ASSESSMENT OF THE SUITABILITY OF THE FALL CONE METHOD AND THE CASAGRANDE CUP METHOD FOR DETERMINING THE LIQUID LIMIT OF SOUTH AFRICAN SOILS

by

PAUL VOSLOO

A dissertation submitted in fulfilment of the requirements for the degree
Master of Engineering in Civil Engineering
in the
Department of Civil Engineering
of the
Faculty of Engineering, Built Environment and Information Technology
of the
Central University of Technology, Free State, South Africa

Supervisor: Prof. Elizabeth Theron (Ph.D)
Co-Supervisor: Dr Philip Stott (Ph.D)

April 2022

DECLARATION

I, the undersigned, declare that the dissertation hereby submitted by me for the degree Master of Engineering in Civil Engineering at the Central University of Technology, Free State, is my own independent work and has not been submitted by me to another university and/or faculty in order to obtain a degree. I further cede copyright of this dissertation in favour of the Central University of Technology, Free State.

Paul Vosloo

Date: September 2021

Bloemfontein, South Africa

ABSTRACT

The plasticity index (PI) is one of the most important soil variables in the design of soil related structures. Most engineers rely on PI values determined by commercial laboratories. Commercial laboratories strive to make their services competitive and affordable to their clients. The liquid limit (LL) is one of the variables used to determine the PI and is determined by laboratory soil tests, therefore it is important to determine the LL accurately.

Two techniques, the Casagrande percussion cup and fall-cone (penetrometer) methods, have been adopted as the standard LL measurement approaches globally. The Casagrande cup method is implemented in South Africa (SANS, 2011) as well as in the USA, whilst the fall-cone method is accepted in the UK (BS 1377-2, 1990).

According to many researchers such as Karlsson (1961), Sherwood and Ryley (1970), Weston (1978), Sampson (1983), Sridharan and Prakash (2000), Feng (2000), the Casagrande cup method is operator dependent, less reliable and soils of low plasticity tend to slide in the Casagrande cup while the LL cannot be measured. On the other hand, the fall-cone test is a simple shear strength test that is much less operator dependent and can measure the liquid limit for a soil of any plasticity accurately.

According to Sampson and Netterberg (1984), the British variant of the Casagrande cup produced LL results that directly correlated with the BS fall-cone LL results, while the SANS variant Casagrande cup correlated indirectly with BS fall-cone LL results with a constant difference of about 4 units. It is important to note that the indirect correlation, does not refer to an inverse correlation, but a correlation with an offset.

This indirect correlation was caused by the international variance of the base hardness of the Casagrande cup devices and lead to poor precision limits (Haigh, 2015; Sampson and Netterberg, 1984)

The aim of this research is to modify the standard British fall-cone method in order to produce a fall-cone procedure that is optimised for South African soils, in order to replace the Casagrande cup method for the determination of the liquid limit for South African soils.

To optimise the sample preparation procedure, the BS fall-cone cup was modified by removing the bottom plate of the cup and sharpening its bottom edges to form a specimen ring. The specimen ring LL results were compared to the results of the BS cup and showed that there was a negligible difference in results due to the removal of bottom plate.

To optimise the amount of sample required to perform the test, four specimen rings were manufactured with diameters 54mm, 35mm, 30mm and 22mm to test whether the smaller diameter LL results would differ from the standard diameter. The results showed that the 35mm specimen ring could be used for testing, while the 30mm and 22mm diameters showed the effects of mould confinement, where the soil heave created by the cone affected the penetration depth of the cone.

The indirect correlation would be corrected by adjusting the standard 20mm corresponding penetration. The 54mm and 35mm diameter rings in the modified fall-cone tests showed a direct correlation with the SANS Casagrande cup when the corresponding penetration was adjusted from 20mm to 16mm.

Further tests were conducted where the cone weight was increased in order to investigate the correlation between the fall-cone and the SANS casagrande cup. However, this method was not considered since it was impractical to change the standard apparatus and move further from achieving an international standard.

A draft SANS fall-cone procedure manual was compiled from the research conducted and the results obtained in this dissertation and is attached as Annexure A. This manual will be submitted to SABS for the approval of the modified fall-cone as a South African standard method.

Keywords: Casagrande cup, fall-cone, plasticity index (PI), liquid limit (LL), British Standard cup (BS cup), specimen ring, corresponding penetration depth.

ACKNOWLEDGEMENTS

A number of special acknowledgements deserve specific mention:

a. The Rectorate and relevant functionaries from the Central University of Technology, Free State, for the opportunity of completing this research;

b. The Central University of Technology and the Royal Academy of Engineering for funding this research;

c. Prof. E Theron, my supervisor, for giving me guidance, support and having much patience with me;

d. Mr L Sampson, research author of numerous research papers, for his knowledge that shaped and evolved this research;

e. My wife, Dané Vosloo, for her unconditional love, support and motivation;

f. My family, for their continued support and motivation; and

g. Acknowledgement above all to my Heavenly Father for enabling me to do all things through Him that strengthens me (Philippians 4:13).

TABLE OF CONTENTS

CHAPTER 3: RESEARCH METHODOLOGY 49

CHAPTER 4: RESULTS AND DISCUSSION ... 75

CHAPTER 5: RESEARCH CONCLUSIONS ... 105

CHAPTER 6: LIST OF REFERENCES ... 108

List of Figures

LIST OF TABLES

List of Annexures

CHAPTER 1: INTRODUCTION OF RESEARCH

1.1 Project Background

The plasticity index (PI) is a function of the liquid limit (LL) and the plastic limit (PL) in that PI = LL - PL. The PI is one of the most important soil variables and an index for clay activity in the design of soil related structures, especially lightweight structures that are prone to structural defects when constructed on clayey soil. The LL is one of the variables used to determine the PI.

Both the LL and PL are determined by laboratory soil testing and are highly dependent on the precision of the tests. The precision of these tests is measured by the precision limits in terms of repeatability and reproducibility. Therefore, it is important to determine the LL and PL with a test method that possesses a high degree of result precision and confidence.

The Casagrande cup method was developed by Albert Atterberg in 1911 (cited in Haigh, 2012) and later standardized by Karl von Terzaghi (1926). The apparatus, the Casagrande cup was introduced by Arthur Casagrande (1932). The SANS Casagrande cup method is conventionally used as the test method for determining the LL in South Africa as specified in SANS 3001-GR12 (2011).

The fall-cone method was originally developed in Sweden in the 1910s, to determine the undrained shear strength of cohesive soils (Koumoto and Houlsby, 2001; Shimobea and Spagnolib, 2019). The correlation between the shear strength and the LL was later established by Hansbo (1957). Houlsby (1982) stated that the fall-cone test was already used widely as a method to determine the LL of clays.

The fall-cone apparatus variant applicable to this research is the British standard variant (BS 1377-2, 1990).

Sampson and Netterberg (1984) started research in South Africa on the introduction of the British Standard fall-cone method to replace the South African Casagrande cup method specified in TMH 1 which at that time was the definitive method for road construction in South Africa. The research showed very good correlation between the two methods, with the BS fall-cone LL being on average 4 units higher than the SA Casagrande cup LL for the range of soils typically used for road construction and a correction factor was proposed. It was also shown that the BS fall-cone method gave more repeatable LL results than those of the SA Casagrande cup.

In 1985, Sampson and Netterberg investigated the inter-laboratory reproducibility of the fall-cone and found that it had a much improved reproducibility than that of the Casagrande cup. In the same article, Sampson and Netterberg suggested that the fall-cone method should replace the conventional method for determining the LL.

It has been 35 years since their research and suggestions, and no further attempt has been made to include the fall-cone method into the South African standards. The following problem statement provides some possible indication why that is.

1.2 Problem Statement and Motivation

It is noted by many researchers, namely Hrubesova et al.(2016); Mitchell and Smith (1974); Sampson and Netterberg (1984) and Sherwood and Ryley (1970) that the Casagrande cup method is operator-dependent with poor precision limits in terms of repeatability and reproducibility, whereas the fall-cone is less subjective and more precise.

However, Sampson and Netterberg (1984), mentioned that the British variant of the Casagrande cup produced LL results that directly correlated with the BS fall-cone LL results. According to Sampson and Netterberg (1985), there is also strong correlation between the SANS variant Casagrande cup and the BS fall-cone LL results, however this correlation is not direct and the results have a constant difference of about 4 units. According to Sampson and Netterberg (1985) and Haigh (2015) this indirect correlation is caused by the international variance of the base hardness of the Casagrande cup devices. The base hardness that varies with the different international standards leads to poor precision limits such as the reproducibility.

According to Haigh (2012), the Casagrande cup is a measure of the friction resistance or slope stability of the soil. Soils of low plasticity might slide down the Casagrande cup’s smooth surface, resulting in a wrong LL result of that test.

On the other hand, the fall-cone is a direct strength test and an assessment of the soil shear, and will be able to produce more precise and reproducible results for soils of any plasticity (Haigh, 2012; Sampson and Netterberg, 1985).

Research conducted over the past three decades clearly indicates that there is a strong correlation between the Casagrande cup and the BS fall-cone (Di Matteo, 2012; Feng, 2000; Grønbech et al 2011; Hrubesova et al. 2016; Sampson and Netterberg, 1984; Sherwood and Ryley, 1970; Wood, 1985).

Despite this, as mentioned before, the fall-cone test is still not conventionally used in South Africa and a reason for this, according to Sampson and Netterberg, was that the conventional operator susceptable PL method, the thread rolling method, had very poor reproducibility and did not improve the precision of the PI.

According to Haigh (2015) and Sampson and Netterberg (1985), the Casagrande cup devices differ internationally with regard to the cup surface roughness and base hardness, both having a substantial influence on the determined LL value.

The average 4-unit difference between the tests found by Sampson and Netterberg (1984), should be correlated directly rather than using a correction factor. This can be done by adjusting the corresponding penetration depth for the LL (Netterberg and Haupt, 1981). An alternative to directly correlate the test results is to adjust the weight of the cone assembly (Evans and Simpson, 2015).

According to Feng (2000), the filling procedure of the fall-cone is the most difficult part of the test because there is the risk of entrapping air voids in the bottom corners of the cup and influencing the results. Feng proposed that the fall-cone test could be conducted more quickly and with more reliability by removing the bottom plate of the cup and sharpening the bottom edges, forming a specimen ring.

If the above-mentioned proposed procedure is followed, and the sharpened ring is cut into the prepared soil sample, the standard BS cup/specimen ring size with a depth of 40mm and a diameter of 54mm requires more soil to form a large enough soil mound to cut into.

The standard British fall-cone method already requires around 300g to conduct the test, which is five times more than the 62g required to conduct the Casagrande cup one-point method. This indicates an area for optimization on the British fall-cone method. Feng (2000) mentioned that the cup size could be reduced if the LL result did not differ and in effect reduce the amount of soil required.

From the information above and a preliminary literature review the objectives formulated are discussed in the following section.

1.3 Objectives of Study

The following are objectives inspired by previous research, and if they are achieved, the fall-cone method should appear more desirable as a South African standard:

1.3.1 To optimize the test sample preparation procedure for the fall-cone test method

It will be attempted to reduce the air void uncertainty when filling up the standard fall-cone cup by modifying the geometry of the cup to form a specimen ring. This will improve accuracy of the LL result.

1.3.2 To optimize the amount of soil sample required for the fall-cone test procedure

The optimization of the soil sample required will be done by reducing the size of the standard cup/specimen ring and proving that the results remain identical, thereby effectively reducing the amount of soil required to conduct the test.

1.3.3 Investigate the establishment of a direct correlation by adjusting the required penetration depth for the LL, of the fall-cone

The modified fall-cone LL results will be calibrated against the Casagrande cup results by adjusting the cone penetration depth corresponding to the LL to establish a direct correlation between the methods.

1.3.4 Investigate the establishment of a direct correlation by adjusting the weight of the fall-cone assembly

The modified fall-cone LL results will be calibrated against the Casagrande cup results by adjusting the weight of the cone to establish a direct correlation between the methods.

1.3.5 Produce a more suitable procedure for the determination of the LL to be adopted by the SABS

The final objective for this research project will be to standardize the fall-cone method for LL determination and motivate the acceptance thereof by the SABS. This will be done by compiling a standard test protocol for the modified fall-cone method.

1.4 Structure of the Research Project and Dissertation

The framework and phases of the project as well as the procedures followed during the research project are shown in Figure 1-1 in the form of a flow diagram that visually depicts the structure of the project.

The project commenced by reviewing some of the past literature and formulating the research objectives. The following step was to conduct preliminary tests with the fall-cone method to become familiar with the procedure and formulate a preliminary methodology as well as a suitable timeframe for testing as it isa very time consuming.

The problem statement was compiled, the objectives were then formulated and formal testing could begin. Objectives one to three were carried out simultaneously. Objectives four and five followed subsequently. The dissertation was written along with the formal testing and only additional results were added afterwards. After the dissertation had been completed, a draft of the standard procedure for the modified fall-cone test was compiled and the submission to the SABS will be done separately from the dissertation. A more detailed description of the methodology of the research project is discussed in Chapter 3 - Experimental Study of Research.

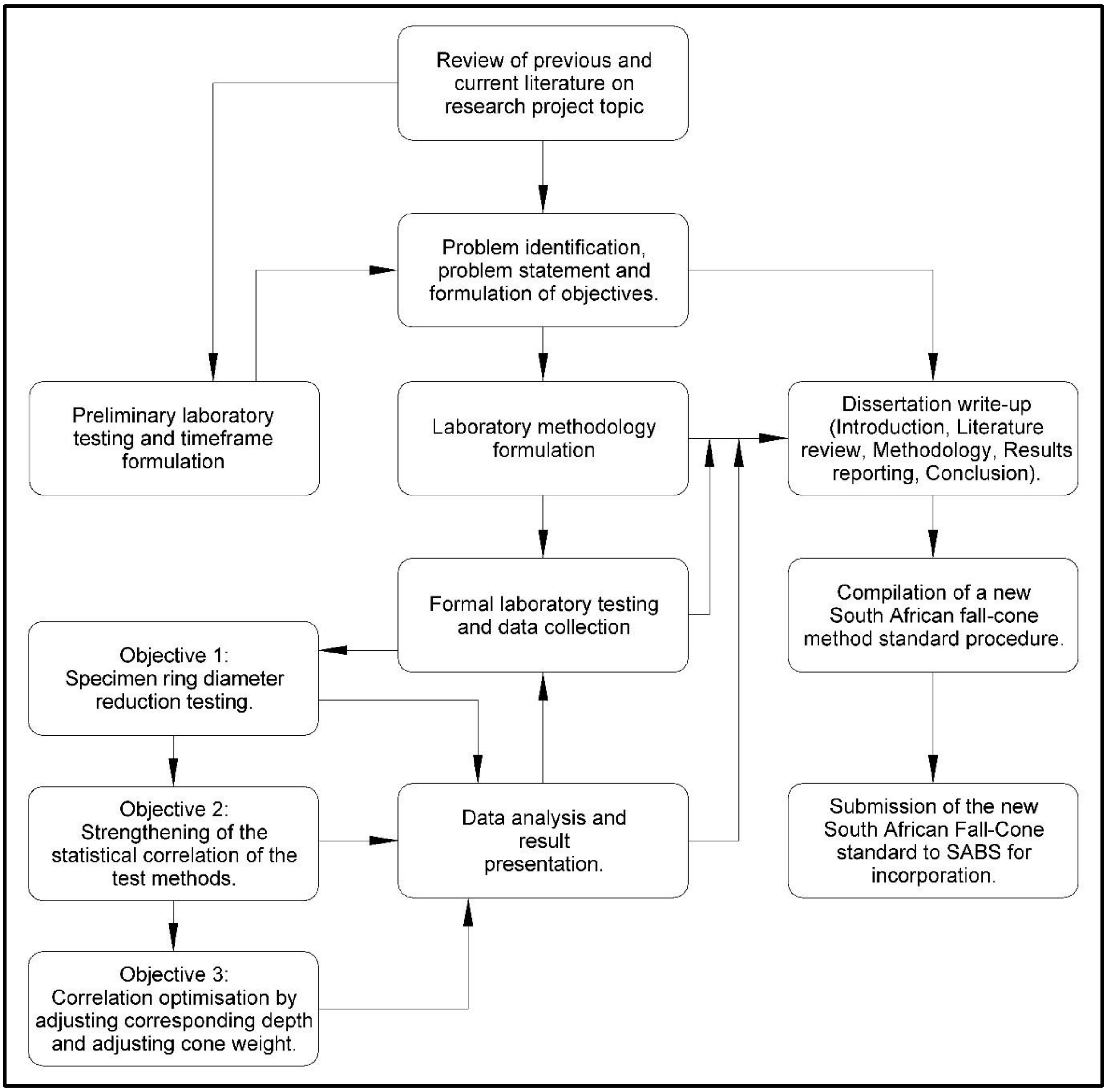


Figure 1-1: Research project flowchart

1.5 Project Outcomes

The following were some outcomes that were achieved by this research:

1.5.1 Scientific outcomes

Some technical and scientific outcomes were the following:

- A method for measuring LL that is more repeatable and reproducible, less operator susceptible and time consuming, less prone to equipment variations, and capable of giving results for a wide variety of soil types;
- At least one paper submitted to a journal or conference proceedings; and
- A standard test protocol for the modified (South African) fall-cone method and the acceptance thereof by SABS.

1.5.2 Social impacts

The social impact would be the improvement of the design of soil-related structures such as low cost and sustainable housing as well as roads, which would improve the quality of life for the community.

CHAPTER 2: LITERATURE REVIEW

2.1 Soil Consistency

Cohesive soil consistency could be defined as the resistance of a soil to mechanical stress or manipulations. It is characterized at critical stages by its water content/moisture content (MC) such as the liquid state, plastic state and solid-state (Hrubesova et al., 2016).

In this context, the word ‘consistency’ mainly refers to the degree of stiffness and plasticity of a moulded soil as described by Karlsson (1961). The consistency of soil is physico-chemically defined by the inner bonds between soil particles, which is the cohesion (Karlsson and Hansbo, 1981). Karlsson and Hansbo (1981) also noted that a characteristic of cohesive soil is that it has a plastic consistency in its moulded state within certain MC limits.

According to Hrubesova et al. (2016), a soil has a firmer consistency at lower MCs and a more fluid-like consistency or state at higher MCs. According to Karlsson (1961), the solid state of a soil sample is not plastic and a slight applied deformation will cause a fragile rupture. The semi-solid state is distinguished as a transitional state between the solid and the plastic state. Grønbech et al. (2011) noted that the plastic state or the plasticity of clay gives an attribute that enables the moulding of moist clay into a specific shape when pressure is applied and retains its form after deformation. A soil sample in the liquid state or with a liquid consistency will, through its own weight, flow out more freely (Karlsson and Hansbo, 1981). The consistency states are indicated in Figure 2-1.

In 1911, Albert Atterberg (cited in Grønbech et al., 2011) differentiated the behaviour of clay into categories according to the MC of the clays. These categories or consistency limits are called the shrinkage limit (SL), plastic limit (PL) and liquid limit (LL). They are generally known as the Atterberg limits.

The MC limit or the consistency limit of soil, when it changes from a solid to a semi-solid state refers to the SL; when it changes from a semi-solid to a plastic state, it is called the PL and when it changes from a plastic to a liquid state it is known as the LL, The difference between the LL and PL is the plastic range which is known as the plasticity index (PI), as shown in Figure 2-1 below (Grønbech et al, 2011).

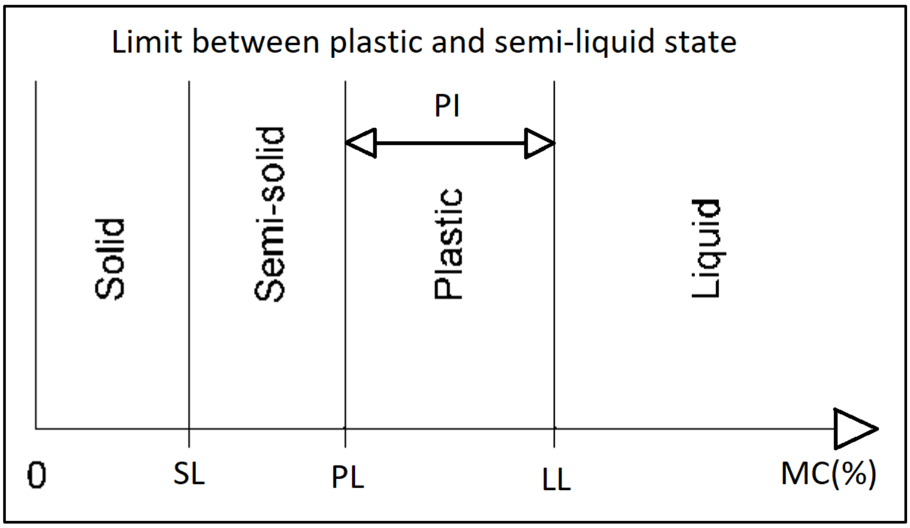


Figure 2-1: Consistency states and consistency limits (Grønbech et al, 2011)

According to Karlsson (1961), the liquid state range was also split into subdivisions by Atterberg. He distinguished between the semi-liquid and liquid state. Atterberg referred to the liquid percussion limit, which is also referred to as the Casagrande cup LL in further sections, as being the limit between plastic and semi-liquid state as cited in Karlsson (1961).

According to O’Kelly et al. (2018), the limits between these physical soil conditions were specified in 1911 by Albert Atterberg, then standardised for use in civil engineering applications by Terzaghi (1926) and Casagrande in 1932 and 1958 respectively as cited in O’Kelly et al. (2018).

According to Andrade et al. (2011), plasticity is commonly used across many fields of engineering and scientific studies and various factors such as mineralogical composition, distribution of particles in size, organic substances and additives can influence the plasticity of cohesive soils.

The Atterberg limits play a significant role in the assessment and classification of clay (Grønbech et al. 2011), to determine the soil volume swelling-shrinking potential. The soil swelling-shrinking potential dictates the design of foundations and roads and relies heavily on precise soil consistency limit determination (Mitchell J. , 2005).

2.2 Atterberg Limits / Consistency Limits

The consistency limits are predominant factors for identifying and classifying a soil (Nini, 2014). Since the transitions from semi-solid to plastic consistency and from plastic to liquid consistency take place progressively as the MC of the re-moulded sample varies, the concepts of PL and LL are based on their methods of determination. On the other hand, the concept of the shrinkage limit is associated with a defined physical state of the soil.

The consistency limit values are primarily based on the soil's water-binding and water retention ability in the remoulded state. The ability for water binding relies mainly on the content and composition of clay minerals and organic colloids.

Since the establishment of the Atterberg limits in (1911), attempts have been made to better understand the limits as well as continually developing new and improved methods to determine the limit accurately: the research contributions still continue to this day. Some Atterberg limits are described in the following sections.

It should be noted that Atterberg limits are the primary parameters used in soil classification for the design and construction of civil engineering structures.

2.2.1 Other defined consistency limits

Atterberg (1911), cited in Abbas (2018), originally defined seven consistency limits to classify cohesive soils; however, general engineering practice mostly tends to use only the LL, PL and the PI.

The following are the consistency limits not mentioned previously; these will not be discussed in detail further in this review.

The sticky limit was defined by Atterberg as lowest MC, when a spatula is placed on the surface of the remoulded soil sample, at which the soil sticks onto a metal spatula blade (Atterberg, 1916).

The liquidity index (LI) is the measurement of the soil consistency at the natural MC in a remoulded state and is often used as an indicator of soil sensitivity (Sivakugan and Das, 2009). The liquidity index is defined as:

$$\mathrm{LI} = \frac{natural\ MC - PL}{PI} \tag{1}$$

According to Vardanega et al. (2012) and Vardanega and Haigh (2014), the liquidity index parameter is also used in modern design approaches to characterize soils for deep foundations in Russia as well as in more regional-level geomorphological studies.

The consistency index (CI), like the liquidity index, is an indicator of the consistency of the soil at the natural MC in the remoulded state. There is a direct connection between the consistency index and the liquidity index and is derived as the following:

$$CI = 1 - \mathrm{LI} \tag{2}$$

Activity is an indicator of a clay's colloidal properties which depends mainly on the content and type of clay minerals, organic colloids and the electrolyte content of the pore water (Skempton, 1953).

2.2.2 Liquid limit (LL)

When a MC of a soil is referred to as the LL, it refers to the boundary between the plastic and liquid state or the specified MC at which a soil transitions from liquid to plastic behaviour and vice versa, as the moisture in the soil changes (Hrubesova et al. 2016).

Another way to define the LL, according to Wood (1990), is as the maximum MC value in the plastic state range of a clayey soil, as well as “a measure of the viscous resistance or shear strength of a soil that is so soft it approaches the liquid state” (Sowers et al. 1960, page 216)

This value largely depends on soil grading, composition and mineralogical characteristics, especially those of the clay content. In the case of expansive clay minerals, the amount of interlayer water is important (Trauner et al. 2005; O’Kelly et al. 2018).

The LL is measured as the MC associated with an arbitrarily selected low shear strength on a scale of ever-weakening activity with increasing MC because the soil never has zero shear strength (O’Kelly et al. 2018). In the case of the LL determined by fall-cone, the MC would be associated with a cone-specific selected low shear strength (Houlsby, 1982).

Since the LL can only be determined by laboratory test methods, the value obtained for the LL is dependent on the specific test method used to measure it. In other words, the LL is fundamentally arbitrary and cannot be distinctly observed with a sudden physical change in the soil behaviour (Haigh, 2015).

This is a cause for concern since LL determination procedures and equipment, which will be discussed in the following section, are not standardised internationally (O'Kelly et al. 2018).

2.2.3 Determination of the LL

The LL is currently determined by either using the Casagrande cup method developed by Casagrande (1932) or the fall-cone method, which according to Hansbo (1957) was originally developed in Scandinavia between 1914 and 1922 by John Olsson, Secretary of the Geotechnical Commission of the Swedish State Railways as a method to estimate shear strength. Both of these methods will be discussed in detail in the following chapters.

Classification and preliminary evaluation of clayey soils in engineering works make use of the LL value, which can differ across a wide range of soils. Therefore, inconsistent determination of the LL may result in the wrong classification and rejection of satisfactory materials, or alternatively, acceptance of inappropriate materials that could lead to potentially unnecessarily expensive treatments or structural failure**.**

2.2.3.1 The Casagrande Cup LL

The LL determined by the South African Casagrande cup device (CCLL) is defined as the MC at which a remoulded soil sample, placed in the cup of the device and divided into halves by a standard V-shaped groove, has a consistency in that the divided two sample halves flow together 10 mm along the bottom of the groove when the cup is dropped from a height of 10 mm around 25 times as described by Karlsson (1961). It should be noted that the South African Casagrande cup device and LL results are similar to the ASTM (2010) device and LL results.

2.2.3.2 The fall-Cone LL

The LL determined by the British Standard fall-cone method (BSLL) is defined as the MC at which a remoulded soil sample has a consistency in which the penetration of a freely dropped 80g/30° fall-cone is 20 mm. The BSLL generally corresponds well with the British Casagrande cup LL, according to Karlsson (1961) and Sampson and Netterberg (1985). This is not the case when the BSLL is compared to the ASTM CCLL according to Sampson and Netterberg (1984). This is discussed further in later sections.

2.2.4 Plastic Limit (PL)

A soil's PL is defined as the MC at which it changes from ductile/plastic to brittle/semi-solid soil state, unlike the LL. This is a sudden definite change of the soil state that can be physically observed and could in principle give the same result if measured with a variety of different tests.

2.2.5 Determination of the PL

Atterberg started from a soil sample near plastic consistency when evaluating its PL. In a wad of water-absorbing paper, he rolled the sample to a thin thread. The thread was then kneaded together and the sample rolled out. This procedure was repeated until the thread started to crumble, after which the MC of the sample was determined. This MC became the indicator of the PL, as cited in Karlsson (1961). This procedure defines the PL as the lowest MC at which a remoulded soil sample can be rolled to a thread with a specified diameter without crumbling (O’Kelly et al. 2018). The crumbling of the soil is possibly caused by air intrusion or cavitation from the inside of the soil thread (Haigh et al. 2013).

Terzaghi recommended in 1926 that the sample be rolled to a thread of 3 mm in thickness/diameter in order to make the assessment of the PL more rational or consistent. This has enabled the distinction between plastic materials such as clay and non-plastic materials such as silt to be clearly recognized (Karlsson and Hansbo, 1981).

The BS 1377-2 (1990) and ASTM (2010) methods specify the thread diameter at which the crumbling state should occur as either 3 mm or 3.2 mm. According to Haigh (2013) and Prakash et al. (2009), the thread thickness is not critical since there is no significant statistical pattern of MC differing with the soil thread diameter in the crumbling state, which was examined to be in range of 2–6 mm, identified for a selection of minerals or organic material (O’Kelly, 2015).

Internationally, rolling the sample on a glass sheet is standard procedure. Unglazed or water-absorbing paper is usually used in certain countries such as Sweden as it has a rougher surface than glass, which makes rolling the thread easier. Using water absorbing-paper to conduct the test will also reduce the time taken since the test is performed to reduce moisture in the soil. However, silty soils lose moisture more rapidly and a glass surface would then be better suited.

In South Africa, the PL is determined using the code SANS 3001-GR10 (2011) which is the thread rolling method similar to the BS 1377-2 (1990).

2.2.6 Plasticity index (PI)

The PI is defined as the difference between the LL and the PL, as shown below:

$$PI = LL - PL \tag{3}$$

According to Terzaghi (1926), the PI can be regarded as a plasticity indicator of a soil or the MC range of the plastic state. Any non-plastic soils have a PI of zero, as indicated by Karlsson and Hansbo (1981).

With respect to plasticity, clays are divided into four categories, either on the basis of the LL or the PI, as shown in Table 2-1 below:

Table 2-1: Classification of soil plasticity (Karlsson, 1961)

Designation	PI (%)	LL (%)
Low plasticity	<10	<30
Medium plasticity	10-25	30-50
High plasticity	>25	>50-80
Very high plasticity	>50	>80

Research conducted by Grønbech et al. (2011), as discussed in section 2.8.1.4, observed LLs much higher than those made provision for in Table 2-1, and therefore proposed an extended classification as shown in Table 2-2:

Table 2-2: Extended classification of soil plasticity (Grønbech et al., 2011)

Designation	LL (%)	USC system
Low plasticity	<30	CL
Medium plasticity	30-50	CM
High plasticity	50-80	CH
Very high plasticity	80-100	CV
Super high plasticity	100-200	CS
Extremely high plasticity	200-350	CE

2.2.7 Linear shrinkage (LS)

According to Sampson and Netterberg (1984), the LS of a material, as defined in South Africa, is the shrinkage or decrease of a soil bar length which takes place in a standard trough when dried from the liquid limit moisture content to an oven dried state as described in SANS 3001-GR10 (2011).

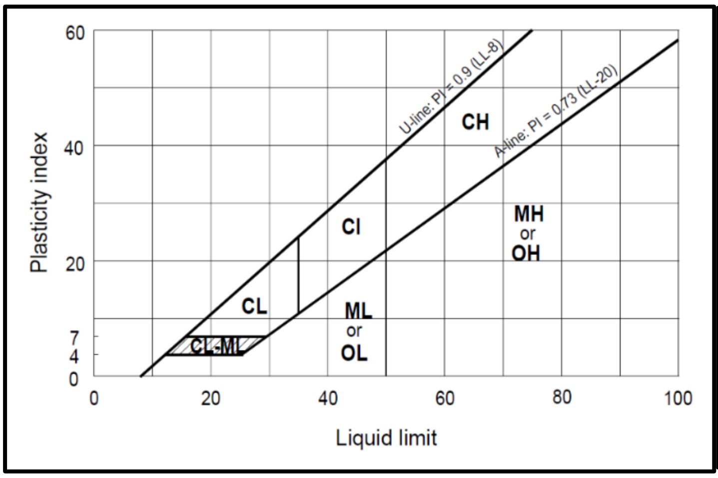
After the Atterberg limits are determined, soil classification follows.

2.3 Soil Classification

The classification of clayey soils is determined by the Atterberg limits and is one of the most important factors for the design of successful foundations (Grønbech et al.2011). It is therefore of significance that the Atterberg limits are determined as accurately as possible (Abbas, 2018). The two most common classification systems are the American Association of State Highway and Transportation Officials (AASHTO) system and the Unified Soil Classification System (USCS) which will be discussed in the following section.

2.3.1 USCS

According to Sivakugan and Das (2009), the USCS is the most popular system used worldwide. Coarse-grained soils such as gravels would be classified using the soil grading characteristics whereas fine-grained soils such as clays and silts would be classified using the Atterberg limits (Carter and Bentley, 2016). Fine-grained classification is carried out by making use of the plasticity chart developed by Casagrande (1948). This makes provision for LLs up to 100% and PIs up to 60% as shown in Figure 2-2 below.



USCS	
ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity.
CL	Inorganic clays of low to medium plasticity, gravely clays, sandy clays, silty clays, lean clays.
OL	Organic silts and organic silty clays of low plasticity.
MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts.
CH	Inorganic clays of high plasticity, fat clays.
OH	Organic clays of medium to high plasticity, organic silts.

Figure 2-2: Casagrande’s plasticity chart

The ‘U-line’ shown in the figure refers to the approximate upper limit line for natural soils while the ‘A-Line” separates the clay material from the silt material (Carter and Bentley, 2016).

The LL and PI are plotted on the plasticity chart. The data point(s) then fall(s) within a certain soil classification, and the soil-related structure design is influenced by the classification. The soil strength also plays a significant role as discussed in the following section.

2.4 Soil Shear Strength

The most widely used parameter for defining soil strength is the shear strength which is influenced by past stratification or segregation and compaction and is therefore not constant for a certain type of soil; rather, it varies with the soil circumstances externally and internally, according to Wu (1996).

The fall-cone is a measure of the shear strength for remoulded cohesive soils as discussed in Chapter 1 and more specifically, a measure of the undrained shear strength, which will be discussed in the following section

2.4.1 Undrained shear strength (S_U) of soil

According to Henkel (1960), the undrained shear strength (S_U) in soil mechanics defines a type of shear strength which is distinguished from drained shear strength. Henkel further explains that, although the S_U of a soil does physically not exist, it depends on a number of factors such as the orientation of stresses, the stress path, the rate of shearing and the volume of material such as that for fractured clays or rock mass.

Another way to define the S_U, according to Sharma and Bora (2003), is the shear strength of a moistened soil at a specified MC under loading conditions where there is no drainage of pore water and it is independent of the stresses applied, and can therefore be measured at any stress level, given that the void ratio remains constant.

According to Hansbo (1957), the fall-cone shear values had remarkable agreement with the values determined by the laboratory vane test (LVT).

According to Canelas et al (2018)**,** the recently published ISO 17892-6 (2016) standard describes the fall-cone method as an estimation of shear strength which makes the test as valid as the LVT, direct shear box test or the triaxial test of Eurocode 7.

2.4.2 The S_U at the LL

The fall-cone test method is used to estimate the S_U of cohesive soils, according to Hansbo (1957). At the LL of a remoulded plastic soil, the S_U is virtually a constant, with only a slight variation between 1.47 to 2.45 kPa (Youssef et al. 1965). Therefore, it is the premise for determining the LL of a plastic soil with the fall-cone method, using the equation developed by Hansbo (1957) shown below (Wood and Wroth, 1978). The equation shows the relationship between the fall-cone penetration depth and the S_U of a soil and is applicable for fall-cones of various configurations and masses:

$$S_u = k.\frac{W}{d^2} \tag{4}$$

Where $\boldsymbol{S_U}$ is the undrained shear strength, $\boldsymbol{d}$ is the fall-cone penetration, $\boldsymbol{W}$ is the weight of the cone, $\boldsymbol{k}$ is the fall-cone factor, a constant depending on cone geometry. Therefore, if the S_U is constant for all remoulded plastic soils at the LL, then the penetration depth must be the same for all plastic soils when using a constant cone weight and geometry (Evans and Simpson, 2015).

However, the relationship between the shear strength and MC was found by Karlsson (1961) and Youssef et al. (1965) not to be a linear correlation; therefore a bi-logarithmic correlation was proposed.

2.4.2.1 The variability of the fall-cone factor (k)

The cone factor k has been recognised by Houlsby (1982) and Brown and Huxley (1996) as being a function of the fall-cone penetration depth. However, Feng (2005) stated that no relevant data have been reported and that the k-factor variation should be established at varying penetration depths. This would mean that the fall-cone can be calibrated when determining the Su between the LL and PL.

Feng (2005) also confirmed this theory with experimental data and found that the k-factor decreases greatly when the S_U increases or when the penetration depth decreases. He also found that this reduction in the k-factor did not alter the standard requirement of the penetration depth for determining the LL as the factor reduction only occurred below the LL penetration depth.

The fall-cone surface roughness has been the subject of consistent arguments as being one of the most significant influencers of the variability of the penetration depth and k-factor as well as the mechanics of the fall-cone (Evans & Simpson, 2015; Hansbo, 1957; Houlsby, 1982; Koumoto & Houlsby, 2001; O'Kelly, 2016; Wood, 1985).

Llano-Serna and Contreras (2019) substantiated these arguments with experimental data and found that the surface roughness has a very low to no level of influence on the penetration depth. They concluded that it could be because of the small contact area or friction force between the cone and the soil during penetration and that it is not large enough to affect the penetration depth.

2.5 Test Methods for Determining the LL

As discussed in 2.2.3, the LL of soils can be determined either by the conventional Casagrande cup method or by the newer fall-cone method, the latter being generally the norm in most of Europe (Haigh, 2012). The following sections will discuss these two methods in detail.

2.5.1 The Casagrande cup method

2.5.1.1 Background

Atterberg first described the LL in 1911 and claimed that it reflected the state in which two small pieces of clay put in a bowl would no longer flow together when the side of the bowl was hit aggressively and continuously. This method of measuring a soil's LL was improved by Casagrande (1932), who standardized the test in such a way that more repeatable findings would be obtained. In the process, he established the LL test apparatus and procedures currently described in global standards. Figure 2-3 shows the apparatus developed by Casagrande.

Figure 2-3: Typical Casagrande cup apparatus

The LL cup test was revisited by Casagrande (1958), who noted that many sources of deviation, including non-standard equipment and rigidity errors, were found in the test from the bench on which the equipment was used. In order to avoid these problems, Casagrande suggested that a simple soil strength measure could surpass the cup as a method of measuring the LL.

The Casagrande method procedure can be summarised as a standard metal cup, filled with a soil paste and levelled. The soil is then divided by cutting a groove of standard width. The cup is then dropped on a base made of a hard rubber. This rubber hardness varies with different countries and will be discussed in following sections.

The LL is then defined as the MC of the soil, corresponding to the closing of groove along a length of 10 mm caused by the impact of 25 percussions of the Casagrande cup.

2.5.2 Mechanics of the Casagrande cup

Wroth (1979) recognized that the Casagrande cup test was basically a dynamic slope stability test. This means that owing to each vertical acceleration pulse applied to the cup with the effect of the cup geometry, the slope shifts/fails at a gradual rate.

A study conducted by Haigh (2012) on the mechanics of the Casagrande cup using the Newmarkian sliding-block mechanics method found that the Casagrande cup is a measure of specific strength, which is soil strength divided by soil density.

2.5.3 Repeatability/reproducibility of the Casagrande’s cup test

According to, Feng (2004), Sowers et al. (1960) and Verástegui-Flores and Di Emidio (2014), the repeatability of the Casagrande cup when one operator repeats the same test or the reproducibility between laboratories can sometimes be of concern. The poor repeatability and reproducibility of the LL test using the Casagrande cup device have also been well documented by Mitchell and Smith (1974) and Sherwood and Ryley (1970).

Sherwood and Ryley (1970) reported results of a study conducted in the UK that showed a high coefficient of variability (about 7–8%) of LLs measured with the Casagrande cup for three soils across multiple laboratories. They also reported that a similar unreferenced study conducted in the US showed an even higher coefficient of variability. Many more repeatability and reproducibility studies are discussed in the following sections.

It should, however, be mentioned that a factor of this poor repeatability could also have been the influence of soil spatial variability as described by Stott and Theron (2016)

2.5.4 Consistency of the Casagrande cup device

Although the Casagrande LL test has been recognized as the standard procedure for determining the LL for more than 80 years, international differences of both standard code procedures and the apparatuses themselves may have a substantial influence on the determined LL value (Haigh, 2015).

According to Haigh (2015) and Evans and Simpson (2015), the problems of repeatability are possibly worsened by the inherent properties of the Casagrande device itself on measurements with regard to the cup surface roughness and base hardness which may vary with use. These problems of repeatability are also possibly exacerbated by the dynamic nature of the test, for example, how low plasticity soils may liquefy and flow in the cup as shown in Figure 2-4 below, rather than deforming plastically as shown in Figure 2-5.

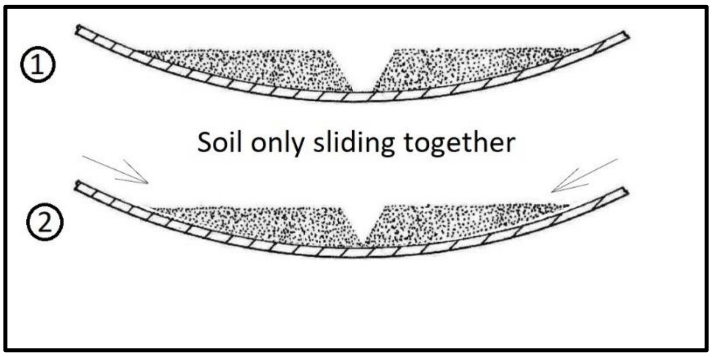


Figure 2-4: Sliding of soil in cup

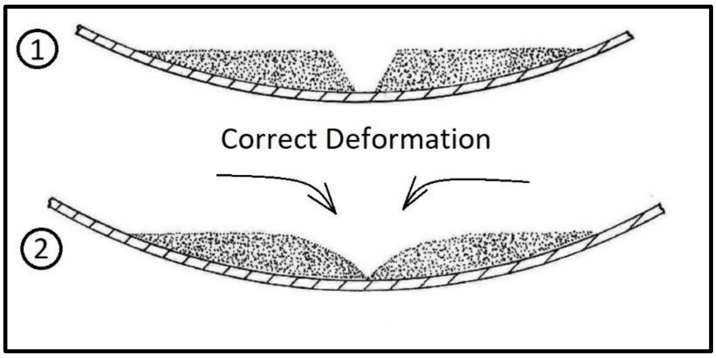


Figure 2-5: Correct deformation of soil in cup

Different Casagrande cup device variants can be used, either the British (BS) or American (ASTM) device, as the base of the British device is softer than that of the American device and therefore produces higher LL results, according to Sampson and Netterberg (1985).

The standard Casagrande device used in South Africa has always been that of the ASTM standard variety, although one or two laboratories in South Africa inadvertently use the softer base British standard devices, without understanding the implications thereof (Sampson & Netterberg, 1984). It is unknown whether some laboratories in South Africa still use the British standard devices.

According to Haigh (2015) and Sampson and Netterberg (1985), both the hardness and elasticity of the Casagrande cup device bases has a significant influence on the determination of the value of the LL of a soil when using the device. The base of the BS device is softer than that of the ASTM device and therefore produced higher LL results according to Sampson and Netterberg (1985).

According to Norman (1958), Whyte (1982), Sridharan and Prakash (2000) and Haigh (2015), when comparing the harder ASTM base to the softer BS base, more energy is absorbed in the softer base when repeated impacts are induced, which is why the BS base will give higher LL results consistently.

Both base hardness and resistance should be regulated in order to obtain reliable and repeatable results between laboratories and it is therefore disturbing that in international standards, the specification of LL systems is so dynamic, even within one of the hard or soft-based device groups, and that the American standard of regular device base testing is not also part of many of the international standards (Haigh, 2015).

2.5.5 The fall-cone method

2.5.5.1 Background

As mentioned in the previous section, the fall-cone test was originally developed as a method for determining the shear strength for remoulded cohesive soils in Scandinavia between 1914 and 1922 by John Olsson, Secretary of the Geotechnical Commission of the Swedish State Railways. Figure 2-6 shows a typical BS fall-cone device. The test has since become a fundamental tool for determining the LL (Canelas et al. 2018). Figure 2-7 shows the typical geometry of a 30º/80g BS fall-cone.

Figure 2-6: Typical BS fall-cone apparatus (BS 1377-2, 1990)

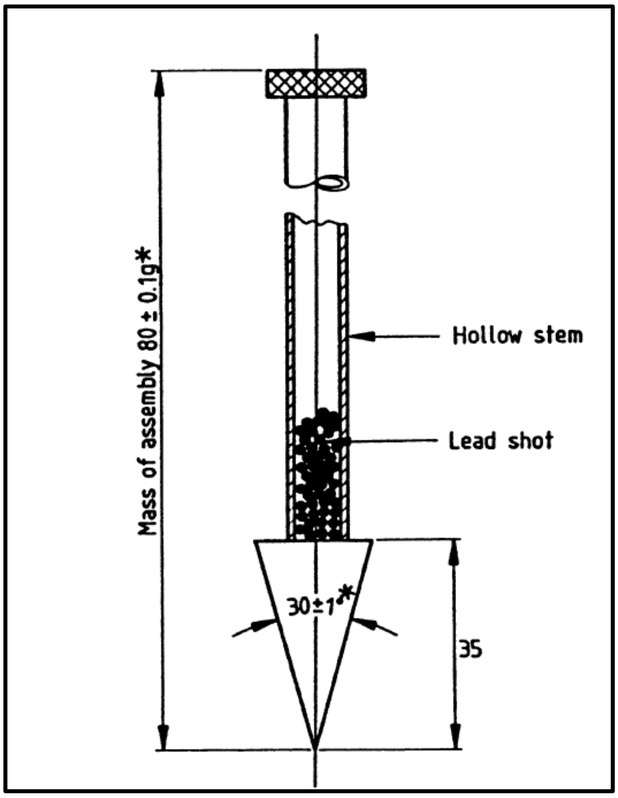


Figure 2-7: Geometry of the fall-cone assembly (BS 1377-2, 1990)

The fall-cone test offers an alternative way to determine the soil LL and potentially the PL, and many researchers such as Casagrande (1958), Sampson and Netterberg (1985), Wasti (1987) and Feng (2000) have recommended using it. Various kinds of fall-cone techniques are currently being used worldwide as a replacement for the Casagrande cup method (Sampson & Netterberg, 1984).

According to Haigh (2012), China and several European countries have recognized the fall-cone test as the preferred or only solution since the 1970s and even earlier (1949) in the case of Russia (GOST 5184-49) for the determination of the soil LL. In several countries, standards for fall-cone testing currently exist, such as the UK (BS 1377-2, 1990), Europe (ISO 17892-6, 2016) and Canada (CAN/BNQ 2501-092, 2006). The fall-cone method according to the British Standard (BS 1377-2, 1990) can be summarized as follows:

The test is performed by filling a standard cup with soil fines slurry and allowing an 80g cone with a 30-degree tip angle to fall freely and penetrate into the soil in the cup. These penetrations are carried out from a drier to wetter state of the soil with incremental increases in MC. The penetration depths are then measured and the moisture of the penetrated soil is determined. The penetrations are then plotted against the MCs on a linear and logarithmic scale to form a plotted curve. The LL is read off the curve to correspond to the 20mm penetration, which would then also correspond to a soil **Su** of 1.7 kPa (Wood & Wroth, 1978).

2.5.6 Mechanics of the fall-cone method

The fall-cone test, according to Wood and Wroth (1978), is a direct measurement of soil strength or specific strength. This would be a different physical parameter measured than that of the Casagrande cup, as shown in the study conducted by Haigh (2012), and therefore different LL values would be expected, according to Haigh (2012).

From the analysis done by Hansbo (1957), he explains that when the cone is released to penetrate into the soil, the soil volume is displaced throughout the cup and the actual strength of the soil will cause resistance to the penetration of the cone, or in other words, the soil will apply a load onto the cone. Figure 2-8 shows an approximate area of soil that is affected by the cone penetration.

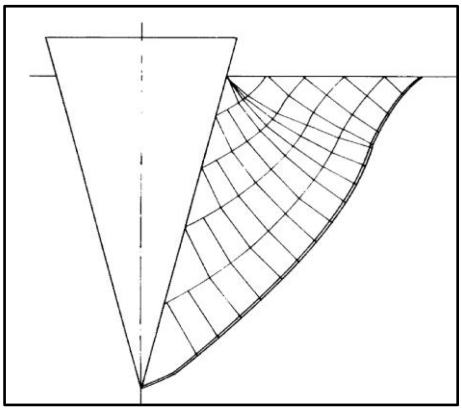


Figure 2-8: Approximate area of resistance to cone (Houlsby, 1982).

In the theoretical analysis done by Houlsby (1982), he stated that when the cone penetrates the soil, some heave occurs around the cone. His analysis assumed that the soil was incompressible and that the heave volume should be equal to the volume of the penetrated cone. Houlsby tested theoretically what the effect of the heave would be on the load applied to the cone.

He found that the soil resistance differed on average by 9.2% whether heave was taken into account or not. Figure 2-9 shows the simplified model used by Houlsby to determine the heave around the cone theoretically.

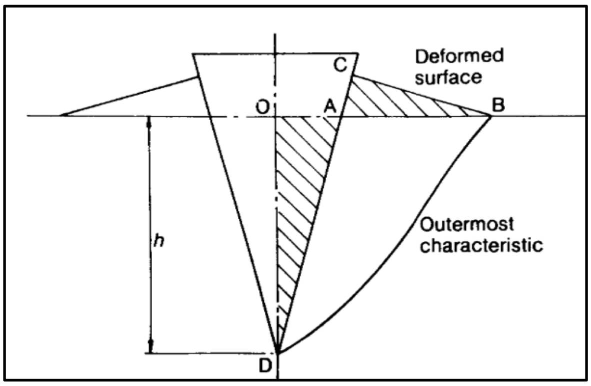


Figure 2-9: Mathematical model for heave calculation (Houlsby, 1982).

Houlsby (1982) mentioned that in practice, the heave profile will not be linear as shown in Figure 2-9; it will rather give a curved surface with higher heave closer to the cone, as shown in Figure 2-10. It was visually noted by Hansbo (1957) that the volume of heave around the cone was substantially less than the volume of the penetrated cone.

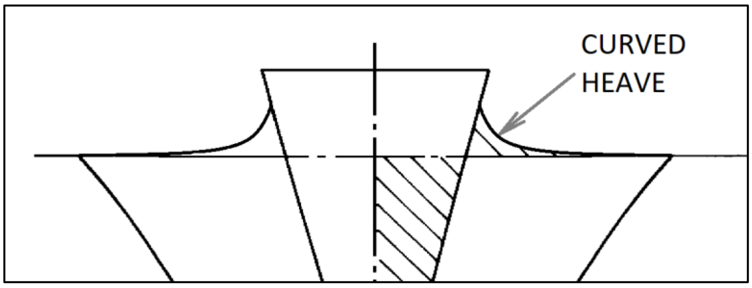


Figure 2-10 Curved heave model

It should be noted that the heave caused by the cone penetration will have a limiting effect on the amount of reduction possible for the fall-cone cup/specimen ring geometry as mentioned in Chapter 1.

2.5.7 Relationship between the cone penetration depth and moisture content

According to Feng (2000), Sampson and Netterberg (1985) and Wood and Wroth (1978), the shape of the relationship between the MC and cone penetration is important for determining the correct curve/line for reading off the correct LL and potentially the PL as shown in Figure 2-11.

Sampson and Netterberg (1985) recommended that for soils of medium to high plasticity which produce a concave curve when plotted, a straight line should not be fitted through the points; instead, the curve should be drawn through the points.

It was suggested by Belviso, Ciampoli, Cotecchia, and Federico (1985) and Wood and Wroth (1978) that the logarithmic depth of penetration versus the MC relationship (log-linear relationship) is linear between the LL and the PL as shown in Figure 2-11.

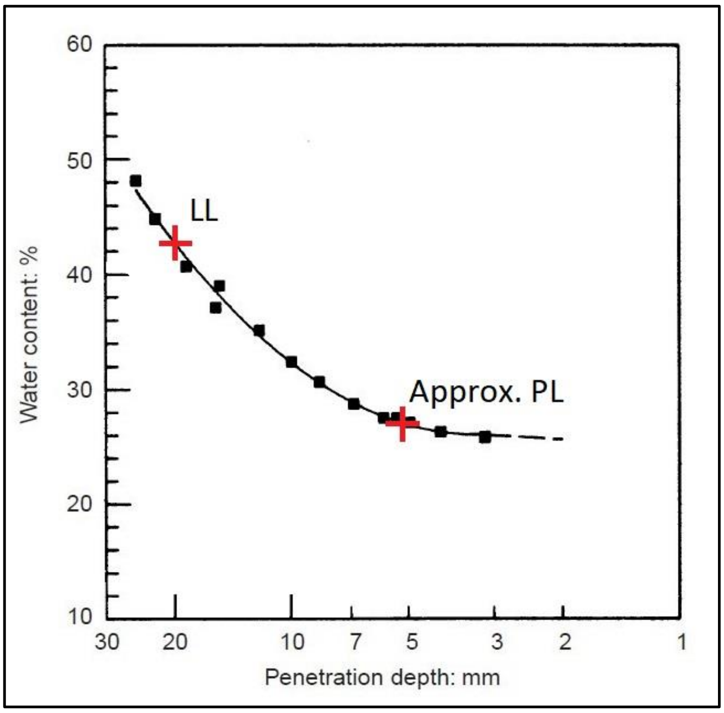


Figure 2-11: MC vs penetration depth on a logarithmic scale (Feng, 2000).

It was suggested by Harison (1988) that the relationship should be a bi-linear model with three penetration points around 14mm penetration and the LL and PL be determined with the extrapolation of the relationship.

Feng (2000) formed well defined curves with many penetration points, and observed that the logarithmic depth of penetration versus the MC relationship is in fact non-linear in nature. The same data was used to check the proposed bi-linear model and proved that the use of the model would result in an under estimation of the soil properties. Feng (2000) further proposed that a linear model is possible with a proposed logarithmic penetration depth versus logarithmic MC relationship (log-log relationship) as shown in Figure 2-12.

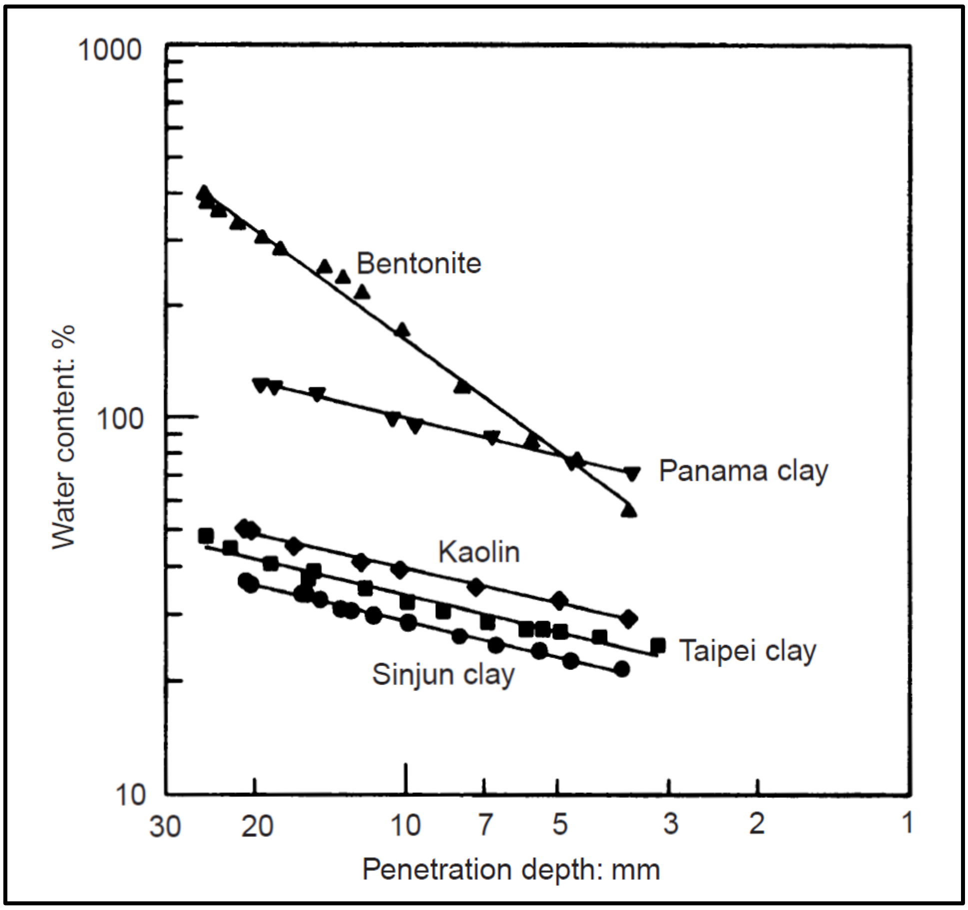


Figure 2-12: logarithmic penetration depth versus logarithmic MC relationship (Feng, 2000).

Feng (2000) expressed the log-log relationship with the equation shown below:

$$\log MC = \log c + m.\log d \qquad (5)$$

where:

$MC =$ moisture content (is the LL when d is equal to 20mm).

$c =$ is the MC when d is equal to 1mm.

$m =$ is the slope of the linear relationship.

$d =$ is the penetration depth.

With this linear model, it is possible to define a linear model with as few as four (4) data points ranging between penetrations of 25mm and 3mm (Feng, 2000).

2.5.7.1 LL underestimation with the fall-cone method

Several authors have noted the underestimation of the LL for high plasticity clays when using the fall-cone method in comparison with the CCLL. Sridharan and Prakash (2000) proposed a distinction between LLs for 23 soils with LLs ranging between 30% and 520%, calculated using ASTM Casagrande hard-base devices and the British Standard fall-cone. However, it should be noted that in practice, it is unlikely to come across soils with such high LLs.

From the data, Sridharan and Prakash (2000) concluded that soils with LLs below 100% showed good agreement between the BS fall-cone LL and the ASTM CCLL. However, when high plasticity soils with LLs above 100% were measured using the fall-cone method, they showed much lower LL values compared to the CCLL (Sridharan & Prakash, 2000).

This divergence was also observed by Budhu (1985), Leroueil and Le Bihan (1996) and O'Kelly et al. (2018), namely that the LL was increasingly underestimated with an increase in MC with the fall-cone method.

Research done by Grønbech et al. (2011) showed the results between the two methods to be nearly identical up to a LL of 200%. Then the LL starts consistently giving lower values than that of the Casagrande cup. It should be noted that the fall-cone used was the 60°/60g, which gives different LL values than the BS 30°/80g cone. The Casagrande cup device variant was not specified in this research.

2.5.8 Impact of the fall-cone method on soil classification

According to Di Matteo et al. (2016), the LL determined with the BS fall-cone method always showed a higher value than the LL determined with the ASTM Casagrande cup. This meant that building materials that had previously been classified as acceptable, were now classified as unstable and potentially unsafe. As mentioned in the previous sections, this difference in LL values was caused by the variation of base hardness of the Casagrande cup devices as the BS fall cone method was correlated with the BS Casagrande cup method which has a softer base than the ASTM/SANS devices (Sampson & Netterberg, 1984).

Di Matteo et al. (2016) further proposed that the classification criteria for earthworks should be reconsidered to transform index properties to sound physical characteristics. This research shows a need for the BS fall-cone method results to be calibrated to the results from the ASTM/SANS Casagrande cup in order to minimize changes in soil classification.

2.5.8.1 Benefits of using the fall-cone method

As described by many researchers such as, Campbell and Blackford (1984), Canelas et al. (2018), Feng (2005), Hrubesova et al. (2016), Sampson and Netterberg (1984), Sherwood and Ryley (1970) and Weston (1978), the fall-cone test method is mostly utilized on cohesive soils. It has numerous benefits over the Casagrande cup method, some of which are listed as follows:

- It produces more repeatable/reproducible results
- It is less susceptible to operator error.
- It is less likely/sensitive to produce variable results from intrinsic equipment variations.
- The settings are easier to maintain and do not require regular adjustment corrections.
- Materials previously classified as non-plastic and sliding into one another in the Casagrande cup such as micaceous soils with low plasticity can be accurately tested for LL with the fall-cone cone (Evans & Simpson, 2015; Kumapley & Boakye, 1980). Therefore, it should also produce reliable results in low plasticity soil aggregate base courses where bar-linear shrinkage tests are currently recommended (Evans & Simpson, 2015).
- It is potentially possible to determine the LL and PL parameters in the same amount of time it takes to determine the LL using the fall-cone cone method. However, reliably determining the PL with the fall-cone is still being investigated.
- It can also be used to calculate **Su** at almost any defined MC and the shear viscosity of clays, both also along with the Atterberg limit determinations (Hansbo, 1957; Houlsby, 1982; Koumoto & Houlsby, 2001; Mahajan & Budhu, 2009; Wood & Wroth, 1978; Youssef, et al., 1965). However, in practice, when the test is performed for a soil with a very low MC, it becomes difficult to perform (Canelas, et al, 2018).

Sampson and Netterberg (1985) believe that the advantages of the fall-cone method greatly outweigh its disadvantages and if further research by other soil organizations supports it, it will have tremendous potential as an international standard method to replace the conventional methods for the determination of the LL, PL and the PI.

2.5.8.2 Disadvantages/implications of the fall-cone method

Although the fall-cone has many benefits to be used as a method for LL determination, there are however several drawbacks that were pointed out by some researchers, as listed on the following page:

- Roughness of the cone surface and tip bluntness can also influence the penetration depth of the test (Hansbo, 1957; Houlsby, 1982). It should be noted that this was disproved by Llano-Serna and Contreras (2019) as discussed previously.
- The more affordable fall-cone apparatuses that do not have timed release mechanisms will leave the judgment of a specific duration of penetration up to the user and will therefore introduce some operator error (Evans & Simpson, 2015).
- If the BS fall-cone replaces the current SANS-based Casagrande cup as a standard method, it would be required to revise certain specifications, soil classifications and formulas relating to soil properties and behaviour with these index properties as there is not a direct correlation between the methods. However, these disadvantages are regarded as being outweighed by the long-term benefits (Sampson & Netterberg, 1985).

2.6 Reproducibility/Repeatability of the Fall-Cone Method

Regarding the fall-cone method as a LL test, Sherwood and Ryley (1970) and Weston (1978) demonstrated that the fall-cone method had a multi-laboratory precision reproducibility considerably higher than that of the Casagrande cup method (Sampson & Netterberg, 1985). These statements were proven with inter-laboratory testing of certain soils, as discussed in the following sections.

2.6.1 Previous studies on the reproducibility/repeatability of the fall-cone method

The following studies that were conducted, illustrate the degree of reproducibility of the fall-cone method.

2.6.1.1 An inter-laboratory study for South African soils by Sampson and Netterberg (1985)

The reproducibility study was conducted by Sampson and Netterberg (1985) with 14 soil samples, each divided into sub-samples and distributed across nine laboratories. The different two-sigma percentage limit (D2S%) was determined for the results of each laboratory. The D2S% limit can be described as a measure of the reproducibility (Sampson & Netterberg, 1985).

The results showed that the BSLL results had a mean D2S% of 12%. This means that in the case of any two laboratories' average test results, their values would not differ from each other by more than 12% of their mean value. The reproducibility of the BSLL was shown to be superior to that of the CCLL. The CCLL results had a mean D2S% of 14.6%, which was better than the D2S% of 25% that Weston (1978) had reported.

In the same study, Sampson and Netterberg (1985) reported that the PI, determined from the ASTM Casagrande cup and the thread-rolling method, had a poor mean D2S% of 47%. According to Sampson and Netterberg (1985), the poor PI D2S% was caused by the PL determined by the thread-rolling method, which also had a poor mean D2S% of 37.4% (Sampson & Netterberg, 1985).

The Cone Penetration Index (CPI) was the PI determined by Sampson and Netterberg (1985) to be the the BS fall-cone LL (20mm penetration) minus the BS fall-cone PL (5mm penetration).

Sampson and Netterberg (1985) stated that the D2S% limits of the fall-cone method were superior to those of conventional methods and it is likely that the precision limits will improve further with continued experience in the method. The reasoning was that more than half of the laboratories that took part in the reproducibility study had not tried using the fall-cone method before the study.

Sampson and Netterberg (1984; 1985) concluded the following:

- The inter-laboratory reproducibility of the PI values determined by the conventional South African Casagrande cup and thread-rolling method was unsatisfactory and was not expected to improve with further experience and improvements to the tests.
- The CPI correlated strongly, but not directly, with the conventional PI and had superior reproducibility which could be further improved with practice and experience with the fall-cone. It was therefore also suggested to replace the conventional PI in South Africa.

2.6.1.2 An inter-laboratory study of Iraqi soils by Abbas (2018)

The study done by Abbas (2018) is similar to the study by Sampson and Netterberg (1985), although with far fewer samples. Two soils with four samples each were tested by four laboratories with the Norwegian Standard fall-cone method (60°/60g cone, which differs from the 30°/80g BS cone) and the thread-rolling method. It was found that that fall-cone LL had an inter-laboratory average relative deviation of 4.3%, which in terms of LL precision, is very low, while the thread rolling PL had a high average relative deviation of 30.2%. This also confirms the findings made by Sampson and Netterberg (1984; 1985).

2.6.1.3 Inter-operator repeatability study done by Sherwood and Ryley (1970)

In a single laboratory inter-operator study, Sherwood and Ryley (1970) found that for eight operators measuring the LL for three soils, the Casagrande cup method showed a spread of deviation that ranged from 5-23% and a COV of 1.6 to 7.5%. For the fall-cone method, the study showed only a spread from 3-11% and a COV of 0.9 to 3.3%.

The spread of deviation and the COV for all three soils for the fall-cone were about half than those of the Casagrande cup (Sherwood & Ryley, 1970). These results correspond well to the findings of Sampson and Netterberg (1985).

2.7 Factors Influencing the Reproducibility of LL Test Methods

Certain factors should be considered when the reproducibility of a method is in question. These factors should be minimised as far as possible if an accurate representation of the reproducibility is to be achieved. Some of these factors will be discussed in this section.

2.7.1 Operator error/experience

According to Sampson and Netterberg (1985), the reproducibility of BSLL could have been influenced by the inexperience of the laboratory testers with the new test method. They indicated that with more practice, the reproducibility could be improved.

2.7.2 The concept of variability in soils

The concept of variability or spatial variability could be explained as the variation of properties within a soil mass from one spatial position to another. This would normally be regarded as being highly homogeneous for general geotechnical purposes (Uzielli, et al, 2006). It is believed that the spatial variation of a soil property is rather connected to formation processes than to the chemical and mechanical information of the soil particles themselves (Uzielli, et al, 2006).

Many observers such as and Phoon and Kulhawy (1999) and Singh and Lee (1970) have noticed the concept of variability in soil properties. However, it would appear that many practising engineers, tertiary-level geotechnical engineering courses as well as many renowned soil mechanics text books have paid little attention to this concept (Stott & Theron, 2016). It is therefore common practice to send one soil sample from each separate test pit to one laboratory to perform one set of standard tests such as the Casagrande cup test, the thread rolling test, the linear shrinkage test and the hydrometer test. However, clear indications have shown that some of these common practices may be inadequate (Stott & Theron, 2016).

With regard to the above-mentioned, a situation was described by Jakobsz (2013) where soil samples extracted from a test pit at a substation were sent to a respectable laboratory. There the usual TMH (now replaced by SANS 3001) specified tests were performed on the soil. The test results showed that the soil was not very expansive and that no significant soil heave would occur. Therefore, the foundation design was done accordingly. Unfortunately, shortly after the completion of the substation, significant heave damage occurred (Jakobsz, 2013).

Another case was noted by Stott and Theron (2016) where soil samples extracted from a housing project were evaluated with a set of tests from the TMH1 (CSIR, 1986). These tests showed that the soil would not experience any risk of heave and the foundations were designed according to the test results. Again, however, heave did in fact occur, and even before the construction was finished, one of the houses was declared as structurally unstable and had to be demolished (Stott & Theron, 2016).

The problem that variability poses is that there might be a significant difference in the expansiveness of a soil in a small area. This could cause laboratory test results to reflect the lower limit of expansiveness for the small area, leading to an inaccurate foundation design (Uzielli, et al, 2006).

A reason for this variability, according to Stott and Theron (2015) and Badenhorst, et al (2015), is that the tests results may depend critically on standard sample preparation which varies among laboratories. Phoon (2008) suggested that there is normally too much reliance on only a single set of tests from each test pit area. The reason for this is primarily related to the cost of testing which may be undesirable for smaller jobs on a tight budget.

2.7.3 Variability in LL apparatuses used

Haigh (2015) conducted an in-depth study on the variation of Casagrande test apparatuses. A high degree of variation between devices was observed, including the devices that were nominally similar.

Casagrande (1958) realized that the 26-year-old (at that time; 88 years at the end of 2020) LL device, had evolved with different characteristics in many different countries.

The study conducted by Haigh (2015) consisted of 18 different soft-base devices and 11 different hard base devices. The hardness of the devices was measured by specific strength. The specific strengths at LL of the soft-based devices ranged from 0.30 – 0.66 m^2s^{-2} with a standard deviation of 0.11 m^2s^{-2} for the hard base devices. The specific strengths ranged from 0.61 to 1.12 m^2s^{-2} with a standard deviation of 0.16 m^2s^{-2}.

Haigh (2015) concluded that the variation in the equipment itself may have significant impacts on the measured LL. This agrees well with the LL correlation difference of four (4) units between the ASTM cup and the BS cone reported by Sampson and Netterberg (1984).

O'Kelly, et al. (2018) stated that the variations in the fall-cone LL devices that involve cones with different masses and apex angles and that are specified in many different standards, also come with an index property value that is usually determined for different penetration depths. This suggests that the estimated **Su** for the LL of the fall-cone method can vary among different standards (Budhu, 1985; Koumoto & Houlsby, 2001; Leroueil & Le Bihan, 1996). Table 2-3 depicts a summary of the different Casagrande cup variants that were compared in the study by Haigh (2015):

Table 2-3: Casagrande cup variants that were compared by Haigh (2015)

	Country	Standard	Base Hardness	Young's Modulus (MPa)
Hard Base	USA	ASTM D4318 (2010)	80-90 D	260-446
	Canada	CAN/BNQ 2501-090 (2005)	Micarta or hard rubber	-
	Brazil	NBR6459 (1984)	ebonite	~500
	Germany	DIN18122-1 (1997)	>80 D	>260
	Sweden	SS27119 (1989)	ebonite	~500
	Spain	UNE 103103 (1994)	80-90 D	260-446
	South Africa	SANS3001-GR10 (2013)	Hard rubber	-
		TMH1 (1986)	85-95 D	340-585
Soft Base	South Korea	KSF2303 (2000)	83-93 A	11-31
	Japan	JIS A1205 (1999)	83-93 A	11-31
	UK	BS1377-2 (1990)	84-94 IRHD	11-28
	Australia	AS1289.3.1.1 (2009)	84-94 IRHD	13-28
	India	IS2720 (1985)	84-90 IRHD	13-18
Either	New Zealand	NZS4402 (1986)	79-99 IRHD	8-221
	Switzerland	SN670345a (1989)	Not specified	-
	France	NFP94-051 (1993)	Not specified	-

2.7.4 Effect of moisture absorption time on LL determination

During research by Stott and Theron (2015) on the consistency of specified procedure, five samples were tested for the comparison between the SANS Casagrande cup one-point method and the flow curve method. They found considerable differences in results with the very plastic clays.

Stott and Theron (2015) suspected that the cause of this difference was due to the time dependence of water absorption after being oven dried and that the time allowed for a soil sample to absorb moisture was more for the flow curve method than the one-point method. Stott and Theron (2015) further performed tests to monitor the absorption time dependence of 22 clayey soils and the results were plotted, PI versus time as shown in Figure 2-13 and Figure 2-14.

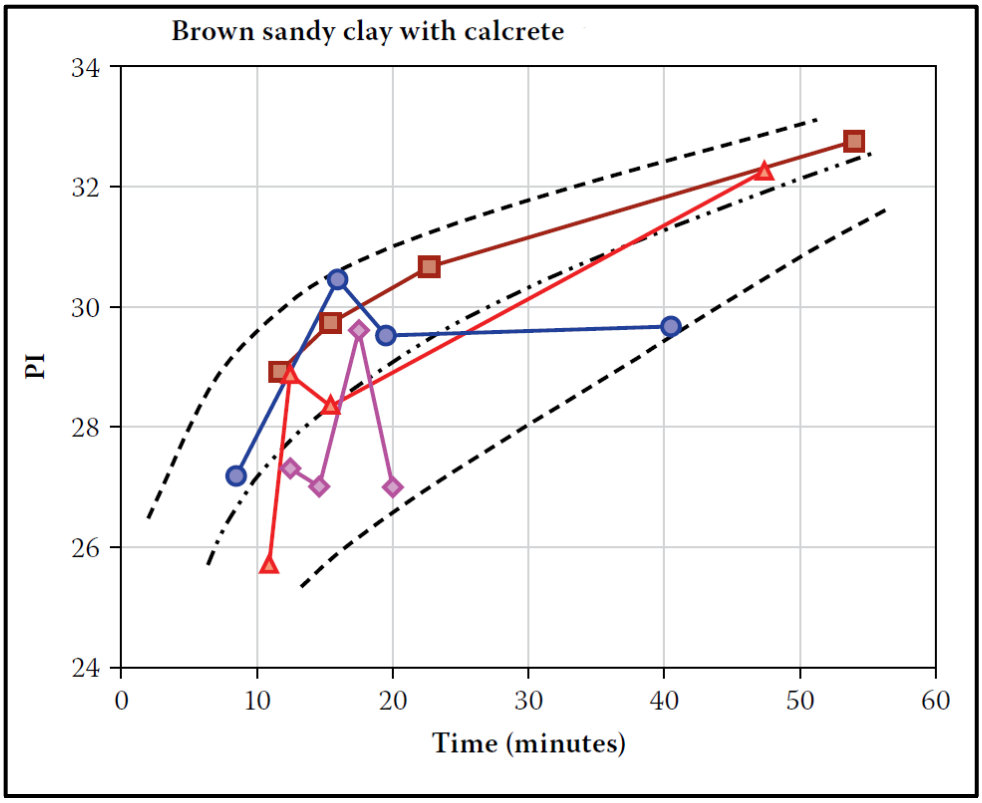


Figure 2-13: High plasticity clay time dependence result (Stott & Theron, 2015).

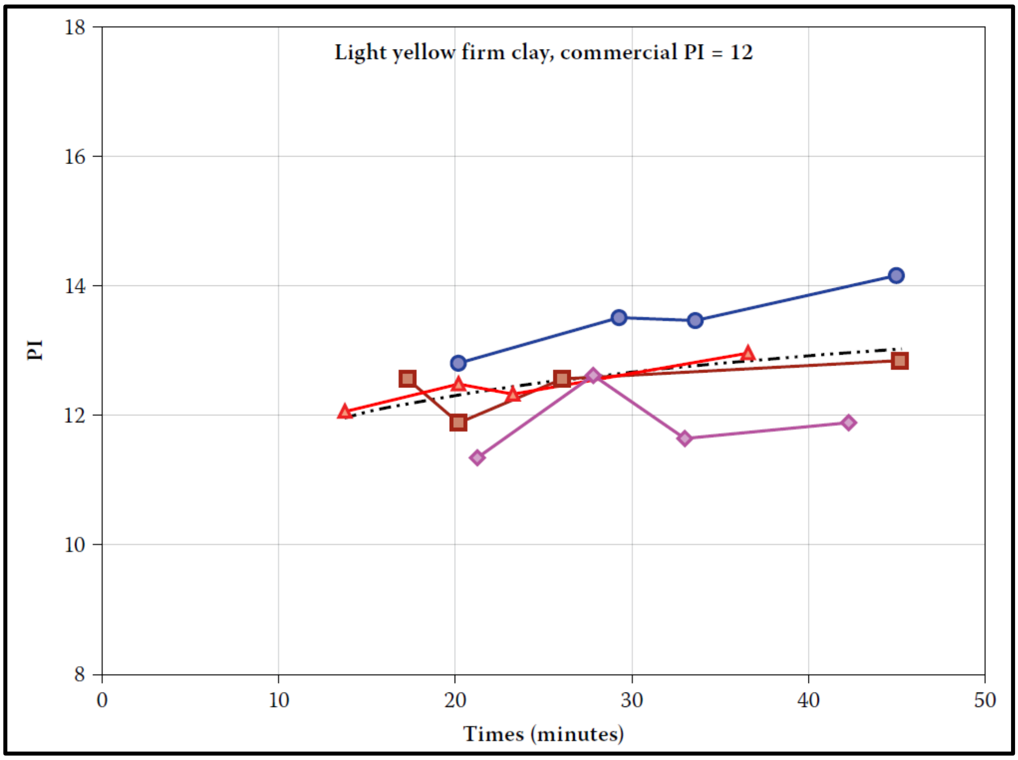


Figure 2-14: Low plasticity clay time dependence result (Stott & Theron, 2015).

The upward envelope trends (dotted lines) shown in Figure 2-13 for the three different high plasticity clays, indicate a higher absorption time dependency than that of the four low plasticity clays shown in Figure 2-14, with a time dependant PI difference of almost 20% in 40 minutes (Stott & Theron, 2015). This shows that the soils require more time to be fully saturated. Stott and Theron (2015) therefore recommended that the sample should be enclosed and set aside for around 30 minutes before initiating the mixing procedure. Although the waiting period is not likely to bring the sample to final equilibrium, it should give a PI close to the value determined by the procedures normally used for heave estimation.

Grønbech et al. (2011) found that the effect of absorption time showed a clear influence on the Atterberg limit results and that a longer absorption time played an important role in the improvement of accuracy. According to the Indian Standard (IS: 2720-5, 1985) as well as the British Standard (BS 1377-2, 1990), the moistened soil paste is left to stand for a period of 24 hours before carrying out the LL test to ensure a uniform distribution of MC in the soil sample and avoid a potential influence on reproducibility.

2.7.5 Effects of oven drying soils

According to Blight (2012), it is well known that oven-drying or even air-drying of some soils has an effect on their properties and can also lead to the underestimation of the LL and the PI.

Moreover, Casagrande (1932) stated that the water-retaining capability, especially of clayey and organic soils, can be affected by drying of soils, and that some soils are also oxidized during the process of air drying. This applies to soils that have not been exposed in nature to the impact of the atmosphere (Karlsson, 1961).

It is therefore suggested by Blight (2012) and Stott and Theron (Some shortcomings in the standard South African testing procedures for assessing heaving clay, 2015) that Atterberg limits should be established wherever possible without any drying, and that testing soil in its natural moisture condition, or as close as possible, is required. Another effect pointed out by Blight (2012) is that when the soil is in its natural state, long mixing periods can negatively affect the cemented bonds between clay clusters and can lead to an overestimation of the LL and PI.

2.8 Comparison Between the Casagrande Cup and the Fall-Cone Method

The relationship of the ASTM Casagrande LL versus the BS fall-cone LL, has been well documented around the world according to Sampson and Netterberg (1985) and the following quote should be considered when the two methods are compared:

According to Wood (1981):

> It is evident that in making a radical change in the method to be used to determine the liquid limit the values determined by the new and old methods will not necessarily correspond precisely. Indeed, whereas the Casagrande apparatus was an attempt to standardize the procedure described by Atterberg in 1911 for detecting the moisture content of soils at which a transition between liquid and plastic types of behavior occurred, the cone penetrometer is more plausibly detecting the moisture content at which soils have a certain strength. Perhaps it is incorrect to call this the liquid limit, but what use, is actually going to be made by an engineer of a liquid limit, however it has been determined? Equally, we may ask what use is actually going to be made by an engineer of a PI as traditionally determined? We can argue that the "pseudo” plasticity determined with the cone penetrometer by the method described by Wood & Wroth (1978) is an indication of the change in MC which will give a hundred-

> fold change in strength. Perhaps this is a measure which will be of direct usefulness to the engineer. (cited in Campbell & Blackford, 1984)

Interestingly, Casagrande (1958) stated that:

> A simple direct shear test, or an indirect shear test, e.g., a static penetration test, would eliminate many of the difficulties one faces in the use of the liquid limit device (Casagrande cup). Unfortunately, so far none of these tests has been simplified to an extent that it could compete in simplicity and cost with the present form of the liquid limit test. (Casagrande, 1958)

Since the fall-cone method is the standard used method in most of Europe, it now competes well with the Casagrande cup test, according to Haigh (2012). However, according to Sampson and Netterberg (1985), the fall-cone method would only be truly competitive when the LL as well as the PL can be reliably determined with the fall-cone.

2.8.1 Previous comparisons and analysis of the test methods

2.8.1.1 Comparison by Sherwood and Ryley (1970)

As discussed in 2.6.1.3, Sherwood and Ryley (1970) found a strong correlation between the two methods. For the British Casagrande cup device (softer base), the LL results between 20% and 100% correlated very well and directly to the 20 mm BS cone penetration MC as shown in the equation below:

$$BSLL = 0.95 \cdot CCLL + 0.95 \qquad (6)$$

Owing to the strong correlation and the benefits that the fall-cone has over the Casagrande cup method, Sherwood and Ryley (1970) recommended that it replaces the Casagrande cup method as the standard LL determination method.

2.8.1.2 Comparison by Weston (1978) and Sampson (1983)

An investigation by Weston (1978) for nine soils with LLs ranging from 20% to 80% found that although the BS fall-cone LL gave very repeatable results as well as having a superior reproducibility to the CCLL, it overestimated LLs with two to five units, depending on the soil’s LL, when comparing it to the CCLL.

Sampson (1983) tested another 80 results across six laboratories, and added these to the nine soil's results in order to improve or confirm the result trends. The following regression equation was derived from the combined 89 tests:

$$CCLL = 1.006 \cdot BSLL - 4.5 \tag{7}$$

$$r = 0.990 \; and \; 95 \; percent \; limits = \; \pm 4 \; units$$

As seen from the equation and according to Sampson (1983), there was a constant overestimation from the fall-cone of approximately four (4) units. It was decided that four (4) units would be subtracted from all the results, and the following regression was derived:

$$CCLL = 1.006 \cdot BSLL - 0.43 \tag{8}$$

2.8.1.3 Comparison by Sampson and Netterberg (1984; 1985)

Sampson and Netterberg (1984) conducted a comparison study on 34 samples. They found that there was an overestimation present from the fall-cone of around four (4) units. They then subtracted four (4) units from the fall-cone test results and derived the regression equation as shown below:

$$BSLL = 0.935 \cdot CLLL + 2.9 \tag{9}$$

$$r = 0.991 \; and \; 95 \; percent \; limits = \; \pm 5.4 \; units$$

Sampson and Netterberg (1985) found that the American standard Casagrande cup (harder base) LL was approximately 4 LL units lower than that of the fall-cone LL over the 20% - 80% range. The test results from Sampson and Netterberg (1985) confirmed this with the linear regression equation obtained from LLs ranging from 19 to 125:

$$CCLL = 0.96 \cdot BSLL - 3.2 \tag{10}$$

$$r = 0.988 \; and \; \mathrm{COV} = 7.2\%$$

With a correlation coefficient (r) of 0,988 and a coefficient of variation (COV) of 7.2%, the results compared well with the linear regression results reported by Sampson and Netterberg (1984).

Sampson and Netterberg (1985) concluded that the MC at a penetration depth of 20 mm with the fall-cone method correlated very strongly with the LL (with a (r) value of 0.99) and that the fall-cone method LL has a superior degree of reproducibility to that of the Casagrande cup LL.

Sampson and Netterberg (1985) further stated that no international standard method for soils testing has been agreed upon to date and that the adoption of these new indices as an international standard would resolve the choice of which Atterberg limit method to implement.

It was therefore suggested by Sampson and Netterberg (1985) that the BSLL determined using the BS fall-cone method should replace the existing CCLL determined using the ASTM Casagrande cup method. They indicated that the BSLL was 4 units higher than that of the CCLL between the ranges of 20 to 100.

2.8.1.4 Comparison by Grønbech et al. (2011)

The study conducted by Grønbech et al. (2011) was conducted with soils with a very wide range of high LLs, ranging from 85-350%. It was reported by Grønbech et al. (2011) that the results from the ASTM CCLL and Norwegian fall-cone (60°/60g cone) were approximately identical up to 200% LL The following equation was derived:

$$FCLL = 0.95 \cdot CCLL + 9.4 \tag{11}$$

2.8.1.5 Comparison by Spagnoli (2012)

The comparison study that was done by Spagnoli (2012) with 50 pure kaolinitic and illitic clays using the DIN CCLL (similar to the ASTM cup) and BS fall-cone method. The regression analysis on these 50 tests showed a very strong correlation between the two methods as shown with the derived equation:

$$FCLL = 0.99 \cdot CCLL + 1.05 \tag{12}$$

$$r^2 = 0.990$$

Spagnoli (2012) concluded that there was a strong correlation between the methods and that the fall-cone method could be considered for similar clays to those used in the study.

2.8.2 Summary of comparisons by other researchers

Almost all researchers that have compared the two methods with each other could not deny the strong relationship between the two methods.

The following is a summary of many other researchers’ regression analysis equations as shown in Table 2-4. This serves as an indicator of the international interest in and motivation for improving current standards. It should be noted that the variants of devices used are not specified in Table 2-4.

Table 2-4: Summary of international research findings

Researcher reference	No. of tests (n)	Linear Regression equation	LL range of samples
Karlsson (1961)	Approx. 150	$CCLL = 1.13 \cdot FCLL - 5$	20-110%
Karlsson & Hansbo (1981)	47	$CCLL = 1.28 \cdot FCLL - 13$	50-175%
Sherwood & Ryley (1970)	25	$FCLL = 0.95 \cdot CCLL + 0.95$	30-72%
Weston (1978) (9 tests) and Sampson (1983) (80 tests)	89	$CCLL = 1.006 \cdot FCLL - 4.5$	20-80%
Wires (1984)	40	$FCLL = 0.94 \cdot CCLL + 0.97$	38-55%
Sampson & Netterberg (1984)	34	$FCLL = 0.935 \cdot CCLL + 2.9$	20-100%
Sampson & Netterberg (1985)	43	$CCLL = 0.96 \cdot FCLL - 3.2$	19-125%
Belviso et al. (1985)	16	$FCLL = 0.97 \cdot CCLL + 1.19$	34-134%
Wasti (1987)	25	$FCLL = 1.01 \cdot CCLL + 4.92$	27-110%
Leroueil & Le Bihan (1996)	3	$FCLL = 0.86 \cdot CCLL + 6.34$	28-74%
Koumoto & Houlsby (2001)	10	$CCLL = 1.191 \cdot FCLL - 23.15$	60-400%
Dragoni et al. (2008)	30	$FCLL = 1.02 \cdot CCLL + 2.87$	28-74%
Özer (2009)	32	$FCLL = 0.90 \cdot CCLL + 6.04$	29-104%
Fojtová et al. (2009)	52	$FCLL = 1.0 \cdot CCLL + 2.44$	20-50%
Grønbech et al. (2011)	32	$FCLL = 0.95 \cdot CCLL + 9.4$	85-350%
Di Matteo (2012)	6	$FCLL = 1.0 \cdot CCLL + 1.05$	24-40%
Spagnoli (2012)	50	$FCLL = 0.99 \cdot CCLL + 1.05$	18-62%
Nini (2014)	29	$CCLL = 0.99 \cdot FCLL + 0.19$	30-61%
Hrubesova et al. (2016)	2	$FCLL = 1.016 \cdot CCLL - 6.71$	50-500%

2.9 Proposed Modifications/Improvements of the Fall-Cone Test

The following are the proposed improvements by researchers that are applicable to the objectives of this research project:

2.9.1 Modification of existing British standard fall-cone specimen cup and specimen preparation

According to Feng (2000), pushing soil into the standard fall-cone cup could prove problematic as air may become entrapped and the effect of repeated soil loading will exacerbate this. The filling of the standard fall-cone cup could also be influenced by individual operator judgement and could be considered the most difficult step in the test (Feng, 2000).

Feng therefore proposed that the standard cup be modified by removing the bottom of the cup, thereby forming a ring. The bottom edges of the ring were then sharpened. This changed the sample preparation process from filling up a cup to cutting into a compacted soil mound with the sharpened ring as shown in Figure 2-15. This reduced the possibility of entrapping air in the cup while filling it.

Brown and Downing (2001) discussed the research done by Feng (2000) and tested whether there would be a difference in LL values between using the normal preparation procedure according to BS 1377-2 (1990) and compacting soil in the cup with a concrete plinth. According to Brown and Downing (2001), this resembled the “compacted mound” that Feng (2000) would cut into with the specimen ring.

Brown and Downing (2001) found that there was very little difference in LL values between the two preparation methods. Feng (2000) stated that since the dimensions of the specimen ring and cup were the same, it would not affect the LL determination.

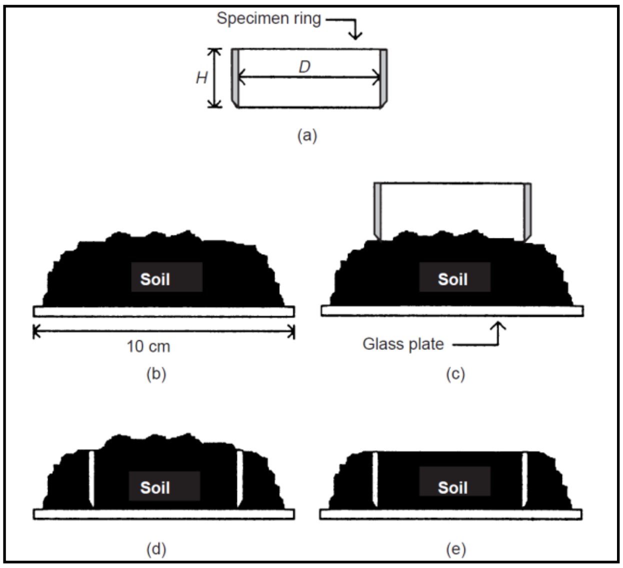


Figure 2-15: Feng’s proposed specimen ring and function (2000).

2.9.2 Modification of the cone weight

Evans and Simpson (2015) made use of an inexpensive technique for data collection, namely a linear variable differential transformer (LVDT) and a digital multi-meter (DMM) to measure cone displacement instead of purchasing a more expensive fall-cone apparatus with an automatic penetration duration controller.

The LVDT shaft and bolt spacer's additional mass gave a combined dropping mass of 116.3g. This deviation from the standard 80g cone mass required the depth of penetration at the LL to be recalculated and redefined, as shown in the equation below (Evans & Simpson, 2015; Wood & Wroth, 1978):

$$\frac{S_u \cdot (20mm)^2}{80g} = \frac{S_u \cdot (d_{LVDT})^2}{116.3g} \rightarrow d_{LVDT} = 24.1mm \qquad (13)$$

The new penetration depth corresponding to the LL increased with the added cone weight. This showed that the LL could also be adjusted by adjusting the weight of the cone.

2.9.3 Modification of the sample size required to perform the fall-cone test

Although Feng (2000) did not mention any reduction in the ring diameter, he did propose that the ring depth could possibly be reduced so that less soil would be required to perform the test.

According to the SANS 3001-GR10 (2011), a dry mass of 60g of soil passing through the 425μm sieve is required to perform the Casagrande cup test, as well as the PL and SL tests. According to BS 1377-2 (1990), a moistened soil sample mass of 300g that passed through the 425μm sieve is required when performing the definitive fall-cone test along with the PL and LS.

Although the difference in requirements between the two methods is significant, it should be noted that the soil required for the fall-cone test is moistened and could already have an approximate MC of between 30% and 50%. This would reduce the weight of the soil if the same sample was weighed in a dry state (BS 1377-2, 1990).

2.10 Conclusion of the Literature Review

From the literature reviewed, the following points stood out and will have an effect on the research methodology:

Determination of the LL

The LL concept is arbitrary and cannot be visually observed as in the case of the PL. The accuracy in determining of the LL is therefore of the highest importance.

Effect of LL on soil classification

Inaccurate determination of the LL could have a negative effect on the classification of the soil, such as structural or financial effects.

Factors affecting LL results

The LL results can easily be affected by factors such as operator susceptible errors which indicates that consistency and integrity will be important when conducting the research.

One of the most significant factors influencing the LL results is the variation of LL test devices, such as the base hardness of the Casagrande cup. Certain laboratories or researchers might not even notice that the device base differs from the country standard since its shape is normally similar. The device should be correctly identified before testing can be done, after which the device should be calibrated regularly.

The bluntness of the fall cone tip influences the LL result (although marginally), and should be checked on a regular basis.

Spatial variability exists within soils samples. Therefore, when the fall-cone and Casagrande cup methods are compared and tested, the soil specimen used in the Casagrande cup will be directly transferred into the fall cone cup for testing or vice versa in order to minimize the effect of the spatial variability.

Since soil absorption time has an influence, albeit small, on the LL results, it is recommended that a soil sample should be given a longer time to sufficiently absorb moisture.

Oven-drying soils at high temperatures before they are tested has an effect on the soil properties and LL results. The soil fines (<0.425mm) will be dried in the oven at a temperature of 45°C as specified in SANS 3001-GR5 (2011).

Relationship between cone penetration and MC for LL

Many relationships between cone penetration and MC have been suggested to read the LL MC for the corresponding penetration accurately. It was decided to use the log-log relationship proposed by Feng (2000) for LL calculations.

Fall-cone apparatus modifications

The modification of the BS fall-cone cup by removing the bottom plate and sharpening the edge as proposed by Feng (2000) improved the sample preparation procedure and its reliability and will be incorporated into this research.

The modification of the size of the specimen ring will influence the soil sample size required to perform the test. Therefore, smaller ring diameters will be tested and the difference (if any) compared to the standard size. There will be a limit to how small the ring can become when the heave that the penetration causes around the cone is considered as described by Hansbo (1957) and Houlsby (1982).

Fall-cone penetration depth modification for LL

According to Sampson and Netterberg (1984), when the BS fall-cone LL (BSLL) was compared with the SANS Casagrande cup LL (CCLL), the BSLL was showed a consistent over-estimation of the LL of approximately four (4) units. A modification to the penetration depth for the LL could possibly give a direct correlation, instead of applying a correction factor.

This will be done by simply correcting the equation to allow the LL to be determined with a different penetration. Another way to correct the correlation would be to be increase the weight of the cone as done by Evans and Simpson (2015). This will also be investigated in this research.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

In this chapter the detailed methodology of the research will be explained. It will highlight the attention to detail when tests were conducted and how reliable the test results would be. This would contribute to achieving the objectives set out in Chapter 1.

This chapter includes the procedure for sample preparation, the modification of the standard fall cone cup to form a specimen ring to optimise the filling procedure, the manufacture of smaller specimen rings to optimise the amount of soil required to perform the fall cone test, the procedures followed to conduct the research, the calculations used to directly correlate the modified FCLL with the ASTM compliant CCLL, and the time consumption in conducting each test.

The completion of this research project was highly dependent on physical laboratory experimentation and the accuracy and consistency thereof as well as an in-depth theoretical analysis of the experimental results.

3.2 Variety of Soil Samples Used in Project

The soil samples that were used for testing were drawn from two major geotechnical investigations as well as several smaller investigations conducted in the Free State and the Limpopo Provinces. In addition, a limited number of samples were drawn from the North West Province, resulting in a total number of 199 tests. The soil properties of these samples varied widely, with liquid limits ranging from 20 to 110 as shown in Table 3-1.

Table 3-1: Samples used for experimentation

Sample Name	**Location**	**Province**	**Liquid limits**	**Number of tests**
Koster Reagile 3798	RDP project in Koster,	NW Province	20-25	4
Co Tp2 Letsatsi	Solar power station, Krugerdrift Dam	Free State	45	1
TPY S38	Witherow Dam, Bloemfontein	Free State	50	1
HS/HG02 to HS/HG134	Hillside Phase 2, Bloemfontein	Free State	25-80	55
NMC 1 and NMC 2	Shopping Centre on M10, Bloemfontein	Free State	55-80	33
F-01		Free State	20-50	20
TP1 -	Steelpoort	Limpopo	80-110	31
TP2 – CP1	Cecelia Park, Bloemfontein	Free State	40-50	19
B1	-*	Free State	20-30	15
HDL T2L5	-*	Free State	40-55	4
CCT L31/ CUT L22	-*	Free State	60-65	2
AB2A	-*	Free State	45	1
DR 04	-*	Free State	40	1
Cecilia 2	Cecelia Park, Bloemfontein	Free State	40	1
FHP 1	Fichardt Park, Bloemfontein	Free State	60	1
HA	Dan Pienaar, Bloemfontein	Free State	65	7
TP5	Cecelia Park, Bloemfontein	Free State	40	3
			TOTAL=	**199**

*These soil samples were labelled vaguely when they were sampled on site and the location could not be established

3.3 Soil Sample Preparation

This section describes the procedure followed after the soil samples were brought to the laboratory from the geotechnical Investigation. The sample preparation consisted of the drying of the natural soil, the crushing, the sieving and the wetting of the soil fines as well as the storage thereof. Following this, the sample was prepared and left to absorb the moisture for 24 hours. This step was based on the research by Stott and Theron (2015) and Grønbech et al. (2011), as discussed in Chapter 2, section 2.7.4. It could therefore be used immediately afterwards for LL testing purposes.

3.3.1 Apparatus used to prepare soil samples

The following equipment was used to prepare the soil samples for various tests:

- Metal basins
- Laboratory scale with 0.01g precision
- Mortar and pestle
- SANS Standard sieves
- Zip lock plastic bags
- Spatulas
- Squeeze bottle with distilled water
- Laboratory oven that can be used uninterrupted

3.3.2 Soil sample preparation procedure

The disturbed samples from the investigation were broken down and placed in an oven at a temperature set to 40-50ºC to dry the soil out according to SANS 3001-GR5 (2011) as shown in Figure 3-1 and Figure 3-2. At higher temperatures, the soil molecules could melt or fuse and affect the soil composition.

Figure 3-1: Disturbed samples placed in an oven.

Figure 3-2: Oven used with temperature set to 45ºC

After the drying had been completed, the disturbed samples were evenly separated into large enough chunks so that when they were sieved, there would be between 150g and 200g of soil fines (<0.425mm) per chunk (see Figure 3-3 and Figure 3-4).

Figure 3-3: Chunk of clayey “slicken sided” soil

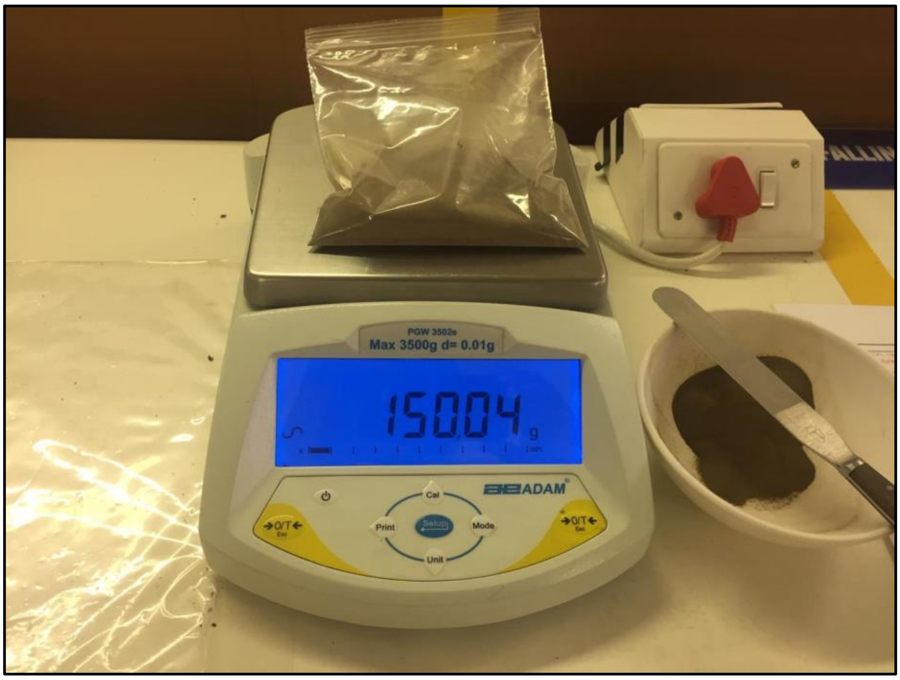


Figure 3-4: Soils fines weighed to 150g

If chunks were too small to only use one chunk, adjacent chunks were grouped and sieved together (see Figure 3-5).

Figure 3-5: Soil chunks considered small

The dried-out soil chunks were then broken and crushed into smaller pieces and eventually sieved according to SANS 3001-GR10 (2011) to acquire the desired amount of soil fines (<0.425mm). Care was taken to keep the soil fines from the original chunks separate from one another as shown in Figure 3-6.

Figure 3-6: Mortar and pestle and SANS sieves

The separated soil fines were placed in airtight containers such as plastic zip lock bags in order to seal the soil moisture and protect it from evaporation (see Figure 3-7).

A small amount of water was then added to the bagged soil fines. The water was then either massaged through the plastic bag or mixed with a spatula into the soil to distribute the moisture evenly throughout all the soil fines. Additional water was added if the water was absorbed too quickly to distribute the moisture evenly throughout the soil.

The bagging and wetting of the soil are not the standard procedures according to SANS 3001-GR10 (2011) and 3001-GR5 (2011), the main difference being that the soil is left to absorb the moisture for longer.

This procedure was done with at least 10 samples per testing cycle in order to reduce the time consumption for testing as multiple tests had to be conducted the following day. This should also ensure proper moistening of the clay particles and improve the accuracy of the results (Grønbech, et al, 2011). However, further research is required in this area.

Figure 3-7: Zip lock bags containing dry soil fines

The water was added in small amounts to avoid over-saturation of the soil, which would result in a delay when having to wait for the soil to dry out. This could take hours with very clayey soils.

The soil sample inside the bag should be moistened just past the plastic limit and be free of any drier lumps. At this degree of saturation, the soil could be mixed immediately and used to conduct the modified fall cone test and take the first penetration reading without having to add moisture to the soil mixed in the bowl. Figure 3-8 shows the moistened soil after it had been removed from the bag.

Figure 3-8: Soil after at least 16 hours of absorption and with sufficient moisture content to start the fall-cone test

The sufficiently moistened and bagged soils were then left to equilibrate to a uniform moisture content for 16 to 24 hours, after which the soil preparation procedure would be complete and the fall-cone test procedure could start.

3.4 Modified Fall-Cone Method

This section describes the modifications to the fall-cone apparatus in order to achieve the objectives set out in Chapter 1. It also describes in detail the procedure that was followed.

3.4.1 Initial modification of the fall-cone specimen cup/ring

The British Standard fall-cone test (BS 1377-2, 1990) was chosen to be experimented on and to be modified to be compatible with South African practice, using the Casagrande cup method for liquid Limit. First of all, the British standard fall-cone test specimen cup was immediately modified the same way that Feng (2000) proposed in his fall-cone cup modification study. This involved removing the bottom of the cup and sharpening its bottom edges whilst keeping the diameter and depth unchanged.

3.4.2 The optimization of the filling procedure for the fall-cone specimen cup/ring

According to Feng (2000), the filling of the BS specimen cup is the most difficult step in the test as air voids could easily get entrapped in the bottom corners of the cup. Therefore, the modified specimen ring would mitigate the difficulty of the filling procedure.

The moistened soil for the fall-cone test was formed into a compacted mound. The sharp edge side of the specimen ring was pressed onto the soil mound to ensure that the bottom of the ring would be sufficiently filled with no entrapped air voids. The excess soil at the top would be cut and levelled with the spatula as shown in Figure 3-9.

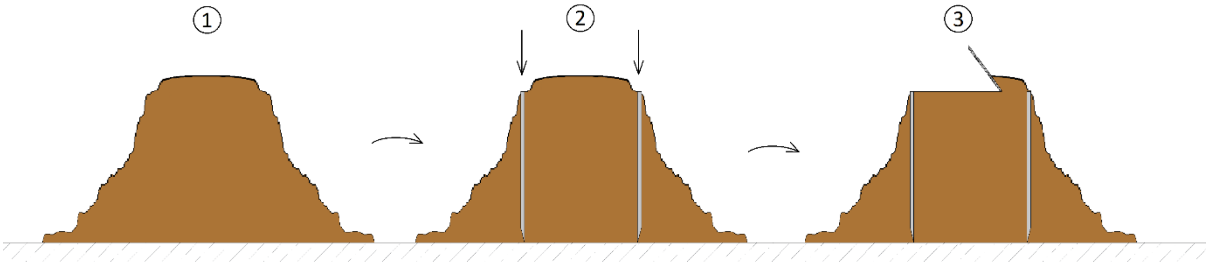


Figure 3-9: Specimen ring cutting into compressed mound

If there was not enough soil to form a large enough mound to fill the 54mm specimen ring completely when pressed into the mound, the mound would be enlarged as much as possible and be cut into. The remaining soil required in the ring would then be added carefully and filled from one corner as shown in Figure 3-10.

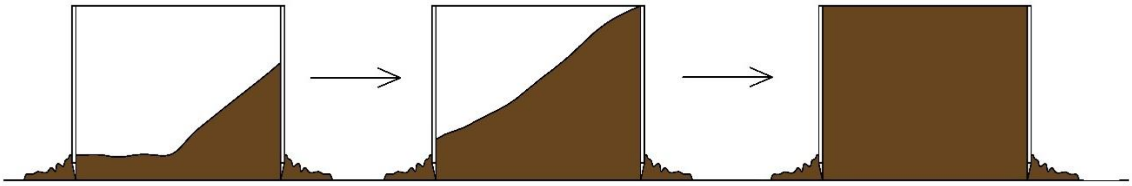


Figure 3-10: Filling procedure

3.4.3 Comparing the specimen ring versus the Standard BS Cup

In order to use the specimen ring to test liquid limits, it first had to be compared with the standard British standard cup. This was done by conducting the fall-cone test according to the BS 1377-2 (1990), using the standard BS cup. Subsequently the modified fall-cone test was conducted using the specimen ring as described in section 3.4.6.

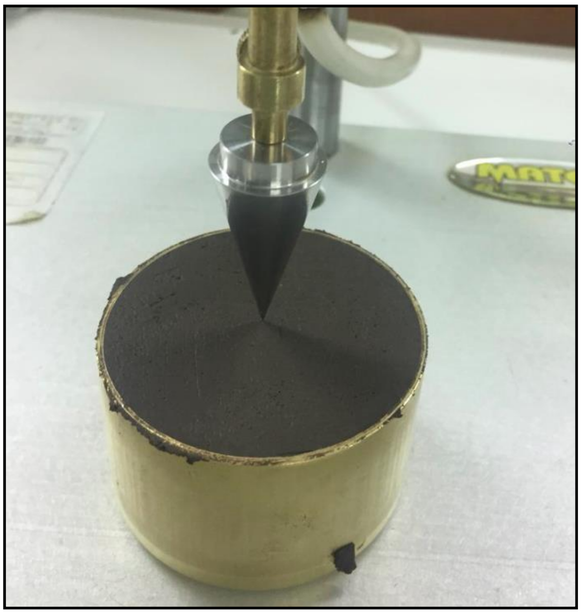


Figure 3-11: Standard BS cup filled according to BS1377-2

The soil used for the BS cup test as shown in Figure 3-11 was transferred directly to the specimen ring as it was important to use the same soil sample for both tests in order to avoid any variability.

The compared results were captured and analysed similarly to the method discussed in section 3.7.1. The results of these tests will be shown and discussed in Chapter 4.

3.4.4 Optimization of minimum sample mass/volume required

As mentioned in the objectives of this project, the specimen ring diameter must be reduced because the amount of soil sample required to conduct the fall-cone test is too large in comparison to the amount of soil sample required for the Casagrande cup.

The simplest way in which the sample volume required could be reduced was by reducing the diameter of the ring while the standard depth of 40mm was left unchanged. As the size of the specimen ring is not a variable in any calculation of the liquid limit, it could therefore be reduced in size before mould confinement would start to affect the penetration of the cone, as long as it gave the same accurate results as the original ring size.

Therefore, four stainless steel fall-cone specimen rings were proposed to be tested for viability and were manufactured at the CUT mechanical workshop.

One of the rings has the same diameter as the standard BS fall-cone cup and the remaining three have smaller diameters than that of the standard cup diameter. All the specimen rings retained the same 40mm depth as the BS fall-cone cup, as shown in the schematics produced (see Figure 3-12 to Figure 3-16).

Figure 3-12: 54mm diameter

Figure 3-13: 35mm diameter.

Figure 3-14: 30mm diameter

Figure 3-15: Specimen ring depth

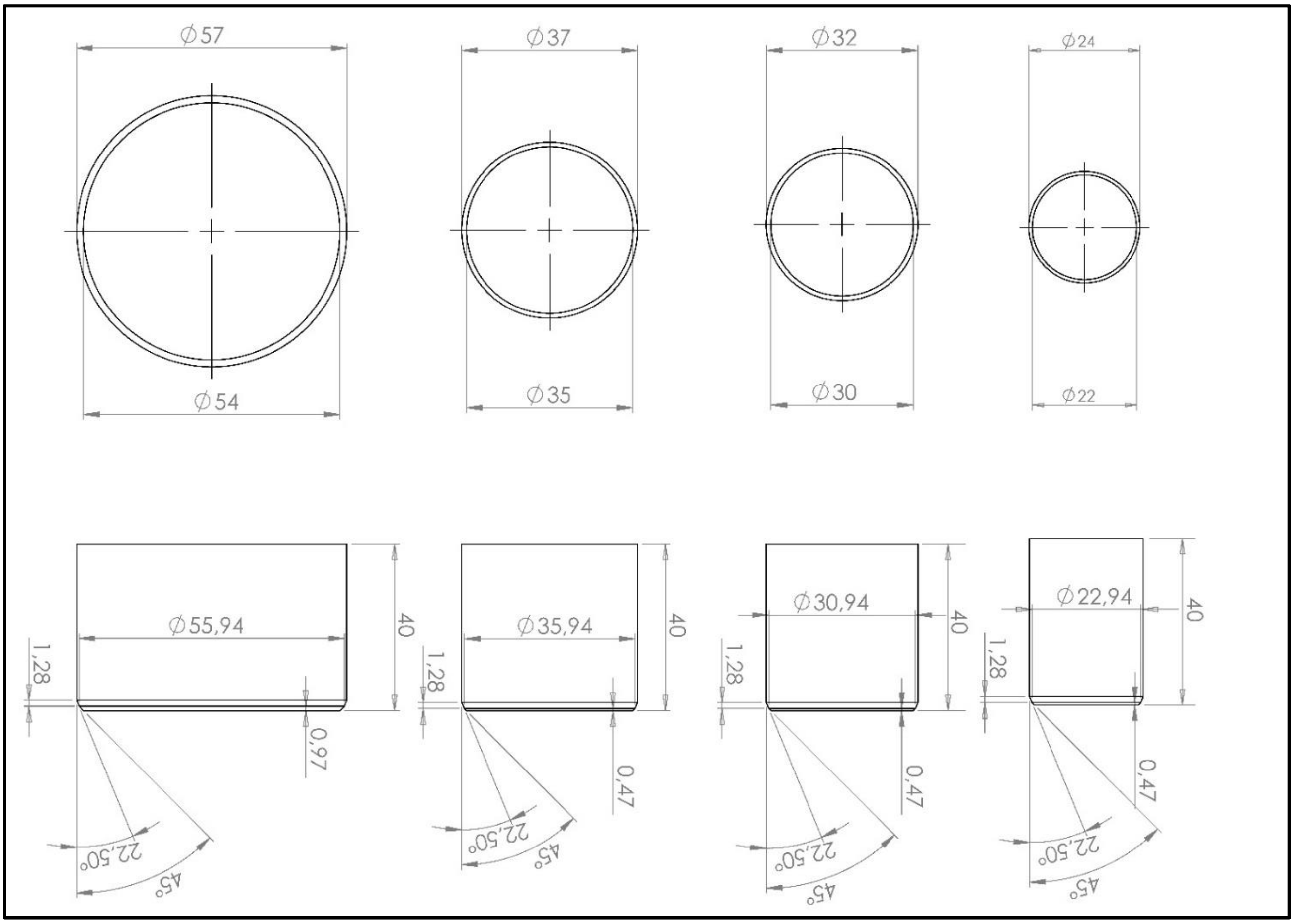


Figure 3-16: Specimen test ring schematics

3.4.4.1 Volume reduction in smaller specimen rings

The volume of soil required was calculated for each specimen ring using the formula shown below and then tabulated for comparison.

$$V = \pi . r^2 . H \tag{14}$$

Table 3-2 indicates the volume of soil required for each specimen ring and the percentage soil of the British standard Specimen ring/cup.

Table 3-2: Volumes of soil required for the different size specimen rings

Specimen ring inside diameter	**Volume of soil required ($mm^3 \times 10^{-4}$)**	**Percentage volume from standard (%)**
54mm ring(standard)	9.161	100.0
35mm	3.848	42.0
30mm	2.827	30.9
22mm	1.521	16.6

As shown in Table 3-2, if the specimen ring could be reduced at least to the 35mm ring, the volume of soil required to fill the cup would already be 58% less than that of the standard volume required.

The fall-cone tests were performed with the standard BS cup compared with the standard diameter ring to be the control test. Afterwards the standard diameter ring was compared with the smaller manufactured rings simultaneously on the same test sample to ensure a minimal spatial variability in the soil specimen when testing.

The liquid limit results from the four different specimen rings that were tested on the same soil specimen were then compared to each other. In theory, the smallest modified specimen ring's liquid limit that had a negligible difference from the standard specimen ring's liquid limit would be suitable to replace the standard ring and in effect reduce the soil volume/weight required to perform the test.

3.4.5 Equipment used to perform the modified fall-cone test

The following equipment was used to perform the modified fall-cone test procedure:

- British standard fall-cone apparatus with an automatic timed-release and locking function to 1 second precision and penetration reading gauge with a 0.1mm precision
- Assembled 30º cone with 80g weight (stem+cone) similar to that of the BS standard cone
- British standard fall-cone cup
- Four specimen rings with diameters of 54mm, 35mm, 30mm, and 22mm, all with a depth of 40mm
- Laboratory scale with 0.01g precision

- SANS 3001 spatulas (the spatula with a width of approximately 10mm was used to sample the moisture content samples and the standard spatula was used for mixing)
- Perspex/glass platform
- Wash bottle containing distilled water
- Airtight metal tins
- Laboratory test sheet (attached as Annexure B)
- Laboratory oven with a temperature of 105-110ºC able to be used uninterrupted

3.4.6 Procedure followed for conducting the modified fall-cone test

3.4.6.1 Modifications of the standard fall-cone test to note

The procedure of the modified fall-cone test was based on the British standard test but with modifications to the required first penetration, the use of a specimen ring instead of a cup, and the four different specimen ring sizes instead of the single standard cup size.

3.4.6.2 Modified fall-cone test procedure

The moistened soil prepared according to section 3.3.2 was removed from the bag and placed into the mixing bowl. The soil was quickly mixed and the filling procedure described in 3.4.2 was carried out immediately afterwards. The 54mm specimen ring centre was positioned below the centre of the cone and the cone was then carefully lowered onto the soil until the tip of the cone just slightly touched the soil (see Figure 3-17).

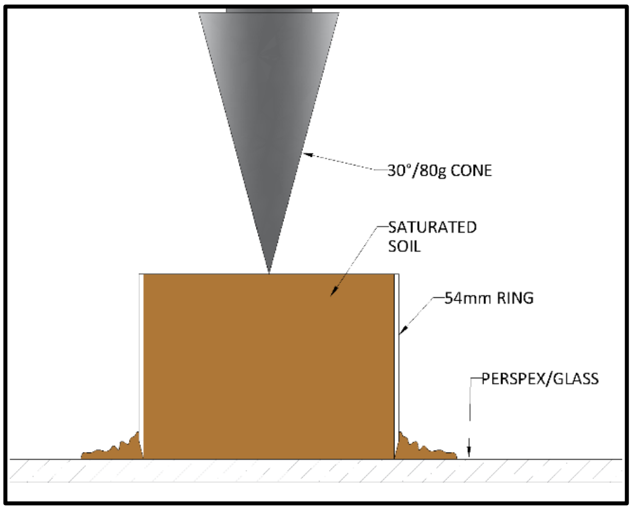


Figure 3-17: Cone edge lowered to just touch the soil

The automatic timed-release mechanism was programmed so that when the mechanism was activated, the cone would be released and fall freely, penetrating the soil for the duration as programmed. Therefore, the mechanism was set for five (5) seconds and the release button was pressed, after which the cone fell and penetrated the soil for five seconds. After the timed duration it was automatically locked.

The built-in penetration depth gauge was lowered onto the released cone and the measured depth in the range of 4-6mm for the first measurement was then recorded on the laboratory sheet.

After the penetration had been captured, the cone was raised to its original position. A soil sample of approximately 10x10x10mm was then taken from the specimen ring where the cone had penetrated and put into one of the airtight tins. The tin was closed for immediate weighing.

Immediately after the smaller 35mm specimen ring has been pushed into the centre of the larger filled specimen ring, the smaller ring usually displaces the soil upwards in the smaller ring. This causes the soil to over-fill the smaller ring while the upward displaced soil could be levelled off the top of the smaller ring to flatten the soil on top.

Therefore, it was not necessary to refill the soil from the bowl. If there was still soil required to fill the smaller ring, residual soil from both the larger and smaller rings was used to carefully fill the smaller ring. The cone was quickly cleaned with paper towel before the next repetition of the test was carried out.

The above-mentioned procedure was repeated with the 30mm and the 22mm rings as well. A moisture content sample was taken with each ring size, after which the four airtight tins with the moistened soil were weighed immediately and the weights were captured onto the laboratory sheet and put aside. This concluded the first penetration measurement.

Figure 3-18 shows all the specimen rings inside the 54mm ring before the cone is dropped inside the 22mm ring.

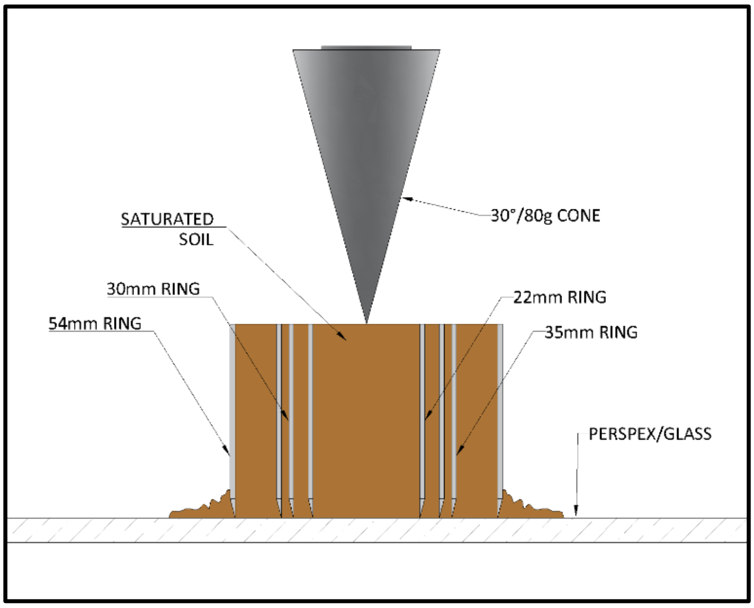


Figure 3-18: After all the specimen rings were pushed into one another

The moistened soil was removed from the specimen rings and returned to the mixing bowl, after which the specimen rings were thoroughly cleaned with a moist cloth. A small amount of distilled water was added to the soil and mixed well until the moisture was evenly distributed throughout the soil sample. This generally took around 10 minutes for very clayey soil. The 54mm specimen was again filled as described in 3.4.2 and the above-mentioned procedure was repeated, with the exception that the soil was more moistened and the penetration depth was a little deeper. The procedure was repeated a total of five times with the penetration depths ranging from 4-6mm, 8-10mm, 12-14mm, 16-18mm and 20-22mm.

All the tins with wet samples were then opened and placed inside the oven and allowed to dry out at 100-105ºC for at least 24 hours.

3.5 Casagrande Cup, Thread Rolling and Linear Shrinkage Method

This section describes the Casagrande Cup, thread-rolling and linear shrinkage methods conducted as per SANS 3001-GR10 (2011) and SANS 3001-GR12 (2011). These tests were conducted immediately after the completion of the fall-cone test.

3.5.1 Apparatus required

The following apparatus was used to perform the Casagrande cup flow curve according to the thread-rolling procedure:

- ASTM Casagrande cup test apparatus
- Grooving tool
- Laboratory scale with 0.01g precision
- Spatulas
- Perspex/glass platform
- Squeeze bottle with distilled water
- Airtight metal tins
- Laboratory test sheet
- Uninterrupted use of a laboratory oven with a temperature of 105-110ºC

3.5.2 Flow curve (3-point) Casagrande cup method test procedure for liquid limit SANS 3001-GR12 (2011)

The Casagrande test procedure was conducted according to the SANS 3001-GR10 (2011), with the exception that it was done in reverse order (wetter to drier state), since it took place right after the completion of the fall-cone test and the soil was still moistened.

The method of proceeding from a wetter to drier state as mentioned in the above paragraph was first compared to the standard SANS 3001-GR12 (2011) method, namely from a dry to wet state, to ensure that it would not have an influence on the LL results. The results of this comparison will be discussed in the following chapter.

The flow curve procedure was started right after the completion of the modified fall-cone test procedure and the last penetration point had been taken around 20mm. The residual soil from the fall-cone was immediately put into the Casagrande cup, levelled and the groove was cut. The Casagrande cup procedure was started and the soil generally deformed together in the 15-22 tap range, which would then be the first point in the flow curve method.

Since the Casagrande cup test was done in reverse, namely from a wetter to drier state, the first point was taken between 15-22 taps, the second between 22-28 taps and the third was taken between 28-35 taps.

The samples that were taken at each point were put into airtight tins, after which the tins were weighed, opened and placed inside the oven with the fall-cone test tin samples.

3.5.3 Thread-rolling method for plastic limit SANS 3001-GR10 (2011)

The thread rolling method was done according to SANS 3001-GR10 (2011) without any modification to the procedure. The plastic limit results that were determined are not applicable to this research project; however, they will be valuable for future research in this field.

3.5.4 Linear shrinkage method SANS 3001-GR10 (2011)

The linear shrinkage method was carried out according to SANS 3001-GR10 (2011) and also without any modification to the procedure. The linear shrinkage results that were determined are also not applicable to this research project; however, they will be valuable for future research in this field.

3.6 Moisture Content Determination SANS 3001-GR20 (2011)

After all the tests had been conducted and all the moisture content samples in the tins had been weighed and recorded, they were opened and carefully put into the oven. The samples were left in the oven for at least 24 hours at a temperature of 105-110ºC.

After the 24-hour period the tins were closed inside the oven before they were removed. After all the tins had been removed from the oven, they were left on a cooling platform for a short while before being weighed and recorded on the same laboratory sheet used for the test methods. After the recording of the weights had been completed, the data capturing commenced.

3.7 Data Capturing and Calculation Thereof

The data from the laboratory sheets was captured onto a spreadsheet where the moisture contents were also calculated. The fall-cone test data was grouped into the four different specimen rings and the BS cup along with their specific penetrations and corresponding moisture contents for the comparison of their results.

The Casagrande cup test data were grouped separately from the fall-cone data containing the moisture contents and their corresponding taps. The plastic limit moisture contents and the linear shrinkage measurements were also captured on the same sheet. An example of the Excel Spread sheet is attached as Annexure B.

3.7.1 Calculation of the modified fall-cone Liquid Limit (FCLL)

From the captured data, the FCLL for each specimen ring was calculated using the log-relationship proposed by Feng (2000) as shown in equation 5 expressed in Chapter 2.

The calculation for the modified FCLL is shown in Figure 3-19 for a sample tested with 35mm specimen ring. The modified FCLL was calculated for corresponding penetrations of 20mm to 10mm in order to determine the penetration to calibrate the modified FCLL to the SANS CCLL.

The calculation shown below was done for each specimen ring, which means that four of the calculations shown below were done for one test. These were later used to compare the results between the different specimen rings.

Sample =	NMC2-017
Cone angle (^{o}) =	30
Cone Weight (g) =	80
Ring Diameter (mm) =	35

Data captured from labsheet					**Log relationship**	
Pen. Depth d (mm)	**tin (g)**	**Wet (g)**	**Dry (g)**	**MC (%)**	**Log Depth**	**Log MC**
4.41	14.52	17.50	16.65	39.9	0.64	1.60
8.51	14.78	18.18	17.05	49.8	0.93	1.70
12.82	14.64	20.10	18.16	55.1	1.11	1.74
15.79	14.72	18.96	17.36	60.6	1.20	1.78
20.16	14.60	19.32	17.32	73.5	1.30	1.87

Calculation	
Linear trendline	
m=	0.37
c=	1.35

Fallcone Liquid Limit	
Pen. Depth d (mm)	**FCLL**
20	68.6
19	67.3
18	65.9
17	64.5
16	63.1
15	61.6
14	60.0
13	58.4
12	56.7
11	54.9
10	53.0

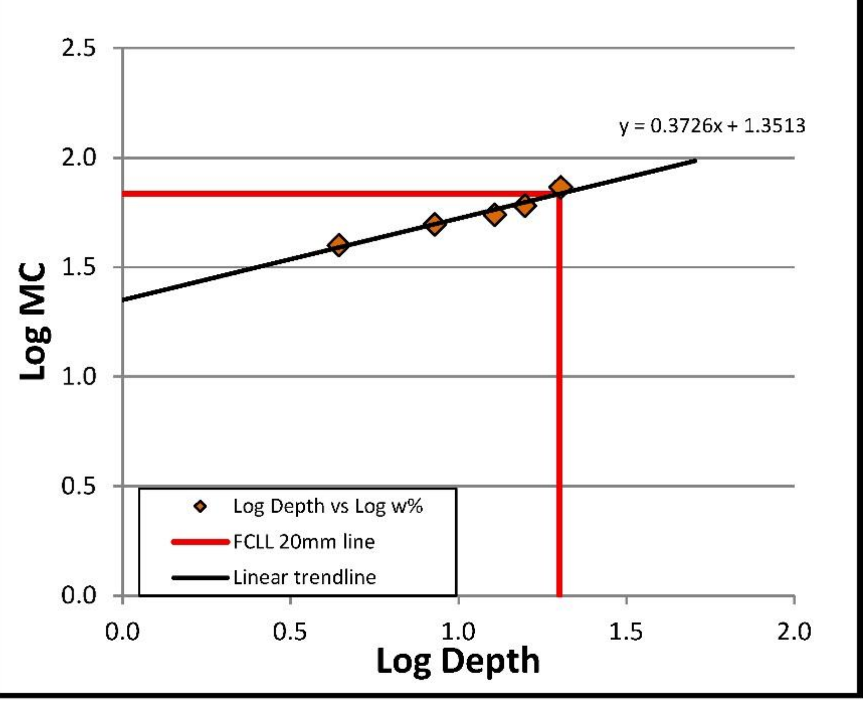
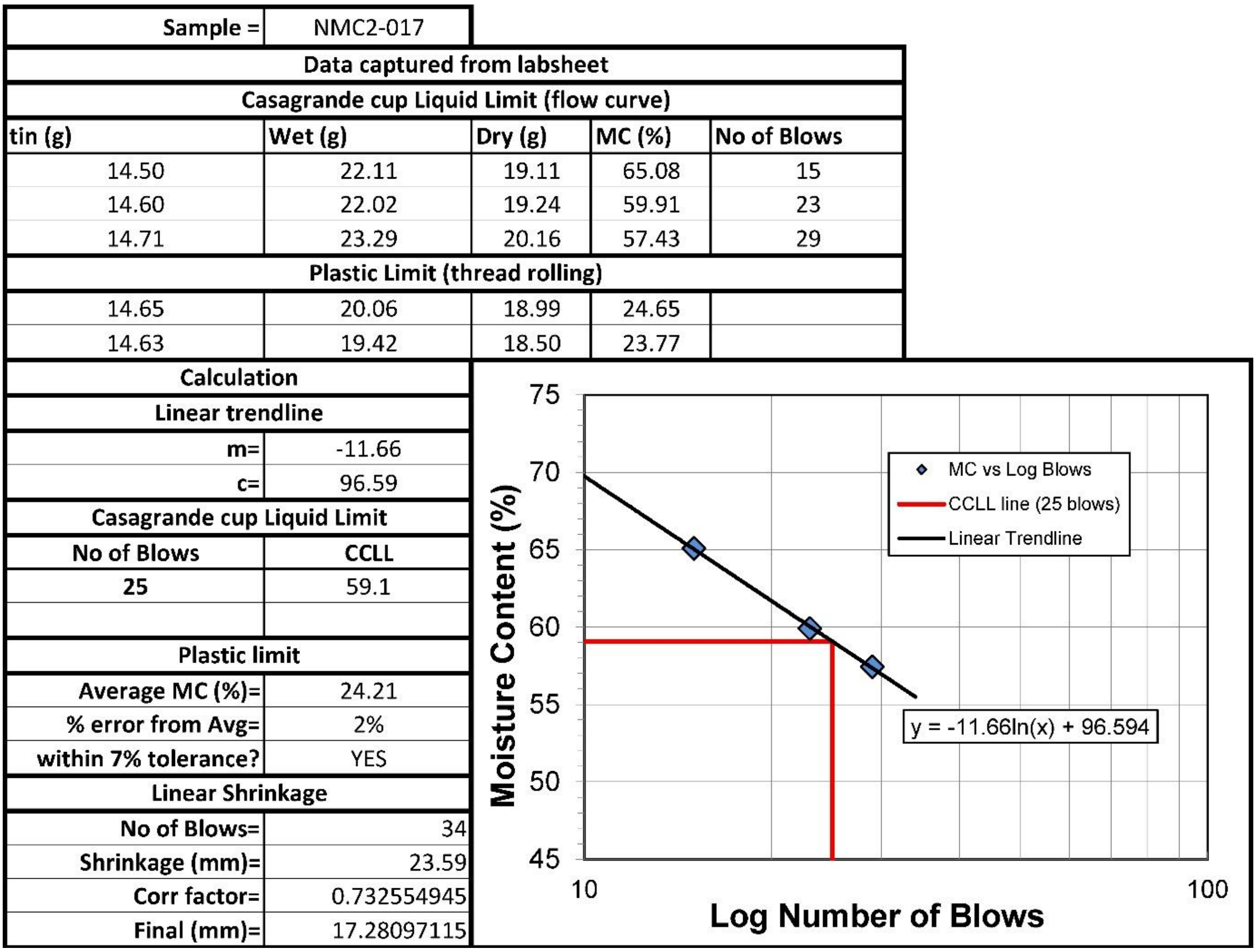


Figure 3-19 Calculation of the FCLL

3.7.2 Calculation of the Casagrande cup liquid limit (CCLL), plastic limit and linear shrinkage

The calculation of the Casagrande cup flow curve liquid limit was done according to the SANS 3001-GR12 (2011) by plotting the three points as described in section 3.5.2 (see Figure 3-20).

The plastic limit and linear shrinkage calculations are shown in Figure 3-20 below, determined according to SANS 3001-GR10 (2011).



Sample =	NMC2-017

Data captured from labsheet				
Casagrande cup Liquid Limit (flow curve)				
tin (g)	**Wet (g)**	**Dry (g)**	**MC (%)**	**No of Blows**
14.50	22.11	19.11	65.08	15
14.60	22.02	19.24	59.91	23
14.71	23.29	20.16	57.43	29
Plastic Limit (thread rolling)				
14.65	20.06	18.99	24.65	
14.63	19.42	18.50	23.77	

Calculation	
Linear trendline	
m=	-11.66
c=	96.59
Casagrande cup Liquid Limit	
No of Blows	**CCLL**
25	59.1
Plastic limit	
Average MC (%)=	24.21
% error from Avg=	2%
within 7% tolerance?	YES
Linear Shrinkage	
No of Blows=	34
Shrinkage (mm)=	23.59
Corr factor=	0.732554945
Final (mm)=	17.28097115

Figure 3-20: Calculation of the CCLL, PL and LS

After all the modified FCLL and SANS CCLL's had been calculated, the results were captured onto a database and analysed. The data analyses are discussed and presented in Chapter 4.

3.7.3 Grouping of calculated results

The calculated results were captured on to an Excel database. This was separated into sections, namely the BS fall-cone cup vs the modified fall-cone specimen ring, dry to wet Casagrande cup vs wet to dry Casagrande cup, the modified fall-cone vs SANS Casagrande cup method, and the fall-cone specimen rings comparison data sets. The results of these groups will also be discussed in Chapter 4.

3.8 Optimisation of the Correlation Strength

During early testing, data capturing and analysis, it was found that the modified FCLL gave a higher LL result than that of the SANS CCLL, which corresponded well with previous researcher reported findings.

Therefore, it was proposed that the difference in liquid limit values between the two methods could possibly be minimized by either adjusting the corresponding penetration depth or adjusting the cone weight of the apparatus.

3.8.1 Adjustment/Calibration of the penetration depth corresponding to the liquid limit

As discussed previously in section 3.7.1, the relationship proposed by Feng (2000) requires a theoretical corresponding penetration depth to determine the modified FCLL.

Therefore, by only reducing the depth “d” in the formula proposed, the effective modified FCLL could be lowered to match the SANS CCLL and in effect optimize the correlation and reduce the deviation between the methods. These methods will be further discussed following the results obtained in Chapter 4.

3.8.2 Fall-cone cone weight (CW) adjustment

Although the following optimisation was later decided to be impractical and uneconomical, it will be discussed, as well as its optimised results, and will be presented in Chapter 4.

As mentioned above, it was decided that this optimisation would not be used as it would result in a possible modification of the standard British cone, which would be unacceptable as a uniform international standard is more desirable.

Early liquid limit results obtained in this study showed that the SANS CCLL correlated closer to the 17mm corresponding penetration depth, instead of the standard 20mm. Therefore, the weight of the cone (CW) would be increased until the SANS CCLL correlated more directly with the standard 20mm corresponding penetration depth.

The desired CW was calculated on the same principle as used by Evans and Simpson (2015) for redefining the corresponding penetration depth for a heavier cone. The equation below shows the standard cone weight correlating with 17mm and is recalculated to redefine the required cone weight to correlate with 20mm penetration:

$$\frac{S_u.(17mm)^2}{80g} = \frac{S_u.(20\text{mm})^2}{\text{CW}} \rightarrow \text{CW} = 110.7\text{g} \qquad (15)$$

The weight of the cone was adjusted by attaching a washer to the stem of the cone. The washer weighed around 25g which increased the effective cone weight from 80g to around 105g. This was close to the calculated weight.

According to the British standard, the stem of the cone is hollow and may be filled with lead shot to increase its weight, as shown in Figure 3-21.

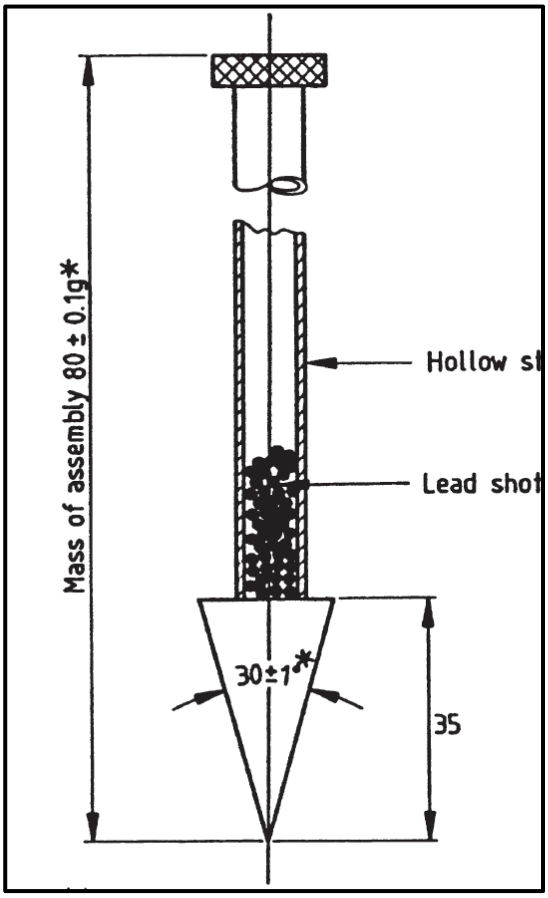


Figure 3-21: British standard fall-cone schematic BS 1377-2 (1990).

It was decided to use a washer as a weight instead in order to reduce the time required for weight calibration as well as reducing the possible variability of the cone weight. The fall-cone tests were conducted normally with the optimisation applied.

3.9 Time Consumption and Optimization of Laboratory Testing

The number of tests that had to be conducted back to back with each soil sample was significant. Along with the cleaning of equipment and weighing of tins, this had a marked effect on the time consumed for each test.

Another effect on the time taken to perform the tests was the type of soil. Clayey soils tended to be more unpredictable when testing, and some retesting had to be done. This could easily have added another hour to the total testing time. Around two sets of tests could be conducted per day if conditions were ideal.

The following given durations were taken while the soil testing was conducted. These durations refer to ideal testing conditions where nothing went wrong in the testing of clayey soils. These durations do not include the sorting, sieving and wetting of the soil, as these were done separately on another day.

1. Preparation of soil, cleaning and weighing of tins, and filling in the preliminary information onto the laboratory sheet: **0.75 to 1 hour**
2. Fall-cone test with all four specimen rings, including the cleaning of each ring and cone after each plot: **1 to 2 hours**
3. The normal Casagrande cup test: **0.75 hour**
4. Plastic limit thread-rolling test: **0.5 to 1 hour**
5. Linear shrinkage test: **0.25 hour**
6. Weighing of all the tins and placing them in the oven: **0.5 hour**

When combining the above steps, the total testing time amounted to a total of 3.75 to 5.5 hours.

After the analysis of the results in Chapter 4, only one specimen ring would be required to perform the fall-cone test. This should significantly reduce the time consumption of the test, effectively reducing it by three quarters. However, this should be further tested.

3.10 Summary of Research Methodology

In conclusion to this chapter, the following can be summarised before leading into the next chapter.

i. All the samples were prepared according to SANS 3001-GR10 (2011) and 3001-GR5 (2011), with exception that the soil was bagged and left to absorb the moisture for longer than specified.
ii. The first modification done to fall-cone method was to remove the bottom plate of the standard specimen cup and sharpening the edges. The filling procedure of the fall-cone cup was changed from manually and carefully filling the standard cup with a spatula to pressing a sharpened specimen ring into a soil mound.
iii. The specimen ring LL results were compared with the standard BS fall-cone cup LL results.
iv. The next modification was to effectively reduce the volume of the specimen ring by producing smaller rings to compare LL results with and choose the ring with the lowest difference in results to the original ring and the smallest volume. These results will be discussed in Chapter 4.
v. The modified fall-cone and Casagrande test methods were conducted for the comparison of their LL results. The same soil sample had to be transferred between the test methods to ensure low variability in the LL results.
vi. The large amount of test data was captured in to an Excel spreadsheet and the LLs were calculated and analysed.
vii. From the data analysis, a correlation between the two methods was expected, although it was not a direct correlation. The correlation could be corrected by adjusting the corresponding cone penetration depth for the LL.
viii. Adjusting the cone weight would also correct the correlation, however this would require modifying the standard fall-cone equipment and was decided not to be used. The results are however discussed in the following chapter.

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Introduction

The soil sample liquid limits were calculated as described in the previous chapter, all the results were captured onto a database in order to make it possible to group and analyze certain types of data comparisons, such as the comparison of the results from the different specimen ring sizes and also the comparison of the SANS Casagrande cup (CCLL) and modified BS fall-cone (FCLL) test methods as discussed in the previous chapter. The liquid limit results obtained from the laboratory experimentation were analysed and are classified as quantitative data.

The analysis considerations and result comparisons as well as the discussions thereof will be discussed in this chapter.

4.2 Initial Considerations Made Regarding the Results

Some considerations and changes were made before the results were analysed. These are discussed below.

4.2.1 Practical problem with the 22mm diameter specimen ring

With laboratory testing early on, it was observed that the 22mm specimen ring was in effect too small because when the fall cone freely fell into the soil-filled ring, some of the soil would start to push back up, hindering the penetration depth of the cone, as shown in Figure 4-1. This effect was discussed in Chapter 2: the heave produced by the cone is too large for the small diameter of the cone.

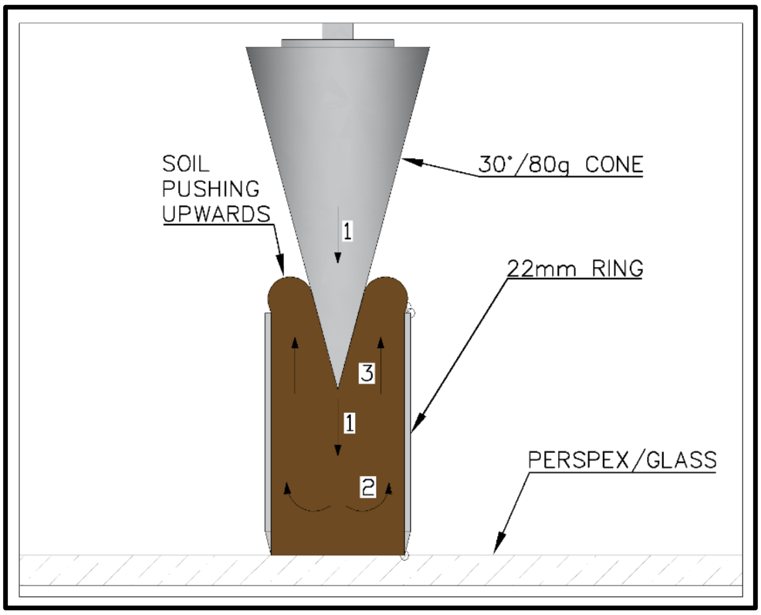


Figure 4-1: Soil pushing cone upwards in the 22mm specimen ring with the effect of mould confinement

The motion of the cone and soil is depicted by means of arrows and numbers. This phenomenon is referred to as the effect of mould confinement and described as the heaving soil that the cone creates that starts affecting the penetration depth of the cone.

Therefore, the results obtained from the 22mm specimen ring were not included in any analysis. This did not have any effect on the comparisons done with the other specimen rings.

4.2.2 Data outliers

Some data outliers were observed which had indicated a significant difference in liquid limits between the two test methods. The inter-quartile ranges (IQR) of the data were calculated, as well as the upper and lower limits and the outliers beyond these limits were then removed from the dataset. The number of outliers that were removed comprised less than 5% of the total data set.

4.3 Comparing the Standard Fall-Cone BS Cup with the 54mm Specimen Ring

As mentioned in Chapter 3, the standard BS cup LL was compared with the 54mm specimen ring LL ($FCLL_{54}$) to establish that there is a negligible to no difference in LL result between the BS cup and the new specimen ring.

The comparison was done with 10 data points as depicted on a comparative bar chart from the samples “HA” and “TP5” from Table 3-1 (see Figure 4-2):

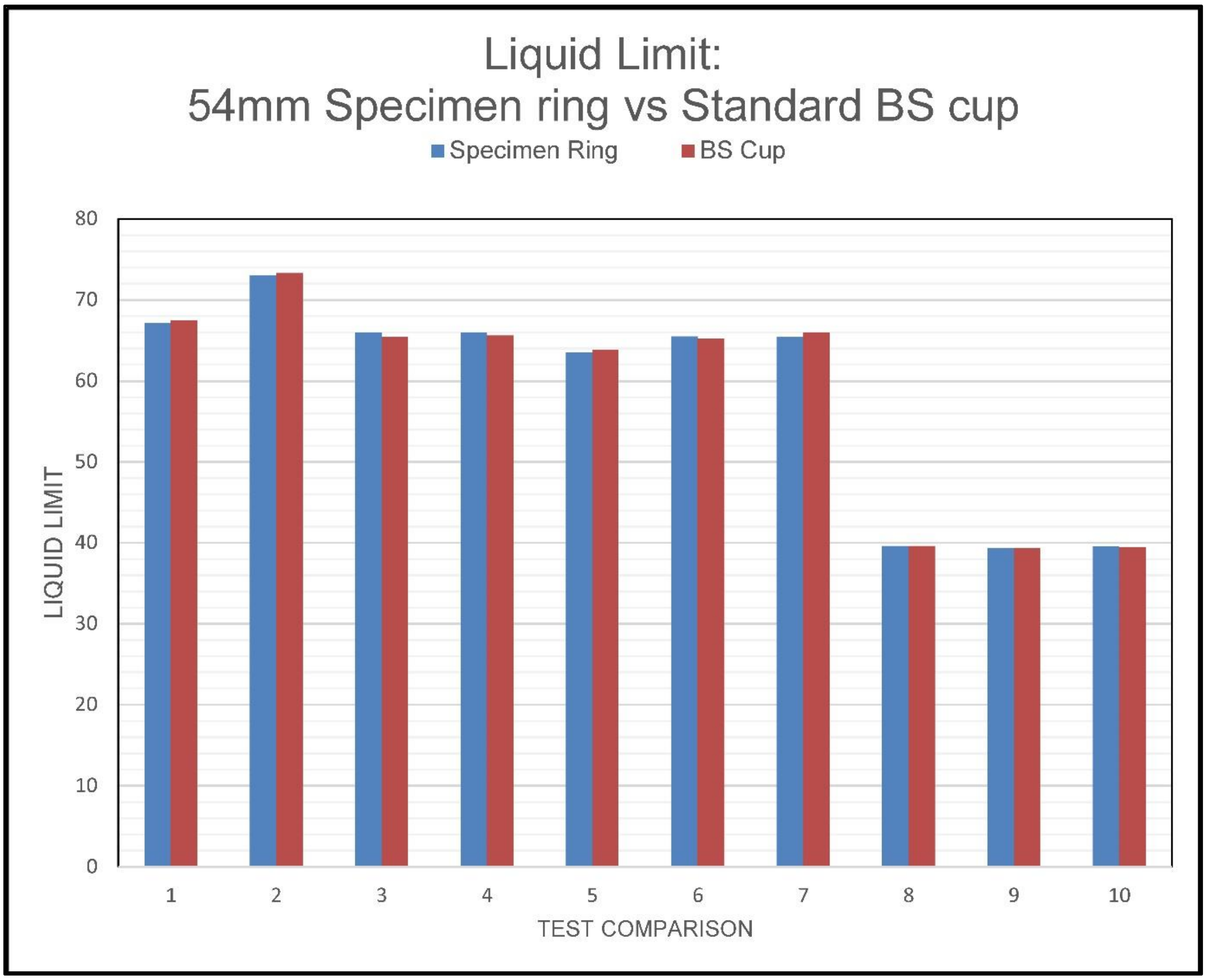


Figure 4-2: $FCLL_{54}$ vs BS cup LL

From Figure 4-2, it can be seen that there is virtually no difference between the BS cup and specimen ring. With a mean error of 0.28 LL units and an error standard deviation of 0.19 LL units it can be concluded that there is no significant difference in result between the standard BS fall-cone cup and the new fall-cone specimen ring.

4.4 Comparing the Fall-Cone 54mm Specimen Ring with Smaller Rings

As discussed in previous chapters, the fall-cone method requires a larger sample size than that of the Casagrande cup method. As also discussed in Chapter 3, three smaller specimen rings were manufactured and tests were conducted with these rings. The idea is that if there is a marginal to no difference in results between these rings and the LL value from the $FCLL_{54}$ result, a smaller ring could be used as a standard size. There could be a 58% to 69% reduction in the soil volume required if this is achieved.

Some other benefits of reducing the required sample size include faster sample preparation, since the soil mound that would have to be made, would be easier and faster to make with less soil. The cutting of the mound would be quicker and the probability of entrapping air voids in the specimen ring might be reduced even further.

Linear regression analyses were done to illustrate the correlation between the specimen rings as discussed below.

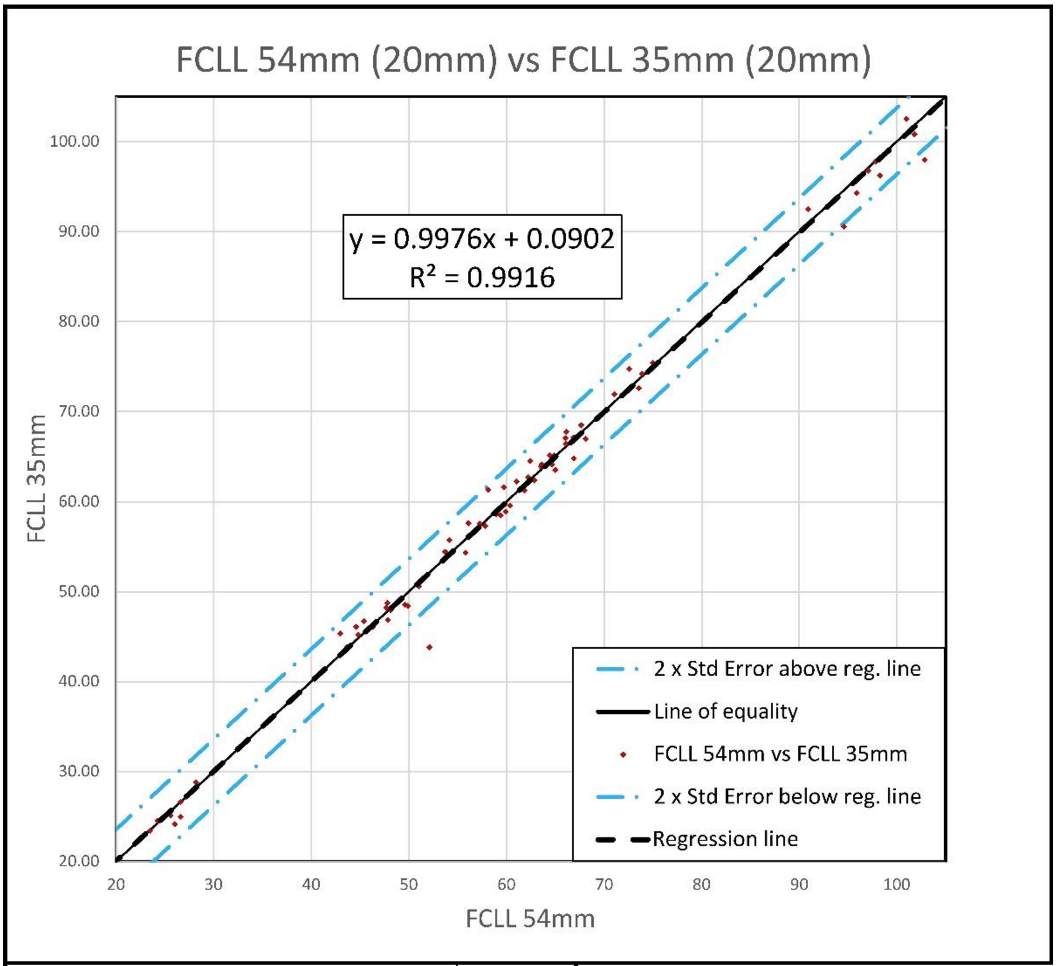
4.4.1 Linear regression analysis

The regression analyses were done between the $FCLL_{54}$ and the smaller 35mm ring ($FCLL_{35}$) as well as between the $FCLL_{54}$ and the 30mm ring ($FCLL_{30}$) with a 68 data point and 70 data point data set respectively. The comparisons among the rings were done with a 20mm corresponding penetration. Lower penetrations will be considered in the following sections.

In the linear regressions shown in this chapter, the standard error of estimates (S) was calculated and represents the average distance that the observed values differ from the regression line, or its precision/goodness of fit of the dispersion of the data points. Just as in the case of a probability distribution with its standard deviations, at least 95% of the data points should fall within plus and minus twice the standard error.

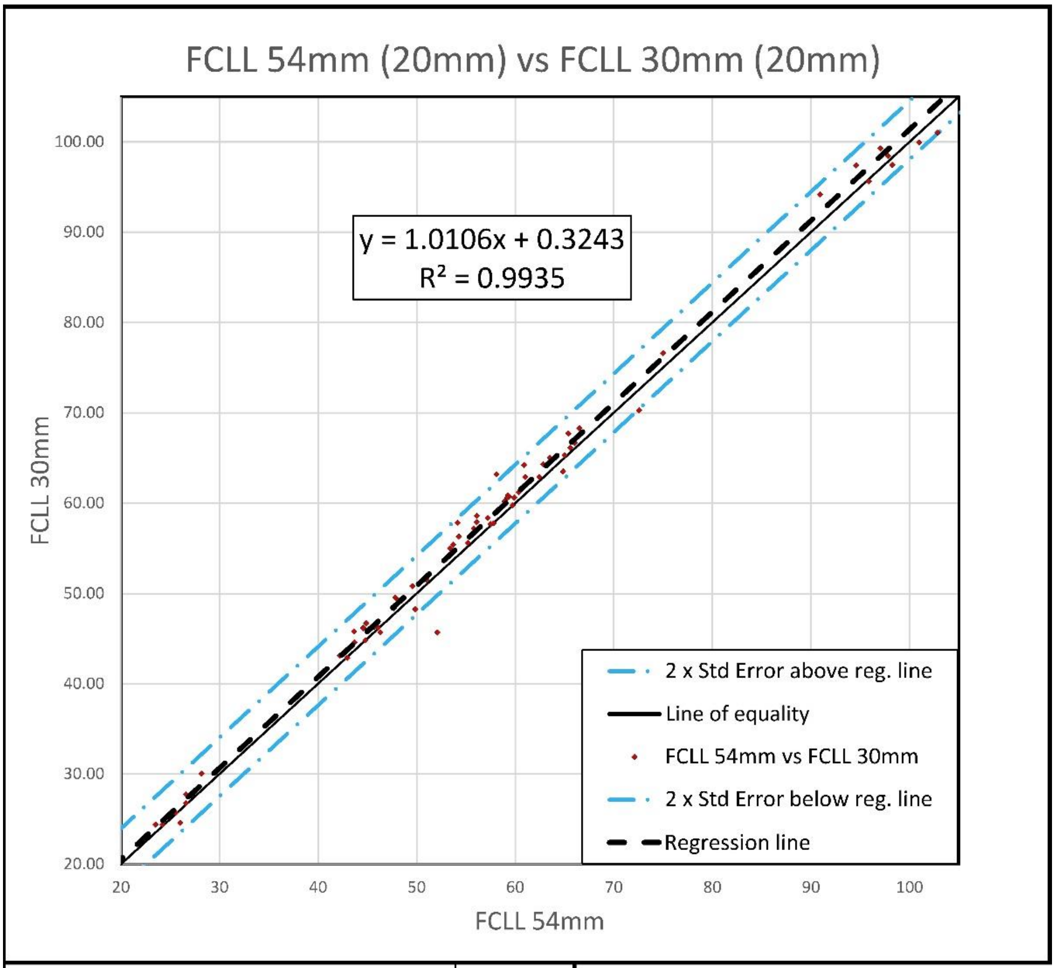
The line of equality represents the line if the deviation of all the data points between the two methods of specimen rings were equal to zero. The Pearson (R^2) coefficient represents the proportion degree between the dependent (FCLL) and independent (CCLL) data, also referred to as the correlation of the data.

Figure 4-3 and Figure 4-4 show the regressions and comparisons between the $FCLL_{54}$ and $FCLL_{35}$ as well as the $FCLL_{54}$ and $FCLL_{30}$.



n=	68
std error (S) =	1.85
% of data within 2 x S	96%
Pearson squared (r^2) =	0.992

Figure 4-3: Regression and comparison between the FCLL_{54} and FCLL_{35}



n=	70
std error (S) =	1.62
% of data within 2 x S	97%
Pearson squared (r^2) =	0.993

Figure 4-4: Regression and comparison between the FCLL$_{54}$ and FCLL$_{30}$

From the regressions, it is clear that there is only a marginal difference between the FCLL$_{54}$ and both the FCLL$_{35}$ and FCLL$_{30}$ rings as well as a low S of 1.62 to 1.85, where 97% and 96% of the data falls within a 2 x ±S range.

Therefore, the FCLL$_{54}$ ring may be reduced to either the FCLL$_{35}$ or FCLL$_{30}$ for conducting a liquid limit test, thereby reducing the required amount of soil by almost 60 to 70%. The comparison between the Casagrande cup and modified fall-cone method is discussed in the following section.

4.5 Comparing the 'Wet to Dry CCLL with the Standard Dry to Wet' CCLL

As mentioned in Chapter 3, the standard 'dry to wet' CCLL was compared with the reversed 'wet to dry' CCLL to confirm that there is a negligible to no difference in LL result between the two variations of the Casagrande cup method.

The comparison was done with 10 data points (shown in Annexure C) as depicted on a comparative bar chart (see Figure 4-5):

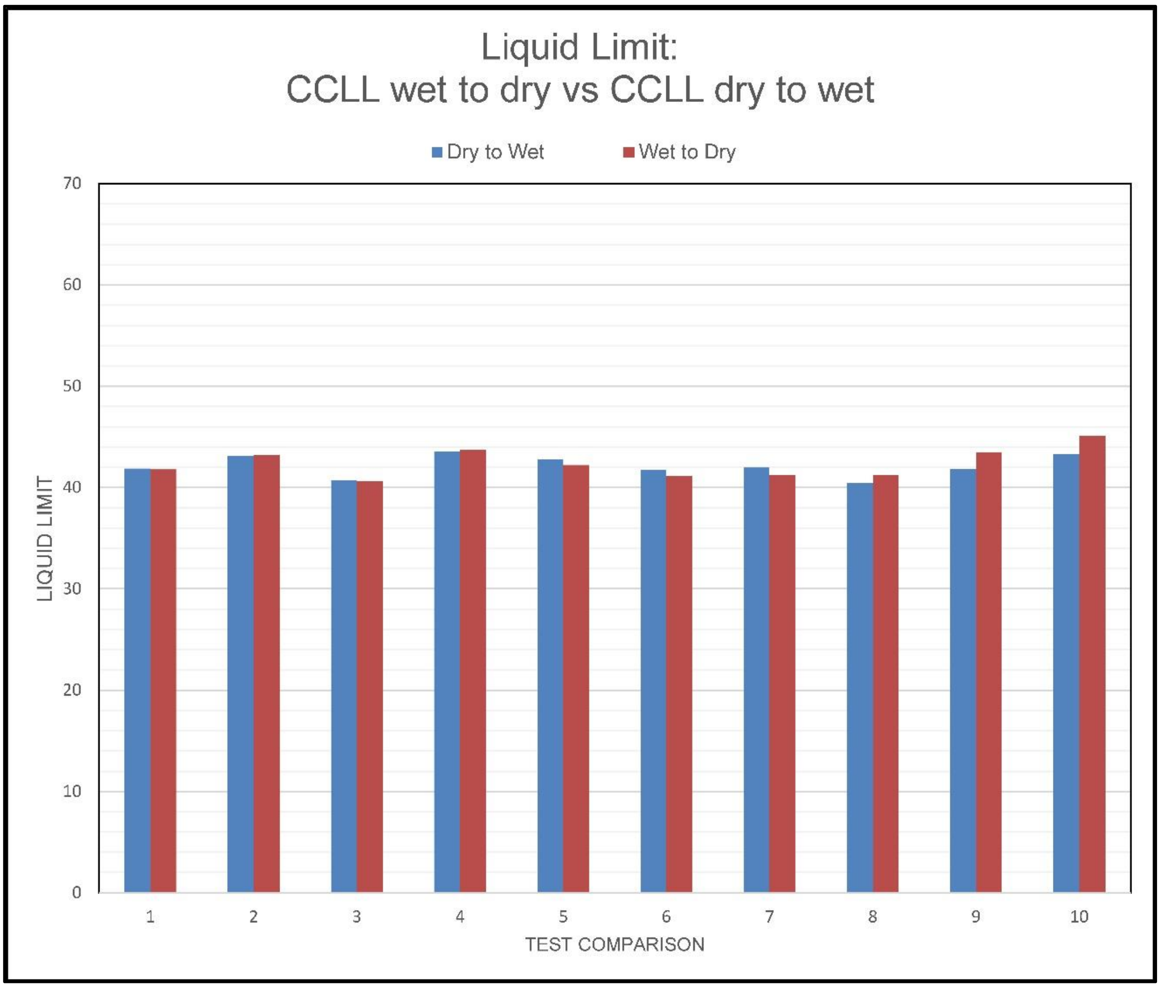


Figure 4-5: CCLL "dry to wet" vs CCL "wet to dry"

Figure 4-5 shows that there is a very low difference between the two CCLL method variations. With a mean error of 0.66 LL units and an error standard deviation of 0.61 LL units it can be concluded that there is effectively no difference in result between the 'dry to wet' CCLL and the reversed 'wet to dry' CCLL.

4.6 Comparing the Modified FC Method (FCLL) with the Conventional Method (CCLL)

The second comparison was between the FCLL and the CCLL to show the correlation and the degree thereof as well as the degree of penetration calibration that was required. This correlation will prove the possibility of replacing the CCLL with the newer FCLL method as a liquid limit determination method for South African soils.

4.6.1 Fall-cone 54mm ring ($FCLL_{54}$) vs CCLL

The analysis of the comparison between the $FCLL_{54}$ and CCLL was conducted with a set of 80 data points. The table of the data set is shown in Annexure C. The corresponding penetration depth is a theoretical variable in the liquid limit formula discussed in Chapter 3, and can be adjusted without any further laboratory testing required to calibrate the FCLL to the CCLL.

The data points were plotted for each penetration from 20mm to 16mm and their linear regressions were drawn on the same chart to compare the 20mm penetration with the penetration closest to the line of equality as shown in Figure 4-6.

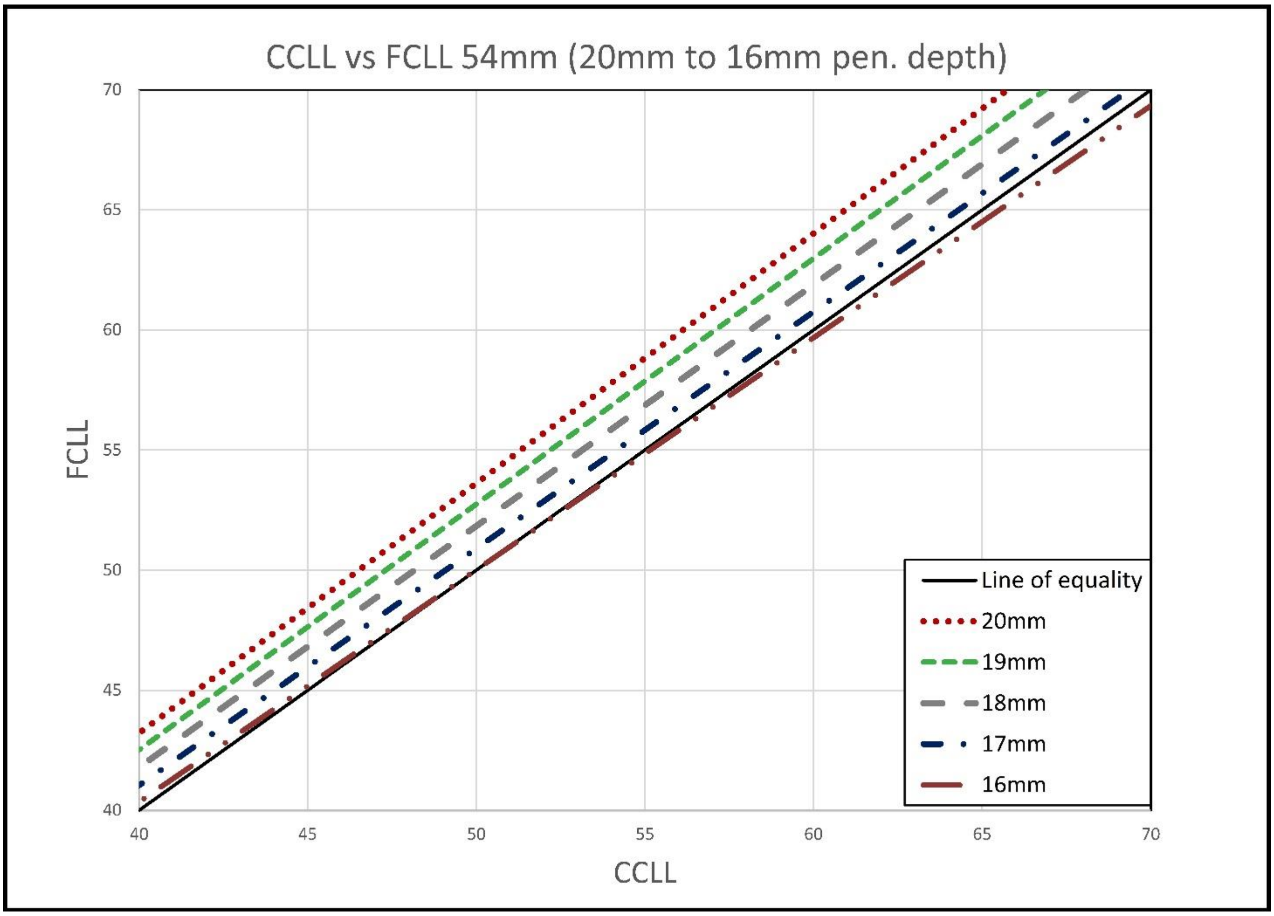
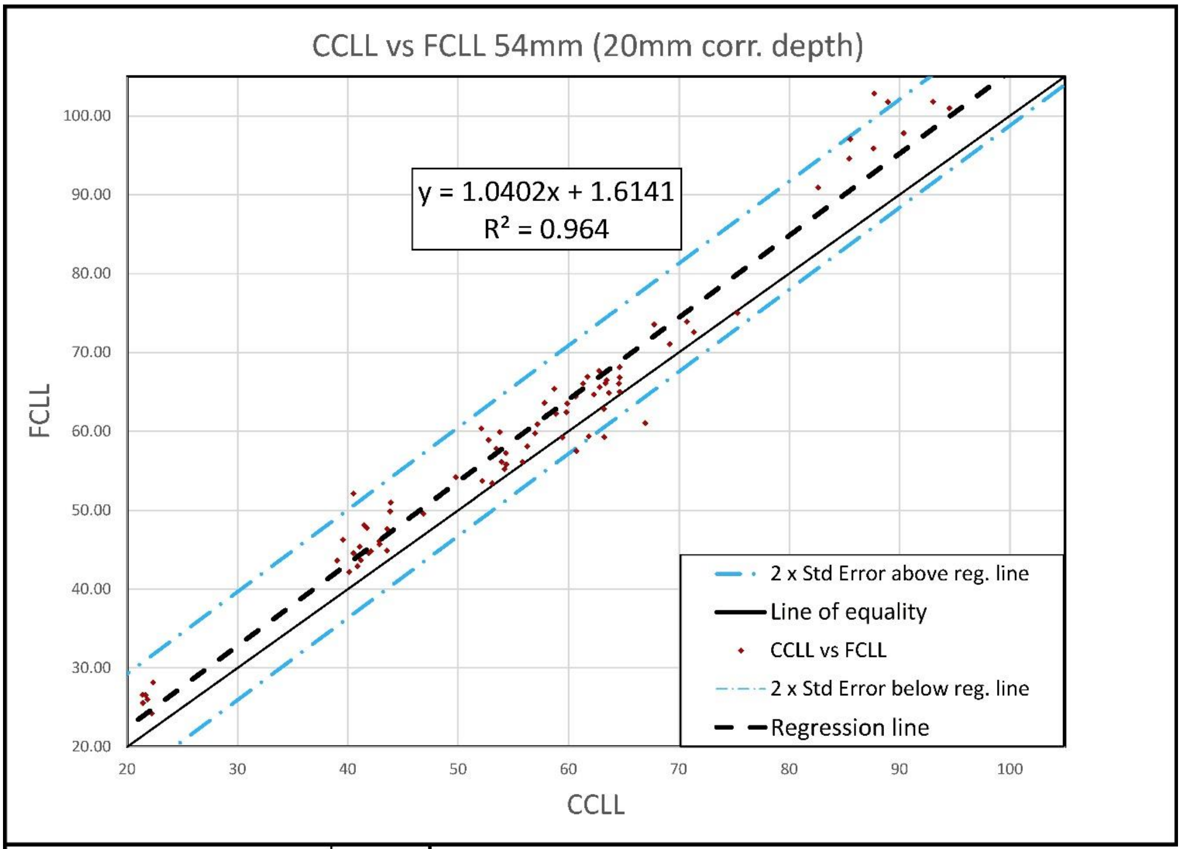


Figure 4-6: Linear reg. of CCLL vs FCLL$_{54}$ for penetrations from 20mm to 15mm

As seen in Figure 4-6, the 16mm penetration is closest to the line of equality. Therefore, the 20mm penetration and 16mm penetration depths were chosen for the analysis and are discussed in the following section.

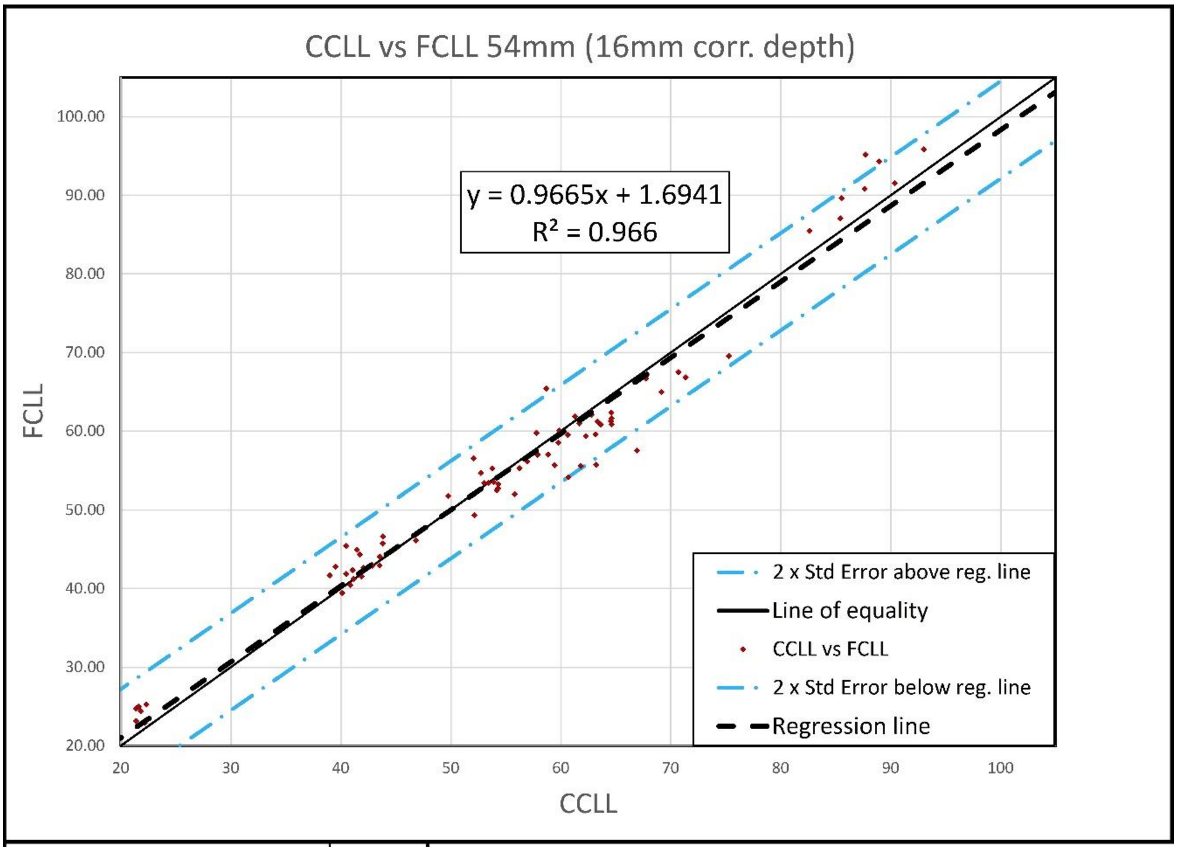
4.6.1.1 Linear regression analysis

From the 80 data points, a linear regression analysis was done for each chosen penetration depth. Only the standard 20mm and the penetration with the best fit to the line of equality are shown in Figure 4-7 and Figure 4-8.



n=	80
std error (S) =	3.43
% of data within 2 x S	93%
Pearson squared (r^2) =	0.9640

Figure 4-7: Linear reg. of CCLL vs $FCLL_{54}$ at 20mm penetration.



n=	80
std error (S) =	3.09
% of data within 2 x S	94%
Pearson squared (r^2) =	0.9660

Figure 4-8: Linear reg. of CCLL vs FCLL$_{54}$ at 16mm penetration.

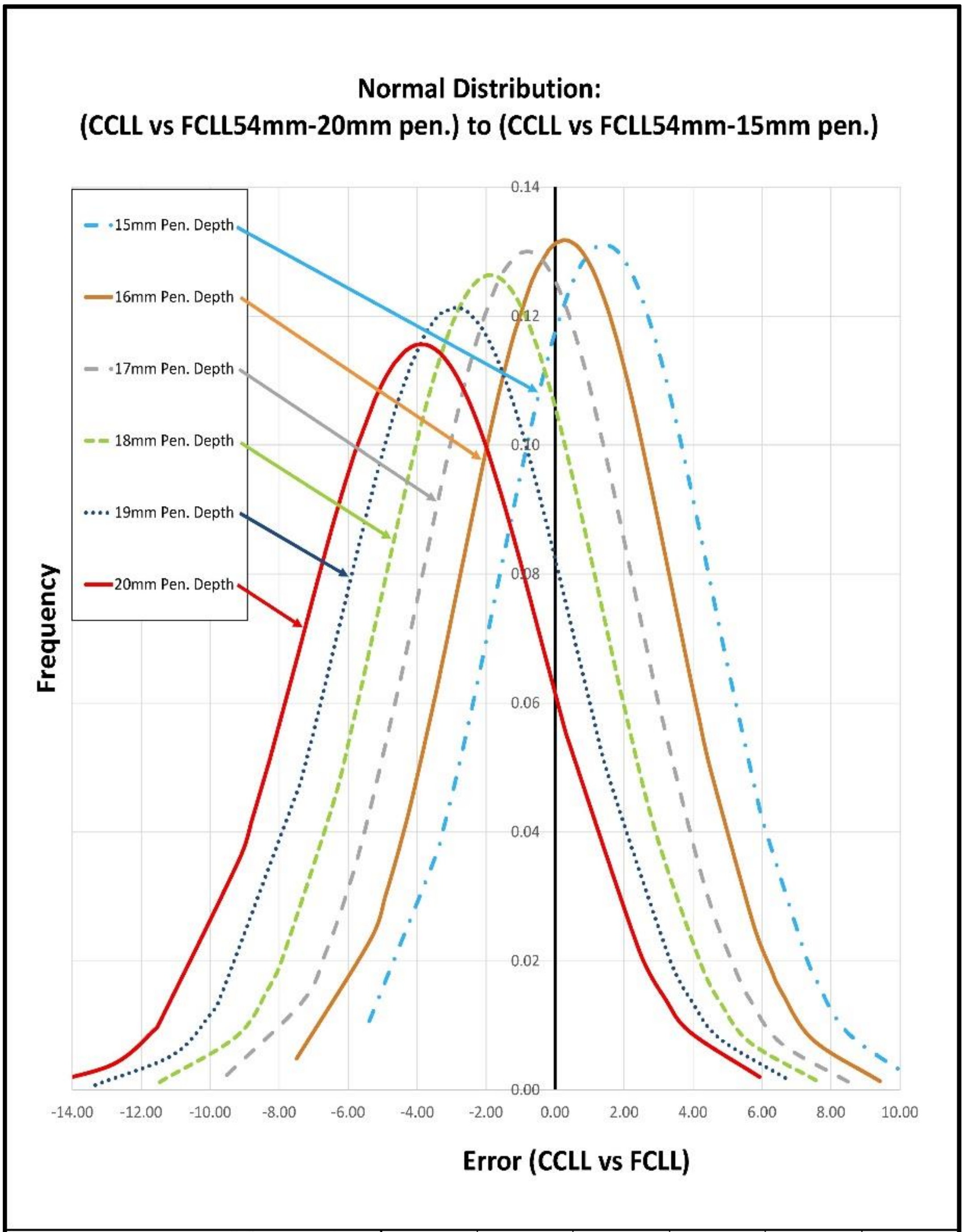
From Figure 4-7, it is seen that the CCLL corresponds well with the FCLL$_{54}$ and that there is a strong correlation. However, the CCLL shows a constant deviation from the line of equality, which correlates very well with the results reported by Sampson and Netterberg (1984).

This deviation is diminished when lowering the corresponding penetration to 16mm as shown Figure 4-8. The 16mm penetration has a low S of 3.09 and 94% of the data falls within 2 x ±S range instead of 95%. This 1% difference was decided to be negligible. It should be noted that the correlation also improved marginally with the reduction in penetration.

4.6.1.2 Probability distributions

The probability distributions of the data were also plotted to see whether they followed a normal distribution. In order for a distribution to be normal, at least 67% of the data points should fall within plus and minus one standard deviation (SD), 95% should fall within plus and minus two SD and lastly, 100% should fall within plus and minus three times the SD.

The type of comparison between the two methods for this project was based on how small the deviation between the two methods was. Therefore, the deviated values between the CCLL and the FCLL$_{54}$ were calculated for each penetration depth from 20mm to 15mm to determine which distribution was plotted closest to the zero-deviation mean line. The distribution for each chosen penetration depth is shown in Figure 4-9.

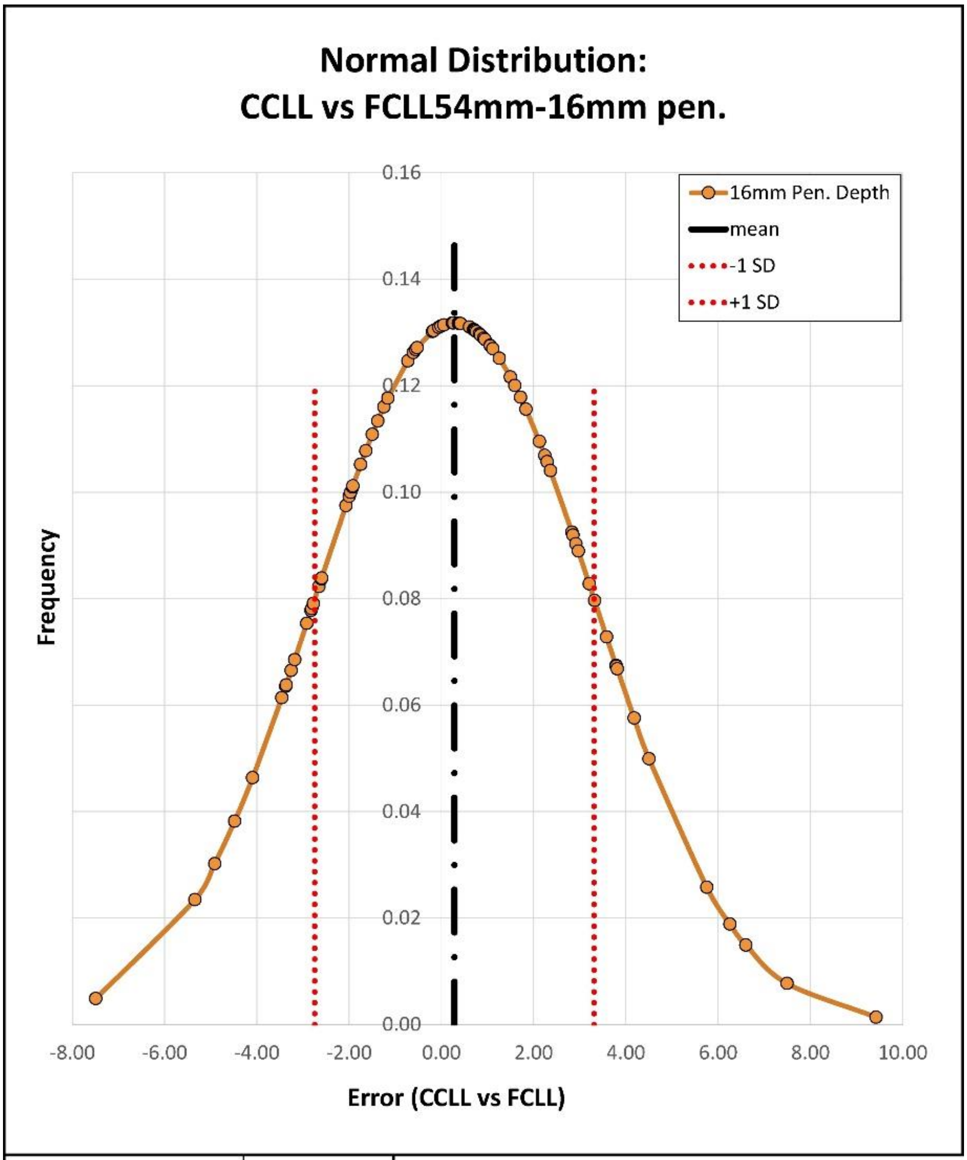


CCLL vs FCLL 54mm - "X" penetration=	20mm	19mm	18mm	17mm	16mm	15mm
n=	**80.00**	**80.00**	**80.00**	**80.00**	**80.00**	**80.00**
Mean=	**-3.87**	**-2.89**	**-1.87**	**-0.82**	**0.28**	**1.43**
S.Dev=	**3.45**	**3.29**	**3.16**	**3.07**	**3.03**	**3.04**

Figure 4-9: Probability distribution of CCLL vs FCLL$_{54}$ for penetrations from 20mm to 15mm

From the distributions shown above, it can be seen that the 16mm penetration probability distribution is closest to the zero-deviation mean line. As well as having the lowest standard deviation, this agrees well with the penetration determined in the regression analysis.

Figure 4-10 shows the chosen 16mm penetration distribution to determine whether the data follows a normal distribution.



count -1SD<x<1SD	54
% prob	**67.5%**
count -2SD<x<2SD	76
% prob	**95.0%**
count -3SD<x<3SD	79
% prob	**99%**

Figure 4-10: Normal distribution of CCLL vs FCLL (54mm) for 16mm pen

As shown above, the curve does indeed follow a normal distribution. From the above results, it is clear that there is a strong correlation between the SANS CCLL and the $FCLL_{54}$ and that the 16mm penetration should be used to directly correlate the $FCLL_{54}$ with the CCLL for South African soils.

Therefore, it is possible to replace the SANS CC method with the modified SA FC method and the corresponding depth of 16mm must be used when calculating the liquid limit.

4.6.2 Fall-cone 35mm ring ($FCLL_{35}$) vs CCLL

As discussed in previous sections, The $FCLL_{54}$ should be calculated using the 16mm corresponding penetration to correlate directly with the CCLL. However, it should be taken into account that this required penetration might change when the smaller diameter rings are tested and mould confinement starts to affect the cone penetration.

In order to test this, the same procedure has been followed as in section 4.6.1, with the exception that the CCLL was compared with the chosen $FCLL_{35}$.

This data set contains 107 data points and the same regression variables are calculated and shown as in section 4.6.1.1. The table of the data points is shown in Annexure C.

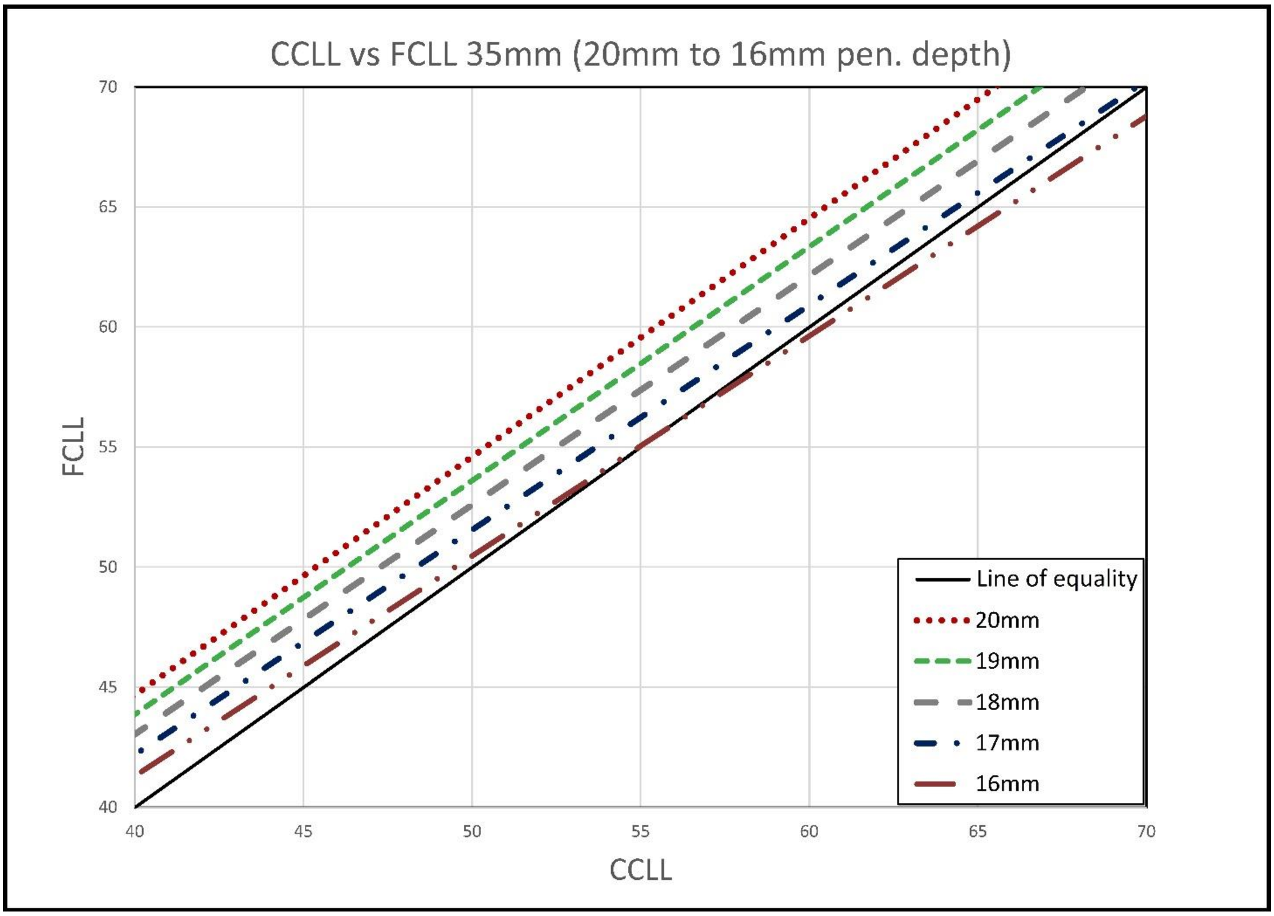
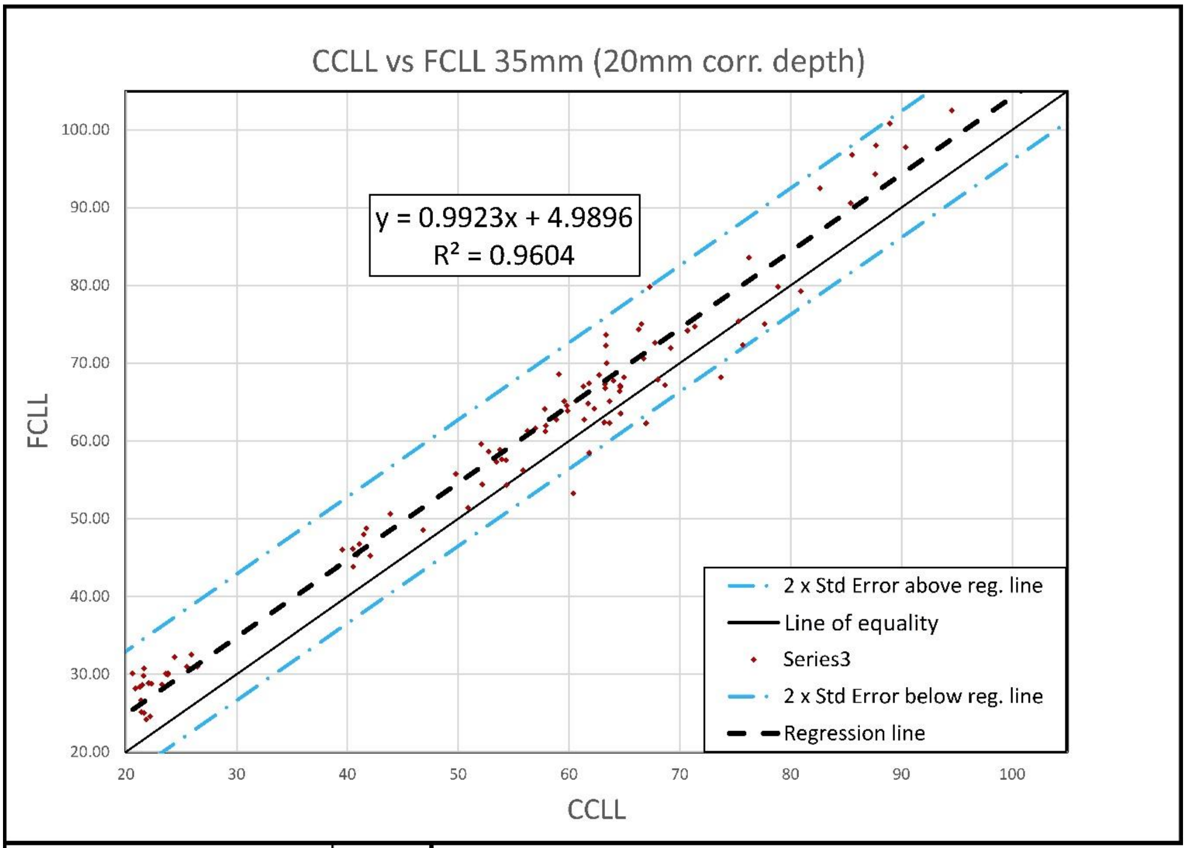


Figure 4-11: Linear reg. of CCLL vs FCLL$_{35}$ for penetrations from 20mm to 15mm

As seen in Figure 4-11, the 16mm penetration is closest to the line of equality. Therefore, the 20mm penetration and 16mm penetration depths were chosen for the analysis and are discussed in the following section.

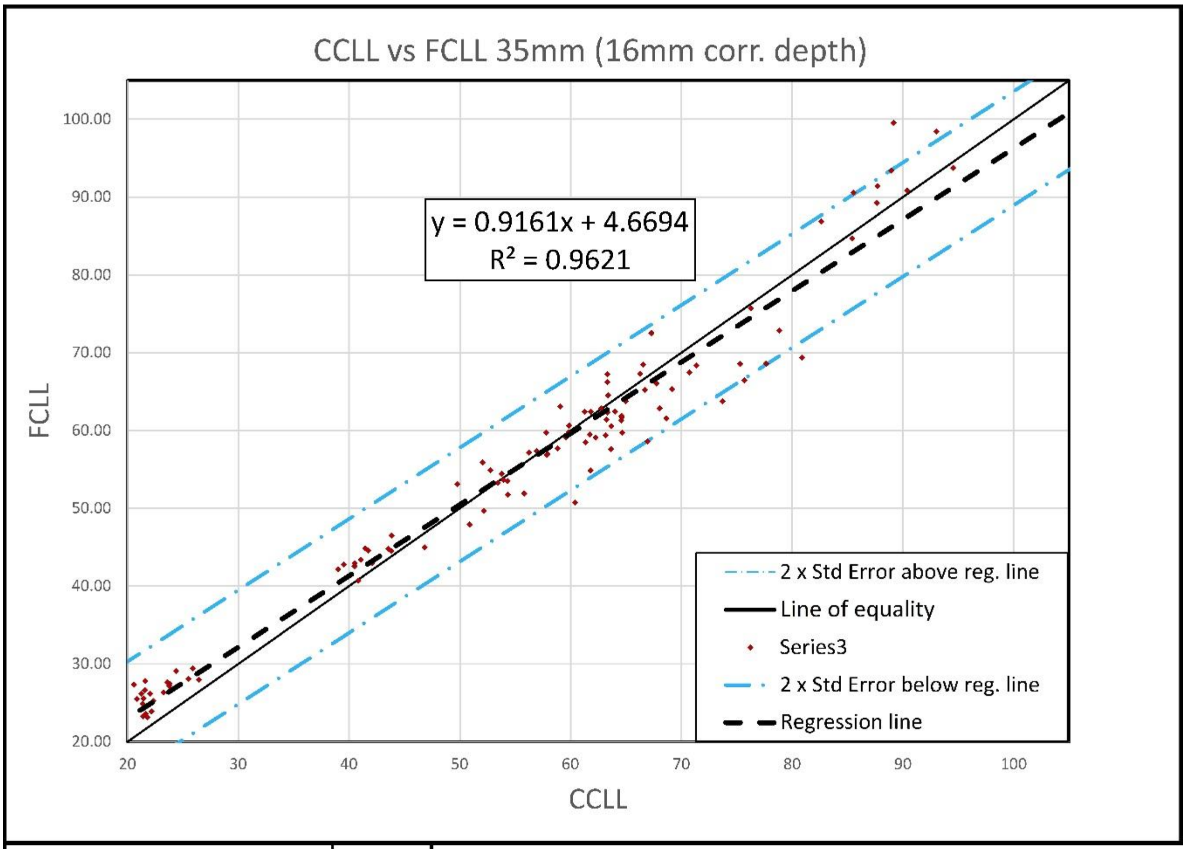
4.6.2.1 Linear regression analysis

From the 107 data points, a linear regression analysis was conducted for each chosen penetration depth. Only the 20mm penetration and the penetration with the best fit to the line of equality is shown in Figure 4-12 and Figure 4-13.



n=	107
std error (S) =	4.06
% of data within 2 x S	97%
Pearson squared (r^2) =	0.9604

Figure 4-12: Linear reg. of CCLL vs FCLL$_{35}$ at 20mm penetration.



n=	107
std error (S) =	3.66
% of data within 2 x S	95%
Pearson squared (r^2) =	0.9621

Figure 4-13: Linear reg. of CCLL vs $FCLL_{35}$ at 16mm penetration.

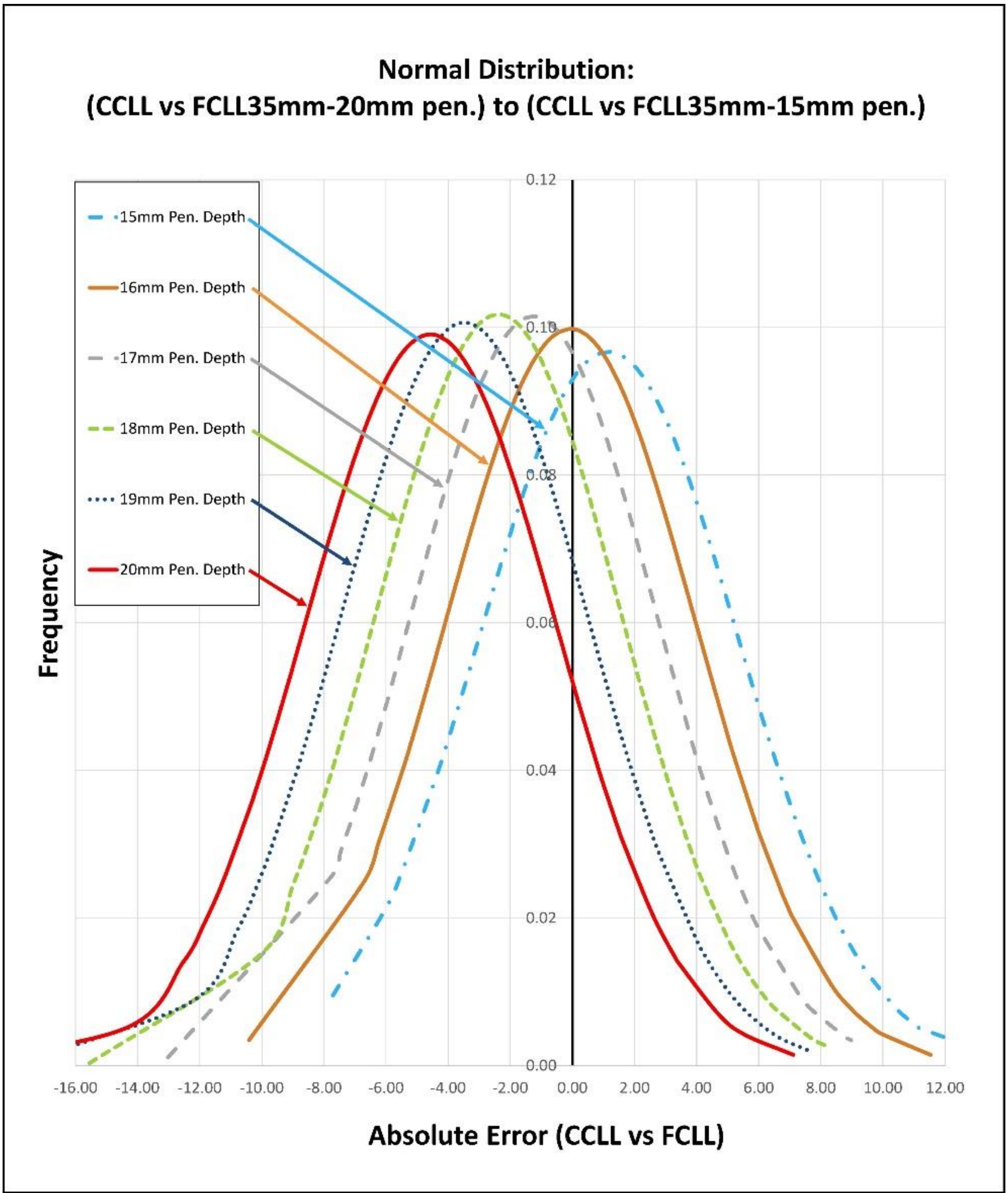
From Figure 4-12, it can be seen that the CCLL corresponds well with the $FCLL_{35}$ and that there is a strong correlation, although the correlation is not direct.

These results are directly correlated by lowering the corresponding penetration to 16mm as shown in Figure 4-13.

The 16mm penetration has a low S of 3.66 and 95% of the data falls within 2 x ±S range. These results correspond well with the results from the $FCLL_{54}$.

4.6.2.2 Probability distributions

The probability distributions of the 107 data samples were plotted to see if they followed normal distribution curves as well as confirm the new corresponding penetration. The distribution for each chosen penetration depth is shown in Figure 4-14.

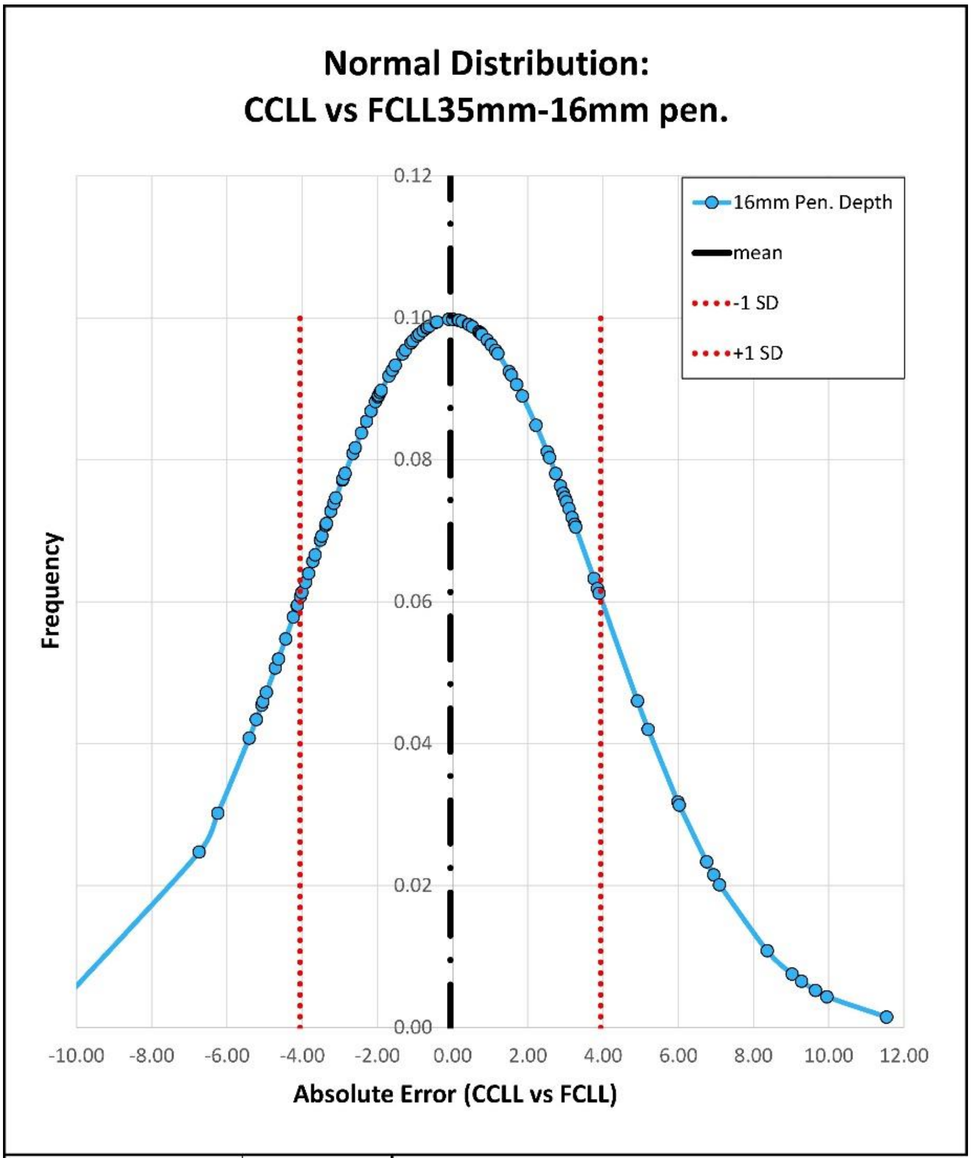


CCLL vs FCLL 35mm - "X" penetration=	20mm	19mm	18mm	17mm	16mm	15mm
n=	107.00	107.00	107.00	107.00	107.00	107.00
Mean=	-4.57	-3.48	-2.38	-1.25	-0.06	1.16
S.Dev=	4.03	3.96	3.92	3.93	4.00	4.12

Figure 4-14: Probability distribution of CCLL vs $FCLL_{35}$ for penetrations from 20mm to 15mm

From the distributions shown in Figure 4-14, it can be seen that the 16mm penetration probability distribution is closest to the zero-deviation mean line. As well as having the lowest standard deviation, this agrees well with the penetration determined in the regression analysis.

Figure 4-15 shows the chosen 16mm penetration distribution to determine whether the data follows a normal distribution.



count -1SD<x<1SD	80
% prob	**75%**
count -2SD<x<2SD	100
% prob	**93%**
count -3SD<x<3SD	107
% prob	**100%**

Figure 4-15: Normal distribution of CCLL vs $FCLL_{35}$ for 16mm pen.

As shown in Figure 4-15, the curve does indeed follow a normal distribution. From the above results, it is clear that there is a strong correlation between the CCLL and FCLL$_{35}$ and that the 16mm penetration should be the penetration used when determining the liquid limit with the modified FC.

4.6.3 Fall-cone 30mm ring (FCLL$_{30}$) vs CCLL

As discussed in previous sections, the FCLL$_{54}$ and FCLL$_{35}$ should be determined using the 16mm corresponding penetration to correlate directly with the CCLL. However, as mentioned before, this required penetration might change when the mould confinement from the smaller ring affects the cone penetration.

In order to test this, the same procedure has been followed as in section 4.6.1, with the exception that the CCLL was compared with the chosen FCLL$_{30}$ instead.

This data set contains 82 data points and the same regression variables are calculated and shown in section 4.6.1.1. The table of the data points is shown in Annexure C.

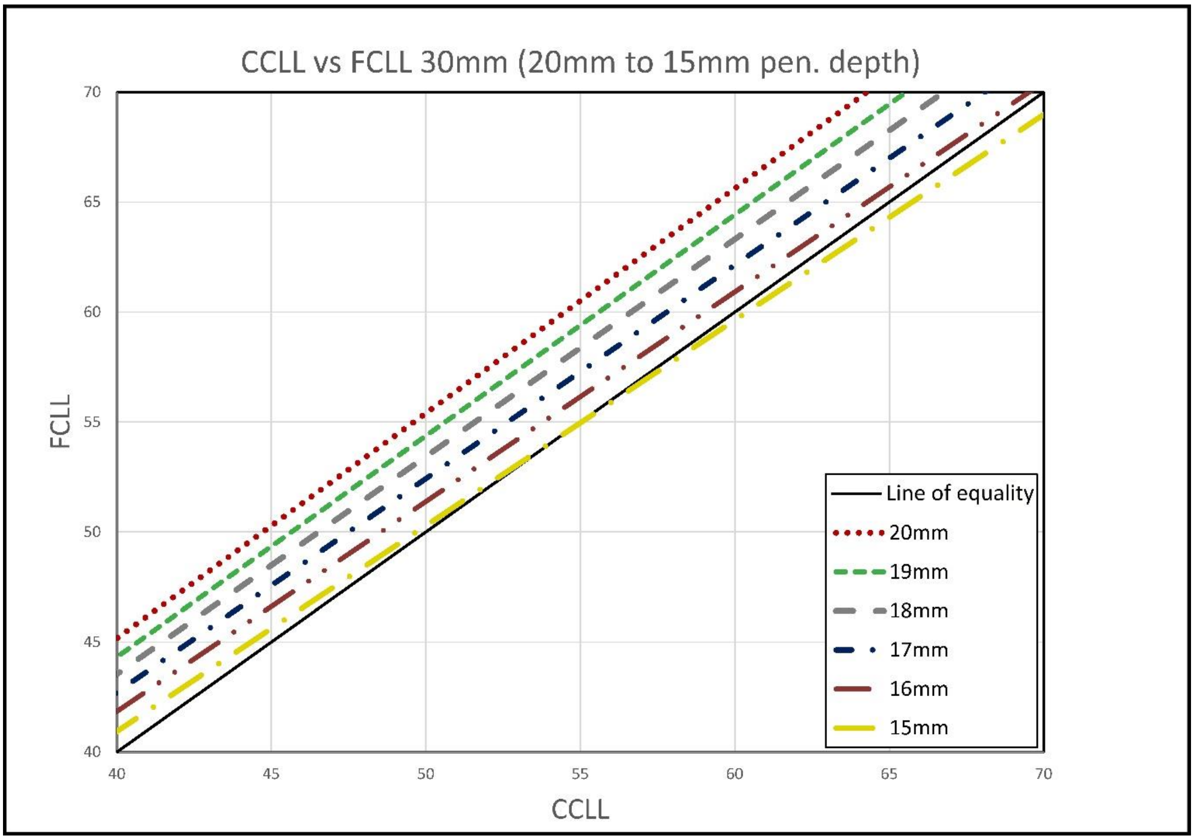
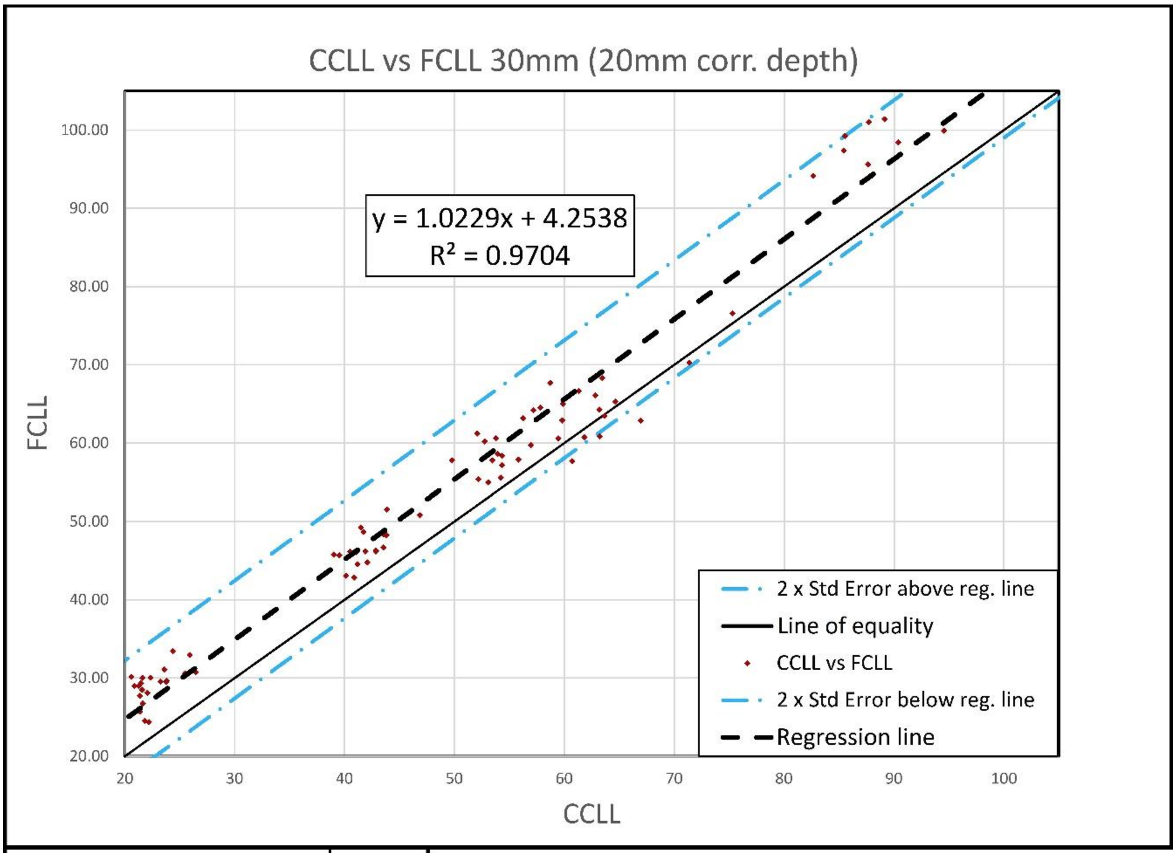


Figure 4-16: Linear reg. of CCLL vs FCLL$_{30}$ for penetrations from 20mm to 15mm

As seen in Figure 4-16, the 15mm penetration is closest to the line of equality. Therefore, the 20mm penetration and 15mm penetration depths were chosen for the analysis and are discussed in the following section.

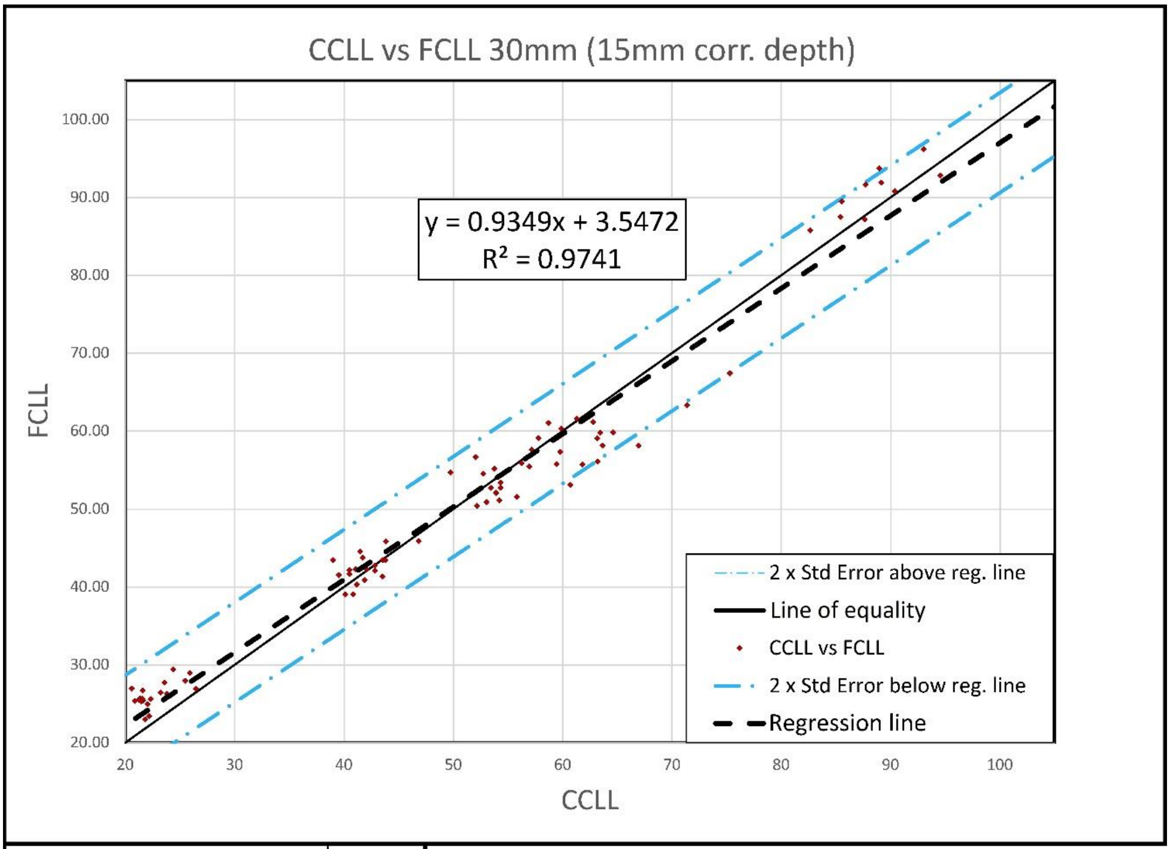
4.6.3.1 Linear regression analysis

From the 82 sample data points, a linear regression analysis was done for each chosen penetration depth. Again, only the standard 20mm and the 15mm penetration are shown in Figure 4-17 and Figure 4-18.



n=	82
std error (S) =	3.76
% of data within 2 x S	96%
Pearson squared (r^2) =	0.9704

Figure 4-17: Linear reg. of CCLL vs FCLL 30mm at 20mm penetration.



n=	82
std error (S) =	3.21
% of data within 2 x S	96%
Pearson squared (r^2) =	0.9741

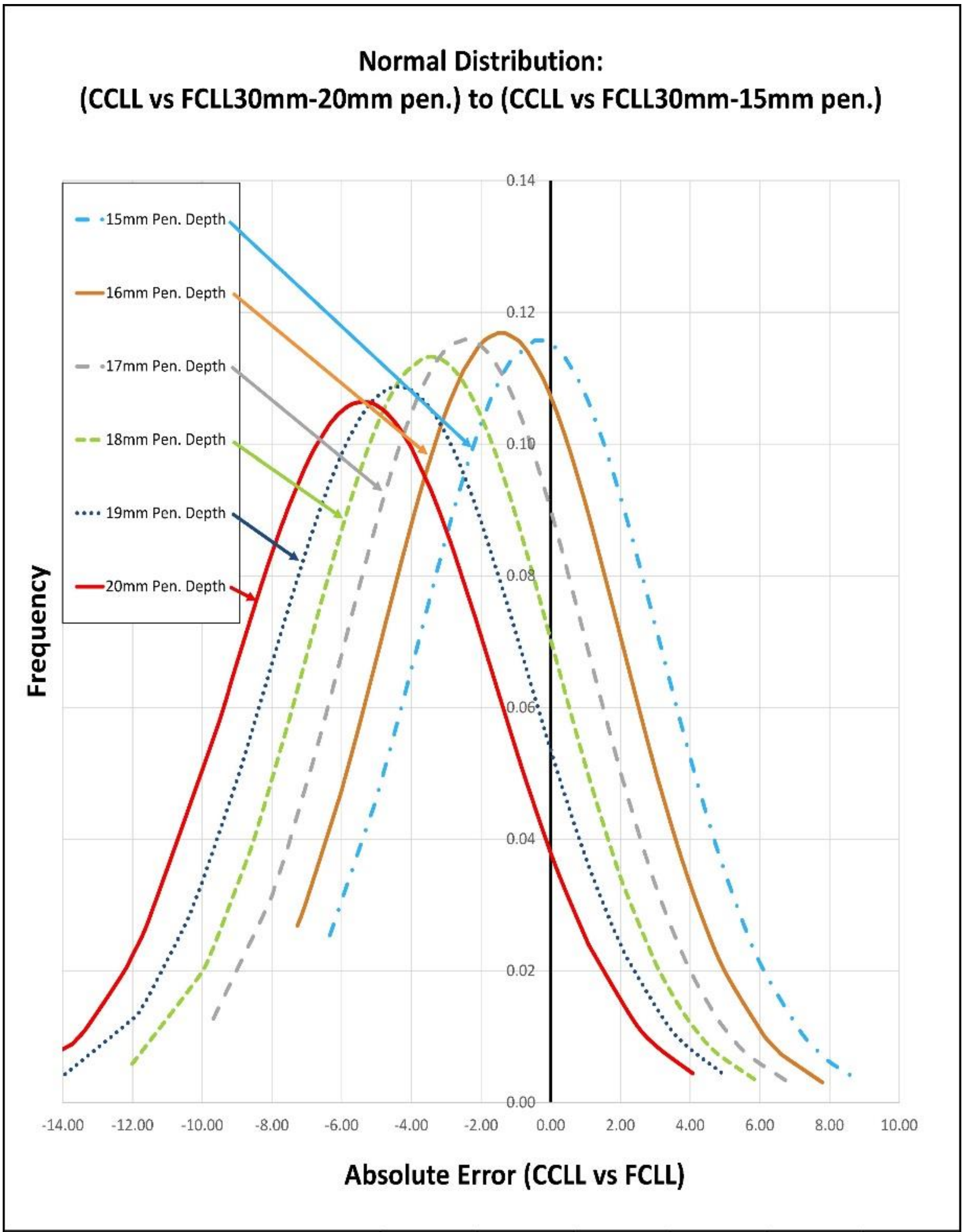
Figure 4-18: Linear reg. of CCLL vs FCLL$_{30}$ at 15mm penetration.

From Figure 4-18 shown above, the CCLL is seen to correspond well with the FCLL$_{30}$ and there is a strong correlation, although the correlation is not direct. This time the deviation was minimized by lowering the corresponding penetration to 15mm as shown in Figure 4-18.

The 15mm penetration has a low S of 3.21 and 96% of the data falls within 2 x ±S range. Therefore, the 30mm specimen ring requires a corresponding penetration depth of 15mm to determine the FCLL$_{30}$. This, however, differs from the FCLL$_{54}$ and FCLL$_{35}$ results.

4.6.3.2 Probability distribution

The probability distributions of the 82 data samples were plotted to determine whether they followed normal distribution curves as well as confirming the new corresponding penetration. The distribution for each chosen penetration depth is shown in Figure 4-19.



CCLL vs FCLL 30mm - "X" penetration=	20mm	19mm	18mm	17mm	16mm	15mm
n=	82.00	82.00	82.00	82.00	82.00	82.00
Mean=	-5.39	-4.37	-3.44	-2.45	-1.42	-0.34
S.Dev=	3.75	3.67	3.52	3.44	3.41	3.45

Figure 4-19: Probability distribution of CCLL vs FCLL$_{30}$ for penetrations from 20mm to 15mm

From the distributions shown in Figure 4-19, it is seen that the 15mm penetration probability distribution is closest to the line of equality. This correlates with the linear regression analysis.

As stated before, the $FCLL_{30}$ has a lower corresponding penetration depth than that of the $FCLL_{54}$ and $FCLL_{35}$. This reduction in corresponding penetration could be the starting effect of mould confinement.

Similar to the 22mm ring, the 30mm specimen ring is becoming too small for the heave produced by the cone and the confined soil is starting to resist the penetration of the cone.

Therefore, the results obtained from $FCLL_{30}$ are unreliable and the $FCLL_{35}$ should be used at a penetration depth of 16mm to determine the LL.

4.7 Comparing the Modified FCLL with the SANS CCLL after Cone Weight is Increased

4.7.1 Introduction

As discussed in Chapter 3, it was decided not to use the following correlation optimization as the reduction of the corresponding penetration depth proved to be adequate to calibrate the CCLL and FCLL. In addition, it has a very low impact on the change required to the standard BS fall-cone apparatus.

As also mentioned in Chapter 3, the cone weight was increased from 80g to 104.5g. Theoretically, this should increase the corresponding penetration depth, instead of lowering it, as was done in the previous tests.

4.7.2 Data analysis

The modified FC method and the SANS CC method were conducted on 49 data points with LLs ranging from 20 to 105. The 35mm diameter specimen ring was used to perform the modified FC test. Linear regressions and probability distributions were plotted as with the previous tests, although only the effect of the heavier cone will be observed.

The data points were plotted for each penetration from 20mm to 16mm and their linear regressions were drawn on the same chart to compare the 20mm penetration with the penetration closest to the line of equality as shown in Figure 4-20.

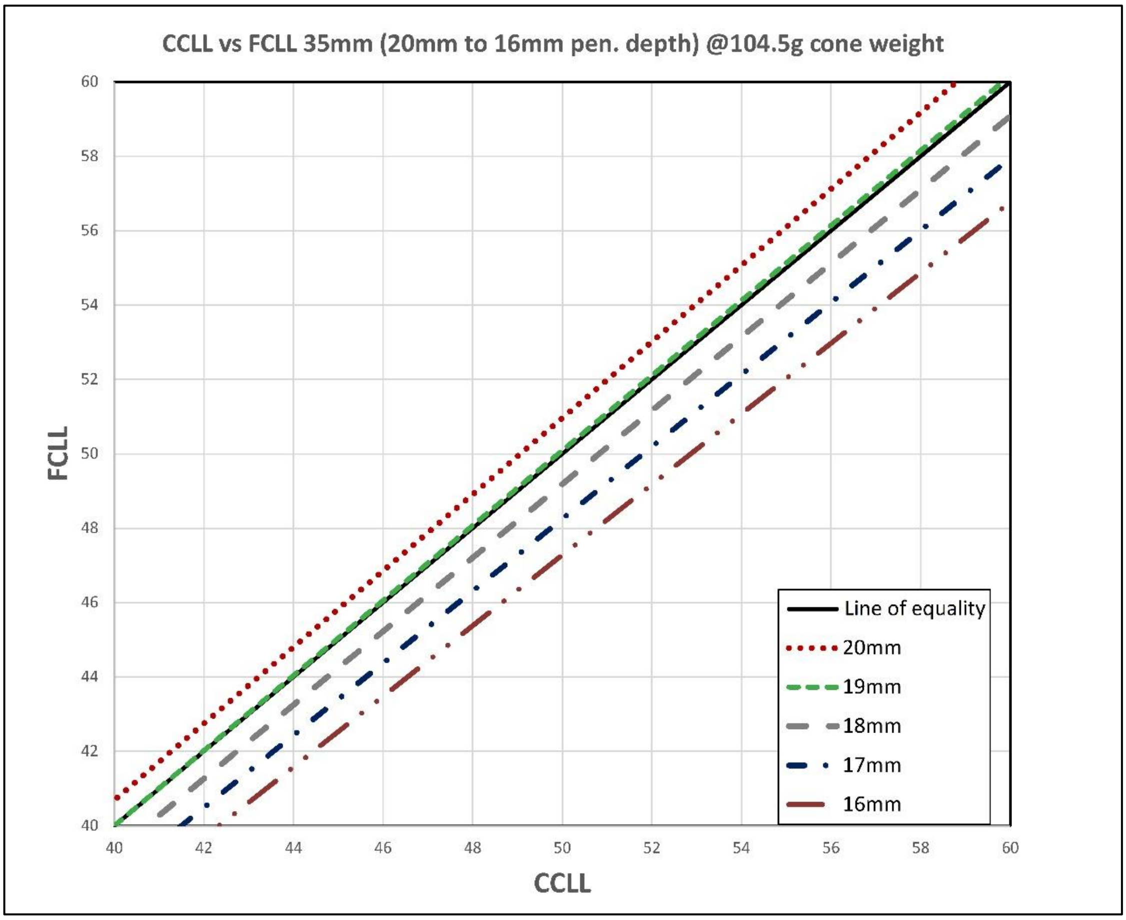
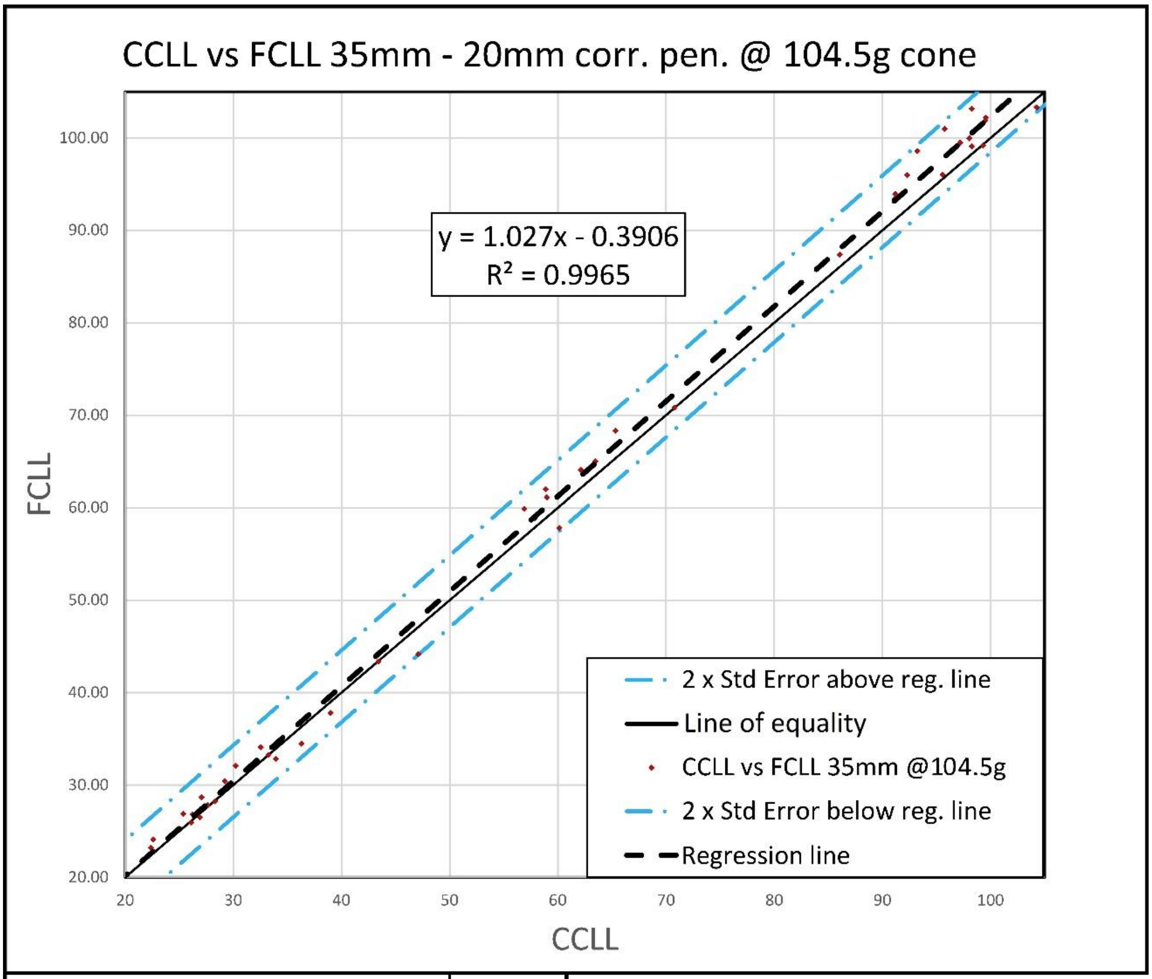


Figure 4-20: Linear reg. of CCLL vs $FCLL_{35}$ for penetrations from 20mm to 16mm @ 104.5g cone weight

As seen in Figure 4-20, the 19mm penetration is now the closest to the line of equality. Therefore, the 20mm penetration and 19mm penetration depths were chosen for the analysis and are discussed in the following section.

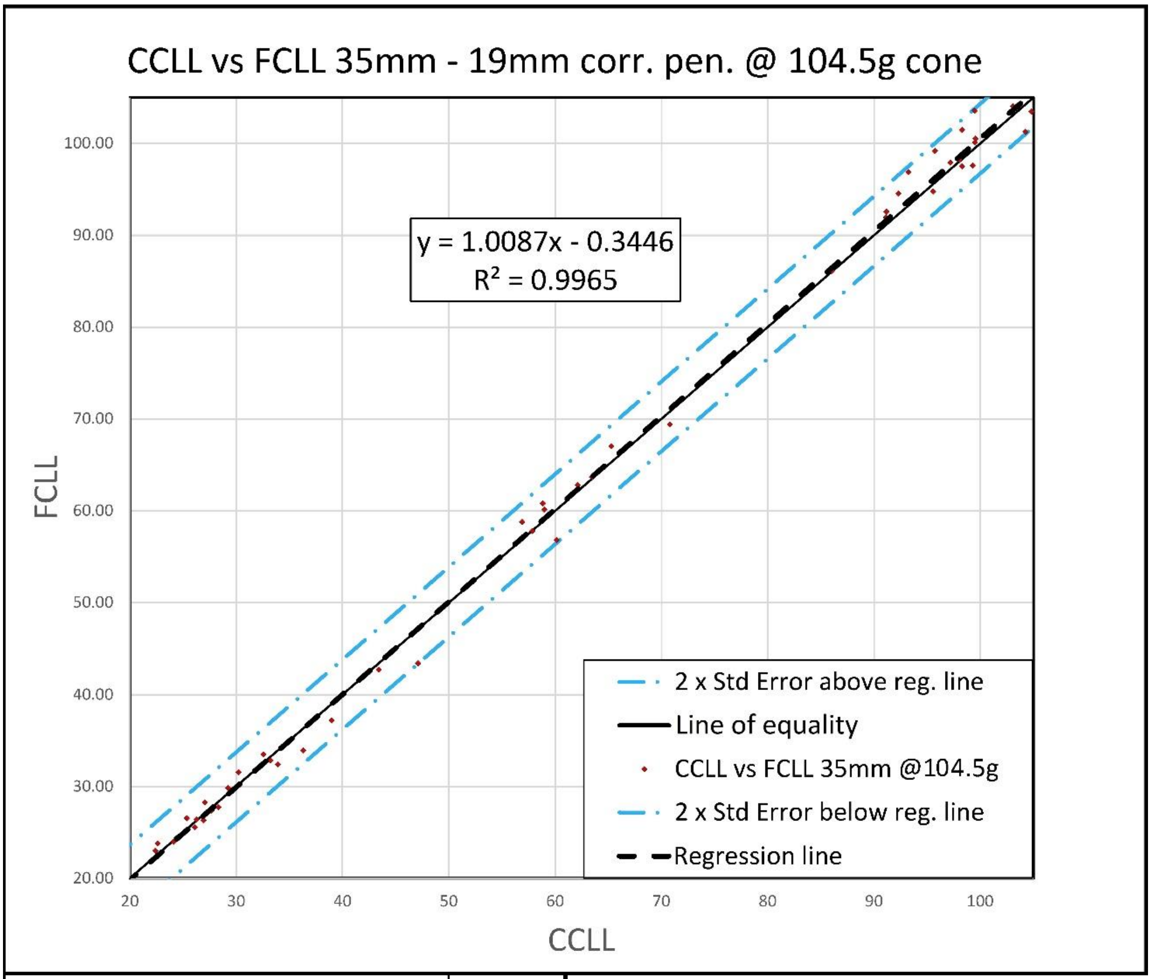
4.7.2.1 Linear regression analysis

The 49 data points were used in linear regressions from the standard 20mm penetration to 16mm. Figure 4-21 shows the regressions with the heavier cone weight of the standard 20mm penetration and the penetration with the best fit to the line of equality, which in this case is the 19mm penetration.



n=	49
std error (S) =	1.94
% of data within 2 x S =	100%
Pearson squared (r^2) =	0.9965

Figure 4-21: Linear reg. of CCLL vs FCLL$_{35}$ 20mm penetration @ 104.5g cone weight



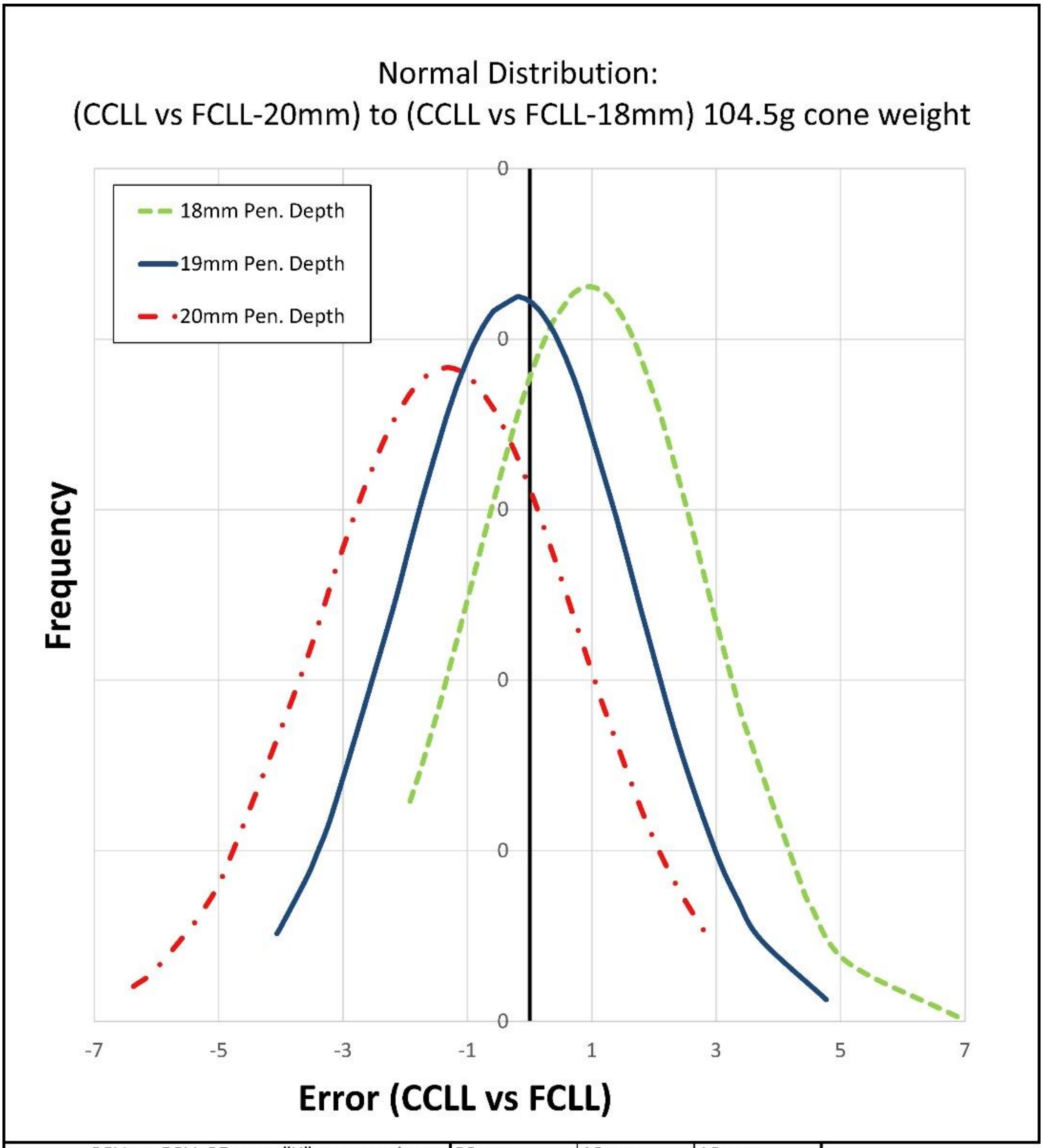
n=	49
std error (S) =	1.90
% of data within 2 x S =	100%
Pearson squared (r^2) =	0.9965

Figure 4-22: Linear reg. of CCLL vs $FCLL_{35}$ 19mm penetration @ 104.5g cone weight

With regard to the figures shown above, the theory of the heavier cone holds true, as the corresponding penetration has increased from the previously observed 16mm to 19mm. It should also be noted that the regression precision and correlation also improved marginally.

4.7.2.2 Probability distributions

The probability distributions were also plotted for the increased cone weight results. The 20mm to 18mm penetrations were plotted to confirm the result observed with the linear regression analysis, as shown in Figure 4-23.



CCLL vs FCLL 35mm - "X" penetration=	20mm	19mm	18mm
n=	49	49	49
Mean=	-1.33	-0.21	0.95
S.Dev=	2.082	1.878	1.852

Figure 4-23: Prob. distribution of CCLL vs FCLL 35mm (20mm to 18mm penetrations) @ 104.5g cone weight

As seen in the Figure 4-23, the 19mm distribution is closest to the zero-deviation mean line: this also agrees with the linear regression result.

In Chapter 3, it was calculated that the weight of the cone would have to be 110g to correspond with the 20mm penetration. The 19mm achieved with the 104.5g cone could be extrapolated and should result in a weight of 110g, giving an approximate 20mm corresponding penetration.

Therefore, the increase of the cone weight increased the corresponding penetration depth. However, it is impractical if an international standard is to be achieved and should therefore not be considered.

All of the results shown and discussed in Chapter 4 will be concluded in the following chapter.

CHAPTER 5: RESEARCH CONCLUSIONS

5.1 Concluding Summary

The main objective and direction of this research study was to modify and optimise the British standard fall cone test, to improve the precision limits, testing time and sample preparation reliability of the method and to calibrate it against the current South African Casagrande Cup method for liquid limit determination for South African soils.

The intention is to make the method sufficiently appealing to be accepted by South African laboratories and by the civil engineering sector and SABS/SANS as the standard test method for determining the liquid limit.

In order to achieve this objective, many soil samples were prepared and were tested using the BS fall cone apparatus, SANS Casagrande cup apparatus. Linear shrinkage and plastic limit tests were also conducted according to SANS for future research as discussed in the following section.

The data recorded on the laboratory sheets were captured onto a Microsoft Excel database/spreadsheet. The linear regressions and probability distribution data analysis as well as the visual representation thereof were also done with the Excel software.

This research study comprised a total of 195 tests, divided among comparisons of the BS standard cup and the new specimen ring, the fall cone test with the four specimen rings, the Casagrande cup, as well as the fall cone tests with the increased cone weights.

From these data comparisons, correlations were established between the BS standard cup and the new specimen ring, between the different specimen ring sizes, between the $CCLL_{SANS}$ and $FCLL_{54}$, $FCLL_{35}$ and $FCLL_{30}$ tests as well as the calibration of the corresponding penetrations to correct the indirect correlation between the $CCLL_{SANS}$ modified FCLL.

A draft SANS standard has been compiled from the conclusions of this research and is attached as Annexure A. The draft standard describes the test procedure for determining the modified FCLL.

5.2 Research Conclusions

i. The comparison done between the standard BS cup and the 54mm specimen ring showed negligible to no difference in LL result. The specimen ring can therefore be used for LL determination. This change will improve the reliability of the sample preparation, according to Feng (2000).

ii. The 22mm specimen ring could not be used in the analysis as the ring demonstrated mould confinement with the soil pushing back up to the cone. This caused a misrepresentation of the penetration compared with the true free fall penetration.

iii. It was found that there was a negligible difference in liquid limit results between the 54mm, 35mm and 30mm specimen rings at the 20mm corresponding penetration.

iv. It was observed that a very strong correlation existed between the CCLL$_{SANS}$ and the modified FCLL, although there was a constant deviation/indirect correlation between the results of the two tests. This was also confirmed in the research by numerous researchers, including Sampson and Netterberg (1985).

v. The deviation observed between the FCLL$_{54}$ and CCLL$_{SANS}$ was reduced to zero and gave a direct correlation when the corresponding penetration was reduced from 20mm to 16mm.

vi. When comparing the FCLL$_{35}$ and FCLL$_{30}$ with the CCLL$_{SANS}$, the indirect correlation was similar to that observed with the FCLL$_{54}$. The indirect correlation was corrected by reducing the corresponding penetration from 20mm to 16mm and 15mm respectively.

vii. The corresponding penetration required to correct the indirect correlation was 16mm for FCLL$_{54}$ and FCLL$_{35}$. However, for FCLL$_{30}$, it was 15mm. This could be the beginning of the effect of the mould confinement that also affected the 22mm specimen ring and could therefore not be accepted.

viii. It is therefore suggested that the modified fall cone method be conducted using the 35mm specimen ring and calculating the LL using 16mm as the corresponding penetration depth.

ix. It was also observed that by increasing the weight of the cone, the corresponding penetration depth rose closer to the CCLL and reduced the indirect correlation. It was also seen that the precision of the regression increased.

x. Increasing the cone weight should not be considered as it would involve changing a standard apparatus. This will move the method further away from achieving an international standard.

5.3 Recommendations for Further Research

From the conducted research, the following aspects have been identified as being points of interest to be investigated:

1. The PI is one of the important parameters used and its precision is influenced by the poorly reproducible PL test, namely the thread rolling method, which is very operator susceptible. Moving to the cone for PL determination will improve the precision and confidence levels of the PI.
2. The one-point method for the modified fall-cone method was already mentioned by Sampson (1983) and should be researched for the modified fall-cone.
3. The effect of hysteresis on liquid limit determination. The effect of hysteresis is the difference in results when testing the soil from a dry to wet state and when testing from a wet to a dry state. The degree of result difference should be investigated with LL determination.
4. Since the fall-cone method is a measure of soil shear strength, a correlation between the fall cone and shear box test could also be investigated as well as the unconsolidated undrained (UU) and consolidated undrained (CU) Triaxial test.
5. The fall-cone method is a soil penetration test and could also be correlated with the DCP test.

CHAPTER 6: LIST OF REFERENCES

Abbas, H. O. (2018). Assessment of accuracy in determining Atterberg limits for four Iraqi local soil laboratories. *IOP Conference Series: Materials Science and Engineering*, *433.* Iraq. doi:10.1088/1757-899X/433/1/012030

Andrade, F. A., Al-Qureshi, H. A., and Hotza, D. (2011, January). Measuring the plasticity of clays: a review. *Applied Clay Science, 51*(1-2), 1-7.

ASTM. (2010). *ASTM D4318-10e1: Standard test methods for liquid limit, plastic limit, and plasticity index of soils.* West Conshohocken, PA, USA: ASTM International.

Atterberg, A. (1911). On the investigation of the physical properties of soil and on the plasticity of clays. *Journal of the Royal Swedish Academy of Agriculture and Forestry, 2*, 133-139.

Atterberg, A. (1916). Consistency Science. *The Swedish Journal of Chemistry, 28*, 29-37.

Badenhorst, W., Theron, E., and and Stott, P. (2015). Duplicate testing conducted on the input parameters for the estimation of potential expansiveness of clay. *Innovative Geotechnics for Africa Bouassida, Khemakhem and Haffoudhi*.

Belviso, R., Ciampoli, S., Cotecchia, V., and Federico, A. (1985, July). Use of the cone penetrometer to determine consistency limits. *Ground Engineering, 18*(5), 21-22.

Blight, G. E. (2012). Microstructure, mineralogy and classification of residual soils. In G. E. Blight, and E. C. Leong (Eds.), *Mechanics of Residual Soils* (pp. 50–54). Boca Raton, FL, US: CRC Press.

Brown, P. J., and Downing, M. C. (2001, November). Discussion: Fall-cone penetration and water content relationships of clays. *Géotechnique, 51*(9), 819-821.

Brown, P. J., and Huxley, M. A. (1996). The cone factor for a 30° cone. *Ground Engineering, 29*(10), 34-36.

BS 1377-2. (1990). *BS 1377-2: Methods of test for soils for civil engineering purposes, Part 2: Classification tests.* London, UK: British Standards Institution(BSi).

Budhu, M. (1985). The effect of clay content on liquid limit from a fall cone and the British cup device. *Geotechnical Testing Journal, 8*(2), 91-95.

Campbell, D. A., and Blackford, J. W. (1984). *Fall Cone Method Used to Determine the Liquid Limit of Soil.* Report no. GR-84-11, Division of Research and Laboratory Services, Engineering and Research Center.

CAN/BNQ 2501-092. (2006). Soils—determination of liquid limit by the Swedish fall cone penetrometer method and determination of plastic limit. *National Standard of Canada*.

Canelas, D., Fernandes, I., and Lopes, M. (2018). Use of Fall Cone Test for the determination of undrained shear strength of cohesive soils. *MATEC Web of Conferences, 251*.

Carter, M., and Bentley, S. P. (2016). *Soil Properties and their Correlations* (2nd ed.). John Wiley and Sons, Ltd.

Casagrande, A. (1932). Research on the Atterberg Limits of Soil. *Public Roads, 13*(8), 121-136.

Casagrande, A. (1948). Classification and identification of soils. *Transactions, ASCE, 113*, 901-903.

Casagrande, A. (1958). Notes of the design of the liquid limit device. *Géotechnique, 8*(2), 84-91.

CSIR. (1986). *Technical Methods for Highways, TMH1, Stand-ard Methods of Testing Road Construction Materials.* CSIR, Pretoria.

Di Matteo, L. (2012). Liquid limit of low- to medium plasticity soils: comparison between Casagrande cup and cone penetrometer test. *Bulletin of Engineering Geology and the Environment, 71*(1), 79-85.

Di Matteo, L., Dragoni, W., Cencetti, C., Ricco, R., and Fucsina, A. (2016). Effects of fall-cone test on classification of soils: some considerations from study of two engineering earthworks in Central Italy. *Bulletin of Engineering Geology and the Environment, 75*(4), 1629-1637. doi:10.1007/s10064-015-0808-8

Dragoni, W., Prosperini, N., and Vinti, G. (2008). Some observations on the procedures for the determination of the liquid limit: an application on Plio-Pleistocenic clayey soils from Umbria region (Italy). *Italian Journal of Engineering Geology and Environment, 1*(Special Issue 2008), 185-197.

Evans, T., and Simpson, D. (2015, May). Innovative Data Acquisition for the Fall Cone Test in Teaching and Research. *Geotechnical Testing Journal., 38*(3), 346-354. doi:10.1520/GTJ20140236.

Feng, T. W. (2000). Fall-cone penetration and water content relationship of clays. *Geotechnique, 50*(2), 181-187.

Feng, T. W. (2004). Using a small ring and a fall-cone to determine the plastic limit. *Journal of Geotechnical and Geoenvironmental Engineering, 130*(6), 630-635.

Feng, T. W. (2005). Reappraisal of the fall cone test. *Proceedings of the International Conference on Soil Mechanics and Geotechnical Engineering*, *16*, pp. 357-360. doi:10.3233/978-1-61499-656-9-357

Fojtová, L., Marschalko, M., Franeková, R., and Kovàr, L. (2009). Study of compatibility of methods for liquid limit measurement according to Czech State Standard and newly adopted European Standard. *GeoScience Engineering, LV*(1), 55-68.

GOST 5184-49. (1949). *Soils: Method for laboratory determination of yield stress.* National Standards for KGS.

Grønbech, G. L., Nielsen, B. N., and Ibsen, L. B. (2011). Comparison of liquid limit of highly plastic clay by means of casagrande and fall cone apparatus. *In Symposium Proceedings: 64th Canadian Geotechnical Conference and 14th Pan-American Conference on Soil Mechanics and Engineering, 5th Pan-American Conference on Teaching and Learning of Geotechnical Engineering Pan-AM CGS Geotechnical Conference.* Toronto, Ontario.

Haigh, S. K. (2012). Corrigendum: Mechanics of the Casagrande liquid limit test. *Canadian Geotechnical Journal., 49*, 1015-1023. doi:10.1139/t2012-066.

Haigh, S. K. (2012). Corrigendum: Mechanics of the Casagrande liquid limit test. *Canadian Geotechnical Journal. 49. 1015-1023. 10.1139/t2012-066.*

Haigh, S. K. (2015, October). Consistency of the Casagrande Liquid Limit Test. *Geotechnical Testing Journal*. doi:10.1520/GTJ20150093

Haigh, S. K., Vardanega, P. J., and Bolton, M. D. (2013). The plastic limit of clays. *Géotechnique, 63*(6), 435-440. Retrieved from https://doi.org/10.1680/geot.11.P.123.

Hansbo, S. (1957). A new approach to the determination of the shear strength of clay by the fall cone test. *Royal Swedish Geotech Institute Proceedings, no. 14*, pp. 1–48.

Harison, J. A. (1988). Using the BS cone penetrometer for the determination of the plastic limits of soils. *Geotechnique, 38*(3), 433-438.

Henkel, D. J. (1960). The Shear Strength of Saturated Remolded Clays. *Research Conference on Shear Strength of Cohesive Soils.* (pp. 533-554). Boulder, Colorado: American Society of Civil Engineers (ASCE).

Houlsby, G. T. (1982, June). Theoretical analysis of the fall cone test. *Géotechnique, 32*(2), 111-118.

Hrubesova, E., Lunackova, B., and Brodzki, O. (2016). Comparison of Liquid Limit of Soils Resulted from Casagrande Test and Modificated Cone Penetrometer Methodology. *Sustainable Development of Civil, Urban and Transportation Engineering Conference, 142*, 364-370.

IS: 2720-5. (1985). *(Reaffirmed 2006), Method of Test for Soils: Part 5 - Determination of Liquid Limit and Plastic Limit* (2nd ed.). Indian Standards Institution.

ISO 17892-6. (2016). *Geotechnical investigation and testing-Laboratory testing of soil-Part 6: Fall cone test* (1 ed.). Brussels: International Organization for Standardization.

Jakobsz, S. W. (2013). Site Investigation on Dry Clayey Soils. *SAICE Geotechnical Division Course on Site Investigation.*

Karlsson, R. (1961). Suggested Improvements in the Liquid Limit Test, with Reference to Flow Properties of Remoulded Clays. *Proceedings 5th International Conference On Soil Mechanics and Foundation Engineering*, *1*, pp. 171-184. Paris.

Karlsson, R., and Hansbo, S. (1981). The Laboratory Manual. In *Part 6: Consistency limits.* Stockholm: Swedish Council for Building Research.

Koumoto, T., and Houlsby, G. T. (2001). Theory and practice of the fall cone test. *Géotechnique, 51*(8), 701-712.

Kumapley, N. K., and Boakye, S. K. (1980). The use of cone penetrometer for the determination of liquid limit of soils of low plasticity. *Proceedings of the 7th Regional Conference for Africa on soils Mechanics and foundation Engineering, Vol. 1*, 167-170.

Leroueil, S., and Le Bihan, J. (1996). Liquid limits and fall cones. *Canadian Geotechnical Journal, 33*(5), 793-798.

Llano-Serna, M. A., and Contreras, L. F. (2019, March). The effect of surface roughness and shear rate during fall-cone calibration. *Géotechnique, 70*(4), 1-39. doi:0.1680/jgeot.18.p.222

Mahajan, S. P., and Budhu, M. (2009). Shear viscosity of clays using the fall cone test. *Géotechnique, 59*(6), 539-543.

Mitchell, J. (2005). Fundamentals of soil behaviour. *Wiley, New York*.

Mitchell, M. F., and Smith, R. A. (1974). Qaulity assurance - whose responsibility? *Proceedings of the 2nd Conference on Asphalt Pavements for South Africa, Section 5*, 48-66.

Netterberg, F., and Haupt, F. J. (1981). Comparison of the TMH1 Casagrande cup and BS cone methods for determining the liquid limit of soils. *National Institute for Transport and Road Research unpUblished Technical Note TS/5/81, Council for Scientific and Industrial Research*.

Nini, R. (2014, April). Effect of the Silt and Clay Fractions on the Liquid Limit Measurements by Atterberg Cup and Fall Cone Penetrometer. *International Journal of Geotechnical Engineering, 8*(2), 239-241. doi:10.1179/1939787913Y.0000000018

Norman, L. E. (1958). A comparison of values of liquid limit determined with apparatus having bases of different hardness. *Géotechnique, 8*(2), 79–83. Retrieved from https://doi.org/10.1680/geot.1958.8.2.79

O’Kelly, B. C. (2015). Atterberg limits are not appropriate for peat soils. *Geotechnical Research Journal, 2*(3), 123-134. doi:10.1680/jgere.15.00007.

O’Kelly, B. C. (2016). Fall-cone strength testing of municipal sludges and residues. *Environmental Geotechnics, 5*(1), 18-30. doi:10.1680/jenge.15.00080.

O’Kelly, B. C., Vardanega, P. J., and Haigh, S. K. (2018). Use of fall cones to determine Atterberg limits: a review. *Géotechnique, 68*(10), 843-856.

Özer, M. (2009, February). Comparison of liquid limit values determined using the hard and soft base Casagrande apparatus and the cone penetrometer. *Bulletin of Engineering Geology and the Environment, 68*(3), 289-296.

Phoon, K. K. (2008). Numerical recipes for reliability analysis – a primer. In K. K. Phoon (Ed.), *In Reliability-Based Design in Geotechnical Engineering.* Oxford: Taylor and Francis.

Phoon, K. K., and Kulhawy, F. H. (1999). Evaluation of geotechnical property variability. *Canadian Geotechnical Journal*, *36*, pp. 625–639.

Prakash, K., Sridharan, A., and Prasanna, H. S. (2009). A note on the determination of plastic limit of fine-grained soils. *Geotechnical Testing Journal, 32*(4), 372-374.

Sampson, L. R. (1983). Investigation into the use of a cone penetration method for the determination of the plastic and liquid limits of South African soils. *National Institute for Transport and Road Research, Technical Note TS/6/83:* .

Sampson, L. R. (1983). Technical Note TS/6/83: Investigation into the use of a cone penetration method for the determination of the plastic and liquid limits of South African soils. *NATIONAL INSTITUTE FOR TRANSPORT AND ROAD RESEARCH (NITRR)*.

Sampson, L., and Netterberg, F. (1984). A cone penetration method for measuring the liquid limits of South African soils and its implications. *Proceedings, 8th Regional Conference for Africa on Soil Mechanics and Foundation Engineering*, *1*, pp. 105-115. Harare.

Sampson, L. R., and Netterberg, F. (1985). The cone penetration index: A simple new soil index test to replace the Plasticity Index. *Proceedings of The Eleventh*

International Conference On Soil Mechanics and Foundation Engineering., *11*, pp. 1041-1048. San Francisco.

SANS. (2011). *South African National Standard SANS 3001:2011 Edition 1.1. Civil Engineering Test Methods. Parts GR1, GR2, GR3, GR5, GR10, GR11, GR12 and GR20;.* South African Bureau of Standards, Pretoria.

SANS 3001-GR10. (2011). *Civil Engineering Test Methods. Part GR10: Determination of the one-point liquid limit, plastic limit, plasticity index and linear shrinkage* (1.1 ed.). Pretoria: SABS Standards Division.

SANS 3001-GR12. (2011). *Civil Engineering Test Methods. Part GR12: Determination of the flow curve liquid limit* (1.1 ed.). Pretoria: SABS Standards Division.

SANS 3001-GR20. (2011). *South African National Standard SANS 3001:2011 Edition 1.1. Civil Engineering Test Methods. Part GR20;.* South African Bureau of Standards, Pretoria.

SANS 3001-GR5. (2011). *Civil Engineering Test Methods. Part GR5: Wet preparation and air-drying of samples for plasticity index and hydrometer tests* (1.1 ed.). Pretoria: SABS Standards Division.

Sharma, B., and Bora, P. K. (2003, August). Plastic Limit, Liquid Limit and Undrained Shear Strength of Soil—Reappraisal. *Journal of Geotechnical and Geoenvironmental Engineering, 129*(8), 774-777. doi:10.1061/(ASCE)1090-0241(2003)129:8(774)

Sherwood, P. T., and Ryley, M. D. (1970). *Investigation of a cone-penetrometer method for the determination of the liquid limit.* Geotechnique, (20), 2, 135-136.

Shimobea, S., and Spagnolib, G. (2019). A global database considering Atterberg limits with the Casagrande and fall cone tests. *Engineering Geology, 260*.

Singh, A., and Lee, K. L. (1970). Variability in soil parameters. *Proceedings of the 8th Annual Engineering Geology and Soils Engineering Symposium*, *8*, pp. 159-185. Idaho.

Sivakugan, N., and Das, B. (2009). Chapter 3: Soil Classification. In *Geotechnical Engineering: A Practical Problem Solving Approach.* J Ross Publishing.

Skempton, A. W. (1953). The colloidal activity of clays. *Proceedings of the third international conference on soil mechanics and foundation engineering.*, (pp. 57-61). Zurich, Switzerland.

Sowers, G. F., Vesic, A., and Grandolfi, M. (1960). Penetration Tests for Liquid Limit. *Papers on Soils 1959 Meetings, ASTM Special Technical Publication, 254*, 216-224.

Spagnoli, G. (2012, November). Comparison between Casagrande and drop-cone methods to calculate liquid limit for pure clay. *Canadian journal of soil science, 92*(6), 859-864. doi:10.1139/CJSS2012-011

Sridharan, A. and Prakash, K. (2000). Percussion and cone methods of determining the liquid limit of soils: controlling mechanisms. *Geotechnical Testing Journal, 23*(2), 236-244.

Stott, P. R. and Theron, E. (2015, June). Some shortcomings in the standard South African testing procedures for assessing heaving clay. *Journal of the South African Institution of Civil Engineering, 57*(2), 36–44.

Stott, P. R. and Theron, E. (2016, April). Variability in soil properties and its consequences for design. *Conference Paper*.

Terzaghi, K. (1926). Principles of final soil classification. *Public Roads, 8*(3), 41-53.

Trauner, L., Dolinar, B., and Mišič, M. (2005). Relationship between the Undrained Shear Strength, Water Content, and Mineralogical Properties of Fine-Grained Soils. *International Journal of Geomechanics 5*(4), 350-355.

Uzielli, M., Lacasse, S., Nadim, F., and Phoon, K. K. (2006). Soil Variability Analysis for Geotechnical Practice. *Proceedings of the 2nd International Workshop on Characterisation and Engineering Properties of Natural Soils*, *3.* Singapore. doi:10.1201/NOE0415426916.ch3

Vardanega, P. J. and Haigh, S. K. (2014). Some recent developments in the determination of the Atterberg limits. *Geo-Hubei 2014 International Conference on Sustainable Civil Infrastructure*, *250*, pp. 48-55. Yichang, Hubei, China.

Vardanega, P. J., Kolody, E., Pennington, S. H., Morrison, P. R., and Simpson, B. (2012). Bored pile design in stiff clay I: codes of practice. *Proceedings of the ICE - Geotechnical Engineering, 165*(4), 213-232. doi:10.1680/geng.11.00062.

Verástegui-Flores, R. D. and Di Emidio, G. (2014). Assessment of clay consistency through conventional methods and indirect extrusion tests. *Applied Clay Science, 101*, 632-636.

Wasti, Y. (1987). Liquid and Plastic limits as determined from the fall cone and the Casagrande methods. *ASTM Geotechnical Testing Journal, 10*(1).

Weston, D. J. (1978). A comparison of the Casagrande cup and BS cone methods for determining the liquid limit of soils and discussion of some of the uses of Atterberg limits. *National Institute for Transport and Road Research. Unpublished Report. RS/5/78, CSIR, Pretoria.*

Whyte, I. L. (1982). Soil plasticity and strength – a new approach using extrusion. *Ground Engineering, 15*(1), 16–24.

Wires, K. C. (1984). The Casagrande method versus the dropcone penetrometer method for the determination of liquid limit. *Canadian Journal of Soil Science, 64*, 297-300.

Wood, D. M. (1981). *Cone Penetrometer and Liquid Limit.* Report No. CUED/D-SOILS/TR-101-1981: Cambridge University Department of Engineering.

Wood, D. M. (1985). Some fall-cone tests. *Géotechnique, 35*(1), 64-68. doi:10.1680/geot.1985.35.1.64.

Wood, D. M. (1990). *Soil behaviour and critical state soil mechanics.* Cambridge, UK: Cambridge University Press.

Wood, D. M. and Wroth, C. P. (1978). The use of the cone penetrometer to determine the plastic limit of soils. *Ground Engineering, 11*(3), 37.

Wroth, C. P. (1979). Correlation of some engineering properties of soils., 2nd Int. *Conf. on Behaviour of Offshore Structures*, (pp. 121-132). London.

Wu, T. H. (1996). Soil Strength Properties and Their Measurement. *Special Report - National Research Council, Transportation Research Board, 247*, 319-336.

Youssef, M. S., El Ramli, A. H., and El Demery, M. (1965). *Proceedings 6th International Conference On Soil Mechanics and Foundation Engineering*, *1*, pp. 126-129. Montreal.

PROPOSED SANS 3001-GR13:2021

Edition 1.0

SOUTH AFRICAN NATIONAL STANDARD PROPOSAL

Civil engineering test methods

Part GR13: Determination of the fall cone liquid limit

Text with a grey colour indicates information that was not changed from SANS 3001-GR12

Acknowledgement

To be added

Foreword

To be added

Introduction

The liquid limit, plastic limit and linear shrinkage are often collectively referred to as the Atterberg Limits. The test method is normally carried out on material passing the 425 µm sieve, and when required, also on material passing the 75 µm sieve. To avoid confusion the results from the test on material passing the 75 µm sieve should be clearly identified. The plastic limit, and where required, the linear shrinkage should be determined as described in SANS 3001-GR10. While SANS 3001-GR10 to SANS 3001-GR12 may be used to determine the liquid limit, this method should be preferred for its method simplicity and result accuracy.

The test method for the liquid limit is similar to the and BS test method (see bibliography), except that the amounts of material tested vary, the geometry of the specimen cup/ring varies from the standard BS specimen cup and the ASTM and BS test methods incorporate the extraction of the material from the field sample to form the test sample. This test method is used to determine the liquid limit.

The results for the liquid limit together with the plastic limit are used to

a) obtain the plasticity index of materials for primary material classification,

b) determine compliance of the plasticity index with applicable specifications,

c) indicate clays of high swell potential, and

d) develop relationships concerning the performance of wearing course gravels.

Table of Contents

Acknowledgement

Foreword

1 Scope

This part of SANS 3001 describes the South African fall cone method for determining the liquid limit of fine material from gravel, sand or soil, consisting of either material smaller than 425 µm prepared in accordance with SANS 3001-GR1.

NOTE The liquid limit using the one-point test method is described in SANS 3001-GR10. The two-point method is described in SANS 3001-GR11. The flow curve method is described in SANS 3001-GR12.

2 Normative references

2.1 Standards

The following referenced documents are indispensable for the application of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies. Information on currently valid national and international standards can be obtained from the SABS Standards Division.

SANS 241, *Drinking water.*

SANS 3001-GR1, *Civil engineering test methods – Part GR1: Wet preparation and particle size analysis.*

SANS 3001-GR10, Civil engineering test methods – Part GR10: Determination of the one-point liquid limit, plastic limit, plasticity index and linear shrinkage.

SANS 3001-GR20, Civil engineering test methods – Part GR20: Determination of the moisture content by oven-drying.

SANS 3001-PR1, Civil engineering test methods – Part PR1: Determination of uncertainty of measurement, repeatability, reproducibility and bias.

BS 1377-2, Methods of test for soils for civil engineering purposes – Part 2: Classification tests.

2.2 Other publications

COLTO. 1998. Standard specifications for road and bridge works for state road authorities. Yoeville: SAICE.

3 Definitions

For the purposes of this document, the following definitions apply.

3.1 Acceptable

Acceptable to the authority administering this standard, or to the parties concluding the purchase contract, as relevant

3.2 Linear shrinkage

LS

Percentage reduction in length of an oven-dried bar of material

3.3 Liquid limit

LL

Empirically established moisture content at the boundary between the liquid and the plastic states

3.4 Plastic limit

PL

Empirically established moisture content at the boundary between the plastic and semi-solid states

3.5 Plasticity index

PI

Difference between the liquid limit and the plastic limit

3.6 Soil

Natural particles of silt and clay size

4 Apparatus

4.1 Fall-cone device (see Figure 1),

a) British standard fall-cone apparatus, preferably with an automatic timed-release and locking function to 1 second precision and penetration depth reading gauge with 0.1mm precision.

b) An assembled 30º cone and stem with a total weight of 80g, similar to that of the BS standard cone.

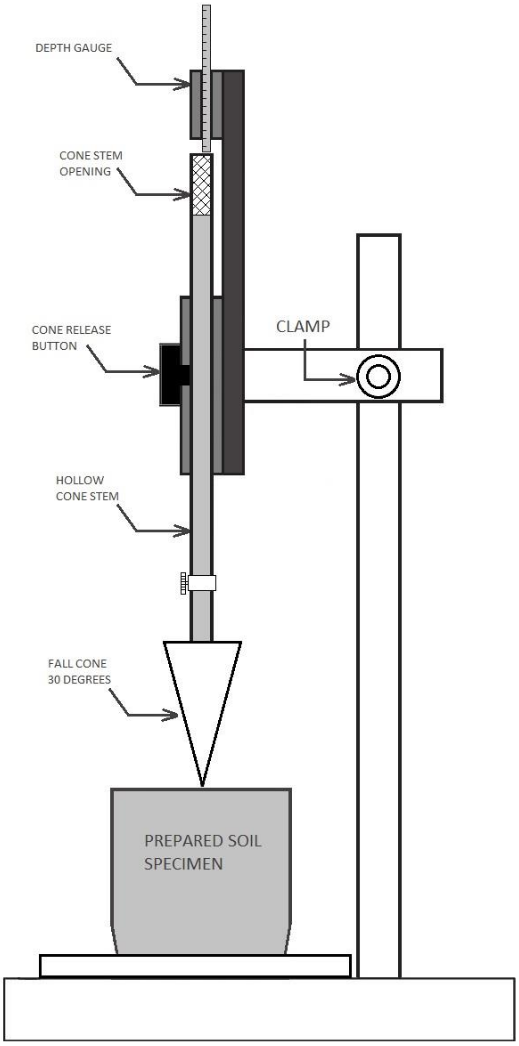


Figure 1: Example of a typical fall cone device

4.2 Specimen ring (see Figure 2).

Fall cone specimen ring with an inside diameter of 35mm, a depth of 40mm and a wall thickness of 1mm. The edge is sharpened on one side.

The dimensions are in millimetres

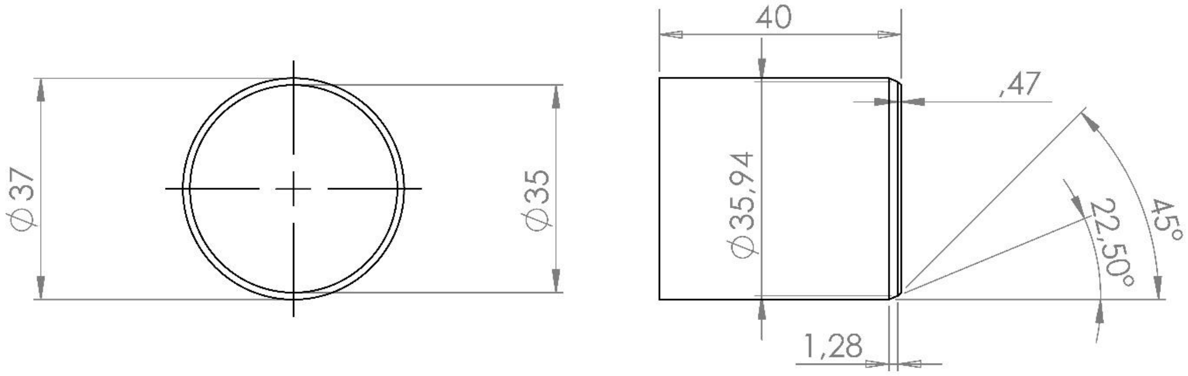


Figure 2: Schematic of the specimen ring

4.3 Perspex/glass platform that can slide the prepared soil specimen to under the cone.

4.4 Mixing dish, approximately 100 mm in diameter, made of porcelain, hard plastic or stainless steel.

4.5 Stainless steel spatula, that is 100 mm × 20 mm and has a slightly flexible blade.

NOTE: A palette knife where only 25 % of the blade towards the tip is flexible would be acceptable.

4.6 Wash-bottle with capacity of 500 mL, and with a cap and tube.

4.7 Weighing bottles or tins, numbered, and with capacity of approximately 30 ml, with tight sealing caps or lids.

5 Equipment and sample preparation

5.1 Fall-cone device

5.1.1

The only part that must be inspected for wear is the sharpness and alignment of the cone tip. The cone must be inspected according to procedure described in BS 1377-2

5.1.2

The cone stem and stem shaft must be kept dry and clean during testing. Lubricant or oil must not be applied in the mentioned areas.

5.1.3

During regular use, the device should be checked daily.

5.2 Test sample

5.2.1

Prepare the material passing the 425 µm sieve as described in SANS 3001-GR1.

5.2.2

Weigh approximately 100 g of the prepared material (see 5.3.1 or 5.3.2) into the mixing dish.

6 Procedure

NOTE: The test flow chart in annex B gives guidance on the manner in which the test can be conducted.

6.1

Add small quantities of class I drinking water (see SANS 241) to the test sample using the wash-bottle to ensure good mixing and to form a stiff consistency so that, after the fall cone penetrates the soil, the penetration depth should be around 4mm.

6.2

Mix with the spatula for a period of 10 min.

NOTE 1: The liquid limit of certain materials such as weathered dolerite and some paedogenic materials is influenced by the mixing time.

NOTE 2: The liquid limit of certain material is influenced by the use of excessive force during mixing.

6.3

After thoroughly mixing the saturated material, pile up and compress the soil on the perspex/glass platform in layers to form a void-free mound that is at least 40mm in height and width.

Press the specimen ring with the sharp edge down into the soil mound and cut off excess soil from the top to form a smooth surface as shown in Figure 3 below.

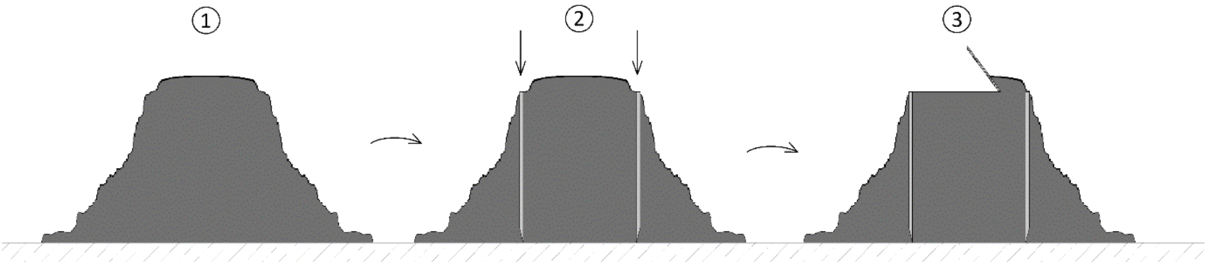


Figure 3: Specimen ring cutting into compressed mound

NOTE: If the amount of soil is not enough to form a compressed mound, a smaller mound may be cut into and then carefully filled in layers from one side as shown in Figure 4 below.

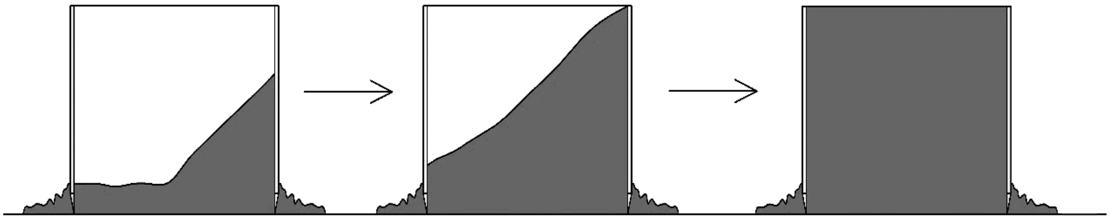


Figure 4: Alternative filling method

6.4

Position the specimen ring to the centre of the cone and the cone is carefully lowered to the soil until the edge of the cone just slightly touches the soil, as shown in Figure 5 below.

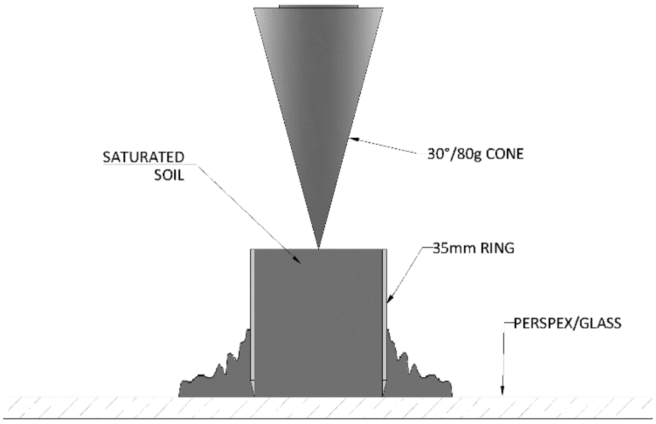


Figure 5: Cone edge lowerered to just touch the soil

6.5

Programme the automatic timed-release mechanism so that when the mechanism is activated, the cone is released to fall freely and penetrate the soil for five (5) seconds, after which the cone is locked at the penetrated depth.

6.6

When the cone is locked, lower the penetration depth gauge carefully to just touch the cone stem. Record the depth reading. The cone may be raised above the ring.

6.7

Take a s sample that measures approximately 10mm in its length, width and depth at the point of penetration.

Transfer the sample to a weighing bottle or tin and determine the moisture content as described in SANS 3001-GR20.

6.8

Return the penetrated soil from the ring back into the mixing bowl. Clean the cone and dry it for each repetition.

6.9

Repeat the test procedure from 6.3 to 6.8 at least four times, each time adding sufficient water to give consistencies that will give penetration depths in a uniform range of approximately 4mm to 20mm.

6.10

If the linear shrinkage is to be determined, carry out the test method as described in SANS 3001-GR10.

6.11

Set aside the moist material in the mixing dish after the second repetition, after which the plastic limit can be determined as described in SANS 3001-GR10.

7 Calculations

7.1 Liquid limit

7.1.1

Plot the log-moisture content results (see 6.7) to two decimal places as ordinates versus the log-penetration depth (see 6.6).

7.1.2

Draw a best-fit straight line through the points. This represents the fall cone line.

7.1.3

Read off the moisture content corresponding to 16mm penetration depth to the first decimal place from the fall cone line. This is the liquid limit as shown in Figure 6 below.

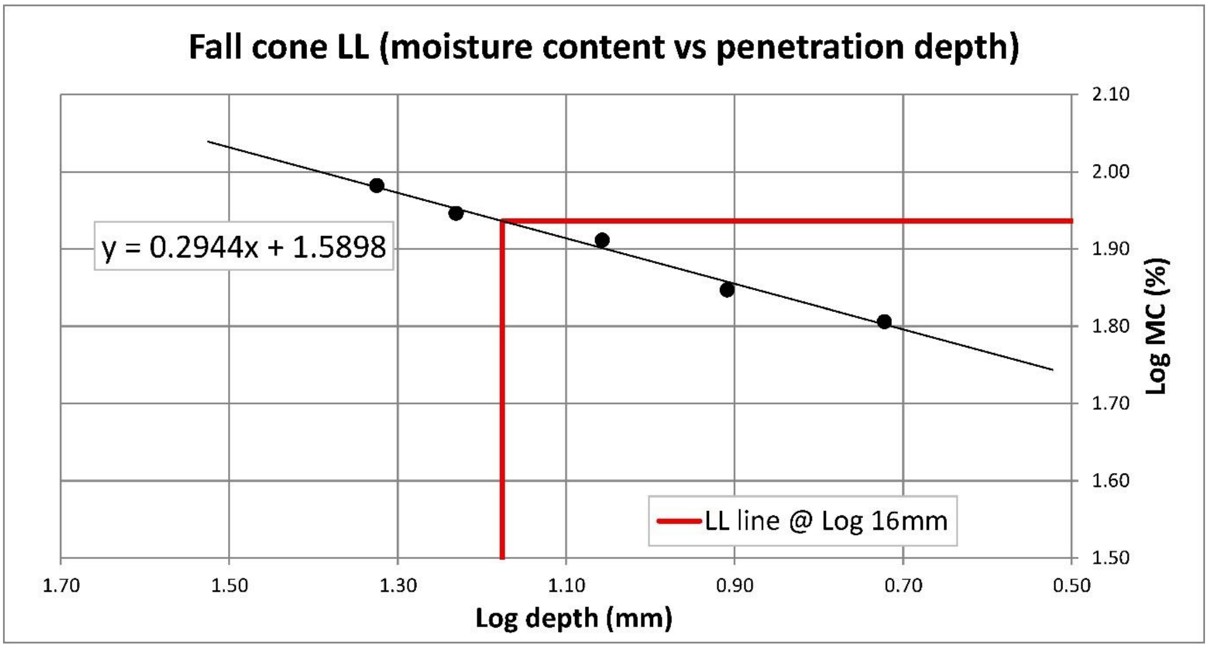


Figure 6: LL read off from the fall cone line

Use the following typical sigma values, *σ*, and the required precision *E* (two-sided case and precision category P_V variable) for the statistical analysis of the test results as described in SANS 3001-PR1.

Table 2 — Typical *σ* and *E* values

1	2	3	4	5	6
Material type[a]	**Statistic**	**LL**	**PL**	**PI**	**LS**
G1, G2, G3	σ	0,8	1,1	1,5	0,7
	E	0,9	1,0	1,2	0,7
G4, G5, G6	σ	1,3	1,5	2,5	1,5
	E	1,5	1,5	2,0	1,3
G7, G8, G9	σ	1,3	1,5	2,8	1,5
	E	1,5	1,5	2,3	1,2
G10	σ	1,5	1,7	3,0	1,7
	E	1,4	1,5	2,5	1,3
NOTE 1 Single-sided limit for PI and double-sided limit for LL, LS and PL. NOTE 2 Where G1 to G3 material is either NP or SP the variability cannot be predicted.					

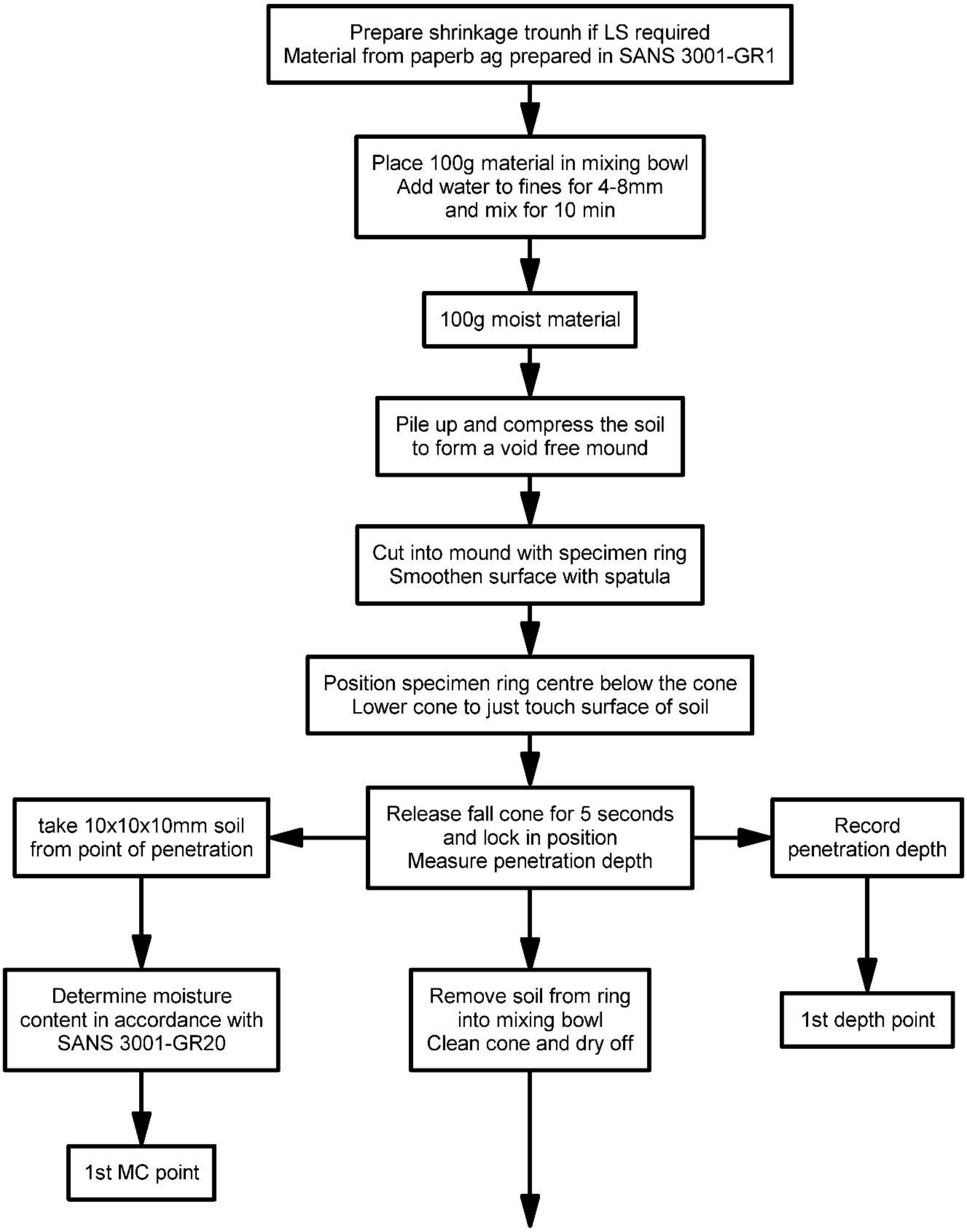
NOTE 3 While the PI value is calculated (i.e. it is not independent) it reflects the combination of the variability in the liquid and plastic limits.
[a] Make an assumption of the material type based on the known properties of the material. See Standard specifications for road and bridge works for state road authorities for definitions of material types G1 to G10.

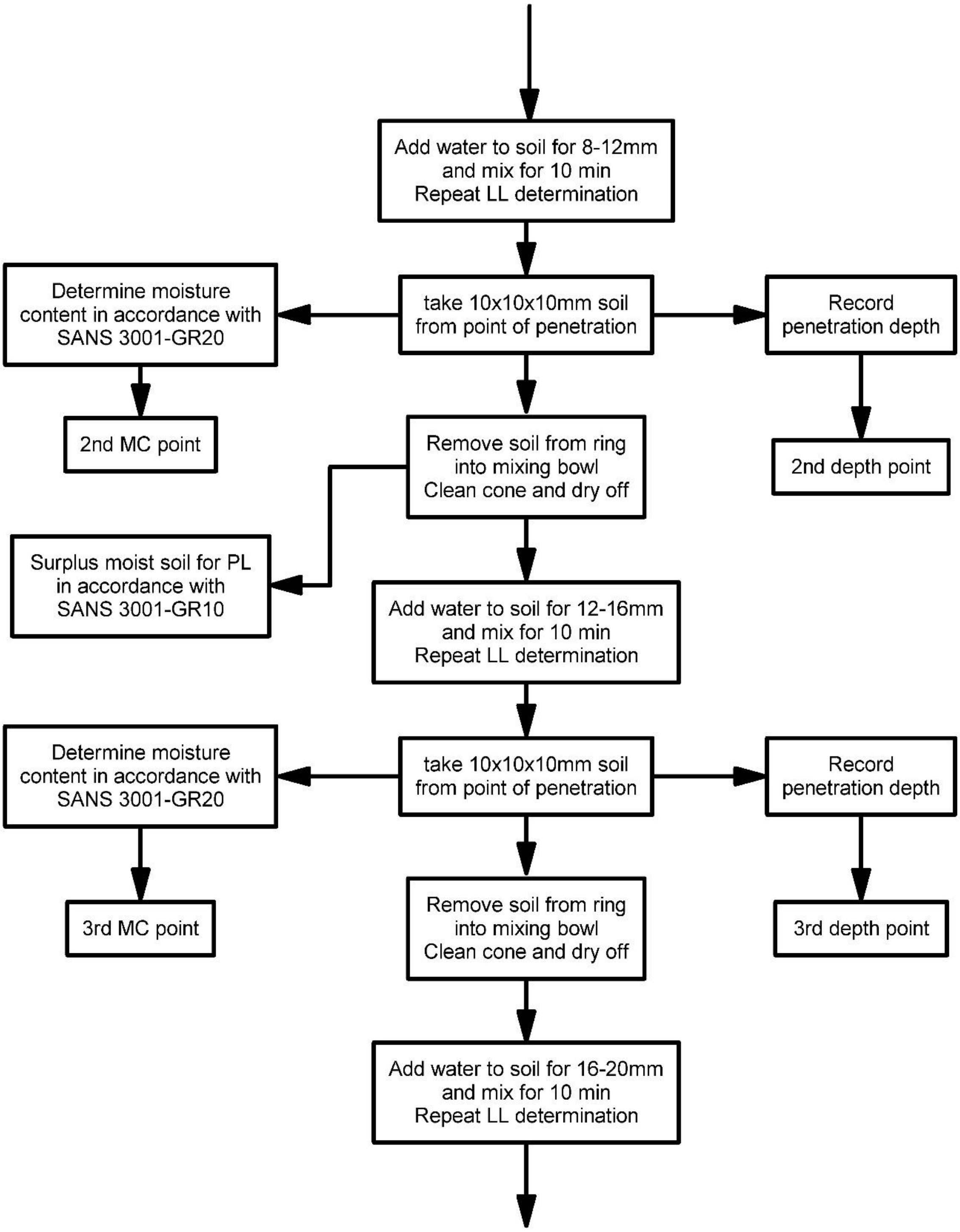
8 Test report

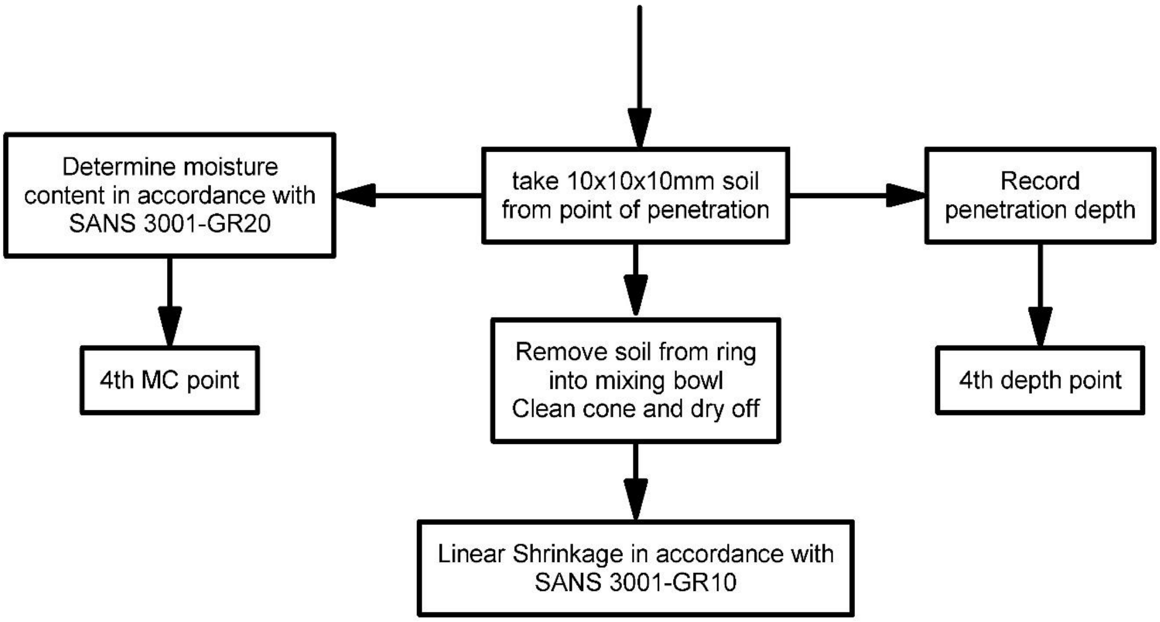
Report the result obtained as the liquid limit to the nearest whole number.

(informative)

Test flow chart




Add water to soil for 8-12mm
and mix for 10 min
Repeat LL determination
Determine moisture content in accordance with SANS 3001-GR20
take 10x10x10mm soil from point of penetration
Record penetration depth
2nd MC point
Remove soil from ring into mixing bowl
Clean cone and dry off
2nd depth point
Surplus moist soil for PL in accordance with SANS 3001-GR10
Add water to soil for 12-16mm
and mix for 10 min
Repeat LL determination
Determine moisture content in accordance with SANS 3001-GR20
take 10x10x10mm soil from point of penetration
Record penetration depth
3rd MC point
Remove soil from ring into mixing bowl
Clean cone and dry off
3rd depth point
Add water to soil for 16-20mm
and mix for 10 min
Repeat LL determination



Bibliography

ASTM D 4318, Standard test methods for liquid limit, plastic limit and plasticity index of soils.

BS 1377-2, Methods of test for soils for civil engineering purposes – Part 2: Classification tests.

SANS 3001-GR11, Civil engineering test methods – Part GR11: Determination of the liquid limit with the two-point method.

ANNEXURE B – L est sheet example

Fallcone Test

Sample Name			
Tester Name	Paul Vosloo	Fallcone Time started	
Date		Fallcone Time ended	

Pen. Depth (mm)		Tin no.	Tin (g)	Tin +wet soil (g)	Tin + Dry soil (g)	MC (%)
54mm	1					
	2					
	3					
	4					
	5					
35mm	1					
	2					
	3					
	4					
	5					
30mm	1					
	2					
	3					
	4					
	5					

Casagrande Cup test (Three point method)

	LL	LL	LL		PL	PL
Time (HH:MM)						
Tin no.						
Tin (g)						
Tin +wet soil (g)						
No. of blows	(15-22)	(22-28)	(28-35)		——	——
Tin + Dry soil (g)						
MC (%)						

Linear Shrinkage (Air dried)

Trough No.		Notes:
No. of blows	(15-35)	
Shrinkage (mm)		
Corr Fact.		

ANNEXURE B – L est sheet example

Fallcone Test

Sample Name	TP1 Steelpoort - test no 6		
Tester Name	Paul Vosloo	Fallcone Time started	
Date		Fallcone Time ended	

	Pen. Depth (mm)	Tin no.	Tin (g)	Tin +wet soil (g)	Tin + Dry soil (g)	MC (%)
54mm	4.2	001	14.57	16.63	15.85	60.94
	6.21	002	14.76	17.26	16.24	68.91
	11.14	003	14.74	17.7	16.35	83.85
	16.89	004	14.76	18.64	16.76	94
	23.68	005	14.91	19.37	17.13	100.9
35mm	3.79	006	16.7	18.39	17.77	57.84
	6.27	007	16.77	18.79	18.01	62.90
	11.42	008	16.74	20.18	18.61	83.96
	16.56	009	16.7	20.19	18.51	92.81
	22.68	010	16.82	20.05	18.43	100.62
30mm	4.5	011	14.78	16.34	15.72	65.95
	6.63	012	14.7	17.16	16.14	10.83
	11.66	013	16.73	19.26	18.12	82.01
	16.48	014	16.67	19.89	18.31	96.34
	21.96	015	16.78	19.85	18.31	100.65

Casagrande Cup test (Three point method)

	LL	LL	LL		PL	PL
Time (HH:MM)						
Tin no.	016	017	018		019	020
Tin (g)	16.89	14.7	16.82		14.62	14.59
Tin +wet soil (g)	20.11	18.26	20.26		20.81	19.71
No. of blows	19 (15-22)	25 (22-28)	30 (28-35)		——	——
Tin + Dry soil (g)	18.55	16.57	18.65		19.25	18.49
MC (%)	93.98	90.37	87.98		33.69	31.28

Linear Shrinkage (Air dried)

Trough No.	T001	Notes:
No. of blows	27 (15-35)	Final shrinkage =18.43mm
Shrinkage (mm)	26.82	
Corr Fact.	0.687	

Fall-cone 54mm specimen ring vs BS fall-cone cup

		54mm Ring LL	54mm BS CUP LL
test no.	test sample	20mm pen.	20mm pen.
1	HA - (1)	67.16	67.52
2	HA - (2)	73.01	73.31
3	HA - (3)	65.96	65.42
4	HA - (4)	65.96	65.60
5	HA - (5)	63.54	63.81
6	HA - (6)	65.50	65.18
7	HA - (7)	65.45	66.01
8	TP5 - (1)	39.61	39.63
9	TP5 - (2)	39.41	39.37
10	TP5 - (3)	39.53	39.48

Casagrande Cup LL (Wet to dry vs dry to wet)

		CCLL	CCLL
test no.	test sample	Dry to wet	Wet to dry
1	TP2 (1)	41.97	41.26
2	TP2 (2)	40.75	40.63
3	TP2 (3)	43.53	43.74
4	TP2 (4)	43.09	43.21
5	TP2 (5)	43.30	45.09
6	TP2 (6)	41.87	41.81
7	TP2 (7)	42.79	42.22
8	TP2 (8)	40.42	41.24
9	TP2 (9)	41.83	43.45
10	TP2 (10)	41.73	41.15

ANNEXURE C · used LL results

54mm ring vs 35mm ring LL results

Test no.	54mm ring			35mm ring		
	20mm	17mm	16mm	20mm	17mm	16mm
1	55.8	53.6	52.7	54.3	52.4	51.8
2	59.7	57.1	56.1	61.6	58.5	57.4
3	64.9	61.9	60.8	65.1	61.8	60.6
4	62.8	60.5	59.6	62.3	60.2	59.4
5	62.4	59.6	58.5	64.5	61.0	59.8
6	72.6	68.4	66.9	74.7	70.0	68.3
7	59.4	56.6	55.6	58.5	55.8	54.9
8	75.0	71.0	69.6	75.4	70.1	68.6
9	65.0	62.0	60.9	63.5	60.7	59.7
10	44.8	43.2	42.6	45.2	43.6	43.0
11	56.1	53.1	52.0	56.2	52.8	51.9
12	23.5	22.6	22.3	23.4	22.6	22.3
13	58.1	56.1	55.3	61.3	58.2	57.2
14	53.7	50.5	49.3	54.4	50.9	49.7
15	57.8	54.5	53.4	57.3	54.4	53.3
16	56.1	54.2	53.5	57.6	54.7	53.7
17	59.9	56.5	55.3	58.9	55.6	54.5
18	58.9	55.8	54.7	58.6	55.9	54.9
19	44.6	42.6	41.9	46.1	43.8	42.9
20	61.0	58.5	57.5	62.3	59.6	58.6
21	66.0	63.0	61.9	67.0	63.6	62.4
22	63.5	61.0	60.0	63.9	61.5	60.7
23	63.6	60.8	59.8	64.1	60.9	59.8
24	57.2	54.3	53.3	57.5	54.6	53.6
25	60.4	57.6	56.6	59.6	56.9	55.9
26	54.2	52.4	51.7	55.7	53.8	53.1
27	43.7	42.2	41.7	43.8	42.6	42.2
28	52.1	47.2	45.4	43.8	42.9	42.6
29	28.2	26.0	25.2	28.8	26.2	25.3
30	25.6	23.8	23.1	25.1	23.8	23.3
31	26.6	25.2	24.7	26.6	25.3	24.9
32	26.0	24.8	24.4	24.2	23.4	23.2
33	26.6	25.4	25.0	25.0	24.0	23.6
34	24.2	23.3	22.9	24.5	24.1	23.9
35	47.8	43.9	42.5	46.8	43.3	42.1
36	73.6	68.5	66.7	72.6	67.8	66.0
37	66.1	62.5	61.2	66.4	62.6	61.3
38	67.7	63.8	62.5	68.5	64.3	62.9
39	64.4	60.8	59.5	65.1	61.5	60.2
40	73.9	69.2	67.5	74.2	69.2	67.5
41	71.1	66.6	65.0	71.9	67.0	65.3
42	66.8	63.0	61.6	67.1	63.1	61.7
43	61.9	58.3	57.0	61.9	58.3	57.0
44	68.1	63.9	62.4	66.9	63.2	61.9
45	61.8	58.3	57.0	61.2	58.0	56.8
46	64.7	60.8	59.4	64.1	60.4	59.1
47	66.9	62.5	61.0	64.8	60.9	59.5
48	62.2	58.4	57.0	62.7	59.0	57.7
49	66.1	62.5	61.2	67.7	63.7	62.3
50	102.9	97.2	95.2	98.0	93.2	91.4
51	101.8	97.4	95.8	107.4	100.8	98.4
52	101.8	96.3	94.3	100.8	95.4	93.4
53	101.0	95.1	93.0	102.5	96.1	93.8
54	97.8	93.2	91.5	97.8	92.7	90.8
55	98.3	92.9	91.0	96.2	90.9	89.0
56	97.1	91.6	89.6	96.8	92.2	90.6
57	95.9	92.2	90.8	94.3	90.6	89.2
58	94.6	89.0	87.1	90.5	86.2	84.7
59	90.9	86.9	85.5	92.5	88.4	86.9
60	49.6	47.0	46.1	48.5	45.9	45.0
61	51.0	47.8	46.6	50.6	47.6	46.5
62	49.9	46.8	45.7	48.4	45.5	44.5
63	47.7	45.0	44.1	48.2	45.7	44.8
64	47.8	45.2	44.3	48.7	45.7	44.6
65	48.1	45.8	44.9	48.0	45.7	44.8
66	45.4	43.1	42.3	46.7	44.3	43.4
67	43.0	41.1	40.4	45.3	41.9	40.7
68	46.3	43.7	42.8	46.0	43.6	42.8

ANNEXURE C - used LL results

54mm ring vs 30mm ring LL results						
Test no.	54mm ring			30mm ring		
	20mm	17mm	16mm	20mm	17mm	16mm
1	53.4	51.5	53.4	55.0	52.6	51.8
2	65.4	62.0	65.4	67.7	63.8	62.5
3	54.3	50.5	49.2	56.3	51.9	50.4
4	65.6	63.0	62.0	66.1	63.2	62.2
5	55.2	53.2	52.5	55.6	53.0	52.1
6	44.9	43.4	42.9	46.7	43.6	42.5
7	59.2	56.6	55.7	60.6	57.8	56.8
8	57.5	55.0	54.1	57.7	55.0	54.1
9	43.7	41.9	41.2	44.6	42.1	41.2
10	46.1	43.9	43.0	46.2	43.8	43.0
11	42.2	40.2	39.4	43.1	40.7	39.9
12	45.7	43.6	42.9	46.3	44.2	43.5
13	44.6	42.3	41.5	46.2	43.1	42.0
14	66.5	62.5	61.1	68.3	63.3	61.6
15	55.8	53.6	52.7	57.2	55.0	54.2
16	59.7	57.1	56.1	59.8	57.3	56.4
17	64.9	61.9	60.8	63.5	60.4	59.3
18	62.8	60.5	59.6	64.3	61.3	60.2
19	62.4	59.6	58.5	62.9	59.7	58.5
20	72.6	68.4	66.9	70.3	66.2	64.8
21	59.4	56.6	55.6	60.7	57.8	56.8
22	75.0	71.0	69.6	76.6	70.6	69.0
23	65.0	62.0	60.9	65.3	61.9	60.9
24	44.8	43.2	42.6	44.8	43.5	42.9
25	56.1	53.1	52.0	57.9	53.7	52.7
26	23.5	22.6	22.3	24.4	23.1	22.7
27	58.1	56.1	55.3	63.2	58.3	57.1
28	53.7	50.5	49.3	55.4	52.5	51.5
29	57.8	54.5	53.4	57.8	54.7	53.7
30	56.1	54.2	53.5	58.6	55.3	54.1
31	59.9	56.5	55.3	60.6	57.5	56.3
32	58.9	55.8	54.7	60.2	56.9	55.8
33	44.6	42.6	41.9	46.2	43.9	43.0
34	61.0	58.5	57.5	62.9	60.1	59.2
35	66.0	63.0	61.9	66.7	63.8	62.7
36	63.5	61.0	60.0	65.0	62.3	61.3
37	63.6	60.8	59.8	64.5	61.4	60.3
38	57.2	54.3	53.3	58.4	55.1	53.9
39	59.3	56.7	55.7	60.8	58.1	57.1
40	60.9	58.0	56.9	64.2	60.4	59.0
41	60.4	57.6	56.6	61.2	58.6	57.6
42	54.2	52.4	51.7	57.8	56.0	55.4
43	43.7	42.2	41.7	45.8	44.5	44.0
44	52.1	47.2	45.4	45.7	43.4	42.5
45	28.2	26.0	25.2	30.0	27.4	26.5
46	25.6	23.8	23.1	25.7	24.4	23.9
47	26.6	25.2	24.7	27.7	26.5	26.1
48	26.0	24.8	24.4	24.6	23.7	23.3
49	26.6	25.4	25.0	26.8	26.0	25.7
50	24.2	23.3	22.9	24.4	23.9	23.7
51	47.8	43.9	42.5	49.6	45.3	43.8
52	102.9	97.2	95.2	101.0	95.6	93.7
53	101.8	97.4	95.8	106.7	100.6	98.4
54	101.8	96.3	94.3	105.4	98.6	96.2
55	101.0	95.1	93.0	99.9	95.8	94.3
56	97.8	93.2	91.5	98.4	94.0	92.4
57	98.3	92.9	91.0	97.5	92.8	91.1
58	97.1	91.6	89.6	99.3	93.6	91.6
59	95.9	92.2	90.8	95.6	90.8	89.0
60	94.6	89.0	87.1	97.4	91.7	89.6
61	90.9	86.9	85.5	94.2	89.3	87.6
62	49.6	47.0	46.1	50.8	48.0	46.9
63	51.0	47.8	46.6	51.5	48.2	47.1
64	49.9	46.8	45.7	48.3	45.5	44.5
65	47.7	45.0	44.1	48.4	45.5	44.5
66	47.8	45.2	44.3	48.7	45.8	44.8
67	48.1	45.8	44.9	49.3	46.5	45.6
68	45.4	43.1	42.3	46.1	43.9	43.1
69	43.0	41.1	40.4	42.9	40.7	39.9
70	46.3	43.7	42.8	45.7	43.3	42.4

ANNEXURE C · used LL results

CCLL vs $FCLL_{54}$

test no.	CCLL	54mm ring		
		20mm	17mm	16mm
1	53.1	53.4	51.5	53.4
2	58.7	65.4	62.0	65.4
3	62.8	65.6	63.0	62.0
4	54.2	55.2	53.2	52.5
5	43.5	44.9	43.4	42.9
6	59.5	59.2	56.6	55.7
7	60.7	57.5	55.0	54.1
8	41.2	43.7	41.9	41.2
9	42.8	46.1	43.9	43.0
10	40.1	42.2	40.2	39.4
11	42.9	45.7	43.6	42.9
12	41.9	44.6	42.3	41.5
13	63.5	66.5	62.5	61.1
14	54.3	55.8	53.6	52.7
15	57.0	59.7	57.1	56.1
16	63.7	64.9	61.9	60.8
17	63.2	62.8	60.5	59.6
18	59.8	62.4	59.6	58.5
19	71.4	72.6	68.4	66.9
20	61.8	59.4	56.6	55.6
21	75.3	75.0	71.0	69.6
22	64.6	65.0	62.0	60.9
23	42.1	44.8	43.2	42.6
24	55.8	56.1	53.1	52.0
25	56.3	58.1	56.1	55.3
26	52.2	53.7	50.5	49.3
27	53.4	57.8	54.5	53.4
28	53.9	56.1	54.2	53.5
29	53.8	59.9	56.5	55.3
30	52.7	58.9	55.8	54.7
31	40.5	44.6	42.6	41.9
32	67.0	61.0	58.5	57.5
33	61.3	66.0	63.0	61.9
34	59.9	63.5	61.0	60.0
35	57.8	63.6	60.8	59.8
36	54.3	57.2	54.3	53.3
37	63.2	59.3	56.7	55.7
38	57.2	60.9	58.0	56.9
39	52.1	60.4	57.6	56.6
40	49.8	54.2	52.4	51.7
41	39.0	43.7	42.2	41.7
42	40.5	52.1	47.2	45.4
43	22.3	28.2	26.0	25.2
44	21.4	25.6	23.8	23.1
45	21.4	26.6	25.2	24.7
46	21.8	26.0	24.8	24.4
47	21.6	26.6	25.4	25.0
48	22.2	24.2	23.3	22.9
49	67.7	73.6	68.5	66.7
50	64.6	66.1	62.5	61.2
51	62.7	67.7	63.8	62.5
52	60.6	64.4	60.8	59.5
53	70.7	73.9	69.2	67.5
54	69.2	71.1	66.6	65.0
55	64.6	66.8	63.0	61.6
56	57.9	61.9	58.3	57.0
57	64.6	68.1	63.9	62.4
58	57.9	61.8	58.3	57.0
59	62.3	64.7	60.8	59.4
60	61.7	66.9	62.5	61.0
61	58.8	62.2	58.4	57.0
62	63.3	66.1	62.5	61.2
63	87.7	102.9	97.2	95.2
64	93.0	101.8	97.4	95.8
65	89.0	101.8	96.3	94.3
66	94.5	101.0	95.1	93.0
67	90.4	97.8	93.2	91.5
68	85.5	97.1	91.6	89.6
69	87.6	95.9	92.2	90.8
70	85.4	94.6	89.0	87.1
71	82.6	90.9	86.9	85.5
72	46.8	49.6	47.0	46.1
73	43.8	51.0	47.8	46.6
74	43.8	49.9	46.8	45.7
75	43.6	47.7	45.0	44.1
76	41.7	47.8	45.2	44.3
77	41.5	48.1	45.8	44.9
78	41.1	45.4	43.1	42.3
79	40.9	43.0	41.1	40.4
80	39.5	46.3	43.7	42.8

CCLL vs FCLL$_{35}$

test no.	CCLL	35mm ring		
		20mm	17mm	16mm
1	54.3	54.3	52.4	51.8
2	57.0	61.6	58.5	57.4
3	63.7	65.1	61.8	60.6
4	63.2	62.3	60.2	59.4
5	59.8	64.5	61.0	59.8
6	71.4	74.7	70.0	68.3
7	61.8	58.5	55.8	54.9
8	75.3	75.4	70.1	68.6
9	64.6	63.5	60.7	59.7
10	42.1	45.2	43.6	43.0
11	55.8	56.2	52.8	51.9
12	56.3	61.3	58.2	57.2
13	52.2	54.4	50.9	49.7
14	53.4	57.3	54.4	53.3
15	53.9	57.6	54.7	53.7
16	53.8	58.9	55.6	54.5
17	52.7	58.6	55.9	54.9
18	40.5	46.1	43.8	42.9
19	67.0	62.3	59.6	58.6
20	61.3	67.0	63.6	62.4
21	59.9	63.9	61.5	60.7
22	57.8	64.1	60.9	59.8
23	54.3	57.5	54.6	53.6
24	52.1	59.6	56.9	55.9
25	49.8	55.7	53.8	53.1
26	39.0	43.8	42.6	42.2
27	40.5	43.8	42.9	42.6
28	22.3	28.8	26.2	25.3
29	21.4	25.1	23.8	23.3
30	21.4	26.6	25.3	24.9
31	21.8	24.2	23.4	23.2
32	21.6	25.0	24.0	23.6
33	22.2	24.5	24.1	23.9
34	26.5	30.9	28.8	28.0
35	25.9	32.5	30.2	29.4
36	25.5	31.0	28.8	28.1
37	24.4	32.2	29.9	29.1
38	23.8	30.1	28.2	27.5
39	23.8	29.9	27.9	27.2
40	23.6	30.1	28.3	27.6
41	23.2	28.7	27.0	26.4
42	22.1	28.8	26.9	26.2
43	21.6	30.7	28.6	27.9
44	21.6	29.8	27.5	26.7
45	21.5	28.6	26.4	25.6
46	21.3	28.3	26.8	26.2
47	20.9	28.2	26.2	25.5
48	20.6	30.1	28.1	27.3
49	78.8	79.8	74.7	72.9
50	76.3	83.6	77.8	75.7
51	68.6	67.2	63.0	61.5
52	63.7	62.3	58.9	57.6
53	63.2	67.3	62.9	61.4
54	60.4	53.3	51.4	50.7
55	61.4	62.7	59.6	58.5
56	80.9	79.3	71.9	69.4
57	50.9	51.4	48.8	47.9
58	73.7	68.1	64.9	63.8
59	65.0	68.1	64.9	63.8
60	63.3	66.8	63.7	62.6
61	61.8	67.4	63.8	62.4
62	63.4	70.0	65.9	64.5
63	67.7	72.6	67.8	66.0
64	64.6	66.4	62.6	61.3
65	62.7	68.5	64.3	62.9
66	60.6	65.1	61.5	60.2
67	70.7	74.2	69.2	67.5
68	69.2	71.9	67.0	65.3
69	64.6	67.1	63.1	61.7
70	57.9	61.9	58.3	57.0
71	64.6	66.9	63.2	61.9
72	57.9	61.2	58.0	56.8
73	62.3	64.1	60.4	59.1
74	61.7	64.8	60.9	59.5
75	58.8	62.7	59.0	57.7
76	63.3	67.7	63.7	62.3
77	75.7	72.3	68.0	66.4
78	59.1	68.6	64.5	63.1
79	68.0	67.9	64.2	62.8
80	63.3	73.6	68.9	67.2
81	59.6	65.1	60.7	59.1
82	77.7	75.1	70.3	68.6
83	66.7	70.6	66.6	65.2
84	66.3	74.3	69.2	67.3
85	66.5	75.0	70.2	68.5
86	63.3	72.2	67.8	66.2
87	67.3	79.8	74.4	72.5
88	64.0	67.7	63.8	62.5
89	87.7	98.0	93.2	91.4
90	93.0	107.4	100.8	98.4
91	89.0	100.8	95.4	93.4
92	94.5	102.5	96.1	93.8
93	90.4	97.8	92.7	90.8
94	85.5	96.8	92.2	90.6
95	87.6	94.3	90.6	89.2
96	85.4	90.5	86.2	84.7
97	82.6	92.5	88.4	86.9
98	89.1	109.5	102.2	99.5
99	46.8	48.5	45.9	45.0
100	43.8	50.6	47.6	46.5
101	43.8	48.4	45.5	44.5
102	43.6	48.2	45.7	44.8
103	41.7	48.7	45.7	44.6
104	41.5	48.0	45.7	44.8
105	41.1	46.7	44.3	43.4
106	40.9	45.3	41.9	40.7
107	39.5	46.0	43.6	42.8

ANNEXURE C · used LL results

CCLL vs FCLL$_{30}$

test no.	CCLL	30mm ring			test no.	CCLL	30mm ring		
		20mm	16mm	15mm			20mm	16mm	15mm
1	53.1	55.0	51.8	50.9	42	40.5	45.7	42.5	41.6
2	58.7	67.7	62.5	61.0	43	22.3	30.0	26.5	25.6
3	62.8	66.1	62.2	61.1	44	21.4	25.7	23.9	23.5
4	54.2	55.6	52.1	51.1	45	21.4	27.7	26.1	25.7
5	43.5	46.7	42.5	41.3	46	21.8	24.6	23.3	23.0
6	59.5	60.6	56.8	55.7	47	21.6	26.8	25.7	25.4
7	60.7	57.7	54.1	53.1	48	22.2	24.4	23.7	23.4
8	41.2	44.6	41.2	40.3	49	26.5	30.8	27.7	26.9
9	42.8	46.2	43.0	42.1	50	25.9	33.0	29.8	28.9
10	40.1	43.1	39.9	39.0	51	25.5	30.6	28.5	28.0
11	42.9	46.3	43.5	42.8	52	24.4	33.4	30.3	29.4
12	41.9	46.2	42.0	40.9	53	23.8	29.7	27.0	26.3
13	63.5	68.3	61.6	59.7	54	23.8	29.5	26.7	25.9
14	54.3	57.2	54.2	53.4	55	23.6	31.1	28.4	27.7
15	57.0	59.8	56.4	55.4	56	23.2	29.6	27.1	26.4
16	63.7	63.5	59.3	58.1	57	22.1	28.1	25.6	24.9
17	63.2	64.3	60.2	59.1	58	21.6	30.0	27.4	26.7
18	59.8	62.9	58.5	57.3	59	21.6	28.5	26.3	25.6
19	71.4	70.3	64.8	63.3	60	21.5	29.3	26.1	25.3
20	61.8	60.7	56.8	55.7	61	21.3	29.0	26.3	25.6
21	75.3	76.6	69.0	67.4	62	20.9	29.0	26.1	25.4
22	64.6	65.3	60.9	59.8	63	20.6	30.2	27.6	26.9
23	42.1	44.8	42.9	42.3	64	87.7	101.0	93.7	91.6
24	55.8	57.9	52.7	51.6	65	93.0	106.7	98.4	96.2
25	56.3	63.2	57.1	55.9	66	89.0	105.4	96.2	93.7
26	52.2	55.4	51.5	50.4	67	94.5	99.9	94.3	92.8
27	53.4	57.8	53.7	52.7	68	90.4	98.4	92.4	90.8
28	53.9	58.6	54.1	52.1	69	85.5	99.3	91.6	89.5
29	53.8	60.6	56.3	55.1	70	87.6	95.6	89.0	87.2
30	52.7	60.2	55.8	54.5	71	85.4	97.4	89.6	87.5
31	40.5	46.2	43.0	42.2	72	82.6	94.2	87.6	85.8
32	67.0	62.9	59.2	58.1	73	89.1	101.4	93.9	91.9
33	61.3	66.7	62.7	61.6	74	46.8	50.8	46.9	45.9
34	59.9	65.0	61.3	60.3	75	43.8	51.5	47.1	45.8
35	57.8	64.5	60.3	59.1	76	43.8	48.3	44.5	43.4
36	54.3	58.4	53.9	52.7	77	43.6	48.4	44.5	43.5
37	63.2	60.8	57.1	56.1	78	41.7	48.7	44.8	43.7
38	57.2	64.2	59.0	57.6	79	41.5	49.3	45.6	44.5
39	52.1	61.2	57.6	56.6	80	41.1	46.1	43.1	42.3
40	49.8	57.8	55.4	54.7	81	40.9	42.9	39.9	39.1
41	39.0	45.8	44.0	43.5	82	39.5	45.7	42.4	41.5

CCLL vs FCLL$_{35}$ @ 104.5g cone weight						
test no.	Cas Cup	35mm ring				
		20mm	19mm	18mm	17mm	16mm
1	47.1	44.2	43.4	42.6	41.7	40.9
2	43.4	43.4	42.7	41.9	41.2	40.4
3	39.0	37.8	37.1	36.4	35.7	35.0
4	36.3	34.5	33.9	33.3	32.7	32.0
5	33.9	32.8	32.4	31.9	31.4	30.8
6	33.2	33.2	32.8	32.3	31.9	31.4
7	32.5	34.1	33.4	32.8	32.1	31.3
8	30.2	32.1	31.5	31.0	30.4	29.7
9	29.2	30.4	29.8	29.2	28.5	27.9
10	28.3	28.2	27.7	27.2	26.7	26.2
11	27.6	27.8	27.3	26.8	26.2	25.7
12	27.0	28.7	28.2	27.7	27.3	26.7
13	26.9	26.5	26.3	26.0	25.7	25.4
14	26.2	26.8	26.4	25.9	25.5	25.0
15	26.1	25.9	25.5	25.1	24.7	24.2
16	25.4	26.9	26.5	26.1	25.7	25.3
17	24.4	24.7	24.3	24.0	23.6	23.2
18	24.1	24.4	23.9	23.4	22.9	22.4
19	22.6	24.1	23.8	23.4	23.0	22.6
20	22.4	23.2	23.0	22.7	22.4	22.1
21	63.5	65.0	63.7	62.3	60.9	59.4
22	62.1	64.1	62.8	61.4	60.0	58.6
23	60.1	57.8	56.8	55.7	54.6	53.4
24	59.0	61.1	60.1	59.0	57.9	56.8
25	58.9	62.0	60.8	59.5	58.2	56.9
26	57.9	58.9	57.8	56.7	55.5	54.3
27	56.9	59.9	58.8	57.6	56.4	55.1
28	70.8	70.8	69.4	67.9	66.4	64.8
29	65.3	68.3	67.0	65.6	64.2	62.7
30	104.8	105.4	103.4	101.4	99.3	97.1
31	109.3	106.6	104.5	102.4	100.2	97.9
32	86.0	87.4	86.1	84.8	83.4	82.0
33	91.2	93.9	92.5	91.1	89.5	88.0
34	93.2	98.6	96.8	95.0	93.1	91.2
35	95.7	101.0	99.1	97.3	95.3	93.3
36	101.7	107.8	105.8	103.7	101.5	99.3
37	98.1	100.0	98.2	96.3	94.4	92.4
38	98.3	103.2	101.4	99.6	97.8	95.8
39	99.5	105.8	103.5	101.2	98.7	96.2
40	91.1	93.4	91.9	90.4	88.8	87.2
41	97.2	99.5	97.9	96.2	94.5	92.8
42	99.5	101.9	100.1	98.3	96.3	94.4
43	103.1	105.7	104.0	102.3	100.4	98.5
44	95.6	96.0	94.8	93.4	92.0	90.6
45	99.3	99.2	97.6	95.9	94.1	92.3
46	99.6	102.2	100.5	98.7	96.9	95.0
47	104.2	103.3	101.3	99.1	96.9	94.7
48	98.3	99.1	97.5	95.8	94.1	92.3
49	92.3	96.0	94.5	93.0	91.4	89.8