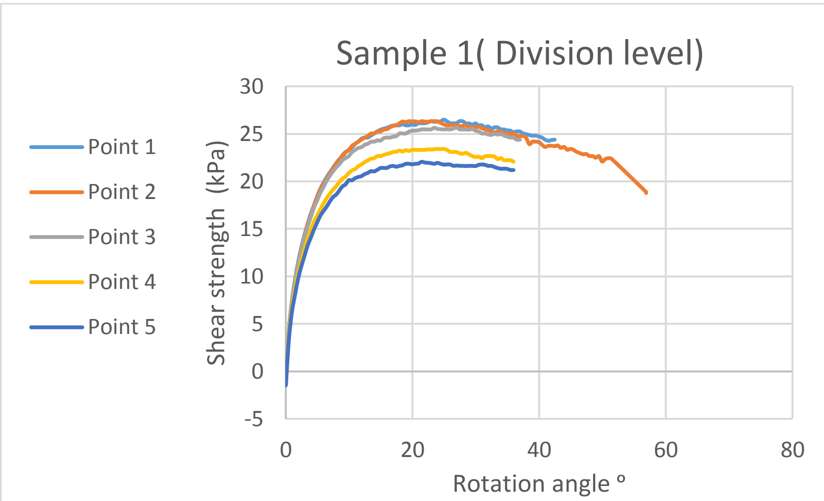


Figure 7-9: Undrained shear strength chart of the specimen with a division level for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	26.49	26.33	25.68	23.42	22.06	24.80
Max. Torque (N.m)	0.20	0.20	0.19	0.18	0.17	0.19
Water content %	16.91					

Table 7-7: Shear strength evaluation results of the specimen with a division level for the soil sample 1

- **The specimen with the same height of the used vane (12.7×25.4)**

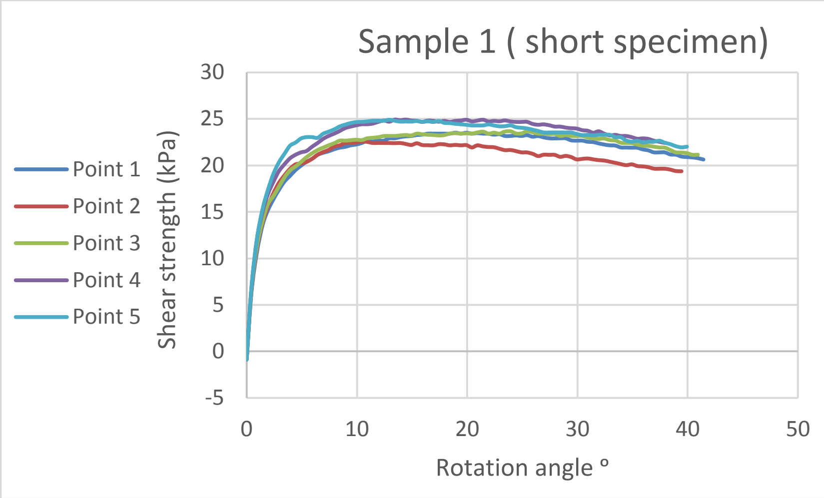


Figure 7-10: Undrained shear strength chart of the short specimen for the soil sample 1

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	23.52	22.56	23.67	24.93	24.91	23.92
Max. Torque (Nm)	0.15	0.15	0.15	0.16	0.16	0.15
Water content %	17.00					

Table 7-8: Shear strength evaluation results of the short specimen for the soil sample 1

- **The standard vane which was entered into the soil only 15 mm of the height of the vane**

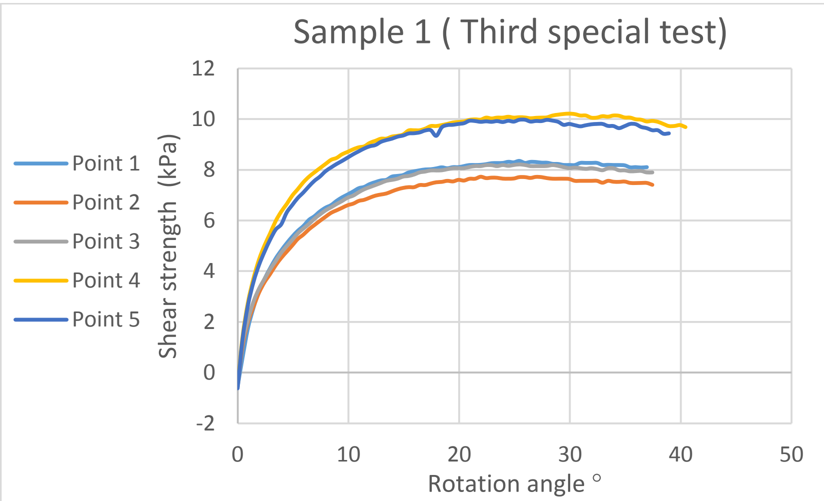


Figure 7-11: Undrained shear strength chart of the third special test for the soil sample 1

	Point 1	Point 2	Point3	Point4	Point 5	Average
Max. shear strength (kPa)	8.35	7.73	8.21	10.22	9.98	8.90
Max. Torque (Nm)	0.16	0.15	0.16	0.20	0.19	0.17
Water content %	16.25					

Table 7-9: shear strength evaluation results of the third special test for the soil sample 1

7.1.2 **Fall cone test**

Cu=c.g. $\frac{m}{i^2}$

		60 g/60 °		
Test No.		**1**	**2**	**3**
Penetration depth	**mm**	1.51	1.40	1.46
Water content	**%**	17.10		

Table 7-10: Fall cone test results for undrained shear strength evaluation of sample 1

Cu= 74.86 kPa

7.1.3 **Torvane test**

Test No.		1	2	3
Result	**Kg/cm^2**	0.380	0.380	0.430
Water content	**%**	16.95		

Table 7-11: Torvane test results for undrained shear evaluation of sample 1

Cu = 38.90 kPa

7.1.4 **Pocket penetrometer test**

Test No.		1	2	3
Result	**ton/ft^2**	0.60	0.80	0.650
Water content	**%**	16.95		

Table 7-12: Packet penetrometer test results for undrained shear strength evaluation of sample 1

Cu**=** 32.72 kPa

7.2 *Sample 2 (sa̅cl̅ Si̅)*

7.2.1 **Laboratory shear vane test**

Rotation speed as a variable

According to the charts, the undrained shear strength rises with an increase in the rotational speed.

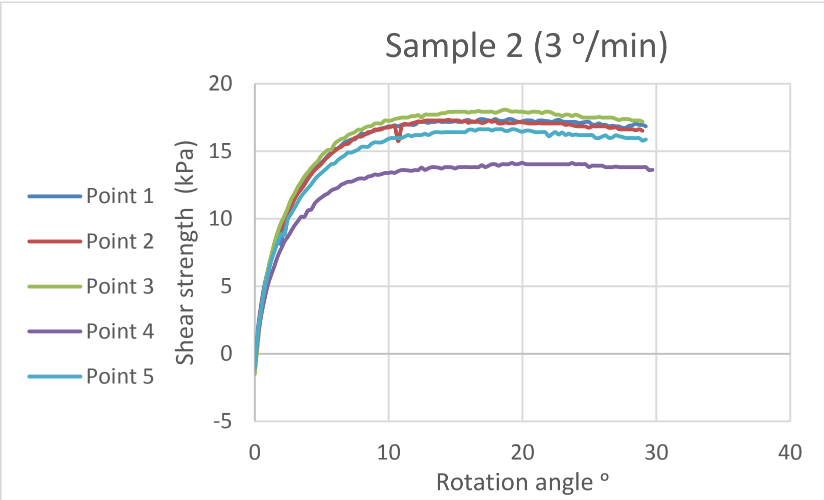


Figure 7-12: Undrained shear strength chart of 3 °/min rotation speed for the soil sample 2

	Point 1	**Point 2**	**Point 3**	**Point 4**	**Point 5**	**Average**
Max. shear strength (kPa)	17.37	17.31	18.07	14.14	16.62	16.70
Max. Torque (Nm)	0.13	0.13	0.14	0.11	0.12	0.12
Water content %	20.02					

Table 7-13: Shear strength evaluation results of 3 °/min rotation speed for the soil sample 2

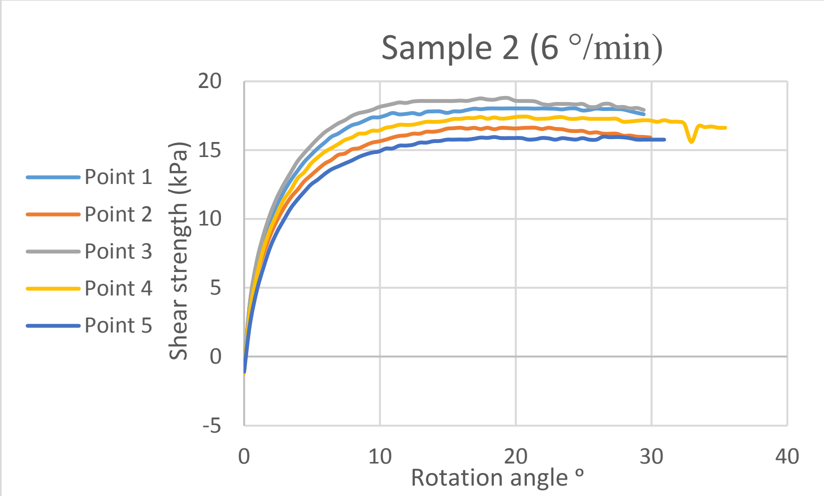


Figure 7-13: Undrained shear strength chart of 6 °/min rotation speed for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	18.02	16.62	18.78	17.43	15.97	17.36
Max. Torque (Nm)	0.14	0.12	0.14	0.13	0.12	0.13
Water content %	19.74					

Table 7-14: Shear strength evaluation results of 6 °/min rotation speed for the soil sample 2

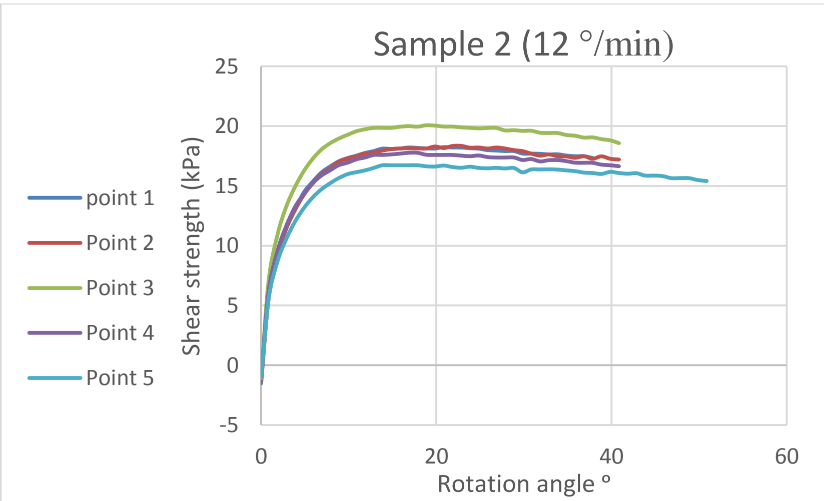


Figure 7-14: Undrained shear strength chart of 12 °/min rotation speed for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	18.24	18.35	20.07	17.77	16.73	18.23
Max. Torque (Nm)	0.14	0.14	0.15	0.13	0.13	0.14
Water content %	20.19					

Table 7-15: Shear strength evaluation results of 12 °/min rotation speed for the soil sample 2

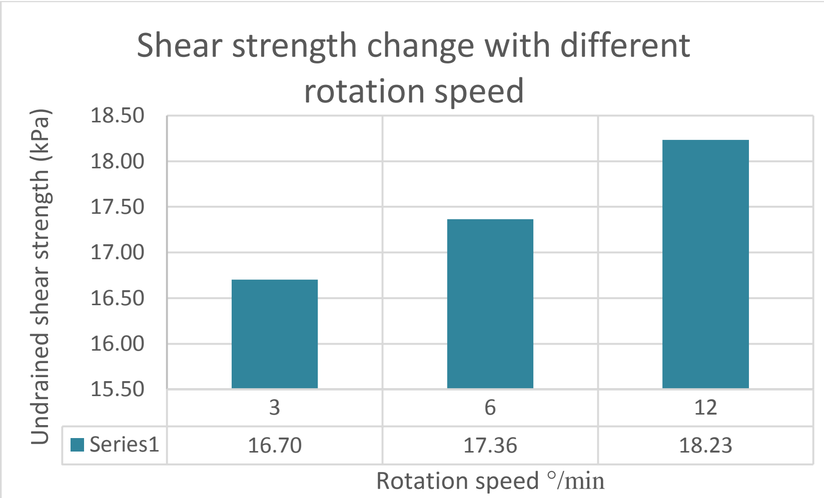


Figure 7-15: Undrained shear strength change chart with the different rotation speed for the soil sample 2

Height of the vane as a variable

As indicated in the charts of this part the undrained shear strength rises from the first vane to the second one, however, its value decreases a little from the second vane to the third one.

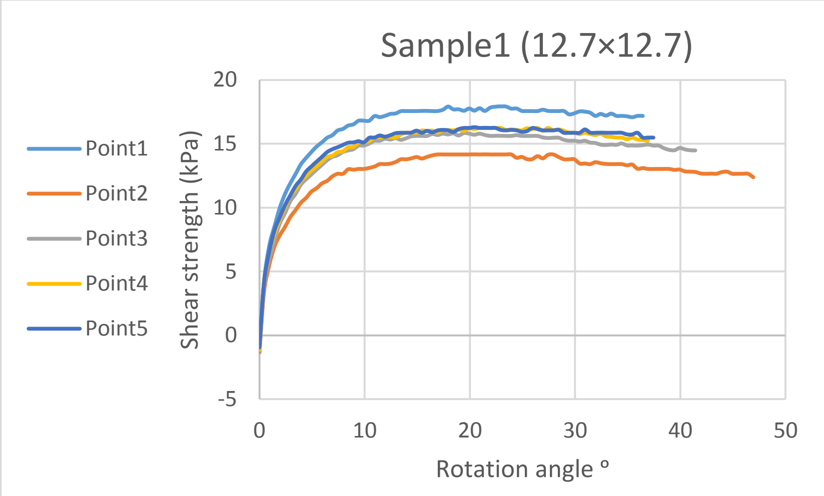


Figure 7-16: Undrained shear strength chart of 12.7×12.7 mm vane for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	17.93	14.18	15.84	16.24	16.30	16.10
Max. Torque (Nm)	0.08	0.06	0.07	0.07	0.07	0.07
Water content %	20.24					

Table 7-16: Shear strength evaluation results of 12.7×12.7 mm vane for the soil sample 2

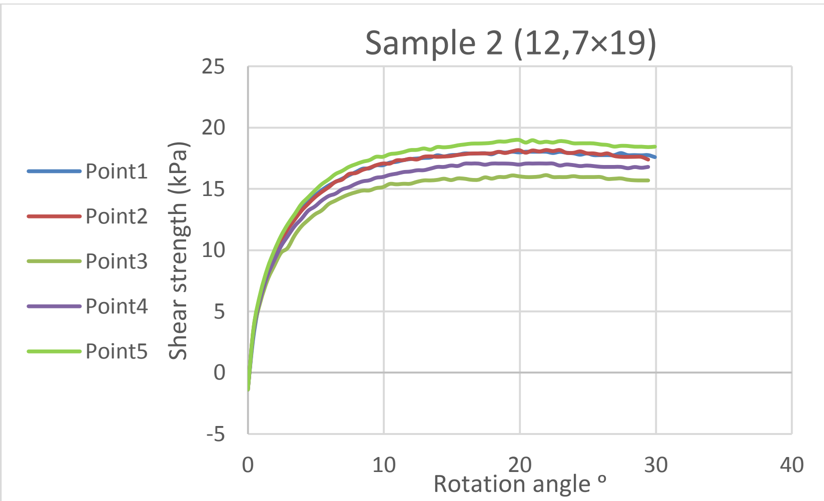


Figure 7-17: Undrained shear strength chart of 12.7×19 mm vane for the soil sample 2

	Point 1	Point 2	Point3	Point4	Point 5	Average
Max. shear strength (kPa)	18.03	18.17	16.12	17.08	18.99	17.68
Max. Torque (Nm)	0.11	0.11	0.09	0.10	0.11	0.10
Water content %	20.13					

Table 7-17: Shear strength evaluation results of 12.7×19 mm vane for the soil sample 2

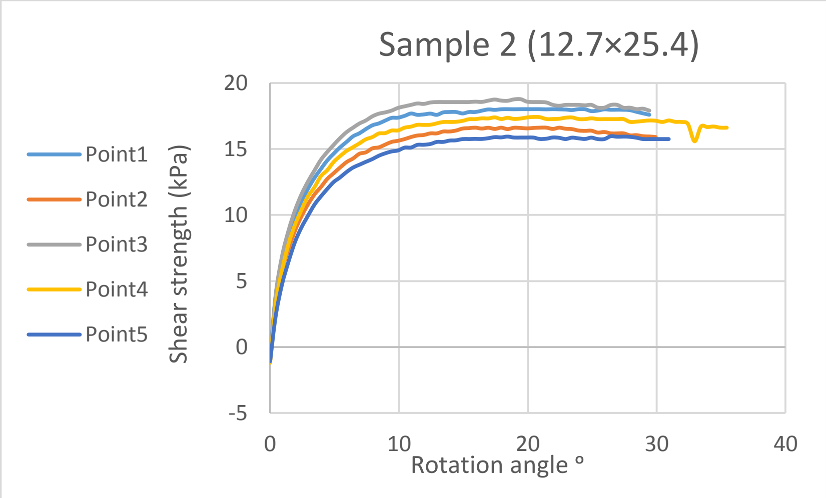


Figure 7-18: Undrained shear strength chart of 12.7×25.4 mm vane for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	18.02	16.62	18.78	17.43	15.97	17.36
Max. Torque (Nm)	0.14	0.12	0.14	0.13	0.12	0.13
Water content %	19.74					

Table 7-18: Shear strength evaluation results of 12.7×25.4 mm vane for the soil sample 2

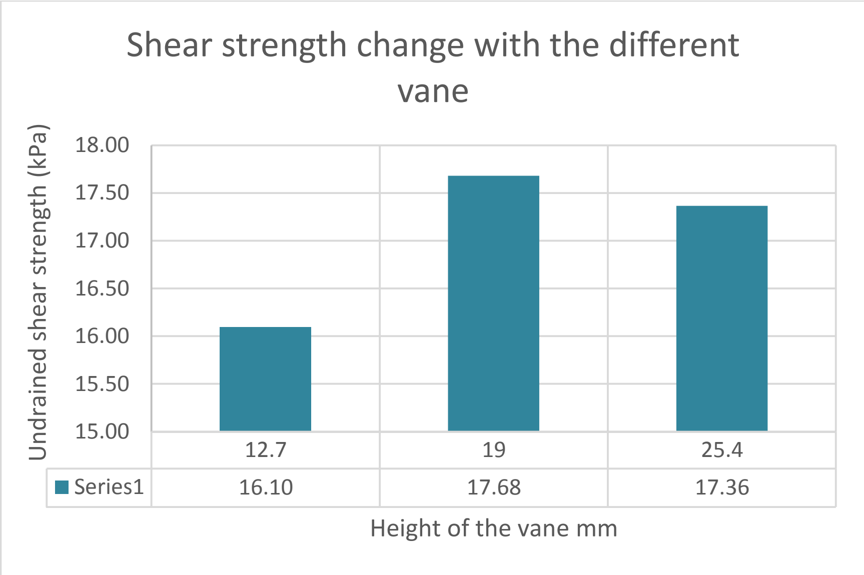


Figure 7-19: Undrained shear strength change chart with the different vane for the soil sample 2

Special experiments

- **The specimen with a division level at 38 mm.**

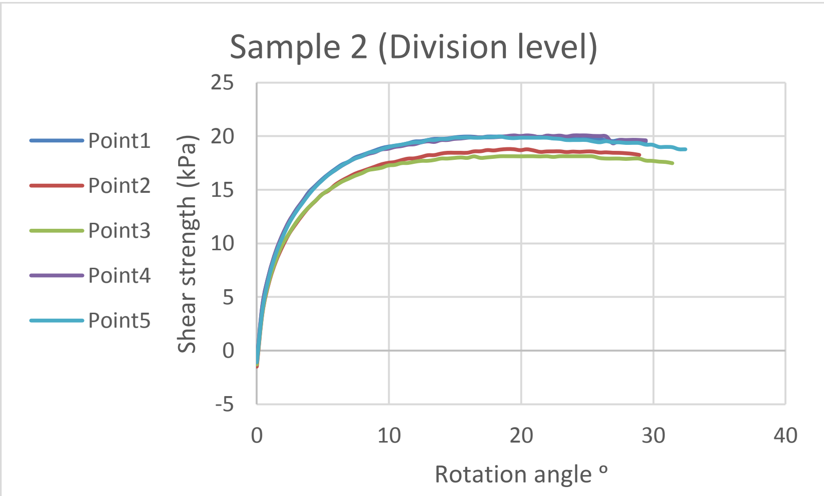


Figure 7-20: Undrained shear strength chart of the specimen with a division level for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	20.02	18.80	18.13	20.07	19.96	19.40
Max. Torque (Nm)	0.15	0.14	0.14	0.15	0.15	0.15
Water content %	20.13					

Table 7-19: Shear strength evaluation results of the specimen with a division level for the soil sample 2

- **The specimen with the same height of the used vane (12.7×25.4).**

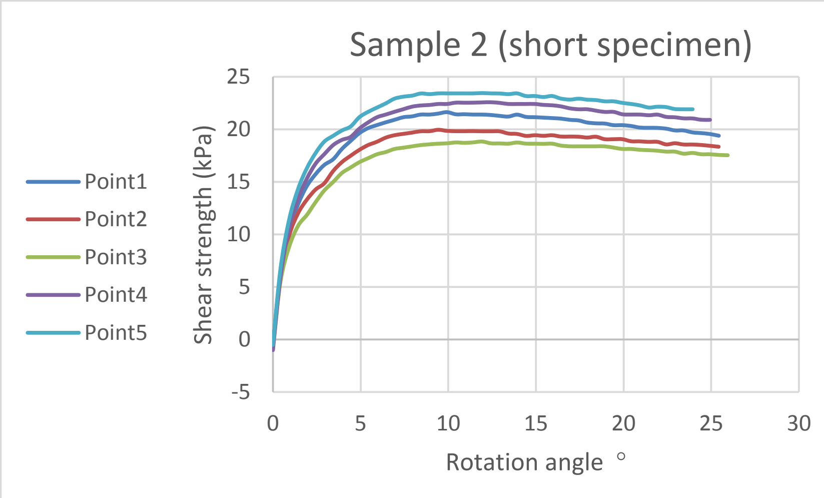


Figure 7-21: Undrained shear strength chart of the short specimen for the soil sample 2

	Point 1	Point 2	Point3	Point4	Point 5	Average
Max. shear strength (kPa)	21.63	19.96	18.84	22.58	23.45	21.29
Max. Torque (Nm)	0.14	0.13	0.12	0.15	0.15	0.14
Water content %	19.46					

Figure 7-22: Shear strength evaluation results of the short specimen for the soil sample 2

- **The standard used vane which was entered into the soil only 15 mm of the height of the vane.**

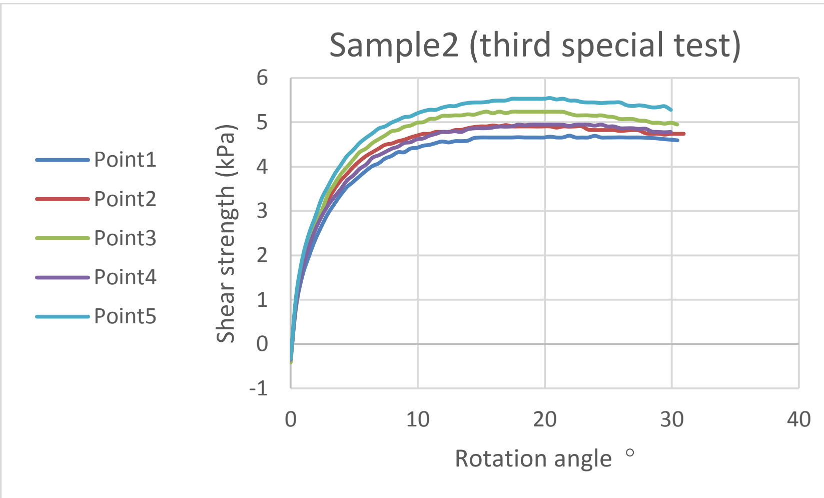


Figure 7-23: Undrained shear strength chart of the third special test for the soil sample 2

	Point 1	Point 2	Point 3	Point 4	Point 5	Averag e
Max. shear strength (kPa)	4.70	4.93	5.24	4.95	5.54	5.07
Max. Torque (Nm)	0.09	0.10	0.10	0.10	0.11	0.10
Water content %	19.06					

Table 7-20: Shear strength evaluation results of the third special test for the soil sample 2

7.2.2 Fall cone test

$Cu = c.g.\frac{m}{i^2}$

		80 g/30 °		
Test No.		**1**	**2**	**3**
Penetration depth	**mm**	3.51	3.8	3.6
Water content	**%**	19.58		

Table 7-21: Fall cone test results for undrained shear strength evaluation of sample 2

Cu=47.47 kPa

7.2.3 Torvane test

Test No.		1	2	3
Result	**Kg/cm^2**	0.360	0.370	0.400
Water content	**%**	20.028		

Table 7-22: Torvane test results for undrained shear evaluation of sample 2

Cu =36.94 kPa

7.2.4 Pocket penetrometer test

Test No.		1	2	3
Result	**ton/ft^2**	4.5	4.25	4.5
Water content	**%**	20.028		

Table 7-23: Packet penetrometer test results for undrained shear strength evaluation of sample 2

Cu=13.217 kPa

7.3 *Sample 3 (sa' cl Si)*

7.3.1 **Laboratory shear vane test**

Rotation speed as a variable

In this sample similar to the others the undrained shear strength increases with an increase in the rotational speed.

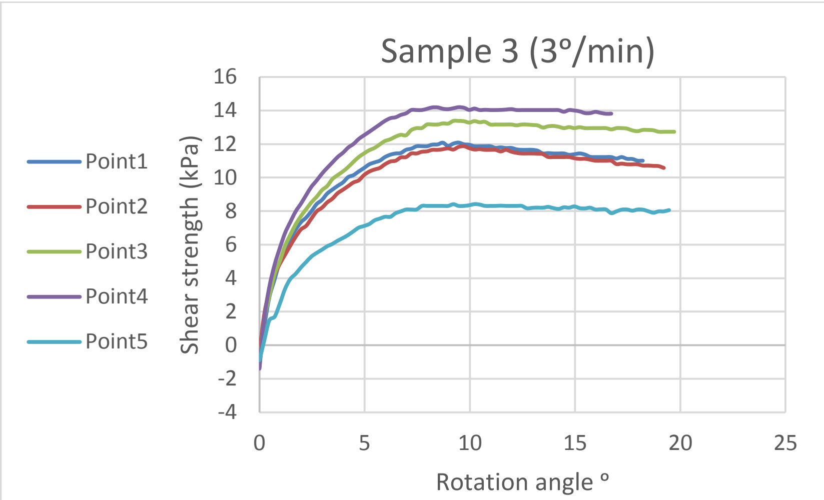


Figure 7-24: Undrained shear strength chart of 3 °/min rotation speed for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	12.09	11.87	13.38	14.20	8.42	11.99
Max. Torque (Nm)	0.09	0.09	0.10	0.11	0.06	0.09
Water content %	24.49					

Table 7-24: Shear strength evaluation results of 3 °/min rotation speed for the soil sample 3

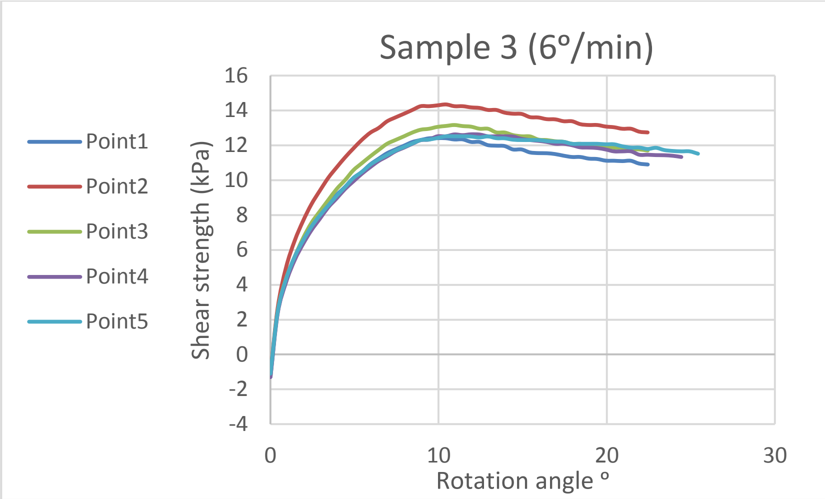


Figure 7-25: Undrained shear strength chart of 6 °/min rotation speed for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	12.41	14.35	13.17	12.63	12.52	13.01
Max. Torque (Nm)	0.09	0.11	0.10	0.09	0.09	0.10
Water content %	24.66					

Table 7-25: Shear strength evaluation results of 6 °/min rotation speed for the soil sample 3

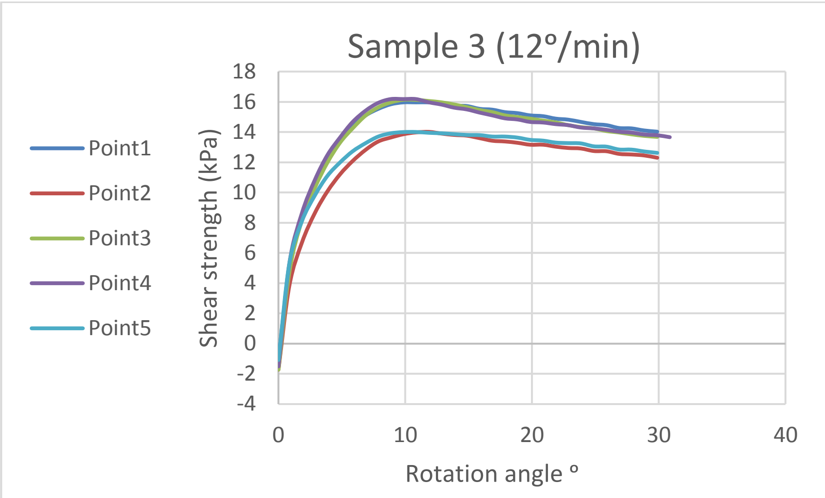


Figure 7-26: Undrained shear strength chart of 12 °/min rotation speed for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	15.97	14.02	16.14	16.19	14.01	15.26
Max. Torque (Nm)	0.12	0.11	0.12	0.12	0.11	0.11
Water content %	24.73					

Table 7-26: Shear strength evaluation results of 12 °/min rotation speed for the soil sample 3

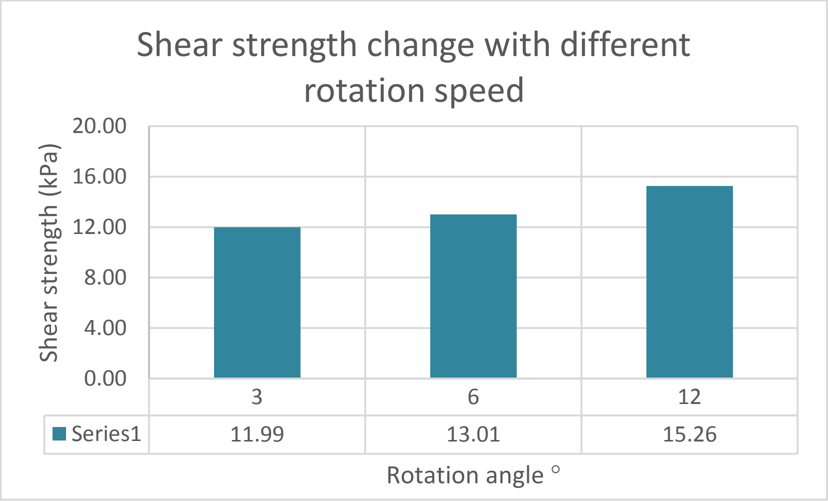


Figure 7-27: Undrained shear strength change chart with the different rotation speed for the soil sample 3

Height of the vane as a variable

The undrained shear strength rises, initially, with an increase in the height of the vane, then it reduces 1.5 kPa with the subsequent change of the height of the vane.

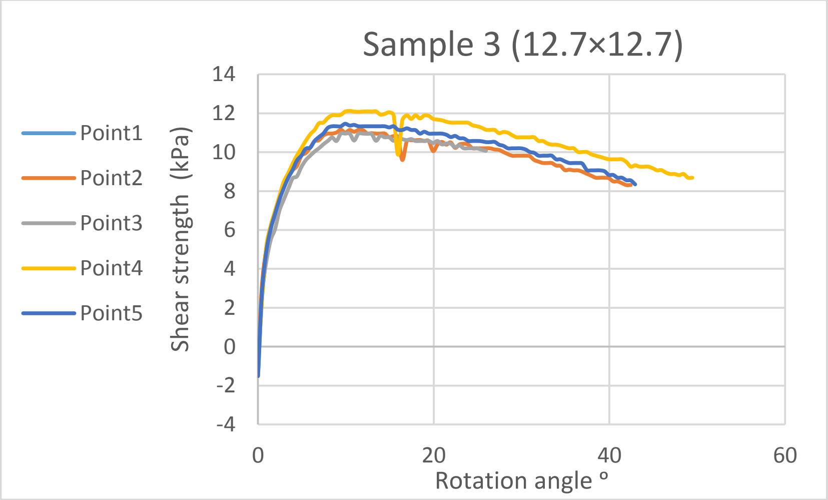


Figure 7-28: Undrained shear strength chart of 12.7×12.7 mm vane for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	10.44	11.15	10.95	12.12	11.46	11.23
Max. Torque (Nm)	0.02	0.05	0.05	0.05	0.05	0.05
Water content %	24.51					

Table 7-27: Shear strength evaluation results of 12.7×12.7 mm vane for the soil sample 3

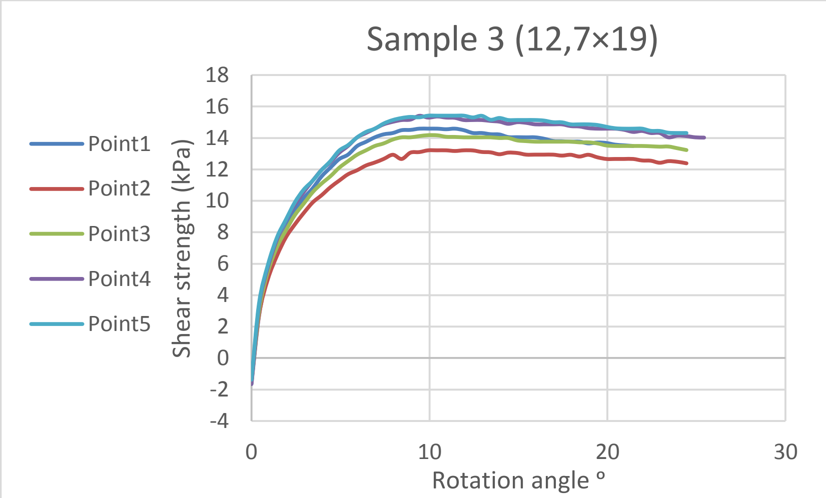


Figure 7-29: Undrained shear strength chart of 12.7×19 mm vane for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	14.59	13.21	14.18	15.41	15.42	14.56
Max. Torque (Nm)	0.086	0.078	0.083	0.091	0.091	0.086
Water content %	24.51					

Table 7-28: Shear strength evaluation results of 12.7×19 mm vane for the soil sample 3

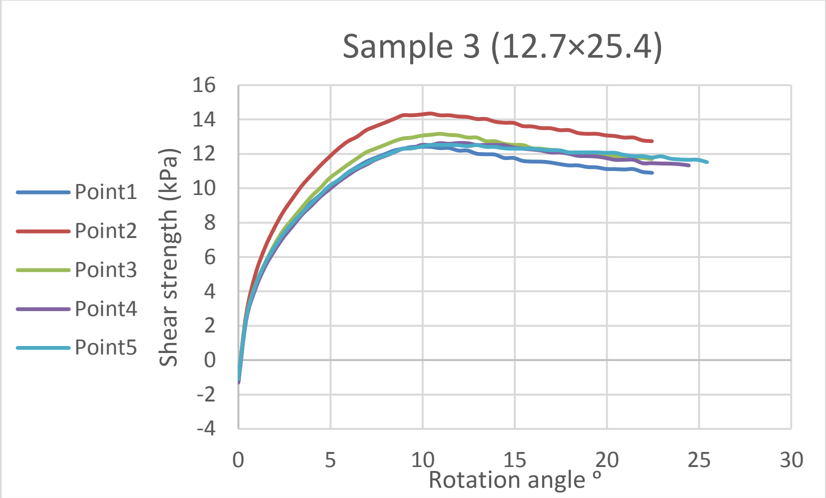


Figure 7-30: Undrained shear strength chart of 12.7×25.4 mm vane for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	12.41	14.35	13.17	12.63	12.52	13.01
Max. Torque (Nm)	0.09	0.11	0.10	0.09	0.09	0.10
Water content %	24.66					

Table 7-29: Shear strength evaluation results of 12.7×25.4 mm vane for the soil sample 3

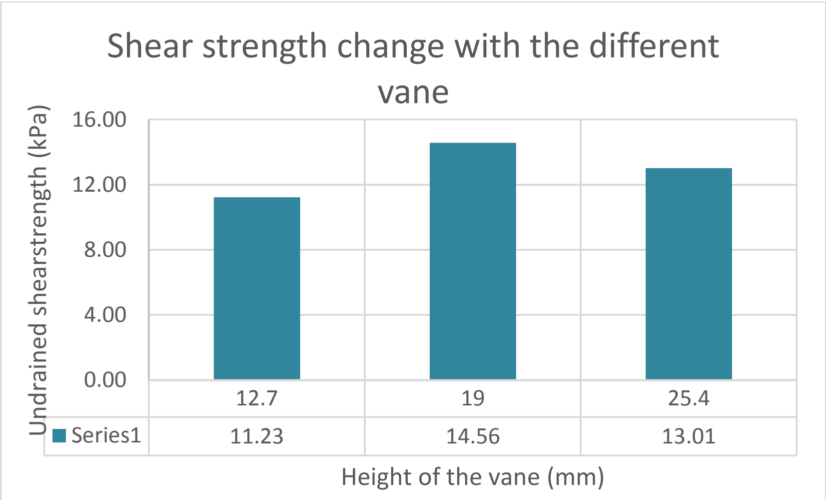


Figure 7-31: Undrained shear strength change chart with the different vane for the soil sample 3

Special experiments

- **The specimen with a division level at 38 mm.**

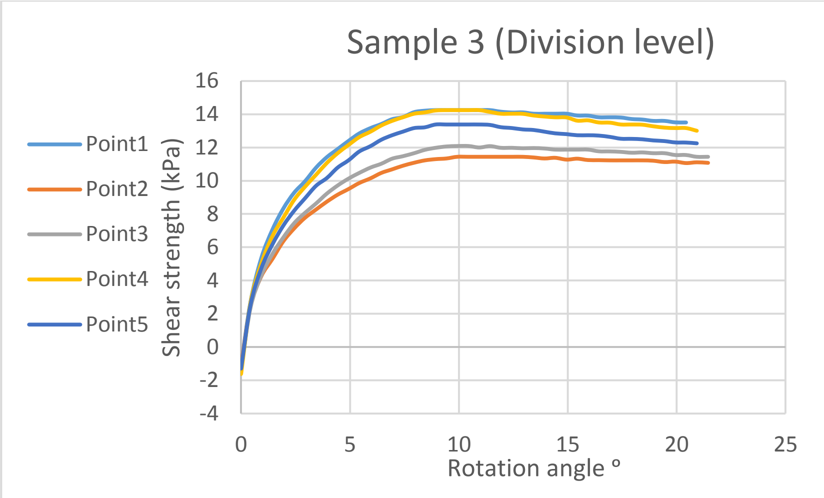


Figure 7-32: Undrained shear strength chart of the specimen with a division level for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	14.25	11.44	12.09	14.25	13.38	13.08
Max. Torque (Nm)	0.11	0.09	0.09	0.11	0.10	0.10
Water content %	24.63					

Table 7-30: Shear strength evaluation results of the specimen with a division level for the soil sample 3

- **The specimen with the same height of the standard vane (12.7×25.4).**

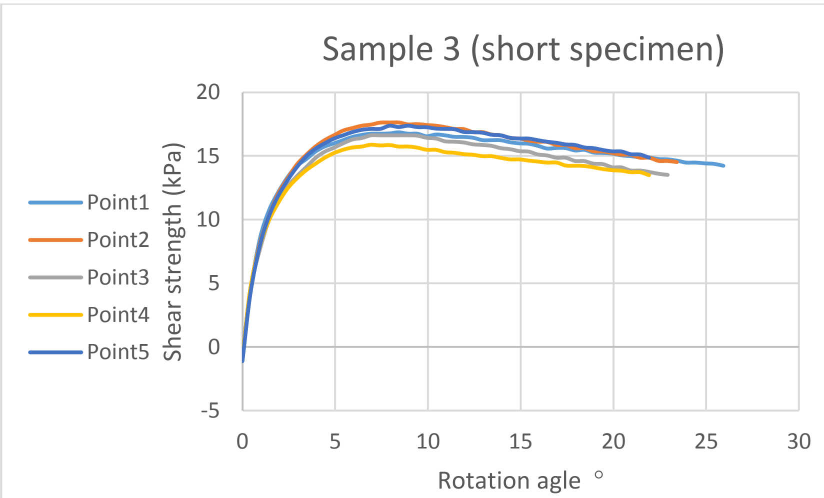


Figure 7-33: Undrained shear strength chart of the short specimen for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	16.86	17.63	16.62	15.88	17.37	16.87
Max. Torque (Nm)	0.11	0.11	0.11	0.10	0.11	0.11
Water content %	24.18					

Table 7-31: Shear strength evaluation results of the short specimen for the soil sample 3

- **The standard used vane which was entered into the soil only 15 mm of the height of the vane.**

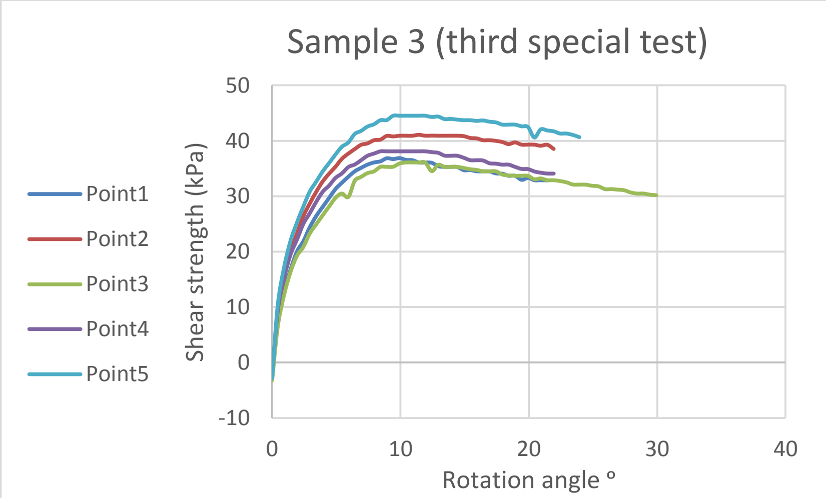


Figure 7-34: Undrained shear strength chart of the third special test for the soil sample 3

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	3.822	4.258	3.741	3.949	4.614	4.077
Max. Torque (Nm)	0.074	0.083	0.073	0.077	0.090	0.079
Water content %	23.66					

Table 7-32: Shear strength evaluation results of the third special test for the soil sample 3

7.3.2 **Fall cone test**

$Cu=c.g.\frac{m}{i^2}$

		60 g/60 °		
Test No.		**1**	**2**	**3**
Penetration depth	**mm**	2.81	3.01	3.17
Water content	**%**	24.26		

Table 7-33: Fall cone test results for undrained shear strength evaluation of sample 3

Cu=17.70 kPa

7.3.3 **Torvane test**

Test No.		**1**	**2**	**3**
Result	**Kg/cm^2**	0.27	0.29	0.28
Water content	**%**	24.202		

Table 7-34: Torvane test results for undrained shear evaluation of sample 3

Cu =27.46 kPa

7.3.4 **Pocket penetrometer test**

Test No.		**1**	**2**	**3**
Result	**ton/ft^2**	3.5	3.00	4.00
Water content	**%**	24.202		

Table 7-35: Packet penetrometer test results for undrained shear strength evaluation of sample 3

Cu**=**10.47 KPa

7.4 *Sample 4 (cl' sa $\overline{Si}$)*

7.4.1 Laboratory vane shear test

Rotation speed as a variable

In this sample, the undrained shear strength increases almost regularly with the increase in the rotational speed.

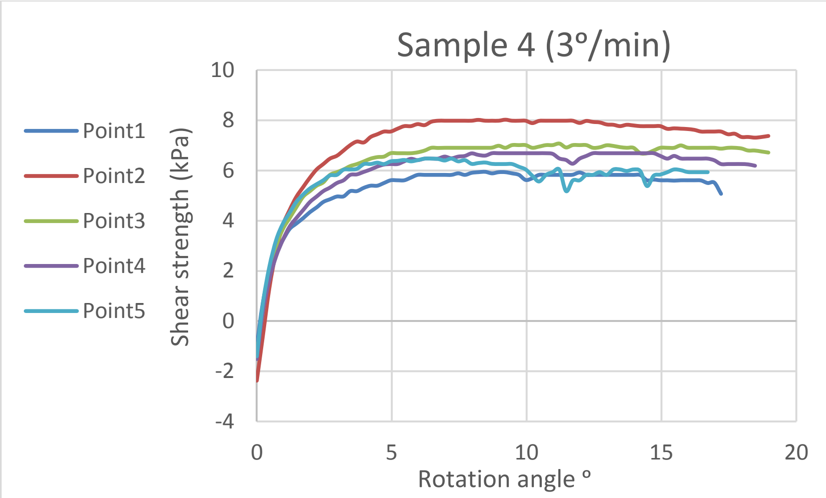


Figure 7-35: Undrained shear strength chart of 3 °/min rotation speed for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	5.95	8.03	7.08	6.69	6.48	6.84
Max. Torque (Nm)	0.04	0.06	0.05	0.05	0.05	0.05
Water content %	20.79					

Table 7-36: Shear strength evaluation results of 3 °/min rotation speed for the soil sample 4

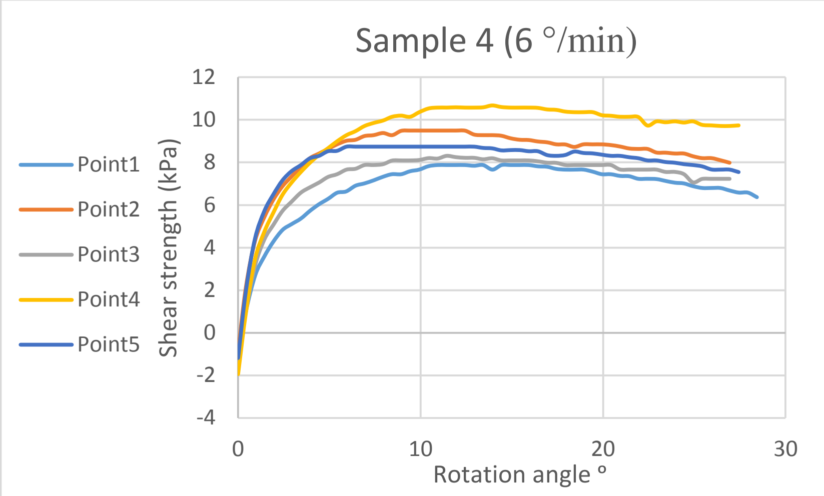


Figure 7-36: Undrained shear strength chart of 6 °/min rotation speed for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	7.88	9.50	8.31	10.68	8.74	9.02
Max. Torque (Nm)	0.06	0.07	0.06	0.08	0.07	0.07
Water content %	20.64					

Table 7-37: Shear strength evaluation results of 6 °/min rotation speed for the soil sample 4

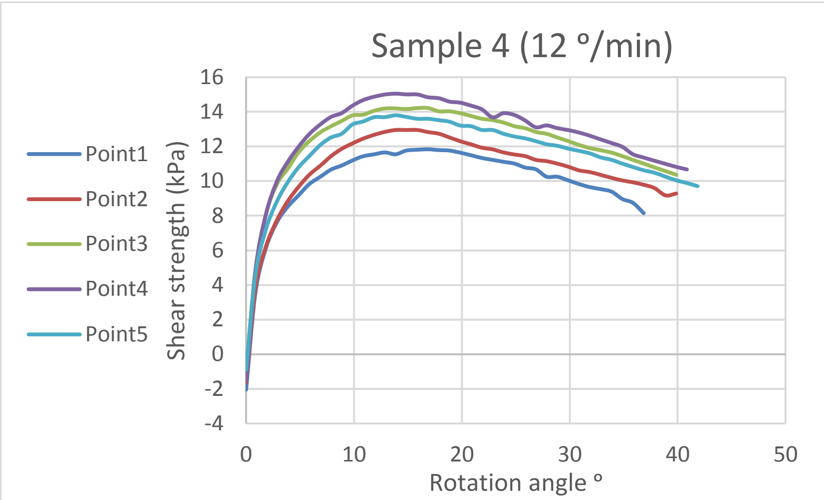


Figure 7-37: Undrained shear strength chart of 12 °/min rotation speed for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	11.84	12.95	14.22	15.05	13.80	13.57
Max. Torque (Nm)	0.09	0.10	0.11	0.11	0.10	0.10
Water content %	20.42					

Table 7-38: Shear strength evaluation results of 12 °/min rotation speed for the soil sample 4

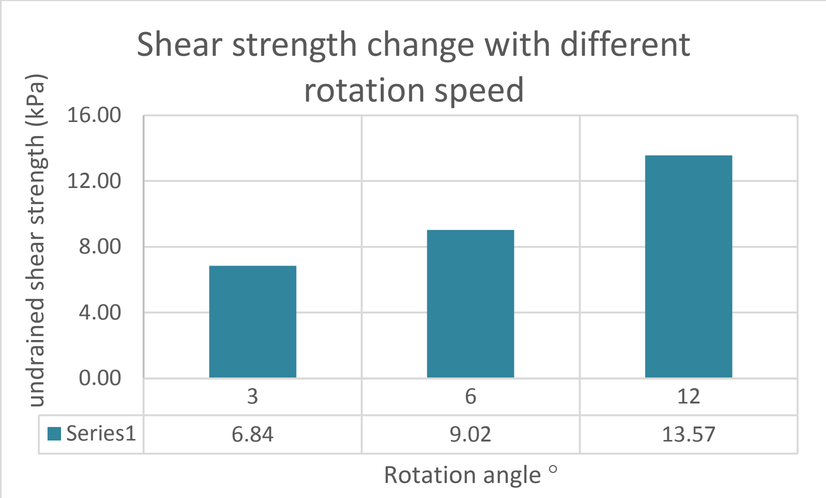


Figure 7-38: Undrained shear strength change chart with the different rotation speed for the soil sample 4

Height of the vane as a variable

The undrained shear strength of this sample grows with the first change of the height of the vane but in the second change, it remains almost equal to the previous amount.

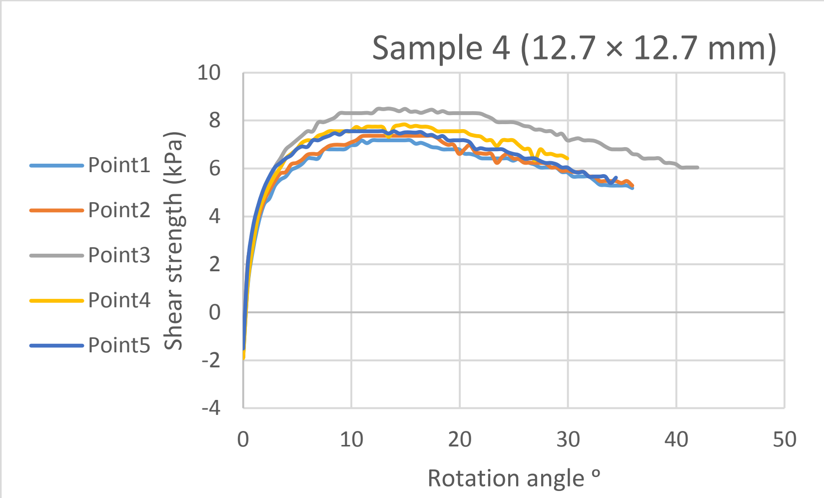


Figure 7-39: Undrained shear strength chart of 12.7 × 12.7 mm vane for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	7.176	7.365	8.498	7.837	7.554	7.686
Max. Torque (Nm)	0.031	0.032	0.036	0.034	0.032	0.033
Water content %	21.50					

Table 7-39: Shear strength evaluation results of 12.7 × 12.7 mm vane for the soil sample 4

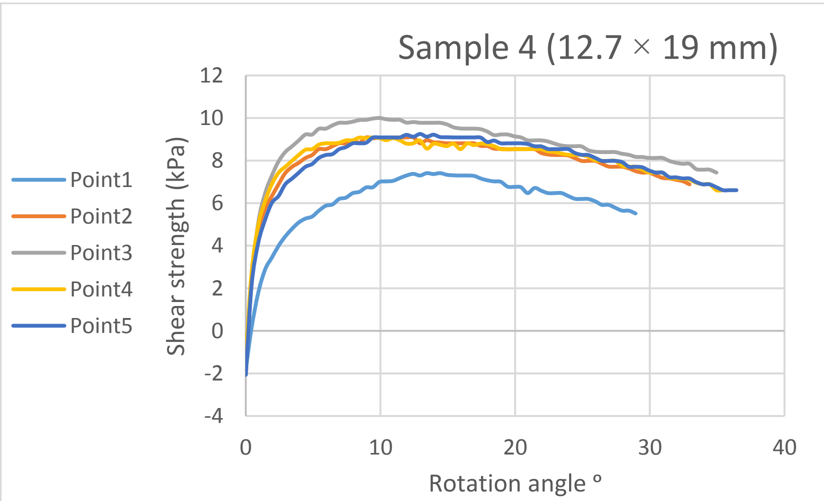


Figure 7-40: Undrained shear strength chart of 12.7 × 19 mm vane for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	7.407	9.085	9.996	9.085	9.248	8.964
Max. Torque (Nm)	0.044	0.053	0.059	0.053	0.054	0.053
Water content %	20.98					

Table 7-40: Shear strength evaluation results of 12.7×19 mm vane for the soil sample 4

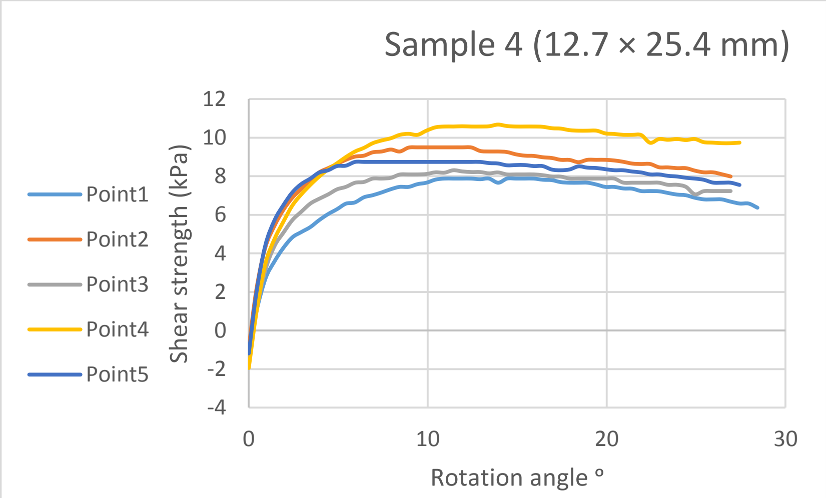


Figure 7-41: Undrained shear strength chart of 12.7 × 25.4 mm vane for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	7.88	9.50	8.31	10.68	8.74	9.02
Max. Torque (Nm)	0.06	0.07	0.06	0.08	0.07	0.07
Water content %	20.64					

Table 7-41: Shear strength evaluation results of 12.7 × 25.4 mm vane for the soil sample 4

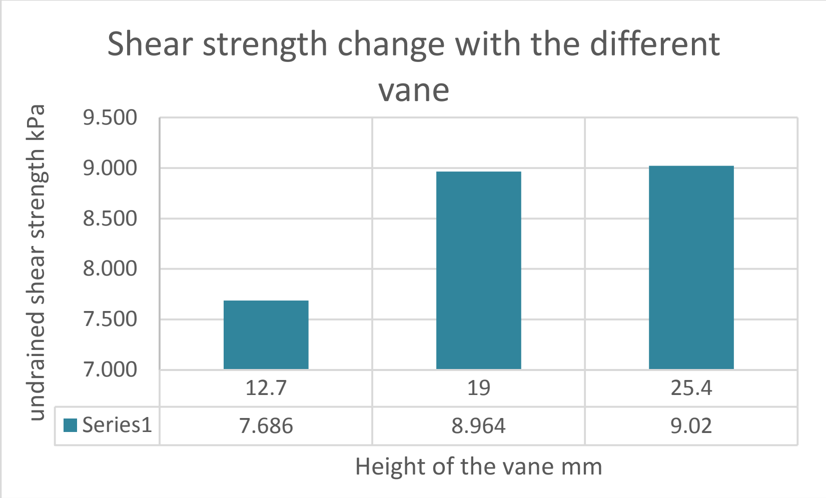


Figure 7-42: Undrained shear strength change chart with the different vane for the soil sample 4

Special experiments

The sample 4 was not at all a plastic soil. Therefore, the second special test which was implemented with a specimen with the same height of the used vane (12.7×25.4) was impossible to be performed.

- **The specimen with a division level at 38 mm.**

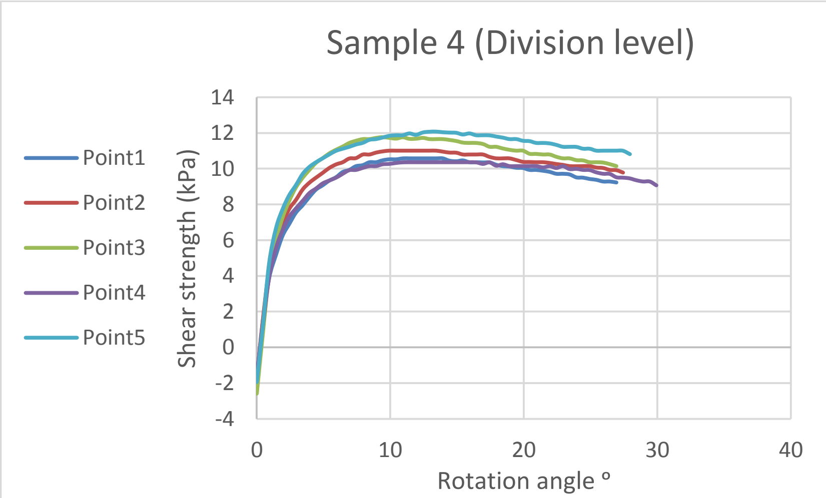


Figure 7-43: Undrained shear strength chart of the specimen with a division level for the soil sample 4

	Point 1	Point 2	Point 3	Point 4	Point 5	Average
Max. shear strength (kPa)	10.58	11.01	11.76	10.36	12.07	11.16
Max. Torque (Nm)	0.08	0.08	0.09	0.08	0.09	0.08
Water content %	21.04					

Table 7-42: Shear strength evaluation results of the specimen with a division level for the soil sample 4

- **The standard used vane which was entered into the soil only 15 mm of the height of the vane.**

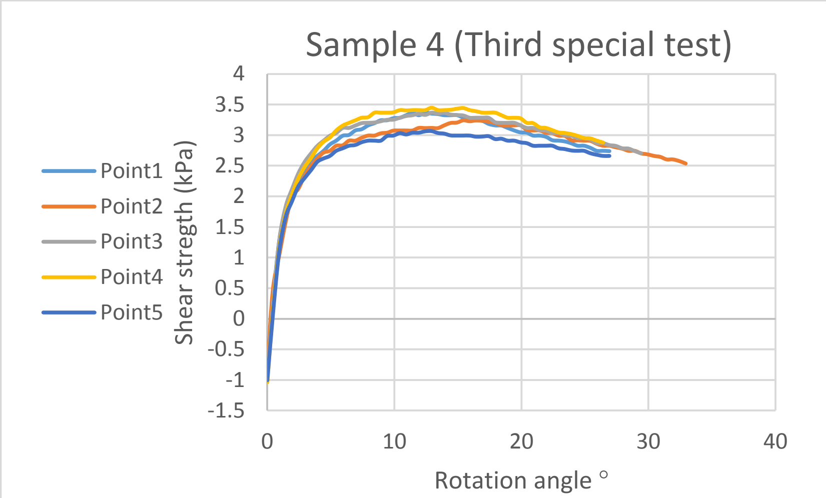


Figure 7-44: Undrained shear strength chart of the third special test for the soil sample 4

	Point 1	Point 2	Point3	Point4	Point 5	Average
Max. shear strength (kPa)	3.37	3.24	3.37	3.45	3.07	3.30
Max. Torque (Nm)	0.07	0.06	0.07	0.07	0.06	0.06
Water content %	20.12					

Table 7-43: Shear strength evaluation results of the third special test for the soil sample 4

7.4.2 Fall cone test

$Cu=c.g.\frac{m}{i^2}$

		80 g/30 °		
Test No.		**1**	**2**	**3**
Penetration depth	**mm**	4.32	4.71	4.10
Water content	**%**	21.20		

Table 7-44: Fall cone test results for undrained shear strength evaluation of sample 4

Cu=32.78 kPa

7.4.3 Torvane test

Test No.		**1**	**2**	**3**
Result	**Kg/cm^2**	0.31	0.36	0.38
Water content	**%**	20.32		

Table 7-45: Torvane test results for undrained shear evaluation of sample 4

Cu =34.32 kPa

7.4.4 Pocket penetrometer test

Test No.		**1**	**2**	**3**
Result	**ton/ft^2**	1.00	1.20	1.00
Water content	**%**	20.32		

Table 7-46: Packet penetrometer test results for undrained shear strength evaluation of sample 4

Cu**=**51.07 kPa

8 Conclusion and discussion

8.1 *Comparison of the liquid limit of soils resulted from Casagrande and fall cone test methodology*

One of the focuses of this work is to investigate the liquid limit test performed on the Casagrande and fall cone apparatus. Table 8-1 shows the liquid limit of the specimens measured by both Atterberg and fall cone methods.

No.	Name	Atterberg W_L	Fall cone W_L	Δ W_L [%]	clay/silt
1	cl' sa Si̅	26.86	32.30	3.44	0.13
2	sa' cl̅ Si̅	34.33	38.23	3.90	0.92
3	cl' sa Si̅	25.53	26.95	1.42	0.12
4	sa' cl' Si̅	29.56	35.34	5.78	0.19
5	sa c̅l Si̅	28.95	32.81	3.86	0.95

Table 8-1: The liquid limit results from Casagrande- and fall cone test

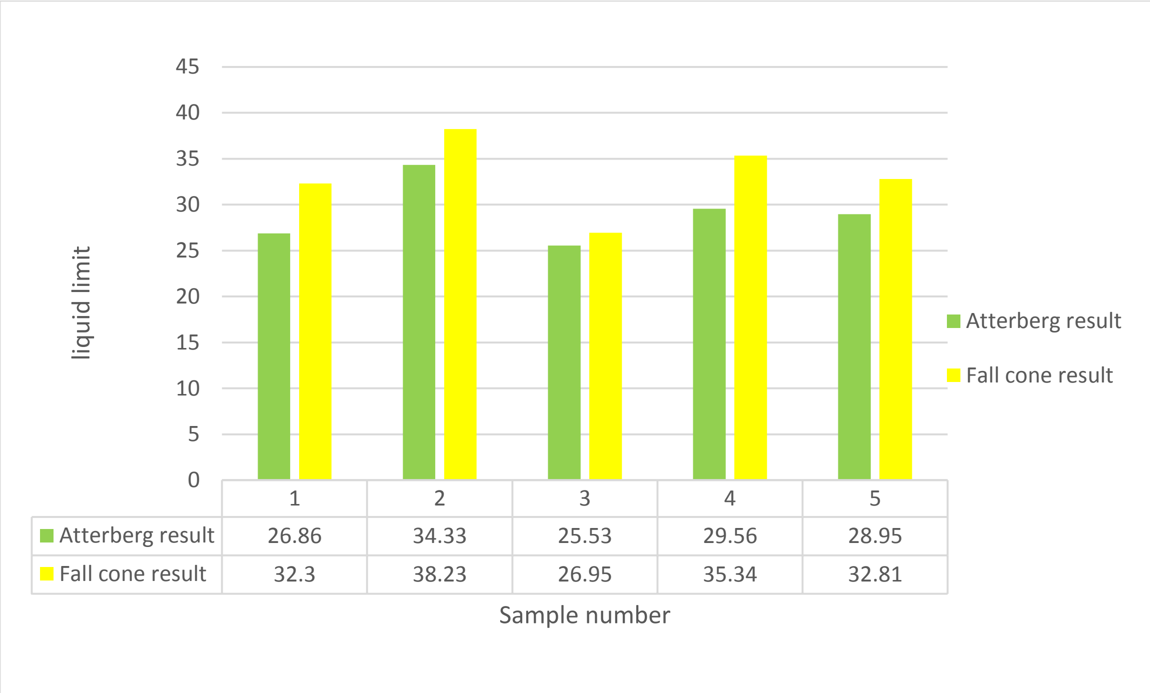


Figure 8-1: Comparison of the liquid limit results

As demonstrated by the results, the fall cone liquid limit is greater than the Casagrande. The difference value of liquid limit determination through these two methods are between 1.42 to 5.78 and the average deviation is 3.6.

This deviation value for two samples, which have almost the same amount of clay and silt, are almost equal and are near the average deviation value. But in samples which have a significantly higher amount of silt in comparison with the clay, the deviation value changes in a wide range. The fewest deviation value belongs to the third sample, which was not a plastic soil. Therefore based on the grain size distribution, it can be suggested that the liquid limit of the samples with a high amount of silt should be determined with the fall cone method and its measurement’s accuracy also increases. Additionally, the cone penetrometer test is less time consuming and also easier to be done because the preparation and implementation of the experiment are defined through the simple boundary conditions and it contains a little scope of sources of errors.

8.2 *Assessment of the cone penetration after 5 s*

In this part, the penetration depth of the cone after 5 s was assessed. In every sample 4 or 5 times after the liquid limit test with the different water content the subsidence of the cone was observed and all of the results were collected in chapter 4 in two charts. The column chart displays the penetration depth in every respective second and the second chart shows the slope of the penetration depth in every single test. Table 8-2 presents the slope of the penetration lines with the water content of the soils and the average slope for every sample.

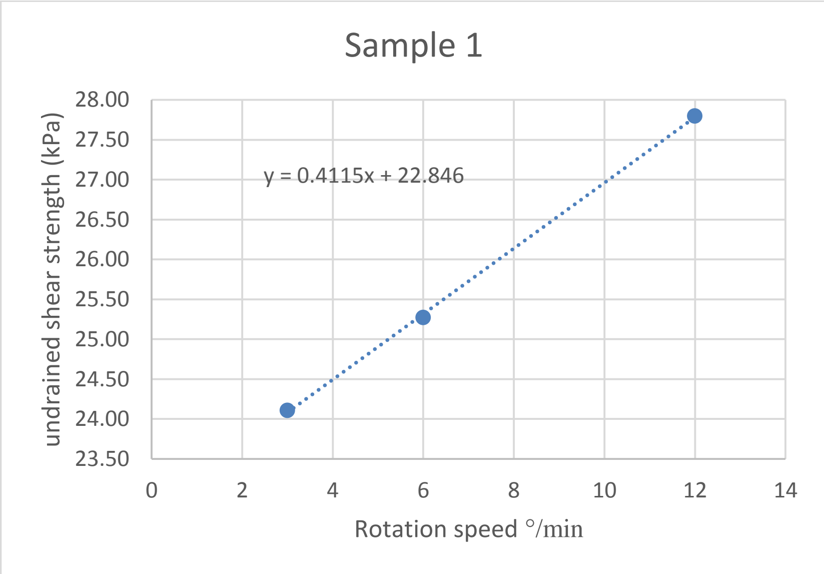
No.	Name	1st test slope	2nd test slope	3rd test slope	4th test slope	5th test slope	average slope	clay/silt	W_L
1	$cl'\ sa\ \overline{Si}$	0.0012	0.0022	0.0042	0.0063	-	0.0035	0.13	32.30
water content [%]		30.57	33.00	35.65	37.53				
2	$sa'\ \overline{cl}\ \overline{Si}$	0.0008	0.0011	0.0004	0.0007	-	0.0008	0.92	38.23
water content [%]		30.47	33.38	37.62	43.25				
3	$cl'\ sa\ \overline{Si}$	0.002	0.002	0.0021	00021	0.0053	0.0027	0.12	26.95
water content [%]		25.82	25.44	27.94	28.53	29.49			
4	$sa'\ cl'\ \overline{Si}$	0.0017	0.0038	0.005	0.0033	-	0.0033	0.19	35.34
water content [%]		31.66	33.83	36.96	37.68				
5	$sa\ \overline{cl}\ \overline{Si}$	0.0013	0.0019	0.0018	0.0021	0.0018	0.0018	0.95	32.81
water content [%]		27.79	38.80	34.09	30.63	29.51			

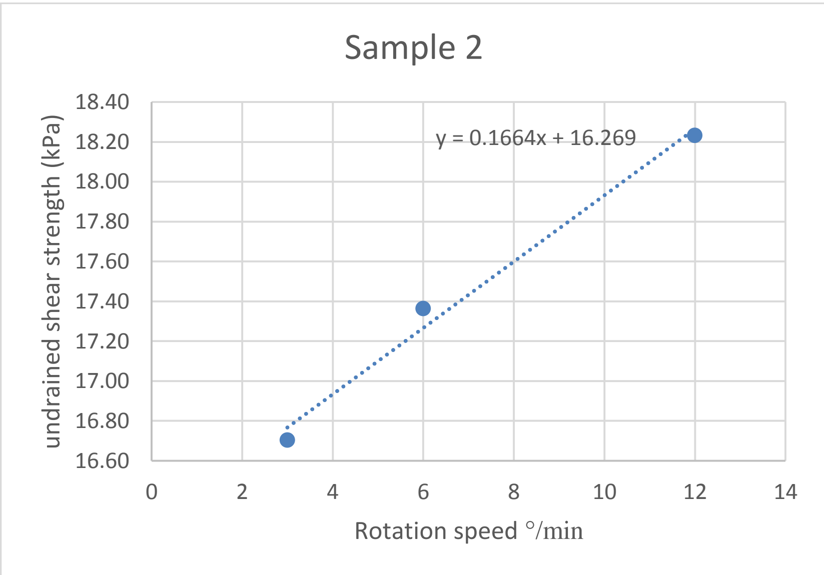
Table 8-2: Cone penetration line slopes of the soil samples

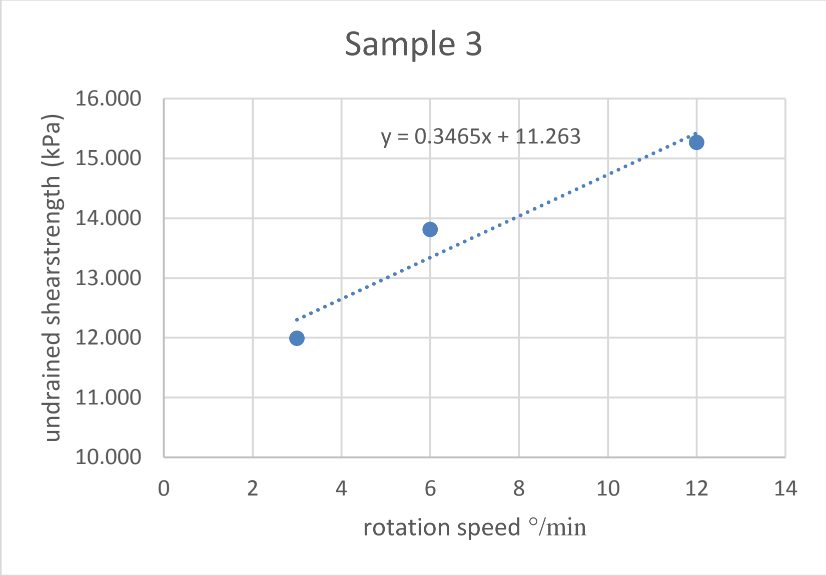
As can be seen from the results given in chapter 4, the penetration depths after 5 s barely change. In most of the tests shown in Table 8-2, the slope of the cone penetration increases with the increase of the water content of the soils. In addition, the samples 1, 3 and 4 with a higher amount of silt in comparison to clay show the higher average slope of penetration. This phenomenon might be due to the dilatancy and the water utilization of these types of soils with high amount of silt. Moreover, the samples 2 and 5, i.e. containing the highest amount of clay, have the smallest amount of the average slope.

8.3 *Undrained shear strength evaluation with increasing the rotation speed*

The undrained shear strength (C_u) was observed on the four soil samples with increasing the rotation speed.







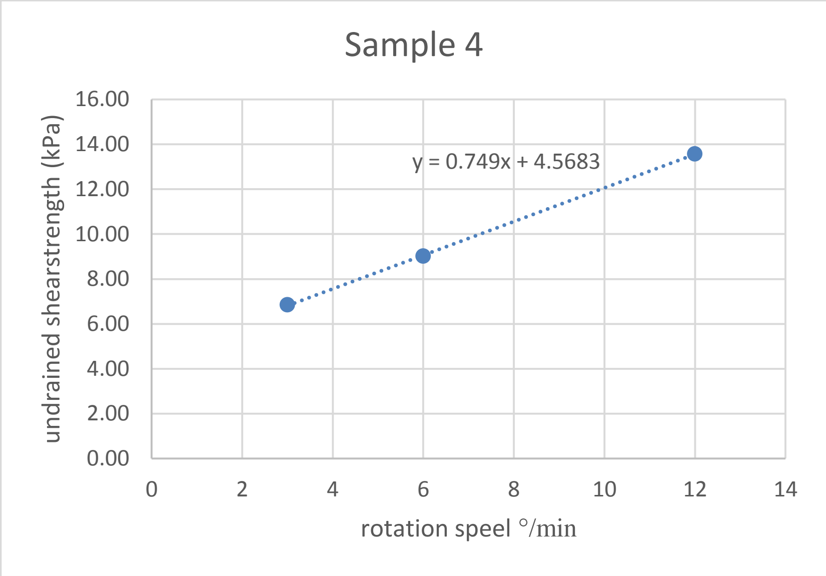
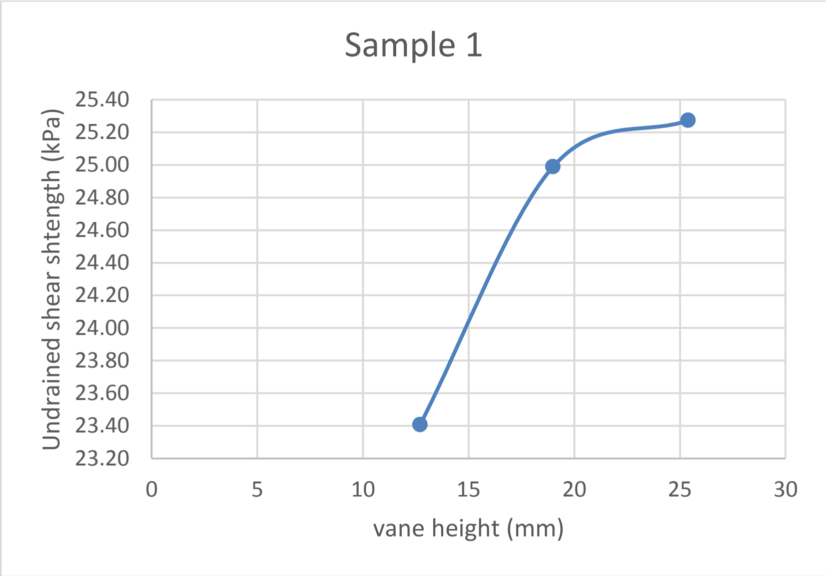


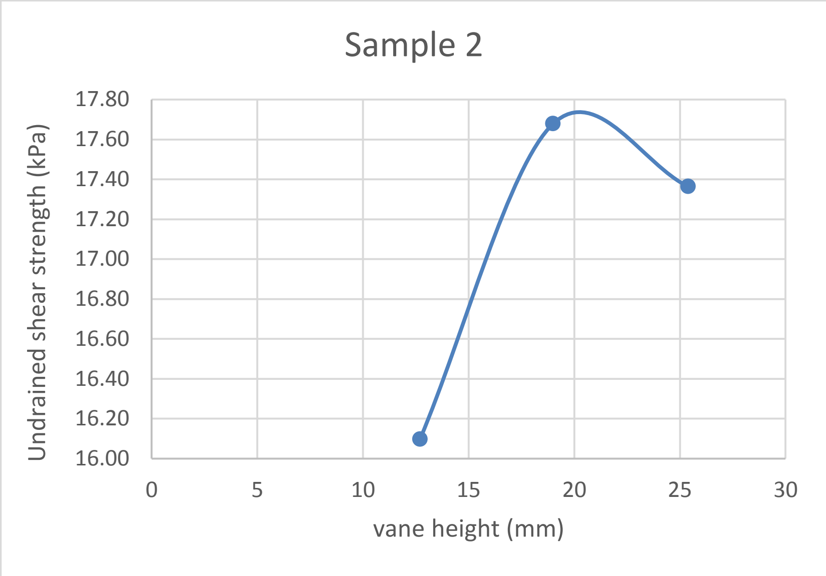
Figure 8-2: Undrained shear strength variation versus the rotation speed change

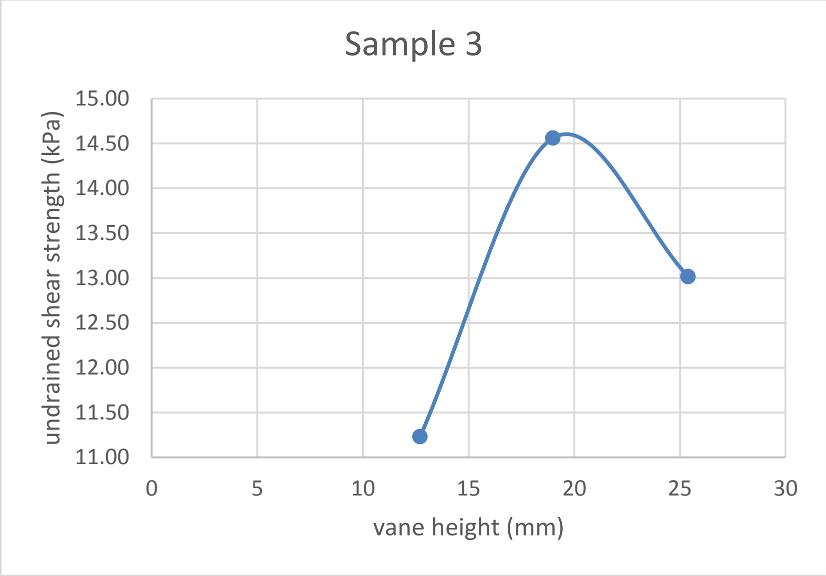
As can be seen from the above figures C_u increases in all of the soil samples with rising the rotation speed. It is remarkable that the mentioned velocity in standards is between 6 °/min to 12 °/min. But in reality is visible that C_u changes significantly from 6 °/min to 12 °/min.

8.4 *Undrained shear strength evaluation with changing the vane height*

This section deals with the change of the C_u with rising the vane height. As the below charts show, the soil samples do not behave the same manner.







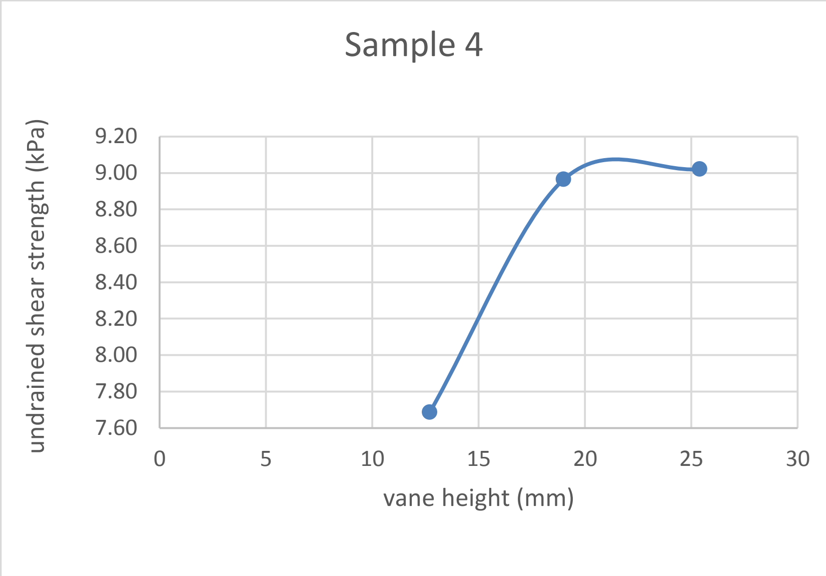


Figure 8-3: The undrained shear strength variation with the vane height increase

In all of the samples the amount of C_u increases significantly with the change of the vane height from 12.7 mm to 19 mm. Therefore, all of the soil samples behave similar to each other in this part of the experiment. But with enhancing the vane height from 19 mm to 25.4 mm they do not show the similar behavior. The third value of C_u rises in the first and fourth soil samples and sinks in the second and third soil samples. The amount of this increase in the first soil sample is just 0.28 kPa and in the fourth soil sample is just 0.06 kPa. Also in the third soil sample the C_u value decreases just in 0.32 kPa. Hence the change of the third amount of C_u was not considerable in this three soil samples. But the third soil sample shows a different behavior. It reduces 1.55 kPa from second value to the third value.

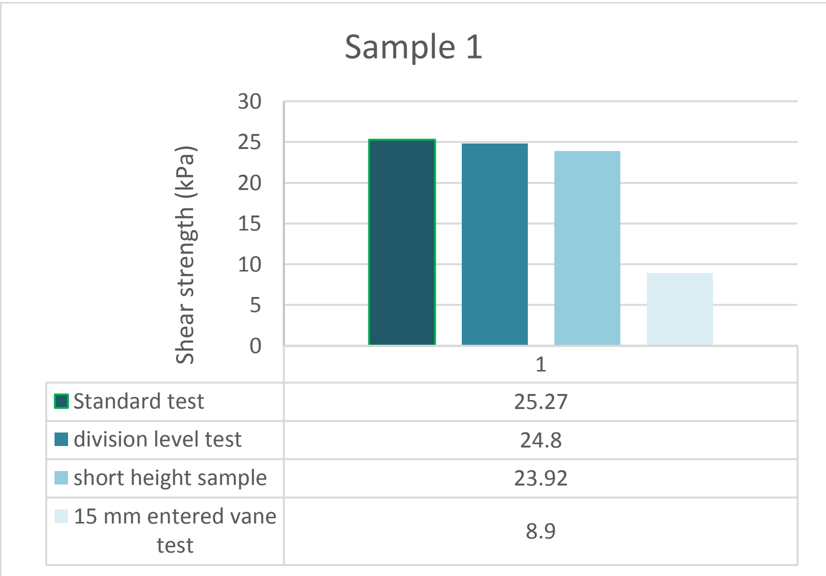
Sample No.	Sand (%)	clay/silt
Sample 1	45.5	0.94
Sample 2	29.8	0.95
Sample 3	10.5	0.92
Sample 4	22.7	0.12

Table 8-3: Sand share and the ration of the clay/silt for the soil samples

Table 8-3: Sand share and the ration of the clay/silt for the soil samples show the amount of the sand share of the sample 3 which is clearly less than the others. In order to assess the influence of the amount of the sand, it can be suggested to sluice out the sand of all the soil samples and repeat the experiments again.

8.5 *Comparison of the special tests with the standard test of vane shear test*

In accordance with the standards, the laboratory vane shear test should be implemented with the rotation speed of 6-12 °/min vane with the ratio of the height/diameter of 2. For this reason, the test with the 6 °/min rotation speed and the vane with 25.4/12.7 mm ratio of the height/diameter was assumed as the standard test. In this part of the study, the results of the special tests were compared with the standard test of laboratory vane shear test for each of the soil samples.



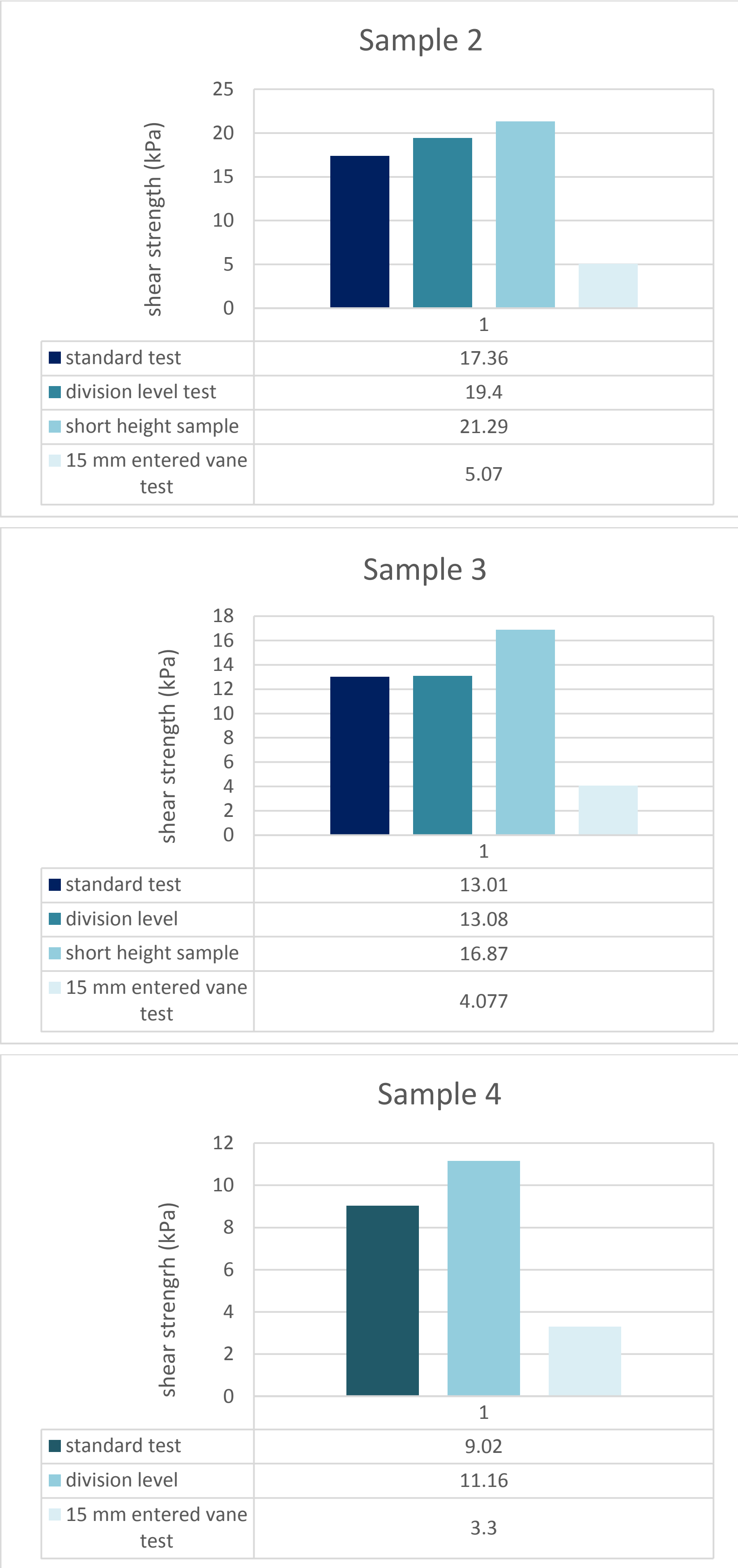


Figure 8-4: Comparison of the special tests results with the standard test

	sample1	sample2	sample3	sample4
division level test - standard test (kPa)	-0.47	2.04	0.07	2.14
short height sample test – standard test (kPa)	-1.35	3.93	3.56	-
15 mm entered vane test-standard test (kPa)	-16.37	-12.29	-8.93	-5.27

Table 8-4: Comparison of the special tests results with the standard test

As the charts and the table show, the first and the second experiments do not behave in a similar manner for every soil sample. The first test with a division level at 38 mm of the sample sometimes shows results which are higher than the standard test and in some cases lower than the standard test. Also, the experiment with the short sample demonstrates higher values than the standard test in the second and third soil samples and a lower value than the standard test for the first soil sample. But the third experiment with the 15 mm entered vane in the sample always underestimates the shear strength of the soils significantly in comparison with the standard test. Hence these special tests are not assessable and cannot be investigated for the undrained shear strength evaluation.

8.6 *The standard laboratory vane shear test in comparison with the fall cone.-, torvane – and pocket penetrometer test*

In the last part of this research, two in situ and one laboratory method were compared with the standard state of the laboratory vane shear test. The obtained results from all of the methods for four tested soils are illustrated in Table 8-5.

Soil sample Nr.	Fall cone test (kPa)	Torvane test (kPa)	Pocket penetrometer (kPa)	Laboratory vane shear test (kPa)
1	74.86	38.9	32.72	25.27
2	47.47	36.94	13.217	17.36
3	17.7	27.46	10.47	13.01
4	32.78	34.32	51.07	9.02

Table 8-5: The obtained tested results from different methods

As mentioned in the previous chapter, the fall cone test's values are calculated from an empirical correlation to φ. As can be seen from the above table the standard fall cone test gives significantly higher values of undrained shear strength in comparison to laboratory vane shear test, but for the higher plastic soil (sample 3) it shows a lower difference. On the other hand, grain size can be the other factor which is responsible for the diversity between the results obtained by the two methods, although it is not clear exactly which factors determine the difference.

According to the results observed, it is visible that the gained torvane test results are significantly higher than the standard laboratory vane shear test. It could be because the shear strength of cohesive soil is dependent upon many factors, including the rate of loading, progressive failure, the orientation of the failure plane, pore water immigration during testing, etc. The torvane does not eliminate the effects of any of these variables. The torvane is rarely used because the available automated vane shear device has a larger range, better precision, and superior accuracy.

The last comparison is the pocket penetrometer test and the laboratory vane shear test. The fourth soil sample behaves differently from the other samples in this test. The difference of the obtained value is visibly high for this sample but in other soil samples are not significant. It can be so concluded that the plasticity is an effective factor in the accuracy of this test. The pocket penetrometer is used to check visual classification and the reading obtained from this method cannot replace laboratory test results due to the fact that a small area of penetration could give a misleading result. The instrument should not be used for obtaining foundation design data.

8.7 *Conclusion*

From the discussions given in this chapter, we can conclude that:

- the value of the liquid limit determined by the fall cone test was always greater than those measured by the Casagrande test
- the samples with higher amount of Silt content had larger value of cone penetration rate after the 5^{th} second
- the undrained shear strength increases with increasing the rotational speed in all of the samples
- the undrained shear strength was for smaller height of the vane, i.e. up to 19 mm, dependent on the height of the vane. This value did not change by a further increase of the height of the vane
- in the special tests, the one with the division level at 38 mm had the closest value of undrained shear strength to that of the standard test. Moreover, the one with the 15 mm entered vane had the largest difference of the undrained shear strength compared to that of the standard test.
- the obtained values of the undrained shear strength of an identical soil sample using different experimental methods were not equal to each other

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