Comparison of liquid limit of highly plastic clay by means of casagrande and fall cone apparatus

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ABSTRACT
The connection between the Liquid Limit found using the Casagrande and the Fall Cone Apparatus is tested for the Danish Eocene Clay that has Liquid Limits up to 350% and Plasticity Index up to 300%, which is well outside the normal range of Casagrande's Plasticity Chart. Based on the high plasticity of the Danish Eocene Clay two new classification categories are introduces to the Plasticity Chart in order to fully describe the clay; super high plasticity Clay (CS) and extremely high plasticity clay (CE), covering the range up to Liquid Limits up to 200% and 350% respectively. A correlation between the Liquid Limit from the Casagrande and the Fall Cone Apparatus is for super high plasticity clay. For extremely high plasticity clay it was found that the Fall Cone method underestimated the Liquid Limit with up to 43 percentage points, making the Fall Cone an unreliable method of finding the Liquid Limit for extremely high plasticity clay

PRESENTACIONES TÉCNICAS
La relación entre el limite liquido es obtenida usando los métodos de Casagrande y el Cono de caída, ensayados para arcillas Danesas del Eoceno las cuales alcanzan limites líquidos de hasta 350% e índices plásticos de hasta 300%, lo cual está muy alejado del rango contemplado en la gráfica de Casagrande. Basándose en la alta plasticidad de las arcillas Danesas del Eoceno, dos nuevas categorías de clasificación son introducidas en el diagrama de plasticidad, de manera que la arcilla queda completamente descrita; arcillas súper plásticas (CS) y arcillas extremadamente plásticas (CE), de tal modo, que el limite liquido superior de 200% y 350% respectivamente queda completamente cubierto. Una correlación entre el limite líquido por Casagrande y el cono de Caída es hallada para arcillas súper plásticas. Para arcillas extremadamente plásticas, se halló que el método del Cono de caída infravalora el limite liquido hasta con un 43 por ciento, lo cual hace del Cono de caída un método poco fiable para determinar el limite liquido de arcillas extremadamente plásticas.

1 INTRODUCTION

The Atterberg Limits play a great role in assessing and classifying clay. Atterberg divided the behavior of clay into types, depended on the water content of the clay, the Atterberg Limits. The plasticity of clay is a property in clay that allows wet clay to be molded into a given shape when pressure is applied, and sustain the shape when pressure is released. The Plastic Limit, w_P, is the water content, at which the clays consistency changes from semi-solid to plastic. The Liquid Limit, w_L is the water content at which the consistency changes from plastic to liquid. The Plasticity Index, I_P, is given as the difference between the Liquid Limit and the Plastic Limit. The definition of the Atterberg Limits can be seen in Figure 1.

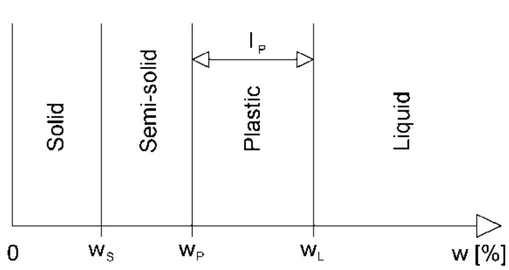

Figure 1. Atterberg Limits.

Classification of clay is done by Casagrande's Plasticity Chart (Casagrand, 1932), which covers a Liquid Limit up to 100% and a Plasticity Index up to 60%. The highly plastic Danish Eocene Clay has Liquid Limits up to 350%, making the normal plasticity chart useless to classify the Danish Eocene Clay. The Plasticity Chart for the Danish Eocene Clay can be seen in Figure 6.

The Liquid Limit is traditionally been determined by use of the Casagrande percussion cup method. This method is however very dependent on the apparatus and the person operating it, possibly resulting in variations of the results of each individual sample. Hansbo (1957) showed through a series of tests, that the Fall Cone Apparatus could be used as a quick and easy way to find the shear strength of soils. Wroth and Wood (1978) found that the Liquid Limit test establishes the water content, at which the clay has a certain undrained shear strength. They suggested, based on series of tests, that the Liquid Limit corresponds to a fall depth of 10 mm, when using a cone weighing 60 grams and having an angle of 60°.

Wasti (1987) compared Liquid Limits in the range between 27% and 110%, found by using the Casagrande and the Fall Cone method, of 15 soils from different locations in Turkey. The correlation found was given by:

$$w_{L(FC)} = 1.0056 \cdot w_{L(C)} + 4.92 \qquad [1]$$

where $w_{L(FC)}$ and $w_{L(C)}$ is the Liquid Limit found by respectively the Fall Cone and the Casagrande method, most of these tests were covered by the Plasticity Chart. The correlation between the two methods becomes more unclear, due to lack of data, for clay with extremely high Liquid Limits, like the Danish Eocene Clay. Head (2006) and Karlsson (1977) shoved that the Fall Cone tends to underestimate the Liquid Limit for clay which exceed the normal range of the Plasticity Chart.

The plastic properties of clay are, among other things, dependent on its ability to bind water to the crystal structure; this ability depends on the mineral composition of the clay. A description of the clay minerals in the tested Danish Eocene Clay can be seen in section 2.1.

In recent years the Fall Cone penetration method has however started to become the preferred method of determining the Liquid Limit compared to the Casagrande Apparatus method. It is wanted to find if this comparability of the two methods also applies to clays with an extremely high Liquid Limit, such as the Danish Eocene Clay.

In this paper the correlation between Liquid Limit found by the Fall Cone and the Casagrande method is assessed for highly plastic clays with Liquid Limits up to 350%, and a modification of Casagrande's Plasticity Chart is considered.

2 DESCRIPTION OF THE DANISH EOCENE CLAY

The climate of the Eocene period was in Northern Europe tropical or subtropical, and the sediments of the period are all deposited in the ocean of the time. The changes in the characteristic of the sediments are due to the changes in the water level and the degree of living organisms of the time. The sediments changes from limestone in the earlier deposits to clays and silt in the latest deposits. Through the Eocene layers around 180 layers of ashes from volcanic eruption can be found, evidence of a great and long lasting geological change. Above the layers of ashes large quantities of plastic clay is found. In Århus, Denmark the Danish Eocene Clay is located to depths of more than 70 meters and has a very high concentration of lime. The lime concentration varies from very light, 1 %, to highly limy, 65 % (Grontmij | Carl Bro 2008). The lime originates from coccoliths that lived when the Danish Eocene Clay was deposited.

Based on the coccoliths the age of the Danish Eocene Clay from a location in Århus, Denmark is determined. The coccoliths are all from NP zone 15 and 16, estimating the age of the Danish Eocene Clay to be between 40.5 and 46 million years old. It was determined that all the samples were from the Middle Eocene age, and the formations are located in a correct stratigraphic order, with no overlapping. (Thomsen, 2008)

2.1 Mineralogy

An analysis of the composition of the clay minerals in the Danish Eocene Clay has been made by Balic-Žunić (2008), it showed a very large percentage, up to 95%, of the clay have a grain diameter less than 2 μm. The composition of the clay minerals can be seen in Table 1.

The Clay mineralogy is the primary factor controlling the physical and chemical properties of clay. There are big differences on the behavior of each mineral type, and how big an influence it has on the plasticity. The clay mineral Smectite has a very large influence on the swelling of clay, since it has a big tendency to expand when it comes in contact with water. As can be seen in Table 1, almost half of the clay particles are Smectite, making the Danish Eocene Clay a very expansive clay, capable of absorbing large amounts of water.

Table 1. The composition of the clay minerals in the Danish Eocene Clay. The percentage of each clay mineral is in relation to the clay portion of the soil, and not the total soil sample. (Balic-Žunić, T. 2008.)

Depth (m)	15	30	45	60
Clay (%)	95.6	72.8	76.4	74.0
Kaolinite (%)	19	12	14	15
Illite (%)	33	15	12	17
Smectite (%)	44	34	42	33
Calcite (%)	2	25	30	34
Quartz (%)	2	1	1	1
Siderite (%)	-	7	1	-
Rhodochrosite (%)	-	6	-	-

2.2 Geotechnical properties

During and after boring a number of classification test was made on the Danish Eocene Clay and the pore water in the clay, the geotechnical properties can be seen in Table 2. Classification tests were made by Grontmij | Carl Bro (2008).

Table 2. Information and geotechnical properties of the Danish Eocene Clay. (Grontmij | Carl Bro 2008)

Age (mil. Years)	-	40.5 - 46
Depth[1] (m)	-	10 - 70
Water Content (%)	w	20 - 55
Liquid Limit (%)	w_L	87– 350
Plastic Limit (%)	w_P	31 – 60
Plasticity Index (%)	I_P	55– 285
Unit weight (kN/m^3)	γ	16.7 – 18.1
Vain strength (kPa)	c_v	280 - >715
Angle of friction (^{o})	φ'	12 - 25
Lime content (%)	-	1 - 65
pH	-	8.6 – 9.6
Cl^- content (%)	-	0.5 – 1.6

[1] The depth of which the Danish Eocene Clay is present.

The natural water content of the samples is similar to the Plastic Limit of the clay, meaning the soil in its natural state is semi-solid to only just plastic, cf. Figure 1. The pH and the Chloride concentration of the sample is measured in pore water extracted from the soil.

3 METHODS

Two methods have been use to determine the Plasticity Index of the Danish Eocene Clay, and there are found pro and cons with both.

3.1 Casagrande

The Casagrande Apparatus tests are carried out on an apparatus with a base of bakelite and a brass cup with a manual handle, Figure 2. A similar apparatus, but with an automatic handle, was also used for a portion of the tests, and the tests gave identical results independent of the apparatus used, the measured water content and the resulting Liquid Limit.

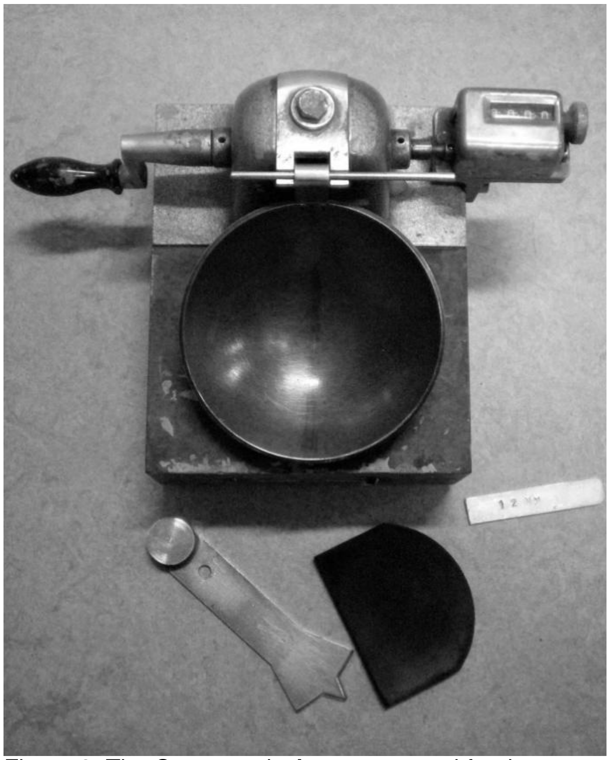

Figure 2. The Casagrande Apparatus used for the tests.

When using a Casagrande Apparatus, the Liquid Limit is defined as the water content at which the groove closes over a distance of 12 mm after 25 strokes at a rate of 2 strokes per second.

The results obtained by the Casagrande Apparatus method is however very dependent on the person operation the Casagrande Apparatus, thus making it hard to replicate the results when the same test is carried out on the same material, but by a different person. The factors dependent on the operator includes the rate at which the cup is dropped, judgment on when the sample is touching over a distance of 12mm, the placement of the sample in the cup and the making of the groove. Small variations in the height of the vertical drop of the cup also have a large influence in the number of strokes used to close the groove. Other factors that might influence the results are the material and state of the base and the cup, the fundaments stability and the grooving tool. (Prakasha et al., 2002)

3.2 Fall Cone

The Fall Cone tests are carried out on a Geonor Fall Cone Apparatus with a 60 grams / 60° cone, Figure 3. The water content corresponding to a fall depth of 10 mm 5 seconds after release of the cone is described as the Liquid Limit.

Figure 3. The Fall Cone Apparatus used for the tests.

The Fall Cone is widely known throughout the world, and the accepted standard for finding the Liquid Limit in many countries. The Fall Cone has the advantage over the Casagrande Apparatus that the operation of the apparatus is not affected by the operator, and the results are thereby comparable independent of the user. When using the Fall Cone Apparatus, one should be aware of the state of the cone, since a worn cone can affect the fall depth, and thereby the results of the Liquid Limit. Air pockets trapped in the clay around the point of impact can also influence the measured fall depth.

3.3 Plastic Limit

The Plastic Limit is found by rolling the clay on a glass plate into stings with a diameter of 3 mm, until they just do not crumble. Air drying is used to decrease the water content in the material. This is done to avoid a dry crust on the material that can occur when drying is done by slowly heating the material.

3.4 Homogenizing

For both the Casagrande cup and the Fall Cone method, the clay should be homogenize and the water content brought to a level close to yet under the Liquid Limit, which is a time-consuming process. The homogenizing of the clay is a very important part of finding the Liquid Limit, and should be done carefully. Not homogenizing the clay sufficient or mixing air in the clay can have a great influence on the outcome of the Liquid Limit.

The tests are made while gradually adding more de-ionized water. The tests are carried out simultaneously on both apparatus on the same material.

Through the tests, it became evident that the homogenization process has a great influence on the results of the tests, making it highly important to be meticulous.

Based on the high plasticity of the clay, a special homogenizing process was used. The material was first grated to small pieces with a maximum length of 1.5 cm and a thickness of 1-2 mm. The pieces were gathered in a plastic bag and added de-ionized water. The material was left over night to fully absorb the water. Hereafter the material was gently massaged through a sieve with a mesh aperture of 0.42 mm to discard any larger particles and to reduce any lumps of clay. There were no particles left at the sieve in any of the samples of the Danish Eocene Clay. The material was then placed in small portions at a glass plate, and a large spatula was used to further homogenize the material, Figure 4.

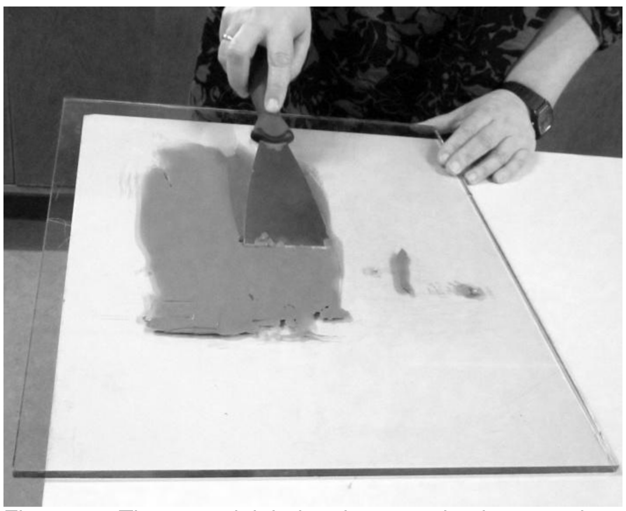

Figure 4. The material being homogenized on a glass plate.

The homogenizing was continued until no visual imperfections were left and the material had a glossy surface. This was done to all the material, and the material was finally collected in a bowl, where the material was molded together until it appeared as a uniform mass.

The homogenizing process is hard and time consuming, making it a costly process. At least two hours were used to sift and homogenize each sample prior to the tests, before an acceptable homogenization of the material was obtained.

During the tests when de-ionized was added to increase the water content of the material, homogenization was also proven to be important. A significant amount of water could be added to the material without an influence on the number of stroke or fall depth. If, however, the material was covered by a damp cloth and left to absorb the water for 15 min, there was a clear difference in the results of the tests. The effect of the absorption time was particularly clear for clay with an extremely high plasticity.

The lengthy duration of the homogenization before and during the test, one test could easily last up to 6 hours. This causes for a need to simplify or automate the homogenization process saving valuable man power.

4 RESULTS

The plasticity of the Danish Eocene Clay is found for 33 samples, for depth up to 69 meters under the surface. The results from both the Casagrande and Fall Cone Apparatus can be seen in Table 3.

Table 3. The measured Liquid and Plastic Limits for the samples of the Danish Eocene Clay. (C) marks results from the Casagrande Apparatus and (FC) marks the results from the Fall Cone Apparatus. - symbolize that the test was not preformed.

Sample No.	Depth (m)	w_P (%)	w_L (C) (%)	I_P (C) (%)	w_L (FC) (%)	I_P (FC) (%)
1	15.5	-	154.7	-	163.1	-
2	19.5	-	141.1	-	146.2	-
3	31.5	-	151.6	-	158.0	-
4	33.5	-	160.8	-	164.2	-
5	37.5	-	103.7	-	112.5	-
6	39.5	-	143.5	-	150.7	-
7	43.5	-	129.6	-	137.4	-
8	47.5	-	127.9	-	132.2	-
9	51.25	-	178.4	-	191.8	-
10	51.5	-	186.0	-	189.2	-
11	63.5	-	207.7	-	213.4	-
12	67.5	-	156.2	-	170.4	-
13	69.25	-	169.3	-	184.6	-
14	13	49.7	192.6	142.9	190.0	140.3
15	17	44.6	172,6	128.0	161.5	116.9
16	17	48.4	237.5	189.2	221.2	172.9
17	17	40.8	171.2	130.4	175.3	134.5
18	21	32.8	110.2	77.4	110.3	77.5
19	20	43.2	264.1	220.9	250.1	206.9
20	22	51.6	292.1	240.6	270.4	218.9
21	24	44.4	262.1	217.6	250.8	206.4
22	25	31.3	87.0	55.7	87.1	55.8
23	25	35.3	120.8	85.5	114.4	79.1
24	29	32.1	119.6	87.5	126.3	94.2
25	33	35.3	141.4	106.1	143.4	108.1
26	33	42.2	173.2	130.8	160.4	118.0
27	33	36.3	175.6	139.3	159.8	123.5
28	37	33.9	165.0	131.1	162.2	128.3
29	41	31.6	114.7	83.1	119.4	87.9
30	41	33.9	189.0	155.1	145.6	111.7
31	45	31.5	156.2	124.7	156.6	125.1
32	49	32.3	155.9	123.6	156.4	124.1
33	49	60.2	344.9	284.7	311.1	250.9

To see if there is a direct connection between the Liquid Limit from the two methods, the results from each sample is drawn in a chart with the Liquid Limit found using the Casagrande Apparatus at the abscissa axes and the Liquid Limit found using the Fall Cone Apparatus at the ordinate axes, the chart can be Figure 5.

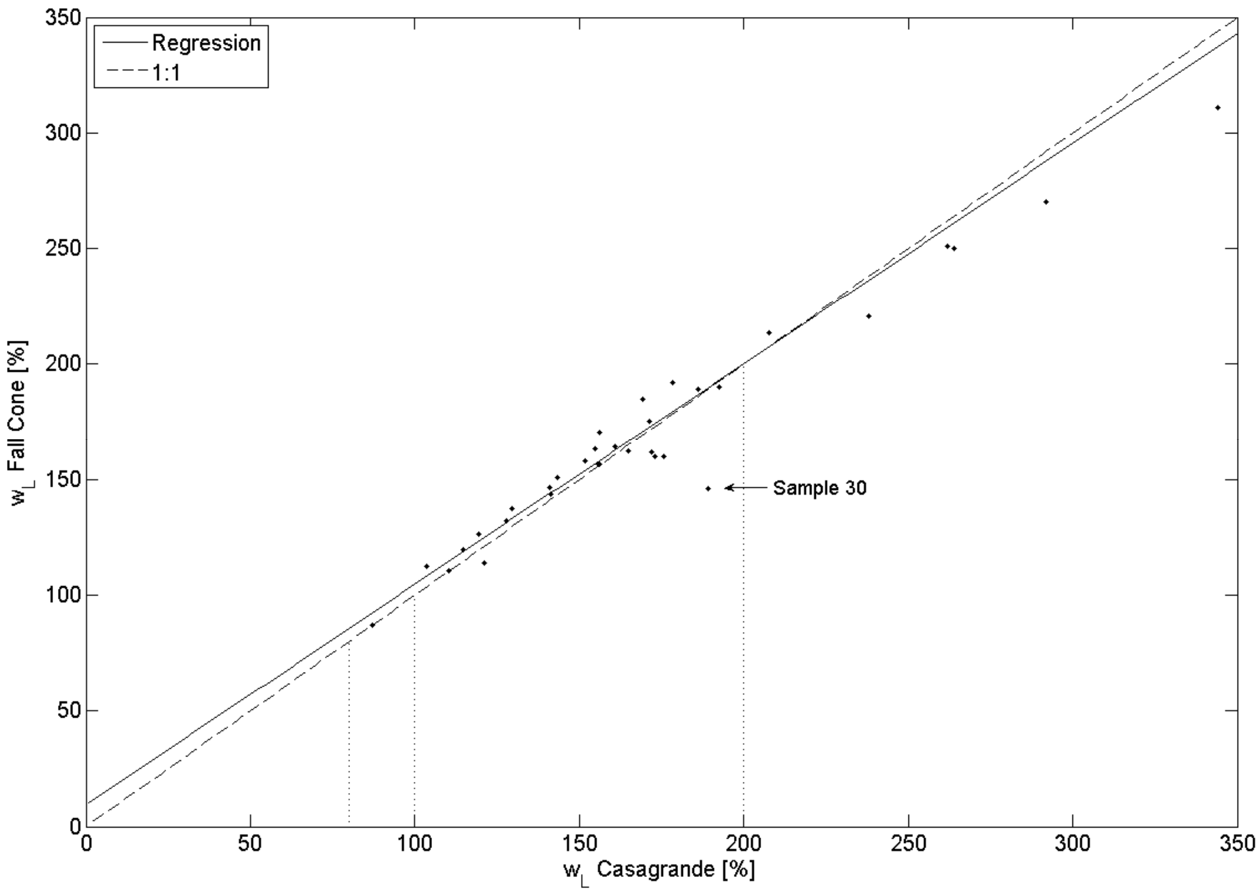

Figure 5. The relation between the Liquid Limit of the Danish Eocene Clay found using the Casagrande and Fall Cone Apparatus respectively.

The results appear to be approximately identical regardless of the methods used until a Liquid Limit of roughly 200%. Here after the results from the Fall Cone consistently gives smaller values for the Liquid Limit. This suggests that results can be divided into two groups, with a Liquid Limit of 200% as the separation point. The relation between the Liquid Limit of the Danish Eocene Clay in the range of 85% to 200% found by the two methods in Figure 5 can by using linear regression analysis using the least squares method be described as:

$$w_L(FC) = 0.95 \cdot w_L(C) + 9.4 \qquad [2]$$

For the relation in Equation 2 sample No. 30 is not included since this is believed to give a false description of the relation. This relation correlates well with the relation found by Wasti (1987) in Equation 1 for up to very high plasticity clays.

The relation in Equation 2 shows that the Fall Cone gives slightly larger results for Liquid Limits up to 200%, which is also the limit for the valid range of the relation, and the Fall Cone results starts to significantly differ from the Casagrande results.

The Plasticity Index of sample no. 14-33 is plotted against the Liquid Limit in a plasticity chart for both methods, which can be seen Figure 6 and Figure 7 for Casagrande and Fall Cone respectively. The A-line in both figures is described by:

$$I_P = 0.73 \cdot (w_L - 20) \qquad [3]$$

Casagrande defined the U-line (Upper Limit Line) as the limit for which results located beyond this line the Plasticity Index is too large for the corresponding Liquid Limit, and no sample can be located above this line, without an indication of an error in the results (Casagrande, as described in Holtz et al., 2011). The U-line is described by:

$$I_P = 0.9 \cdot (w_L - 8) \qquad [4]$$

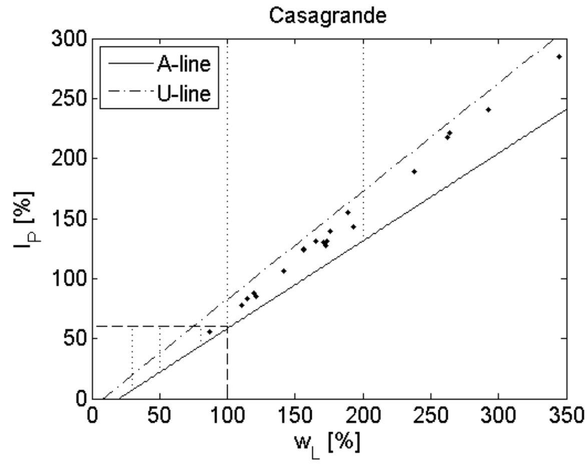

Figure 6. Plasticity Chart for the Danish Eocene Clay using the Casagrande Apparatus. The normal range of the Plasticity Chart is marked with the dashed lines.

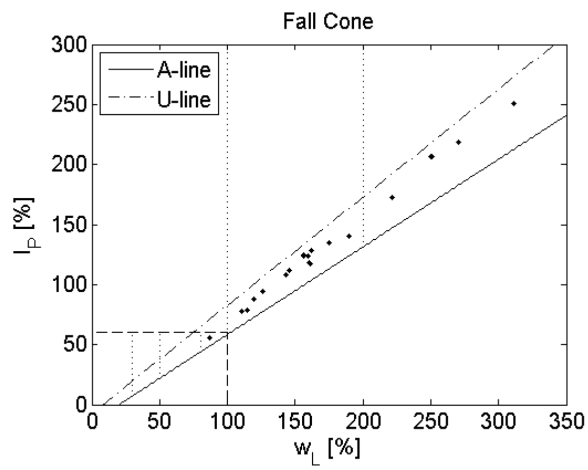

Figure 7. Plasticity Chart for the Danish Eocene Clay using the Fall Cone Apparatus. The normal range of the Plasticity Chart is marked with the dashed lines.

From Table 3 and Figure 6 and Figure 7, it is seen that all but one sample of the Danish Eocene Clay falls outside the normal range of the Plasticity chart, but still well above the A-line (Equation 3) and under the U-line (Equation 4), indicating that it is an exceptional plastic clay. This gives a need to expand the Plasticity Chart in order to include the Danish Eocene Clay. Based on the results found in Figure 5, two new classification categories are introduced; first a category for super high plasticity clay (CS) with a Liquid Limit of 100% to 200%, which is the range in which the results from the two methods correlated, succeed by a category for extremely high plasticity clay (CE) from 200% till 350% where there were no correlation between the results.

The very high concentration of clay particles of between 73 – 95% of the total soil sample, has large influence on the plasticity, and gives super and extremely high plasticity clay. By comparison of Table 1 and Table 3 it is noticed that the extreme high plasticity clay is primary located in depths with a high content of more than 40% of the clay mineral Smectite, which causes a highly expansive clay. The clay mineral composition has an influence on the Liquid Limit and for clays with large content of expansive minerals, like Smectite, the Fall Cone method is unreliable to use for Liquid Limit tests.

5 CONCLUSION

The plasticity and Liquid Limit of Danish Eocene Clay were discussed in this paper. The Danish Eocene Clay has a plasticity which has seldom been seen before, with Liquid Limits up to 350%. The main focus of this paper was to study the relation between Liquid Limit test preformed on the Casagrande and Fall Cone Apparatus.

In order to include the Danish Eocene Clay it has been necessary to modify the Casagrande Plasticity Chart. Only one sample of the Danish Eocene Clay could be described as a very high plasticity clay (CV), whereas the rest laid beyond the normal range of the Plasticity Chart. Two new categories were added; super high plasticity clay (CS) for clays with Liquid Limits between 100% and 200% and extremely high plasticity clay (CE) for clays with Liquid Limits between 200% and 300%. The updated plasticity chart can be seen in Figure 8.

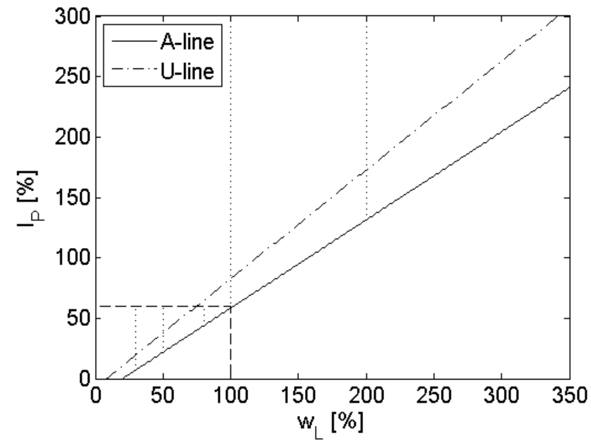

Figure 8. The Plasticity Chart adapted to include the Liquid Limits covered by the Danish Eocene Clay. The normal range of the Plasticity Chart is marked with the dashed line.

The classification of clay based on the Liquid Limit can be seen in Table 4.

Table 4. Classification of Clay.

	w_L (%)	USC-system
Low Plasticity Clay	<30	CL
Medium Plasticity Clay	30-50	CM
High Plasticity Clay	50-80	CH
Very High Plasticity Clay	80-100	CV
Super High Plasticity Clay	100-200	CS
Extremely High Plasticity Clay	200-350	CE

The behavior of the clay during the test varied dependent on the Liquid Limit, and a significant change happened around a Liquid Limit of 200%. For super high plasticity clays (CS) it was found through Equation 2 that there was a good correlation between the results from the two methods making Equation 5 a valid approximation for Danish Eocene Clays with a Liquid Limit up to 200%.

$$w_L(FC) \cong w_L(C) \quad [5]$$

For extremely high plasticity clay (CE) there was found no correlation between the two methods for Danish Eocene Clays, and the Fall Cone largely underestimated the Liquid Limit, making this method unfit for extremely high plasticity clays.

On basis of the present tests the Fall Cone Apparatus only has a limited usability on the Danish Eocene Clay, and thus the results should be used with caution and clear specification on the test method used.

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