COMPARISON OF ATTERBERG LIMITS AND SHEAR STRENGTH VALUES AS DETERMINED FROM FALL CONE AND CONVENTIONAL METHODS

By

Muhammad Farjad Sami

NUST-201463390-MSCEE-15014F

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geotechnical Engineering

NUST Institute of Civil Engineering (NICE),

School of Civil and Environmental Engineering (SCEE),

National University of Sciences and Technology (NUST),

H-12 Sector,

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This is to certify that the

thesis titled

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has been accepted towards the partial fulfillment

of

the requirements

for

Master of Science in Geotechnical Engineering

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Dr. Liaqat Ali

Associate Dean

NUST Institute of Civil Engineering (NICE)

DEDICATED

TO

HOLY PROPHET (P.B.U.H)

MINERAT OF KNOWLEDGE

AND

MY LOVING PARENTS AND INSTITUTE

WHO GAVE ME A LOT OF INSPIRATION,

COURAGE AND

SUPPORT DURING MY STUDIES

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I am highly thankful to Almighty Allah, Who enabled me to complete this research work. Countless Salutations upon Holy Prophet (P.B.U.H), the source of knowledge Who has guided mankind in each and every walk of life. I would like to express the deepest appreciation to my supervisor, Dr. Liaqat Ali who continually and convincingly conveyed a spirit of hard work to complete the project. Without his help and guidance this project completion would not have been possible.

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TABLE OF CONTENTS

LIST OF ABBREVIATIONS

ASTM	American Society of Testing and Materials
AASHTO	American Association of State Highway and Transportation Officials
EME	College of Electrical and Mechanical Engineering
Isb.	Islamabad
kN	Kilo Newton
LL_c	Liquid Limit using Casagarnde Method
LL_f	Liquid Limit using Fall Cone penetrometer
LL_{cone}	Liquid Limit using Fall Cone
LL_{cup}	Liquid Limit using Casagarnde Method
OMC	Optimum moisture content
PL_c	Plastic Limit using method of Thread formation
PL_f	Plastic Limit using Fall Cone Method
PI_c	Plasticity Index using Casagarnde Method
PI_f	Plasticity Index using Fall Cone Method
Psf	Pound per square foot
C_u	Undrained Shear strength
S_u	Unconfined Compression strength

$C_{u\ (Unconfined)}$	Undrained Shear strength using Unconfined Compression test
$C_{u\ (Fall\ Cone)}$	Undrained Shear strength using Fall Cone Method
$C_{u\ (Vane\ shear)}$	Undrained Shear strength using lab Vane Shear test
USCS	Unified soil classification system

LIST OF TABLES

LIST OF FIGURES

ABSTRACT

Index properties play an important role in classifying soil regarding their engineering properties. To find these properties tests were initially given by Atterberg, and introduced by Terzaghi in soil mechanics. For every geotechnical site investigation, these tests form the background and have universal acceptance. This study was carried out to make comparison of Atterberg limits and Shear Strength values as determined from Fall Cone and conventional methods. For this purpose sixteen different samples from different areas in vicinity of Islamabad were obtained. Atterberg limits were determined by using conventional methods, i.e., Casagrande Method, Thread rolling method and Unconfined Compression test was used to determine Undrained Shear strength. These results were compared with those obtained with Fall Cone Method. Regression analysis was then performed and co-relations were determined for the values obtained by using these two methods. In the end established co relations were critically compared with the already established co-relations.

The results of the study shows that Liquid Limit determined from Fall Cone is always greater than the Liquid Limit obtained from Casagrande Method. This is in accordance with the results of previous studies. The Undrained Shear strength obtained from Fall Cone apparatus are very high as compared with those obtained from results of Unconfined Compression test. The comparison of co relations established in this study with the co relations established in previous studies and also with the values obtained experimentally shows that the results of all co relations established are satisfactory.

Chapter 1

INTRODUCTION

1.1 GENERAL

The main purpose of this study was to investigate, the use of Fall Cone Penetrometer as an alternative for determination of Atterberg limits and Undrained Shear strength of fine soils. The study focuses on the determination of co-relations between the values of Liquid Limit, Plastic Limit, Plasticity Index, and Undrained Shear strength as determined from conventional methods and Fall Cone Method (BS 1377, 1990). The conventional methods include Casagrande Method (ASTM D423-66) for determining Liquid Limit, method of Thread formation (ASTM D424-59) and Unconfined Compression test (ASTM D2166). For this purpose, sixteen soil samples from different areas with varying Atterberg limits in vicinity of Islamabad were collected and tested.

Although the American Society for Testing and Materials (ASTM) recommends Casagrande Method (Casagrandae, 1958), and the British Standard (BS) specifies the Fall Cone test, indicating the Casagrande Method as 2^{nd} alternative. The Casagrande apparatus has been widely used, but it has many shortcomings (Norman, 1958; Sowers *et al.*, 1960; Sherwood and Ryley, 1968). An alternative method to find the Liquid Limit is using the "Fall Cone Method" and has been adopted by some east European countries, for example Bulgaria and U.S.S.R. British Standards (BS) Methods of Test for Soils for Civil Engineering Purposes (BS 1377) include the Fall Cone test. The Fall Cone test has also been included in codes of various countries like China, Brazil, United States, India and France.

The Fall Cone test is a simple method, in which a cone is penetrated into soil sample by its weight and the depth of penetration is measured. The Fall Cone test is widely used for evaluating Atterberg limits, i.e., Liquid limit (LL) and Plastic Limit (PL), Undrained Shear strength (Cu) for undisturbed as well as remolded clay sample.

1.2 NEED OF RESEARCH

There are many issues associated with Casagrande Method, for instance, it is difficult to cut an ideal groove, difficulty in estimating the amount of closure of groove, time consuming etc., (Sowers *et al*., 1960; Hanks, 1981). The Fall Cone Method gives Liquid Limit results comparable with those obtained by the Casagrande Method, but the variability in Fall Cone Method due to operator technique is less (Sherwood and Ryley, 1968). Several countries have already shifted to Fall Cone Method as a standard. Moreover using this one apparatus, i.e., Fall Cone, four properties of soil, namely Plastic Limit, Liquid Limit, Plasticity Index and Undrained Shear strength can be determined which will save upon cost and time as well. The Fall Cone apparatus is easy to use, and it is quick and reliable. In Pakistan no research work has been done on this topic.

1.3 RESEARCH OBJECTIVES

Thus the primary goal of this research project outlined in this dissertation is to answer the following question:

What is the co-relation between Atterberg limits and Undrained Shear strength calculated from conventional methods (Casagrande Method, method of Thread formtation and Unconfined Compression test) and Fall Cone Penetrometer Method?

In order to answer this question, a detailed investigation was undertaken, involving laboratory tests and analyses being conducted at NUST Institute of Civil

Engineering (NICE). The collected samples were subjected to hydrometer analysis and the specific gravity test. After that the Atterberg limits and Undrained Shear strength was determined using both conventional and Fall Cone Method.

1.4 SCOPE AND METHODOLOGY

The scope of this research encompasses extensive lab testing for the evaluation of Atterberg limits and Undrained Shear strength of sixteen samples consisting of fine soils. In the coming chapters we will deal with sample preparation, classification of soil samples, determination of Atterberg limits and Undrained Shear strength using the two methods. Finally, a comparison between the results obtained from the two different methods is made and regression analysis is done to establish the co-relations between the values obtained from different methods with Fall Cone Penetrometer.

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

The concept of soil consistency was developed by the early interest of researchers about different ways in which fine soil interact with moisture. Many properties such as shrinkage, permeability, swelling, compressibility, and shear strength are co related with Atterberg limits.

2.1.1 Shrinkage Limit

It can be defined as minimum amount of water required to keep the soil sample in saturated state. Kingery and Fracl (1954) proved that, with decrease in surface tension, the shrinkage at any moisture content reduces linearly. By adding various materials, which are surface active, to water, they obtained solutions of varying surface tension and performed experiments with them. The work of Sridharan and Venkatappa (1979) proved that the stress caused by contact, may it be due to soil particle contact and (or) between soil particles, is responsible for shrinkage.

2.1.2 Liquid Limit

It can be defined as the water content at which, when certain force is applied to particles of soil slip pass one another and keep the new positions. The shear strength of soil at Liquid Limit as determined by Casagrande is 0.025 kg/cm^2, whereas according to Norman (1958) it is 0.02 kg/cm^2. The major proportion of strength at Liquid Limit is because of inter particle forces. These net attractive forces between soil particles are linked to the surface activity of the clay component. The larger the surface area, the more will be the attractive forces and greater will be the Liquid Limit. The increase in Liquid Limit results in an increase in Shrinkage Limit also.

2.1.3 Plastic Limit

It is defined as the water content at which the skeleton of soil changes from the fabric to the plastic. At this moisture content, soil particles slide pass each other when force is applied, but still have enough cohesion to maintain the shape. The arrangement of soil particles take place at this point, as sufficient amount of water is there to make a film around each soil particle. The standard method of Thread rolling is used to find the Plastic Limit. This method has many shortcomings as it requires considerable judgment of the operator.

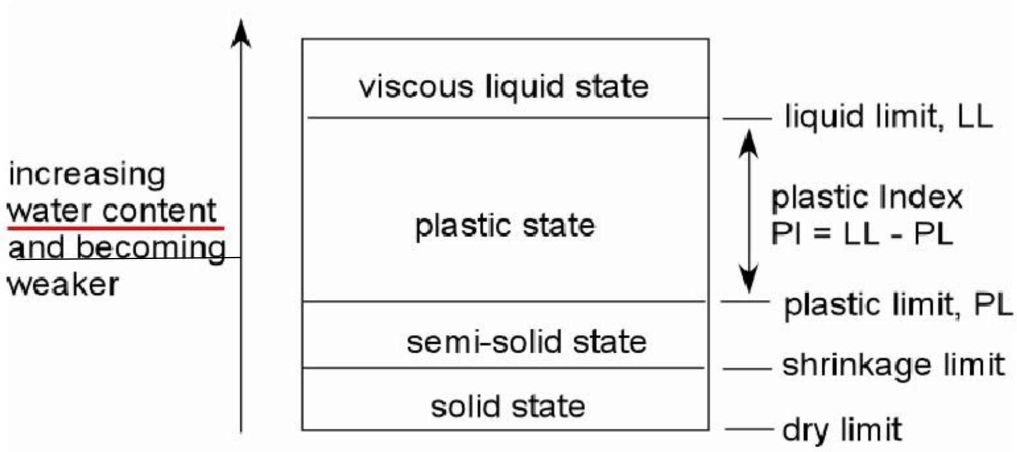

Figure 2.1: Relation of Atterberg limits with moisture content

2.2 FACTORS AFFECTING THE ATTERBERG LIMITS

Baver *et al.* (1984) described the following factors which affect the Atterberg limits:

2.2.1 Clay Content

Plasticity is an important characteristic of fine soils. Atterberg (1911) explained that with increase in clay content, Plastic Limit and Plasticity Index increases. Skempton (1954) showed that the amount of particles less than 2 μm in fine soils is linked directly to Plasticity Index.

2.2.2 Type of Mineral

Plasticity is exhibited by those minerals that have plate or sheet like structure (Atterberg, 1911). Feldspar and Quartz have tetrahedral structure and do not show plasticity whereas Talc, Montmorillonite, Kaolinite, have sheet like structure and exhibit plastic behavior. It is because of more surface area and hence more contact.

2.3 IMPORTANCE OF ATTERBERG LIMITS

Soil engineering problems such as bearing capacity of a foundation, stability of natural slopes, embankments and excavations, magnitude and the time-rate of settlement of a footing, quantity of seepage through an earth dam or beneath a concrete dam or into an excavation, force on a retaining wall. For each of the above purpose it is necessary for the soil engineer to furnish himself with the necessary soil parameters which he must then employ in some empirical or analytical formulae in order to get the desired solution. The needed soil parameters, invariably, must be obtained either through careful laboratory measurements or some other in-situ tests. The shear strength parameters, cohesion and internal friction angle, are needed for the purposes such as, the evaluation of the bearing capacity of a foundation; the assessment of the stability of a slope, accurate measurement of shear strength parameters. As a result of this there is now a tendency in countries all over the world towards building up correlation equations between the above soil properties and the so called soil indices in order to speed-up the design process. This is most pertinent in third world countries where up-to-date testing equipment are lacking together with the trained manpower needed to operate them. For the plastic, clayey soils the Atterberg limits (which are indices of soil behavior) have been found useful for this application. This is because the measurement of the Atterberg limits requires very simple apparatuses and takes up comparatively short periods of time.

During construction of structures which include compacted earth material, e.g. road embankments, river embankments, landfill liners, trench backfills. Material selection is of greater importance in such projects. Liquid and Plastic Limits, grain size distributions are mainly used to classify soils with specific characteristics. The values of Liquid and Plastic Limit of soils are used as parameters, which are linked with many engineering properties for geotechnical design.

With increase in water content, the spacing between particles also increases and the interaction among the adjacent particles will be reduced. As a result the mechanical behavior of the soil gets changed. The particles of soil shift to loosely arranged liquid from a closely packed solid. Atterberg (1911) has used seven limits to explain the changes that takes place in cohesive soils with change in amount of water. Out of these seven, only the Shrinkage Limit, Liquid Limit and Plastic Limits, remained popular. The values of Liquid and Plastic limits are used to find Plasticity Index, which is correlated with many soil properties. The Casagrande's A-line which is used to classify soils using Liquid Limit and Plasticity Index is among the most important correlation. The Plasticity Index is used to obtain Undrained Shear strength (Skempton, 1954).

Plasticity Index is also co-related to many other engineering properties such as, Compression Index (Wood and Worth, 1978), Coefficient of Consolidation (Carrier, 1985), swelling potential (Holtz and Gibbs, 1956), friction angle (Kenney, 1959) Coefficient of earth pressure at rest (Brooker and Ireland, 1965), undrained shear strength (Osterman, 1959), so on and so forth. In addition, the Plasticity Index is required to obtain the parameters like activity, Liquidity Index, etc., which have good correlations with the engineering properties of the soils. In other words, the Plasticity Index, either alone or together with other limits and indices, is used for controlling the specifications and in design process. Because of its wide application in geotechnical engineering, it is desirable to determine it with reasonable accuracy. In other words, it's very important to determine the Liquid and Plastic Limit correctly.

2.4 CALCULATION OF ATTERBERG LIMITS USING CONVENTIONAL METHODS

The tests that we use commonly, now a days, were given by Atterberg (1911), a Swedish agricultural scientist. Depending on water content, originally he thought of these tests as classifying the behavior of clay into distinct types. Thus the water content after which the soil does not flow as a liquid is regarded as Liquid Limit and water content after which sample of soil could not be rolled into thread is regarded as Plastic Limit. These limits along with their difference, called the Plasticity Index, are the base for characterization of different soils.

2.4.1 Liquid Limit

The accurate determination of Liquid Limit is essential, because it is an important parameter in basic estimation of most physical and engineering properties, and is also used in classification of cohesive soils. Either Fall Cone or Casagrande Method can be used to determine Liquid Limit.

Atterberg (1911) devised a technique to measure the Liquid Limit of soils. The basic principle was the stability of a grove cut in clay bed was measured when cup was struck on base. Casagrande (1932 a) standardized this technique as the percussion method. Later on, this was criticized by the author claiming that it is cumbersome in nature (Casagrande, 1958 b). The standard method involves the closure of a 13 mm groove at 25 blows. The corresponding moisture content is measured as Liquid Limit. Because it is not possible to obtain the groove closure every time at 25 blows, data from various tests is plotted. The straight line called Flow Line, is obtained from the graph of water content vs logarithm of number of blows. The moisture content at which flow line crosses 25 blows gives the Liquid Limit.

The American Society for Testing and Materials (ASTM D4318) recommends Casagrande Method. Difference between ASTM and British Standard (BS) is that, Casagrande apparatus described in BS 1377 (BS1377, 1990) has softer base as compared to that recommended by ASTM (D4318). In various parts of world both types are in common practice.

Casagrande has standardized the basic features of the apparatus. He declared the following as critical:

(a) Base material and hardness

(b) Dimensions of base and its insulation from supporting table

(c) Weight, dimensions and material of cup

(d) The drop of the cup at the point when it comes in contact with base

(e) Groove dimensions

2.4.2 Plastic Limit

Different areas of science and engineering involves measuring of plastic behavior. Most of the materials such as clays, soils, plastics and concrete, employed in construction industry has direct relation with plastic behavior. The research work on plasticity was started by Coulomb in 18^{th} century. He studied the stability of embankments and piles. He studied stability of piles and embankments. Plasticity can be defined as the property of a material which allows it to be repeatedly deformed without rupture when acted upon by a force sufficient to cause deformation and which allows it to retain its shape after the applied force has been removed (Perkins, 1995). More force is required to deform a clay– water system having high plasticity and it deforms to higher extent as compared to a system of low plasticity (Brownell, 1977). The morphology of platy minerals of clay, that slide pass each other, is highly related to plasticity of clays. Depending on the nature of the clay, plasticity increases with the increase in amount of water content. According to American Society for Testing and Materials (ASTM D4318) the representative sample of soil passing through No. 40 sieve is taken and water is added to make it enough plastic to be molded with fingers. A ball of soil is then formed from this soil mass, and is rolled between fingers of hand and the glass plate to form threads. When the thread crumbles at 3 mm dia. the process is stopped and the moisture content is determined which gives the Plastic Limit. The Plasticity Index is determined through difference between Liquid and Plastic Limit.

2.5 PROBLEMS RELATED TO DETERMINATION OF ATTERBERG LIMITS USING CONVENTIONAL METHODS

Following ASTM D4318 the Liquid Limit is obtained using Casagrande Method and Plastic Limit is obtained using the method of Thread formation. As compared to Fall Cone Method the degree of repeatability of Casagarnde Method is poor, because the latter is highly dependent on operator (Sherwood and Ryley, 1968; Koumoto and Houlsby, 2001; Feng, 2004).

Another shortcoming in Casagrande Method is that this method is very difficult to adopt in soils having low plasticity. In such a case the soil mass instead of flowing, slides towards groove. Moreover the cutting of grove in such soils is also an issue.

Repeatability across users and sample testing laboratories is also a major issue associated with Casagrande Method (Sowers *et al.*, 1960; Feng, 2004). Other issues linked with Casagrande Method involve the variation of roughness of cup and base hardness with usage. Because of the dynamic nature of the test, the low plastic soils have a potential to liquefy instead of flowing as plastic material. The difference in rate of blows under different circumstances and by different operators is also an issue. This test is also not applicable for sandy and very silty soils. Also nature of this test is such that it involve error because of measurements and rate of blows. Another issue related to Casagrande Method is that it is not applicable on silty and sandy soils (Karlsson, 1977; Rashid *et al*., 2008).

Thread Rolling Method for determination of Plastic Limit has also many shortcomings. The most important among those is operator sensitivity. According to Whyte (1982) assuming full saturation and incompressibility, the theory of plasticity tells that soil yield stress will based on:

(a) Pressure applied to thread of soil

(b) The area of contact between hand and thread

(c) Friction between the base plate, soil and hand

(d) The rate of rolling the soil thread

2.6 DEVELOPMENT OF FALL CONE PENETROMETER APPARATUS

For over 40 years soil classification systems have used the Liquid Limit as measured with the Casagrande Method. The limitations of the Casagrande Method reported by Norman (1958) and were further supported by Casagrande (1958) who favored a static test to determine the Liquid Limit. This renewed interest in alternative methods for determining Liquid Limit and in particular Fall Cone Method.

Swedish railway engineers experimented with a cone located just above the soil surface which when released freely penetrated the soil and the depth of penetration was observed. Their experimental procedure is the basis of the current Fall Cone test. The Swedish engineers evaluated cones of various weights and apex angles but did not correlate their findings with the Liquid Limit. Terzaghi (1927) attempted to show a relation between Undrained Shear strength and cone penetration. Problematical results led to further research which revealed the marked differences in behavior between a remolded and an undisturbed soil sample. With Terzaghi's observations and the introduction of the Casagrande Method (Casagrande, 1932) in America, research with cones for soil classification moved to the Soviet Union. Stefanov (1957) correlated Liquid Limit results obtained with Vassilev's cone apparatus and the Casagrande Method. Numerous East European workers produced similar correlations from either a limited number of results or a restricted range of experiments. Skopek and Ter-Stepanian (1975) resolved these limitations. Using a large number of local and artificial soils, they showed the relationship between the Casagrande Method and Fall Cone to be acceptably linear up to a Liquid Limit of 100 percent but above this value it was nonlinear. Sherwood and Ryley (1986) reviewed the Fall Cone Penetrometers of several countries and found results from the French cone, developed by the Laboratoire Central des Ponts et Chaussees, in favourable agreement with those from Casagrande Method for soils up to 100 percent Liquid Limit. Similarly the Indian Central Road Research Institute cone correlated well for the same range. Generally the Liquid Limit obtained by Fall Cone is lower than with the Casagrande Method.

Koumoto & Houlsby (2001) have presented an analysis on mechanics of Fall

Cone Method. According to them the sensitivities in the Fall Cone test are, roughness of surface of cone, angle of cone, cone bluntness, and heave of cone. The Fall Cone test can be used to evaluate Undrained Shear strength of soils between range of moisture content from Liquid to Plastic limits (Hansbo, 1957). The high strength of soils at low moisture content causes difficulty in penetration of cone. To overcome this issue pseudo static cones have been employed (Stone and Phan, 1995).

The advantages in using Fall Cone Method is that it is simple, easy to perform and gives comparable reproducibility. Further, Fall Cone Method can be used for less plastic soils also, which is difficult in the Casagrnde Method because of the difficulty in cutting the groove and sliding of soil mass rather than flow of soil. Due to its inherent advantages, UK, India, Canada, and many European countries have identified Fall Cone Method as standard procedure for evaluating Liquid Limit of cohesive soils. Two different types of Fall Cone tests are being practice in the world. Some codes like BS: 1377 (1990) and IS: 2720 Part 5 (IS2720, 1985) specify 30°/80 g cone (British cone) and a depth of penetration of 20 mm at Liquid Limit, while countries like Canada and Sweden adopt 60°/60 g cone (Swedish cone) and a depth of penetration of 10 mm corresponds to Liquid Limit (Leroueil and Le Bihan, 1996; Farrell *et al.*, 1997). Recent studies have shown that, both types of test gives same results (Wood, 1990).

2.6.1 Fall Cone and Liquid Limit

The Liquid Limit is defined as, the moisture content at which the soil no more behaves like a semi solid and starts to behave as a viscous fluid. A polished cone made of stainless steel having weight of 80 g and apex angle of 30 degree is allowed to penetrate the soil sample for five seconds. The moisture content corresponding to 20 mm penetration of cone is the Liquid Limit.

2.6.2 Fall Cone and Plastic Limit

Plastic Limit of soil essentially gives the measure of cohesion between soil particles against cracking when the sample is being worked on. The Plastic Limit test is considered to be crude and to produce a large variation of results. A number of procedures, for example, squeeze tests, Soil Suction, Consolidation, Linear Shrinkage, Extrusion, and Fall Cone test have been proposed to replace conventional test. Wood and Wroth, favor the use of Fall Cone Method to obtain the Liquid as well as Plastic Limit. There were two objectives, the method of Thread formation is prone to personal errors and, it is advisable to measure Plastic Limit in terms of strength measurement in the same way as Liquid Limit is determined using Fall Cone Method. e.g. (Hansbo, 1957; Towner, 1973; Campbell, 1975; Belviso *et al.*, 1985). According to Towner (1973), moisture content at 2 mm penetration gives the Plastic Limit while Campbell (1975) suggested it to be 1.36 mm. Sampson and Netterberg (1985) said that the moisture content against 5 mm gives the Plastic Limit.

2.6.3 Fall Cone and Undrained Shear Strength

For quick and simple evaluation of Undrained Shear strength, Fall Cone apparatus is commonly used in Sweden (Hansbo, 1957). Also United Kingdom has adopted this apparatus, i.e., Fall Cone apparatus as a standard for evaluation of Liquid Limit of all soils, because this method evaluates the Undrained Shear strength of all types of fine soils.

Hansbo (1957) presented an equation which relates Undrained Shear strength "C_u" of clay soils with depth of penetration h and the weight Q of the cone. The semi empirical relation is as follow:

$$C_u = k * Q/h^2 \quad (2.1)$$

"K" represents factor of proportionality.

2.7 CO RELATIONS DEVELOPED IN LITERATURE

Spagnoli (2012) described that various authors such as Wires (1984), Belviso *et al.* (1985), Wasti and Bezirci (1986), Dragoni *et al.* (2008), Ozer (2009), Fojtova´ *et al.* (2009), Grønbech *et al.* (2011), Di Matteo (2012) have already developed many co relations between liquid limit obtained using Fall Cone and Casagrande Method. These are presented in tabular form below:

Table 2.1: Co relations in literature between liquid limit determined from Fall Cone Method and Casagrande Method (Spagnoli, 2012)

Reference	Equation	LL range studied
Karlsson (1961, 1977)	$LL_{cone} = 0.85\ LL_{cup} + 5.02$	30–76%
Sherwood and Ryley (1970)	$LL_{cone} = 0.95\ LL_{cup} + 0.95$	30–72%
Wires (1984)	$LL_{cone} = 0.94\ LL_{cup} + 0.97$	38–55%
Belviso et al. (1985)	$LL_{cone} = 0.97\ LL_{cup} + 1.19$	34–134%
Wasti and Bezirci (1986)	$LL_{cone} = 1.01\ LL_{cup} + 4.92$	27–110%
Leroueil and Le Bihan (1996)	$LL_{cone} = 0.86\ LL_{cup} + 6.34$	30–74%
Dragoni et al. (2008)	$LL_{cone} = 1.02\ LL_{cup} + 2.87$	28–74%
Özer (2009)	$LL_{cone} = 0.90\ LL_{cup} + 6.04$	29–104%
Fojtová et al. (2009)	$LL_{cone} = 1.00\ LL_{cup} + 2.44$	20–50%
Grønbech et al. (2011)	$LL_{cone} = 0.95\ LL_{cup} + 9.4$	100–340%
Di Matteo (2012)	$LL_{cone} = 1.00\ LL_{cup} + 2.20$	24–40%

Rajasakeran (2000) measured the Undrained Shear strength of different lime treated and untreated marine soil samples using lab Vane Shear tests and Fall Cone test. Author presented the following co-relation with R^2 value of 0.94:

$$C_{u\ (Vane\ shear)} = 0.9452 C_{u\ (Fall\ Cone)} + 0.1141 \quad (2.2)$$

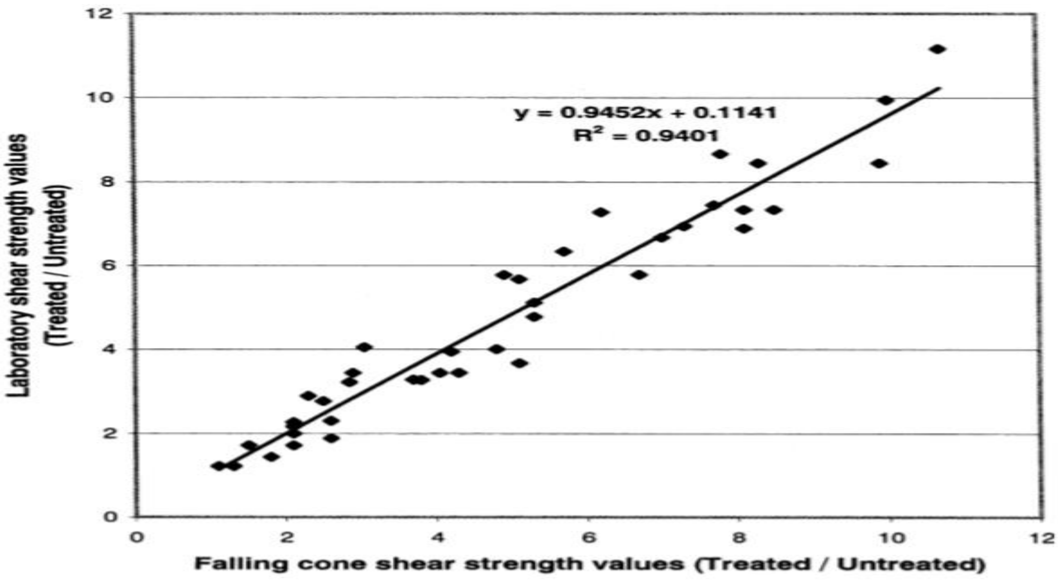

Figure 2.2: Co-relation between Fall Cone and laboratory Vane Shear test

This co relation is between Undrained Shear strength from Vane Shear test and Fall Cone test, while in current study we have compared Undrained Shear strength from unconfined Compression test and Fall Cone test so their comparison with each other is not possible.

Strozyk and Tankiewicz (2013) studied the soils with Plasticity Index above 30 percent and presented the following co relation with R square value of 0.75, between Undrained Shear strength measured from Unconfined Compression test and Fall Cone test.

$$C_{u\ (Unconfined)} = 0.1148C_{u\ (Fall\ Cone)} \quad (2.3)$$

$$R^2 = 0.75$$

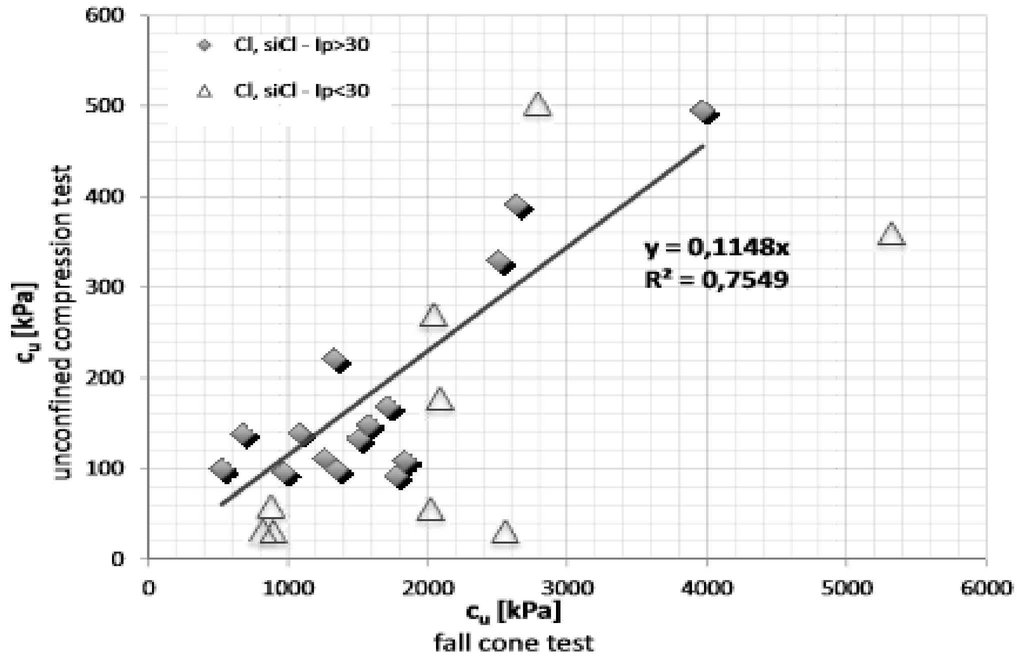

Figure 2.3: Undrained Shear strength (C_u) from Unconfined Compression test and Fall Cone test (only for soils with I_p > 30 percent) (Strozyk, 2013)

Chapter 3

MATERIALS AND METHODOLOGY

3.1 GENERAL

Currently, two methodologies are in use for the obtaining Liquid Limit of a fine-grained soil: (1) Casagrande Method (2) Fall Cone Method. To compare the results of these two methods, is the basic purpose of this study. For this purpose the materials and methodology used is discussed in this chapter.

3.2 MATERIALS

The materials which were used in this study were obtained from various locations in Pakistan, mostly in vicinity of Islamabad (e.g. Fatehjhang, EME College Rawalpindi, Swabi, Nowshera etc). All samples were fine grained soils. The soil samples were obtained from depths of 5 to 6 feet.

Figure 3.1: Location of sites for soil samples (www.google.com)

The reason for sixteen different regions was to find a diversity in the index properties of soils, and to include soils with a wide range of Liquid and Plastic Limit. Thus in order to support the purpose of this research it was deemed necessary to test soil samples with varying Liquid Limit and clay size fraction. Remolded soil samples from the regions listed above have been obtained from depth of about 5– 6 feet to avoid surface vegetation. Samples obtained from respective sites were tested as per the ASTM and BS standard procedures.

3.2.1 Sample Preparation

The method of sample preparation for evaluation of Liquid Limit and Plastic Limit using both methods, .i.e. conventional (Casagrande Method) and Fall Cone Method is same. Both requires an oven dried sample passing no. 40 sieve. Preferably the soil specimen used for obtaining Liquid Limit determination should be in natural state. The process of drying of soils often change the natural, inherent characteristics of soils. For the soil samples containing no soil particle with dia. greater than 0.425 mm (100 percent passing through No. 40 sieve), the Liquid Limit test was carried out on the soil sample in their natural state. For soils containing sand or particles with larger dia., pulverization was carried to make the sample pass through No. 40 sieve for Liquid and Plastic Limit determination. Approximately 250 gm of sample was taken for each Liquid Limit test.

3.3 METHODOLOGY

The material testing was carried out in four phases:

- Phase-I: Characterization of soil samples
- Phase-II: Determination of Atterberg limits using conventional methods

- Phase-III: Determination of Undrained Shear strength using Unconfined Compression test
- Phase-IV: Determination of Atterberg's limit and Undrained Shear strength using Fall Cone apparatus

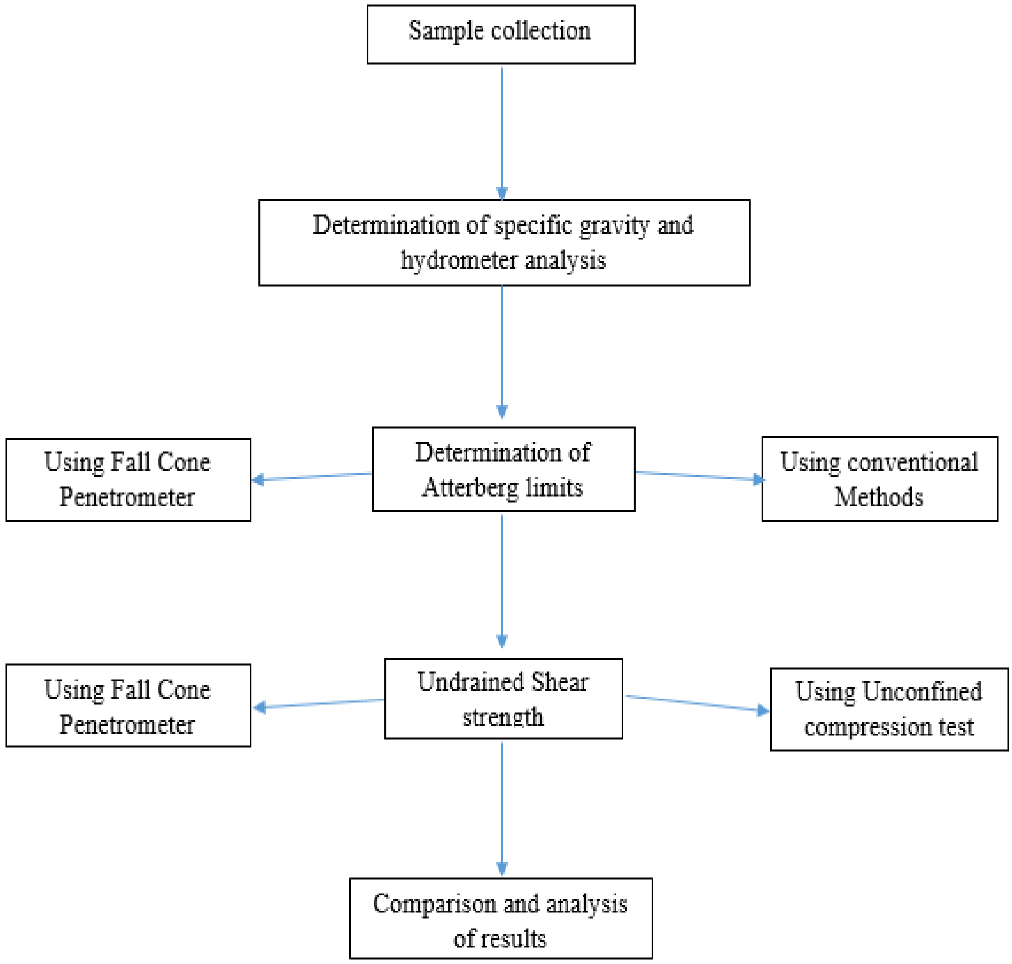

Figure 3.2: Flow chart showing the experimental phases

3.4 CHARACTERIZATION OF SOIL SAMPLES

The 1st phase of testing involved the characterization of soil samples. For this purpose the classification of soil samples, hydrometer analysis and specific gravity tests were performed. It is very important to know the type of soil and percentages of clay and silt content so that it can be established that the results and co relations obtained from the results of this study are valid for which types of soil and furthermore which type of soils can be included in the research for new projects.

Soil samples were classified using the plasticity chart and Atterberg limits determined from conventional methods.

Hydrometer analysis was used to obtain an estimate of the distribution of soil particle sizes from the No. 200 (0.075 mm) sieve to around 0.01 mm. The data was presented on a semi-log plot of percent finer vs. particle diameters as per ASTM D7928.

Specific gravity is one of the most important characteristic of soil. Specific gravity along with other parameters like natural moisture content, degree of saturation, void ratio etc. is used to determine basic soil characteristics. Specific gravities of all sixteen soil samples were determined according to the method described by ASTM (ASTM D854).

3.5 DETERMINATION OF ATTERBERG LIMITS USING CONVENTIOANL METHOD

The 2nd phase of testing involved the determination of Atterberg limits using conventional methods.

3.5.1 Determination of Liquid Limit

The apparatus used to evaluate Liquid Limit of soils is shown in figure 3.5. It is made up of a brass dish, one handle, mounted on base of hard rubber. The process used is as mentioned in ASTM D4318. 250 gm of soil sample passing No. 40 sieve was placed in dish and water is added very slowly using spatula and mixed thoroughly to make it a thick paste. Soil paste was then placed in a cup and surface was made smooth and leveled using spatula. A clean, straight groove of 5/64” (2 mm) was cut in the paste using grooving tool. The handle was rotated at the rate of two revolutions per second.

This process was continued until two halves of soil sample come in contact with each other. This process was stopped when the contact distance of the two soil samples is 13 mm or l/2". The No. of blows required for closure are noted. 20-40 gm of this soil sample was then taken and moisture content measured. This process was repeated for at least 4 times, every time with further small increment of water. The test was proceeded from drier to wetter conditions. After that Liquid Limit was determined using flow curve.

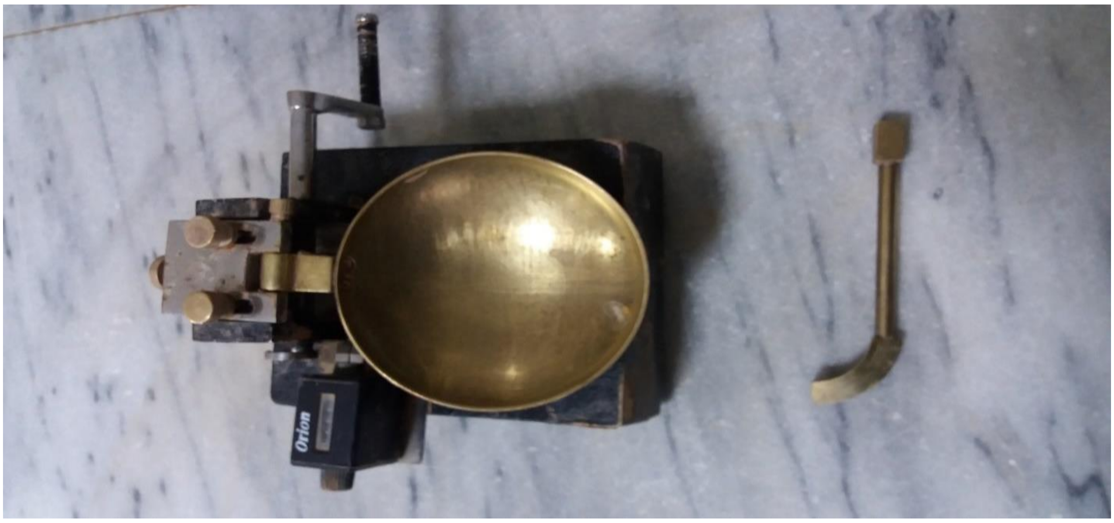

Figure 3.3: Casagrande apparatus with grooving tool

3.5.2 Determination of Plastic Limit

The process used is as mentioned in ASTM D4318. 20 gm of soil sample passing No. 40 sieve was taken and water was added to make it a ball. A ball of about 8 gm was made from the palstic soil and was then rolled between the hand palm and glass plate with just enough pressure to roll the mass of soil sample into thread of 1/8" (3 mm) dia. This process was continued until the thread just crumbles. After that moisture content of the crumbled thread of soil was determined.

3.6 DETERMINATION OF UNDRAINED SHEAR STRENGTH USING UNCONFINED COMPRESSION TEST

Because Unconfined Compression test is a fast and cheap method of measuring Shear strength, therefore it is extensively used worldwide. The test is applied on soil samples recovered from thin walled samplers. ASTM standard (D2166) suggests that, Unconfined Compressive strength is considered as the load per unit area when the axial strain is at 15 percent or maximum load attained per unit area. Among these two whichever occurs first.

A cylindrical soil sample, having length to dia. ratio of 2, was trimmed from ends to make them smooth. The loading of sample was continued until a shearing plane is formed or excessive deformation occurs. The Undrained Shear strength was obtained as half of the Unconfined Compressive strength.

$$C_u = S_u / 2 \tag{3.1}$$

The Unconfined Compression testing machine used in this research was an electrically operated (motorized) machine in which soil specimens of 40 mm dia was used. Load on the sample is applied gradually by an electrically operated load frame and loads are measured on a sensitive proving ring attached to the load frame. The maximum axial load capacity is 0.6 kN.

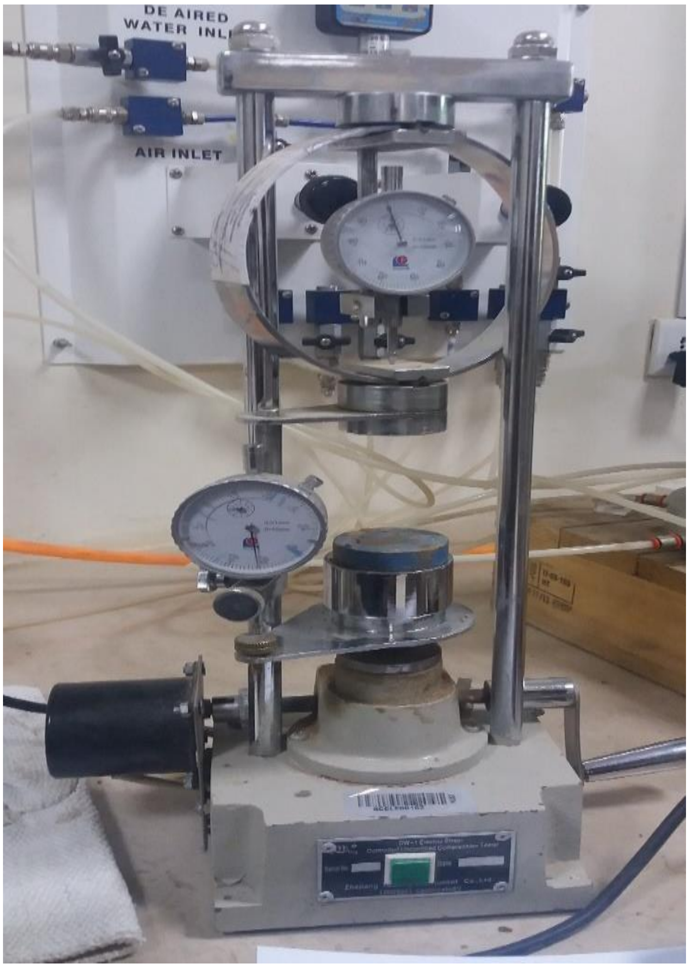

Figure 3.4: Unconfined Compression test apparatus

3.7 DETERMINATION OF ATTERBERG LIMITS AND UNDRAINED SHEAR STRENGTH USING FALL CONE APPARATUS

The 4th and last phase of testing involved the determination of Atterberg limits and Undrained Shear strength using Fall Cone apparatus.

3.7.1 Determination of Liquid Limit

According to method described by BS1377 for determination of Liquid Limit using Fall Cone Method, soil sample was put in a cup of metal (dia. of 55 mm, depth 40 mm). A stainless steel cone (weight 80 g, apex angle 30 degree) was placed in such a way that tip is just above the sample. The cone was allowed to penetrate in soil sample for 5 seconds. The Liquid Limit is defined as water content of soil which allows the cone to penetrate exactly 20 mm during that period of time. It is not possible to get a penetration of 20 mm every time, so test was performed several times and the data was interpolated.

Figure 3.5: Cone and metal ring

3.7.2 Determination of Plastic Limit

The Fall Cone test is not easy to perform when the moisture content is near to Plastic Limit because soil samples become stiff and are not easy to mix (Stone and Phan, 1995; Feng, 2000). Since the difficulties encountered, to find value of Plastic Limit, the relation between logarithmic depth of penetration of Fall Cone and moisture content is used. According to Wood and Wroth (1978), depth of penetration and moisture content has linear relationship between Liquid and Plastic limit. Plasticity Index is half of slope of linear relation. After that Plastic Limit is obtained as difference between Liquid Limit and Plasticity Index. Most researchers have shown that Plastic Limit evaluation using Fall Cone Method is more accurate as compared to Thread Rolling Method. Different researchers have concluded different cone penetration depths varying from 2 to 5 mm, at Plastic Limit. According to Worth and Wood (1978) Plastic Limit is defined at depth of 5 mm, Harrison (1988) describes Plastic Limit at 2 mm depth, and Feng (2000) has shown that at Plastic Limit the penetration of cone is between 2-3 mm. Sharma and Bora (2003) has defined Plastic Limit at depth of 4.4 mm. In this study the Plastic Limit is determined by extrapolating the flow curve to the penetration depth of 2 mm (Feng, 2004).

3.7.3 Determination of Undrained Shear Strength

This test can be done on undisturbed, remolded or reconstituted soil samples. The tip of the cone was made to just touch the specimen. After the tip of cone touches specimen surface, the cone was freely dropped. The cone was allowed to penetrate for 5 seconds and depth of penetration is measured. The Undrained Shear strength is calculated by the following equation given by Hansbo (1957):

$$S_u = k * Q/h^2 \tag{3.2}$$

Where Q is the weight of cone, h is penetration depth, and k is cone factor depending on the cone angle, K = 0.29 was adopted, according to Wood (1990) for the cone angle of 30 degree in this study.

The apparatus used is shown in fig 3.6. The apparatus is mounted on bench. A 150 mm diameter dial is fitted on the apparatus to measure penetration of cone. A stainless steel cone, with apex angle of 30 degree, and 80 gm weight, is attached to it. The apparatus has adjustable feet for levelling.

Figure 3.6: Fall Cone Penetrometer apparatus

Chapter 4

RESULTS AND DISCUSSION

4.1 GENERAL

The testing procedure described in the previous chapter was carried for all the soil samples. The results obtained are discussed in this chapter.

4.2 CHARACHTERIZATION OF SOIL SAMPLES

To characterize the soil samples collected from sixteen different sites, the samples were first pulverized and sieved as required in ASTM standard procedures. After that soil samples were classified and subjected to hydrometer analysis and specific gravity test.

Figure 4.1: Soil samples

4.2.1 Classification of Soil Samples

All sixteen soil samples belong to fine grained soils. The classification was made using Plasticity chart. Liquid Limit and Plasticity Index values were obtained using Casagrande Method (ASTM D4318). The soils were classified according to USCS system of soil classification. The table 4.1 shows the classification of soil samples.

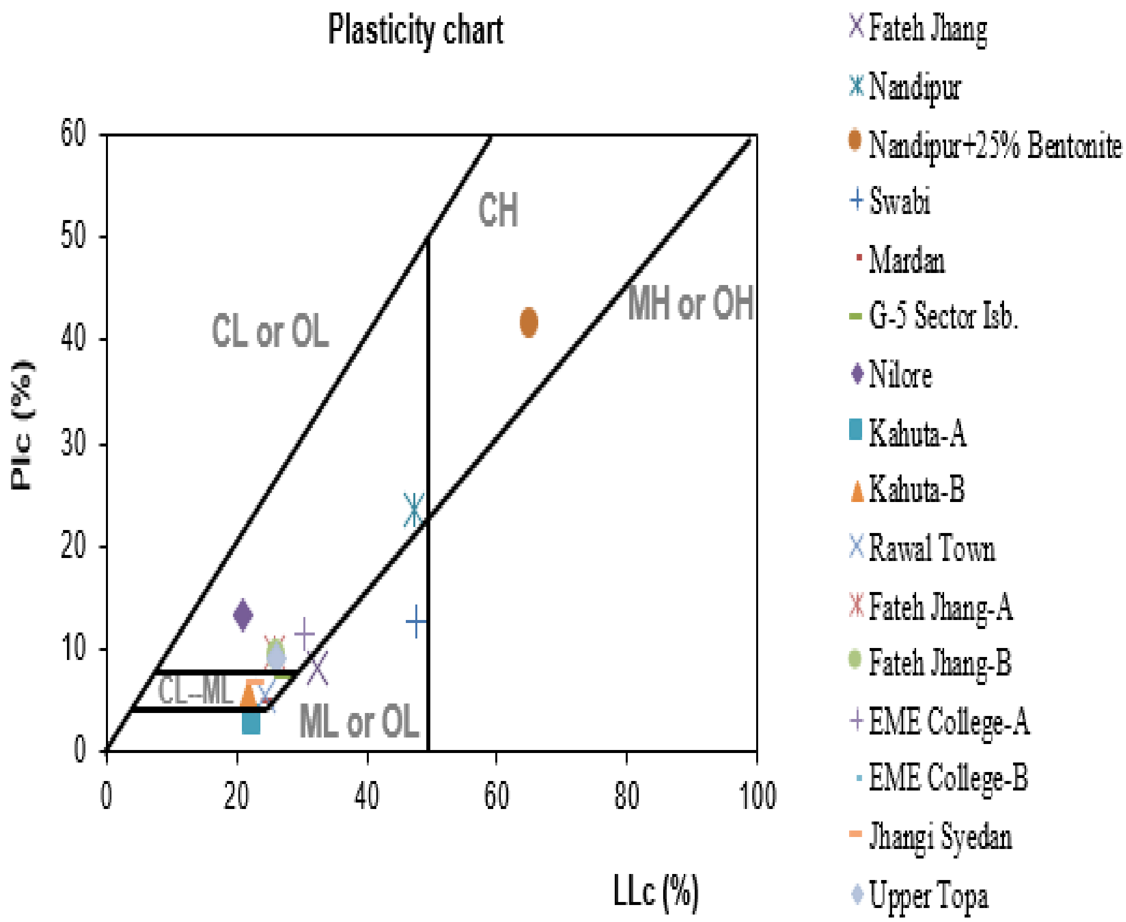

Figure 4.2: Plasticity chart showing the classification of soil samples

Most soil samples were low plastic clay or low plastic-silty clay.

Table 4.1: Classification of soil samples

S. No.	Name of Soil/Sample	Soil Type	Symbol
1	Fateh Jhang	Low Plastic Silt	ML
2	Nandipur	Low Plastic Clay	CL
3	Nandipur+25 percent Bentonite	High Plastic Clay	CH
4	Swabi	Low Plastic Silt	ML
5	Mardan	Low Plastic Silty clay	CL-ML
6	G-5 Sector Isb.	Low Plastic Silty clay	CL-ML
7	Nilore	Low Plastic Clay	CL
8	Kahuta-A	Low Plastic Silty clay	CL-ML
9	Kahuta-B	Low Plastic Silt	ML
10	Upper Topa	Low Plastic Clay	CL
11	Rawal Town	Low Plastic Silty clay	CL-ML
12	Fateh Jhang-A	Low Plastic Clay	CL
13	Fateh Jhang-B	Low Plastic Clay	CL
14	EME College-A	Low Plastic Clay	CL
15	EME College-B	Silty clay	CL-ML
16	Jhangi Syedan	Silty clay	CL-ML

4.2.2 Hydrometer Analysis

All sixteen soil samples were subjected to hydrometer analysis and the particle size distribution curves for particles passing from #200 sieve were obtained.

The hydrometer analysis was carried out because 90 percent of sample passed through No.4 sieve, i.e., it was smaller than 4.75 mm and 20 percent of soil sample passed through No. 200 sieve.

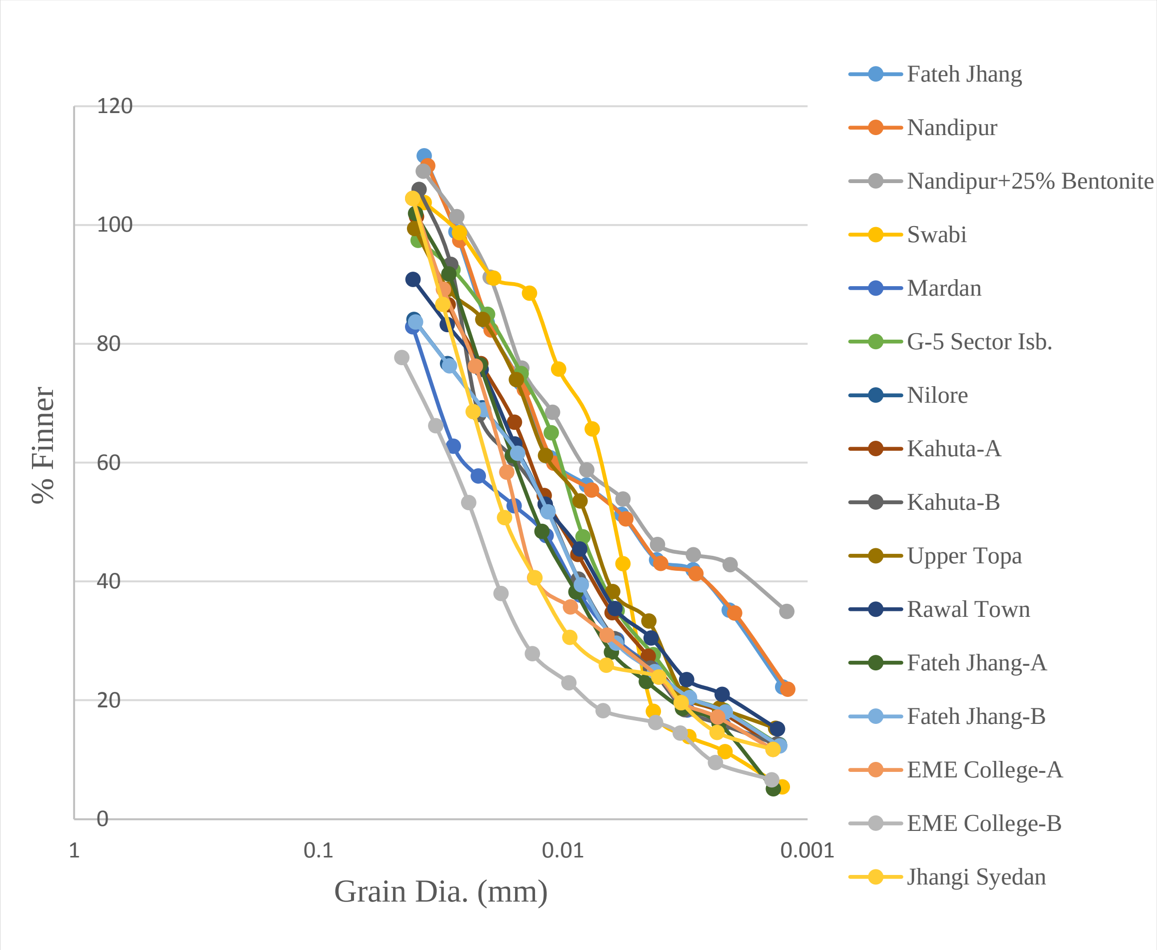

Figure 4.3: Graph of hydrometer analysis

4.2.3 Determination of Specific Gravity

The specific gravities of different soil samples ranged from a maximum of 2.67 to a minimum of 2.14. This shows the variety of soil samples with different soil texture and grain sizes. The results of the specific gravity test are given in table 4.2.

Table 4.2: Specific gravities of soil samples

S. No.	Name of Soil/Sample	Specific Gravity
1	Fateh Jhang	2.57
2	Nandipur	2.67
3	Nandipur+25 percent Bentonite	2.37
4	Swabi	2.67
5	Mardan	2.67
6	G-5 Sector Isb.	2.66
7	Nilore	2.68
8	Kahuta-A	2.55
9	Kahuta-B	2.61
10	Upper Topa	2.55
11	Rawal Town	2.61
12	Fateh Jhang-A	2.4
13	Fateh Jhang-B	2.73
14	EME College-A	2.45
15	EME College-B	2.14
16	Jhangi Syedan	2.19

4.3 DETERMINATION OF ATTERBERG LIMITS USING CONVENTIONAL METHODS

Soil samples were 1st oven dried and then subjected to Casagrande Method and method of Thread formation for evaluation of Liquid Limit and Plastic Limits. The procedure followed is same as described by ASTM (D4318).

Figure 4.4: Determining Liquid Limit of soil samples by Casagrande's method

All sixteen soil samples were subjected to Casagrande's Method. The data for all sixteen soils, showing three trials for each soil sample, including empty weights of container, weight of wet soil, weight of dry soil, and moisture content for each trial is given in Appendix-A. The Liquid Limits obtained included a wide range, with minimum value of 20.4 and a maximum value of 65. The results are given in table 4.3.

Table 4.3: Values of Liquid Limit as determined from Casagrande's method

S. No.	Name of Soil/Sample	Liquid Limit Values (LL_c)
1	Fateh Jhang	32.4
2	Nandipur	47.6
3	Nandipur+25 percent Bentonite	65
4	Swabi	48
5	Mardan	27
6	G-5 Sector Isb.	27
7	Nilore	21.2
8	Kahuta-A	21
9	Kahuta-B	21.9
10	Upper Topa	27
11	Rawal Town	20.4
12	Fateh Jhang-A	25.1
13	Fateh Jhang-B	27.5
14	EME College-A	30
15	EME College-B	28
16	Jhangi Syedan	23

After determination of Liquid Limit values the soil specimens are subjected to method of Thread formation for determination of Plastic Limit, as per the ASTM standard. The results are given in table 4.4.

Table 4.4: Values of Plastic Limit as determined by Thread formation

S. No.	Name of Soil/Sample	Plastic Limit Values (PL_c)
1	Fateh Jhang	24.1
2	Nandipur	23.53
3	Nandipur+25 percent Bentonite	23.44
4	Swabi	35
5	Mardan	19.35
6	G-5 Sector Isb.	20
7	Nilore	7.61
8	Kahuta-A	19.18
9	Kahuta-B	16.22
10	Upper Topa	17.17
11	Rawal Town	18.75
12	Fateh Jhang-A	16.25
13	Fateh Jhang-B	16.88
14	EME College-A	19.12
15	EME College-B	18.99
16	Jhangi Syedan	16.3

The plasticity indices of the sixteen soil samples are given in table 4.5.

Table 4.5: Values of Plasticity Index as determined using conventional method

S. No.	Name of Soil/Sample	Plasticity Index Values (PI_c)
1	Fateh Jhang	8.3
2	Nandipur	24.07
3	Nandipur+25 percent Bentonite	41.56
4	Swabi	13
5	Mardan	7.75
6	G-5 Sector Isb.	7
7	Nilore	13.59
8	Kahuta-A	1.82
9	Kahuta-B	5.68
10	Upper Topa	9.83
11	Rawal Town	1.65
12	Fateh Jhang-A	8.85
13	Fateh Jhang-B	10.62
14	EME College-A	10.88
15	EME College-B	9.01
16	Jhangi Syedan	6.7

4.4 UNCONFINED COMPRESSION TESTING PROGRAM

The undisturbed soil samples by using thin walled samplers or remolded samples are made in lab. In the present study the insitu density and moisture content of the soil samples were not known. To overcome this remolded samples were made at 95 percent of optimum moisture content and 95 percent of max dry density. The value of optimum moisture content and max dry density for clays and silts were averaged for the sake of simplicity, because all sixteen samples belong to either clays or silts. These values are taken from NAVFAC DM 7.2 (NAVFAC, 1986).

An axial strain of 0.5 to 2 percent per minute was applied to start the test. The values of load and deformation were obtained to draw the load-deformation curve. The process of loading the sample continued until 15 percent axial strain is achieved or the load value becomes constant or start to decrease while strain keep on increasing.

Figure 4.5: Unconfined compression testing

All sixteen samples were subjected to Unconfined Compressive test according to the standard procedure (ASTM D 2166). The Undrained Shear strength values were then obtained using following equation.

$$C_u = S_u/2 \qquad (4.1)$$

Table 4.6: Undrained Shear strength values determined by Unconfined Compressive test

S. No.	Name of Soil/Sample	Undrained Shear Strength (Psf) $C_{u\ (Unconfined)}$
1	Fateh Jhang	892.98
2	Nandipur	1535.92
3	Nandipur+25 percent Bentonite	1035.85
4	Swabi	1535.92
5	Mardan	714.38
6	G-5 Sector Isb.	1214.45
7	Nilore	928.69
8	Kahuta-A	821.54
9	Kahuta-B	964.41
10	Upper Topa	571.5
11	Rawal Town	678.66
12	Fateh Jhang-A	857.26
13	Fateh Jhang-B	714.38
14	EME College-A	642.94
15	EME College-B	892.98
16	Jhangi Syedan	464.35

4.5 TESTING PROGRAM ON FALL CONE PENETROMETER

A standard cone of 30 degree and 80 gm weight was allowed to penetrate for 5 seconds as specified in BS 1377. The process was repeated for a range of moisture contents. The moisture content for 20 mm penetration is taken as Liquid Limit. The results are given in table 4.7.

Table 4.7: Liquid Limit values as determined from Fall Cone Method

S. No.	Name of Soil/Sample	Liquid Limit Values (LL_f)
1	Fateh Jhang	47.9
2	Nandipur	54
3	Nandipur+25 percent Bentonite	140
4	Swabi	55.37
5	Mardan	28.5
6	G-5 Sector Isb.	33
7	Nilore	26
8	Kahuta-A	26
9	Kahuta-B	28
10	Upper Topa	30
11	Rawal Town	28
12	Fateh Jhang-A	32.5
13	Fateh Jhang-B	28.5
14	EME College-A	38
15	EME College-B	38
16	Jhangi Syedan	27

Following the procedure established in section 3.7.2, the Plastic Limit of all samples were determined. The values of Plastic Limit obtained using Fall Cone are tabulated in table 4.8.

Figure 4.6: Fall Cone Penetrometer test

The data showing the three trials each for all sixteen samples, including the penetration of cone for each trial, and moisture content against each trial is given in Appendix-B. A maximum value of 46.04 and minimum of 19.12 was observed with exception of sample number 3, which contained Bentonite.

Table 4.8: Plastic Limit values as determined by Fall Cone Method

S. No.	Name of Soil/Sample	Plastic Limit Values (PL_f)
1	Fateh Jhang	38.84
2	Nandipur	35.14
3	Nandipur+25 percent Bentonite	81.29
4	Swabi	46.04
5	Mardan	20.3
6	G-5 Sector Isb.	28.81
7	Nilore	19.12
8	Kahuta-A	23.01
9	Kahuta-B	20.54
10	Upper Topa	20.13
11	Rawal Town	26.69
12	Fateh Jhang-A	27.92
13	Fateh Jhang-B	26.21
14	EME College-A	28.8
15	EME College-B	24.89
16	Jhangi Syedan	22.39

Plasticity Indices were calculated by subtracting the Plastic Limits and Liquid Limits obtained from Fall Cone Method.

$$PI = LL_f - PL_f \qquad (4.1)$$

The results are given in table 4.9.

Table 4.9: Plasticity Index values as determined from Fall Cone Method

S. No.	Name of Soil/Sample	Plasticity Index Values (PI_f)
1	Fateh Jhang	9.06
2	Nandipur	18.86
3	Nandipur+25 percent Bentonite	58.71
4	Swabi	9.33
5	Mardan	8.2
6	G-5 Sector Isb.	4.19
7	Nilore	6.88
8	Kahuta-A	2.99
9	Kahuta-B	7.46
10	Upper Topa	9.87
11	Rawal Town	1.31
12	Fateh Jhang-A	4.58
13	Fateh Jhang-B	2.29
14	EME College-A	9.2
15	EME College-B	13.11
16	Jhangi Syedan	4.61

The Undrained Shear strength was calculated by the equation given by Hansbo (1957) as discussed early in section 3.7.3. The value of "k" used was 0.29, according to Wood (1990), for the cone angle of 30 degree. In this study the field density and moisture content was not known. Typical values of optimum moisture content (OMC), and maximum dry density were taken from literature and at 95 percent of OMC and max dry density remolded samples were made. The results are given in table 4.10.

Table 4.10: Undrained Shear strength values as determined from Fall Cone Method

S. No.	Name of Soil/Sample	Undrained Shear strength values $C_{u\ (Fall\ Cone)}$ (Psf)
1	Fateh Jhang	1233.56
2	Nandipur	1899.41
3	Nandipur+25 percent Bentonite	1743.36
4	Swabi	2077.39
5	Mardan	957.07
6	G-5 Sector Isb.	2356.41
7	Nilore	1695.60
8	Kahuta-A	1137.92
9	Kahuta-B	1464.91
10	Upper Topa	967.07
11	Rawal Town	1248.21
12	Fateh Jhang-A	1030.47
13	Fateh Jhang-B	998.01
14	EME College-A	947.23
15	EME College-B	1325.48
16	Jhangi Syedan	771.23

4.6 COMPARISON OF TEST RESULTS AND ESTABLISHMENT OF CO-RELATIONS

The results obtained were compared and co relations were established as follow:

4.6.1 Liquid Limit

The comparison of Liquid Limit values from Casagrande's Method and Fall Cone Method shows a maximum difference of 32.36 percent and a minimum difference of 10 percent with an average difference of 18.29 percent except for sample No.3 that is, Nandipur + 25 percent Bentonite, which shows a difference of 53.64 percent. As reported in literature, Liquid Limit determined by Fall Cone Method is higher than Liquid Limit determined by Casagrande Method. This is further confirmed by results of current study. Moreover high difference for sample number three is in accordance with data reported by Dragoni *et al.* (2008) which shows, for Liquid Limit values above 50 percent, scatter between values determined from both methods increases.

Table 4.11: Comparison of Liquid Limit values

S. No.	Name of Soil/Sample	Liquid Limit Values		Difference	Difference (percent)
		Casagrande (LL_c)	Fall Cone (LL_f)		
1	Fateh Jhang	32.4	47.9	15.5	32.36
2	Nandipur	47.2	53.7	6.5	12.10
3	Nandipur+25 percent Bentonite	64.9	140	75.1	53.64
4	Swabi	47.7	55.7	8	14.36
5	Mardan	24.2	29	4.8	16.55
6	G-5 Sector Isb.	27.4	31.5	4.1	13.02
7	Nilore	21	26	5	19.23
8	Kahuta-A	22.3	27	4.7	17.41
9	Kahuta-B	21.8	29	7.2	24.83
10	Upper Topa	26.2	30	3.8	12.67
11	Rawal Town	24.3	29	4.7	16.21
12	Fateh Jhang-A	25.9	32	6.1	19.06
13	Fateh Jhang-B	26.1	29	2.9	10.00
14	EME College-A	30.5	39	8.5	21.79
15	EME College-B	26.6	38	11.4	30.00
16	Jhangi Syedan	23	27	4	14.81

The co-relations established using Microsoft excel are given in table 4.12.

Table 4.12: Co relations of Liquid Limit

Type of Relation	Equation	R^2 Value
Exponential	$LL_f = 12.855e^{0.0344\ LL_c}$	0.93
Linear	$LL_f = 2.116\ LL_c – 23.513$	0.84
Logarithmic	$LL_f = 75.09\ln(x) - 211.5$	0.75
Polynomial (2nd order)	$LL_f = 0.0649\ LL_c^{\ 2} - 3.2079\ LL_c + 69.86$	0.95
Power	$LL_f = 0.5163\ LL_c^{\ 1.2676}$	0.89

The graphical representation of the Liquid Limit values is shown in figure 4.8. For the purpose of comparison and to make it similar, with previous studies, only linear relation was used.

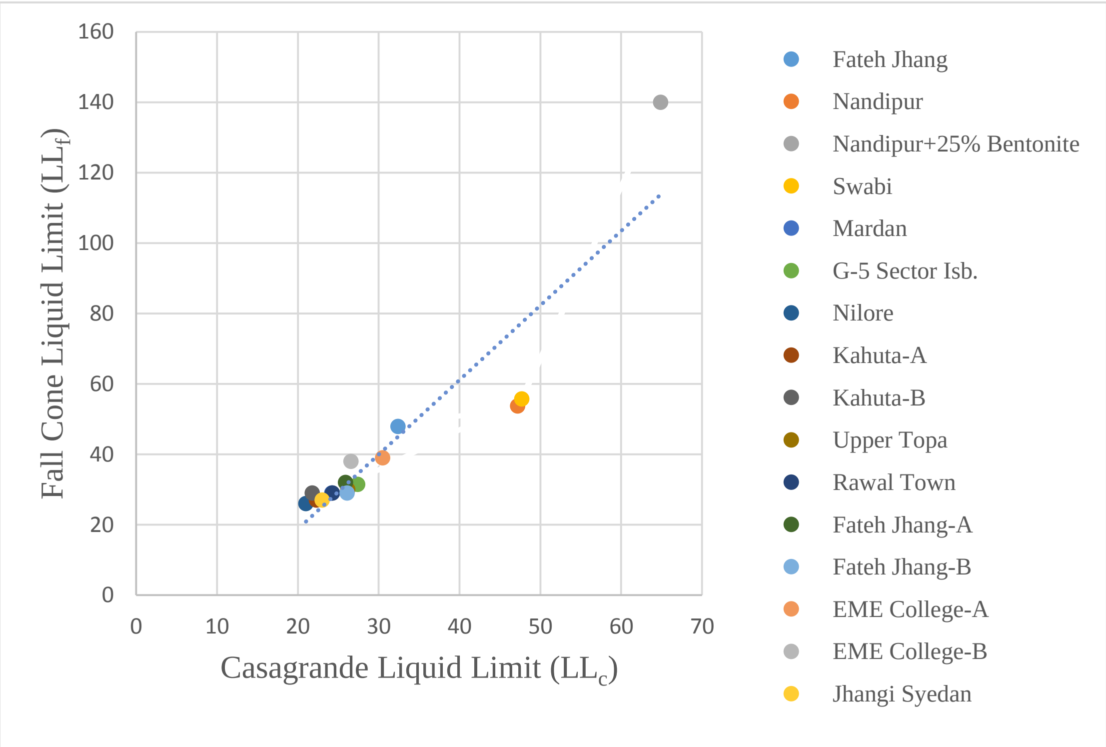

Figure 4.7: Graph showing values of Liquid Limit obtained from Casagrande Method and Fall Cone Method

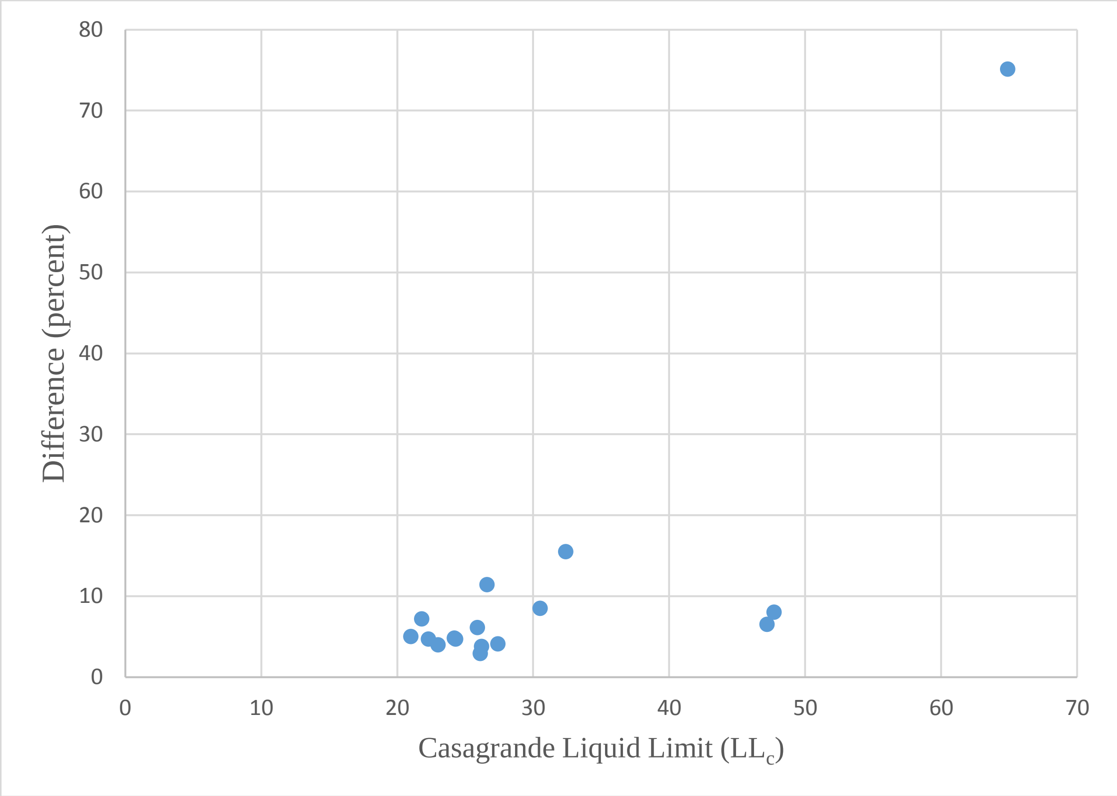

Figure 4.8: Difference between calculated Liquid Limit values using both methods

Sridharan and Prakash (1998) has reported that the dominant clay mineral type and its proportion in the clay content are responsible for the deviations between the results obtained from the Fall Cone and Casagrande Methods. Di Matteo (2012) has studied 100 different soil samples (6 from his own study and 94 soils from previous different studies) with Liquid Limit varying between 20-50 percent and observed a difference of up to 5 percent. The difference in values of Liquid Limits can be regarded to behavior of soils under different methods of deformation in both methods (Budhu, 1985). Another possible reason is stated by Sridharan and Prakash (2000) is that shear strength of soil at Liquid Limit comprises of two parts. One is called Viscous Shear resistance and other is called Frictional Shear resistance. They further stated that it is impossible to measure them simultaneously. The Casagrande Method is good in measurement of Viscous Shear while the Fall Cone Method is good for the measurement of Frictional Shear.

The following figure shows comparison of Liquid Limit values predicted using the co-relation (linear) established vs actual values of Liquid Limit using Casagrande Method.

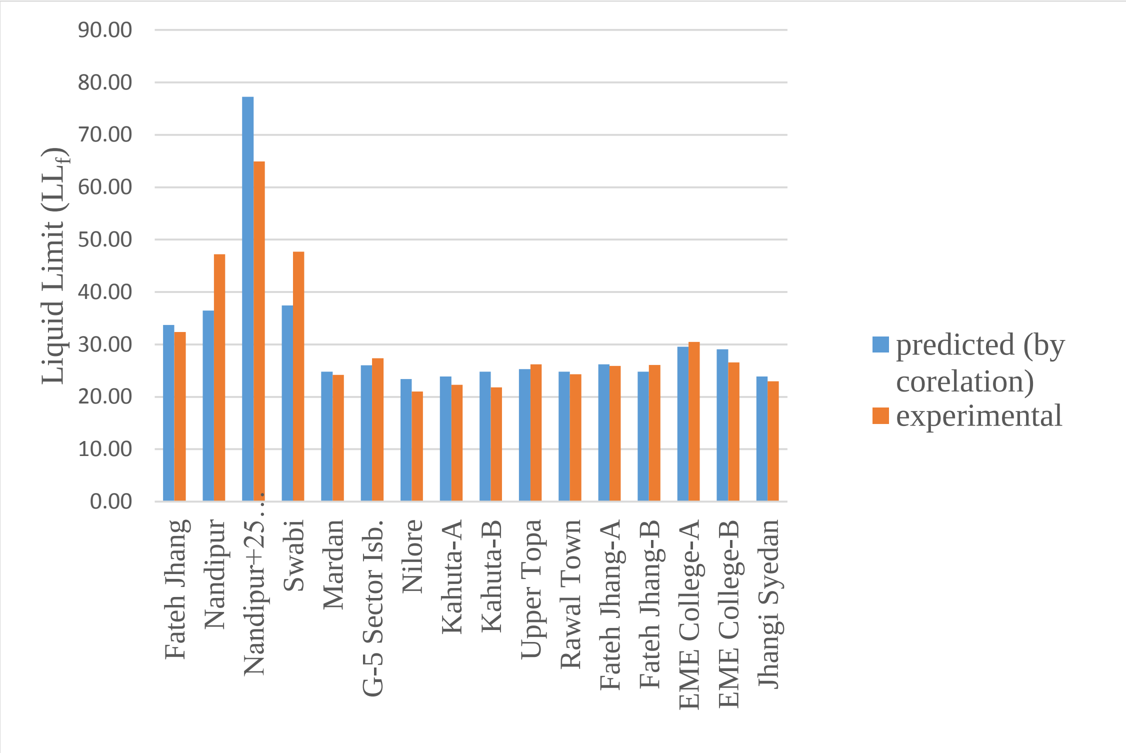

Figure 4.9: Comparison of Liquid Limit values (predicted by co-relation (linear) vs experimental)

The tabular representation of the data of above figure is given in table 4.13.

Table 4.13: Values of Liquid Limit (predicted by co-relation (linear) vs experimental)

S. No.	Name of Soil/Sample	Liquid Limit Values		Difference (percent)
		Predicted by co-relation $LL_{f\ (predicted)}$	Experimental $LL_{c\ (experimental)}$	
1	Fateh Jhang	33.75	32.4	4.00
2	Nandipur	36.49	47.2	-29.35
3	Nandipur+25 percent Bentonite	77.27	64.9	16.01
4	Swabi	37.44	47.7	-27.42
5	Mardan	24.82	24.2	2.49
6	G-5 Sector Isb.	26.00	27.4	-5.39
7	Nilore	23.40	21	10.25
8	Kahuta-A	23.87	22.3	6.58
9	Kahuta-B	24.82	21.8	12.16
10	Upper Topa	25.29	26.2	-3.60
11	Rawal Town	24.82	24.3	2.08
12	Fateh Jhang-A	26.23	25.9	1.28
13	Fateh Jhang-B	24.82	26.1	-5.17
14	EME College-A	29.54	30.5	-3.24
15	EME College-B	29.07	26.6	8.50
16	Jhangi Syedan	23.87	23	3.65

4.6.2 Plastic Limit

The table showing comparison of Plastic Limit values determined from both methods is given in table 4.14. An average difference of 15.17 percent between Plastic Limit values from both methods is observed.

Table 4.14: Comparison of Plastic Limit values

S. No.	Name of Soil/Sample	Plastic Limit Values		Difference	Difference (percent)
		Casagrande (PL_c)	Fall Cone (PL_f)		
1	Fateh Jhang	24.1	31	6.9	22.26
2	Nandipur	23.53	42	18.47	43.98
3	Nandipur+25 percent Bentonite	23.44	30	6.56	21.87
4	Swabi	35	36	1	2.78
5	Mardan	19.35	18	-1.35	-7.50
6	G-5 Sector Isb.	20	18	-2	-11.11
7	Nilore	7.61	19.5	11.89	60.97
8	Kahuta-A	19.18	19.4	0.22	1.13
9	Kahuta-B	16.22	21	4.78	22.76
10	Upper Topa	17.17	20.2	3.03	15.00
11	Rawal Town	18.75	19	0.25	1.32
12	Fateh Jhang-A	16.25	21	4.75	22.62
13	Fateh Jhang-B	16.88	19	2.12	11.16
14	EME College-A	19.12	21	1.88	8.95
15	EME College-B	18.99	24.5	5.51	22.49
16	Jhangi Syedan	16.3	17	0.7	4.12

The difference between Plastic Limit values obtained from both methods varies from a maximum of 18 points to a minimum of 0.2 with an average difference of 4 points. The reason for this variation can be attributed to variation of clay content, difference in nature of tests and most likely due to human error. This difference can be further reduced by performing experiment with more care and under more controlled conditions. For example the soil samples become hard and stiff near Plastic Limit and are difficult to mix, moreover during the process of transferring the soil sample into cup there are chances that air is entrapped. To overcome this, Feng (2000) suggested to use rings instead of cup with same dimensions as that of cup. This will possibly reduce the variation between two methods. The following co-relations were established.

Table 4.15: Co relations of Plastic Limit

Type of Relation	Equation	R^2 Value
Exponential	$PL_f = 11.72e^{0.0338\ PLc}$	0.49
Linear	$PL_f = 0.9084\ PL_c + 5.8305$	0.49
Logarithmic	$PL_f = 14.233\ln(PL_c) - 18.141$	0.36
Polynomial (2nd order)	$PL_f = 0.0157\ PL_c^{\ 2} + 0.2266\ PL_c + 12.688$	0.50
Power	$PL_f = 4.7977\ PL_c^{\ 0.5302}$	0.36

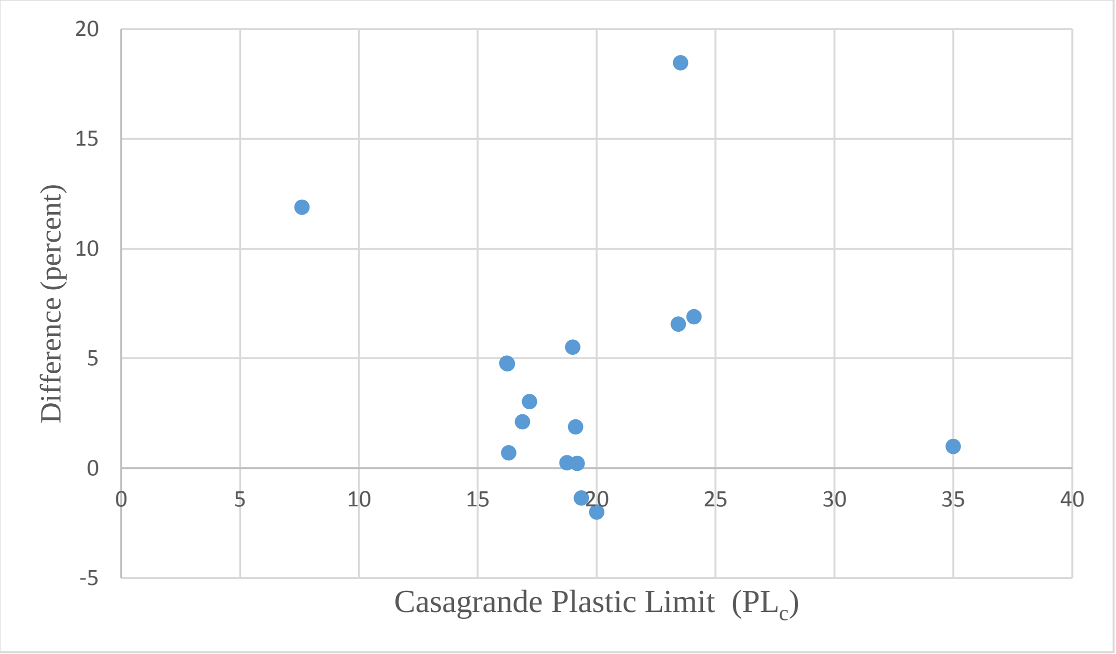

Figure 4.10: Difference between calculated Plastic Limit values using both methods

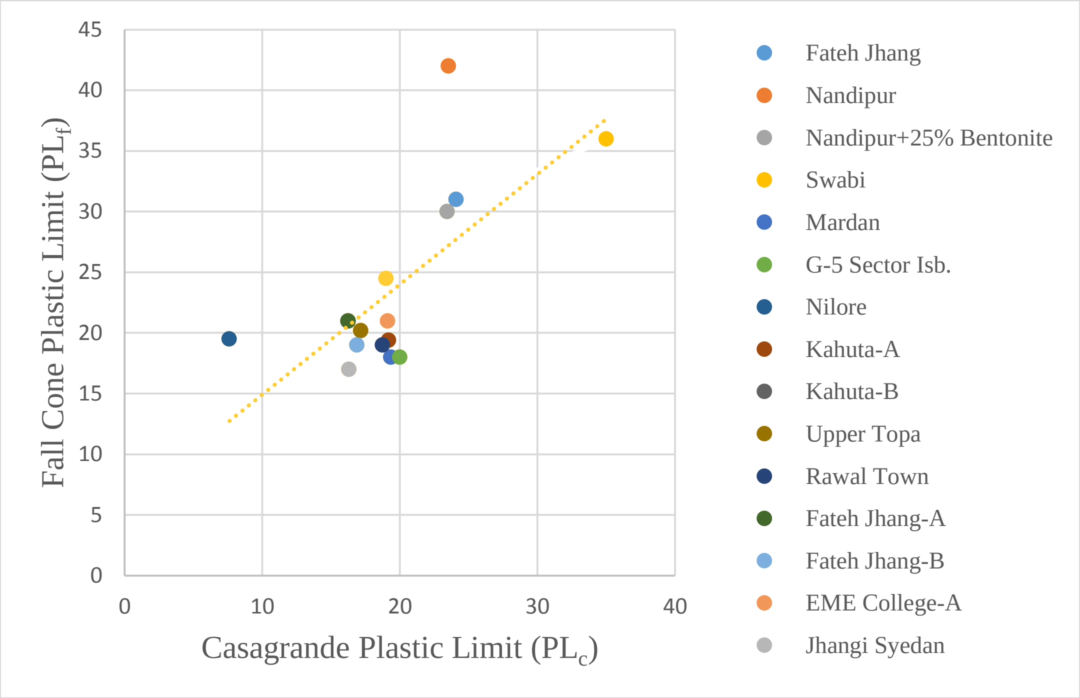

Figure 4.11: Graph showing Plastic Limit values obtained from Fall Cone and Thread forming method

For the purpose of comparison and similarity with previous studies only linear relation was used. For the current study, it can be seen from table 4.15, that no strong co relation exists between Plastic Limit values obtained from both methods. The following figure shows comparison of Plastic Limit values predicted using co-relation (linear) established vs the actual values of Plastic Limit using method of Thread formation:

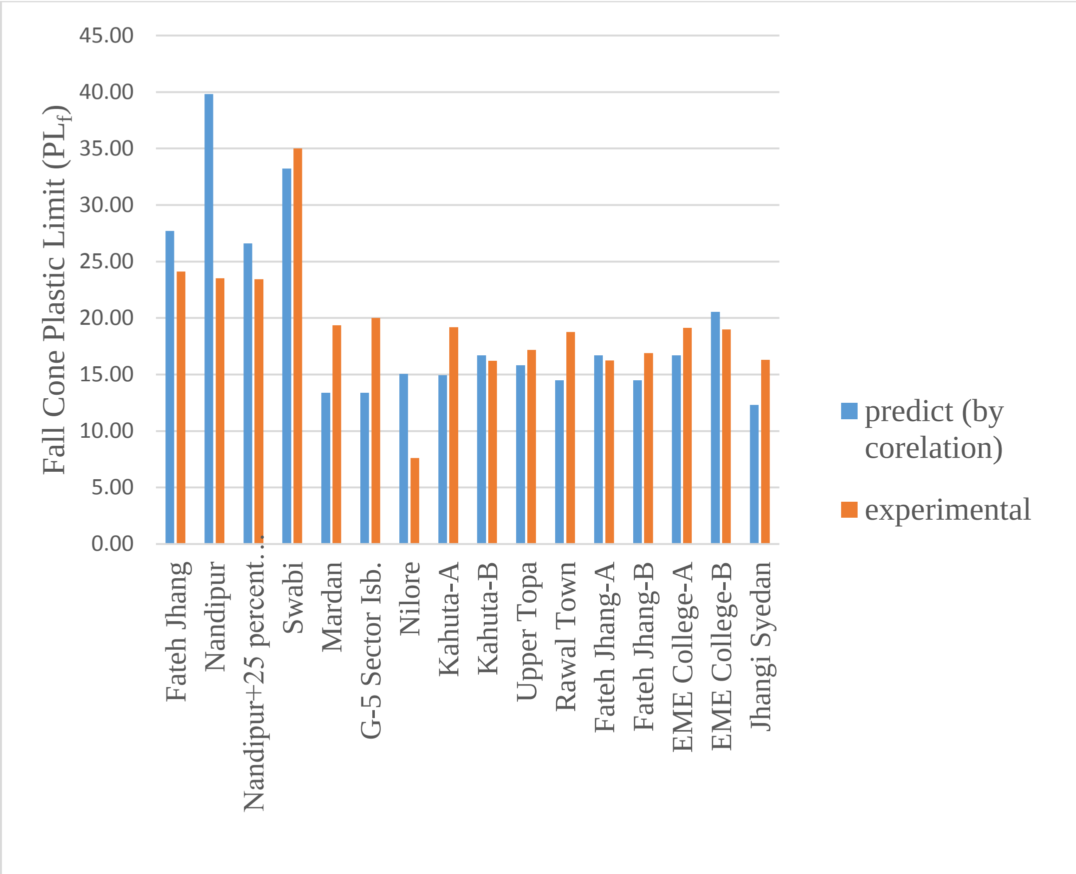

Figure 4.12: Comparison of Plastic Limit values (predicted by co-relation (linear) vs experimental)

The values of Plastic Limit obtained from Casagande Method and those obtained from co relation developed in this study were compared in table 4.16. A maximum difference of 49 percent and minimum difference of 2 percent was observed.

Table 4.16: Values of Plastic Limit (predicted by co-relation (linear) vs experimental)

S. No.	Name of Soil/Sample	Plastic Limit Values		Difference (percent)
		Predicted by co-relation $PL_{f\ (predicted)}$	Experimental $PL_{c\ (experimental)}$	
1	Fateh Jhang	27.71	24.1	13.02
2	Nandipur	39.82	23.53	40.90
3	Nandipur+25 percent Bentonite	26.61	23.44	11.90
4	Swabi	33.21	35	-5.38
5	Mardan	13.40	19.35	-44.44
6	G-5 Sector Isb.	13.40	20	-49.29
7	Nilore	15.05	7.61	49.43
8	Kahuta-A	14.94	19.18	-28.40
9	Kahuta-B	16.70	16.22	2.87
10	Upper Topa	15.82	17.17	-8.54
11	Rawal Town	14.50	18.75	-29.33
12	Fateh Jhang-A	16.70	16.25	2.69
13	Fateh Jhang-B	14.50	16.88	-16.43
14	EME College-A	16.70	19.12	-14.50
15	EME College-B	20.55	18.99	7.60
16	Jhangi Syedan	12.30	16.3	-32.57

4.6.3 Plasticity Index

The comparison of Plasticity Index values from both methods was done. An average difference of 19.7 percent between the Plastic Indices from both methods was observed.

The comparison of Plasticity Index values determined from both methods is given in table 4.17 and the co-relations established are given in table 4.18.

Table 4.17: Comparison of Plasticity Index values

S. No.	Name of Soil/Sample	Plasticity Index Values		Difference	Difference (percent)
		Casagrande (PI_c)	Fall Cone (PI_f)		
1	Fateh Jhang	8.3	16.9	8.6	50.89
2	Nandipur	23.67	11.7	-11.97	-102.31
3	Nandipur+25 percent Bentonite	41.46	110	68.54	62.31
4	Swabi	12.7	19.7	7	35.53
5	Mardan	4.85	11	6.15	55.91
6	G-5 Sector Isb.	7.4	13.5	6.1	45.19
7	Nilore	13.39	6.5	-6.89	-106.00
8	Kahuta-A	3.12	7.6	4.48	58.95
9	Kahuta-B	5.58	8	2.42	30.25
10	Upper Topa	9.03	9.8	0.77	7.86
11	Rawal Town	5.55	10	4.45	44.50
12	Fateh Jhang-A	9.65	11	1.35	12.27
13	Fateh Jhang-B	9.22	10	0.78	7.80
14	EME College-A	11.38	18	6.62	36.78
15	EME College-B	7.61	13.5	5.89	43.63
16	Jhangi Syedan	6.7	10	3.3	33.00

Table 4.18: Co relations of Plasticity Index

Type of Relation	Equation	R^2 Value
Exponential	$PI_f = 6.9283e^{0.056\ PIc}$	0.65
Linear	$PI_f = 2.3049PI_c – 7.9244$	0.75
Logarithmic	$PI_f = 27.546\ln(PI_c) - 42.9$	0.47
Polynomial (2nd order)	$PI_f = 0.1039\ PI_c^{\ 2} - 2.2562\ PI_c + 21.645$	0.93
Power	$PI_f = 2.6142\ PI_c^{\ 0.7258}$	0.48

A graph showing comparison of Plasticity Index values obtained from Fall Cone and Thread rolling method is shown in figure 4.16 and the difference between both methods is also shown graphically in figure 4.17.

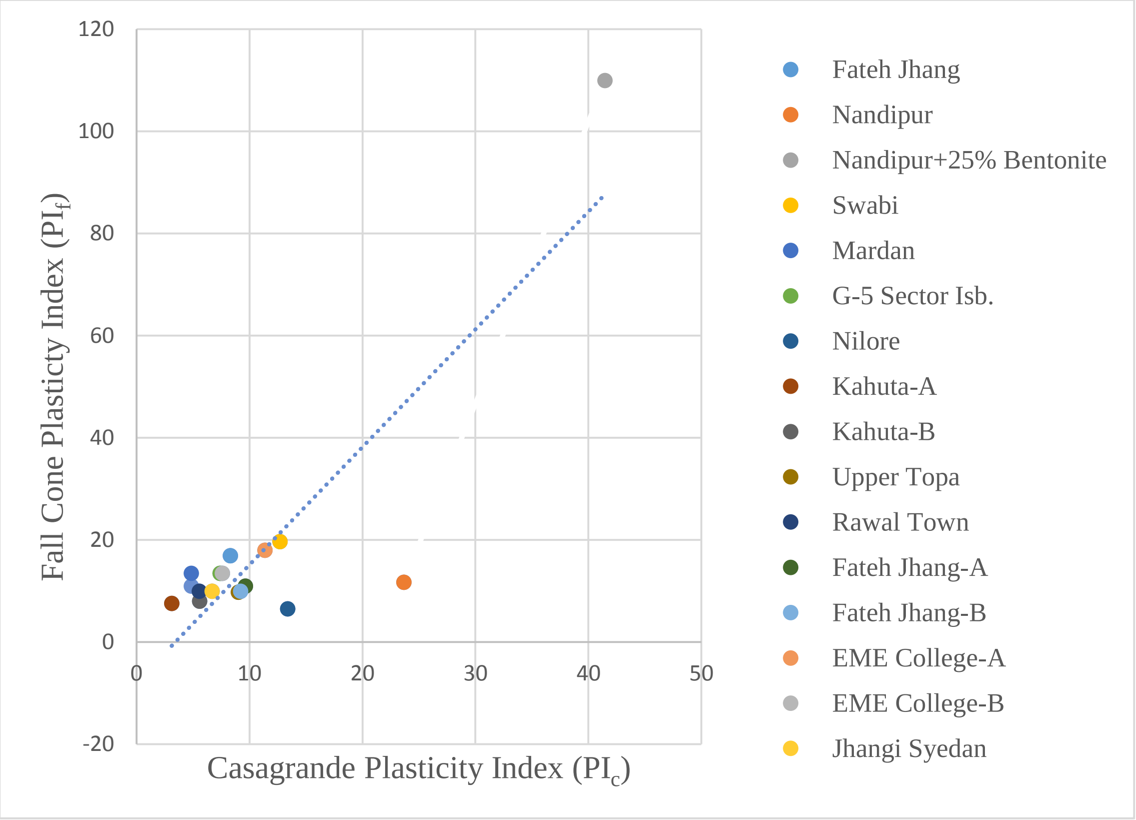

Figure 4.13: Graph showing Plasticity Index values obtained from conventional and Fall Cone Method

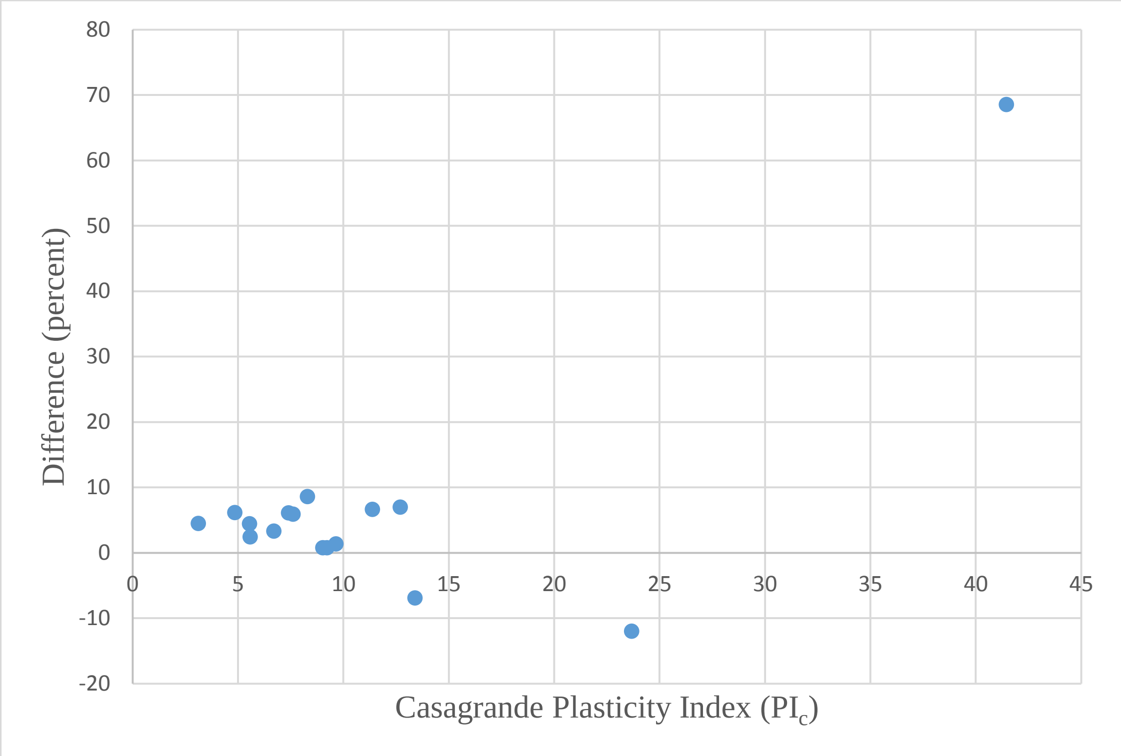

Figure 4.14: Difference between calculated Plasticity Index values using both methods

A comparison between Plastic Index values obtained from conventional methods and values obtained from the co relation predicted in this study was made. The tabular representation of the comparison is as following:

Table 4.19: Values of Plasticity Index (predicted by co-relation (linear) vs experimental).

S. No.	Name of Soil/Sample	Plasticity Index Values		Difference (percent)
		Predicted by co-relation $PI_{f\ (predicted)}$	Experimental $PI_{c\ (experimental)}$	
1	Fateh Jhang	10.77	8.3	22.94
2	Nandipur	8.51	23.67	-178.01
3	Nandipur+25 percent Bentonite	51.16	41.46	18.96
4	Swabi	11.99	12.7	-5.97
5	Mardan	8.21	4.85	40.93
6	G-5 Sector Isb.	9.30	7.4	20.39
7	Nilore	6.26	13.39	-113.96
8	Kahuta-A	6.74	3.12	53.68
9	Kahuta-B	6.91	5.58	19.23
10	Upper Topa	7.69	9.03	-17.43
11	Rawal Town	7.78	5.55	28.63
12	Fateh Jhang-A	8.21	9.65	-17.53
13	Fateh Jhang-B	7.78	9.22	-18.56
14	EME College-A	11.25	11.38	-1.18
15	EME College-B	9.30	7.61	18.13
16	Jhangi Syedan	7.78	6.7	13.84

The figure 4.16 shows comparison of Plasticity Index values predicted using the co-relation established vs the actual values of Plasticity Index using method of Thread formation.

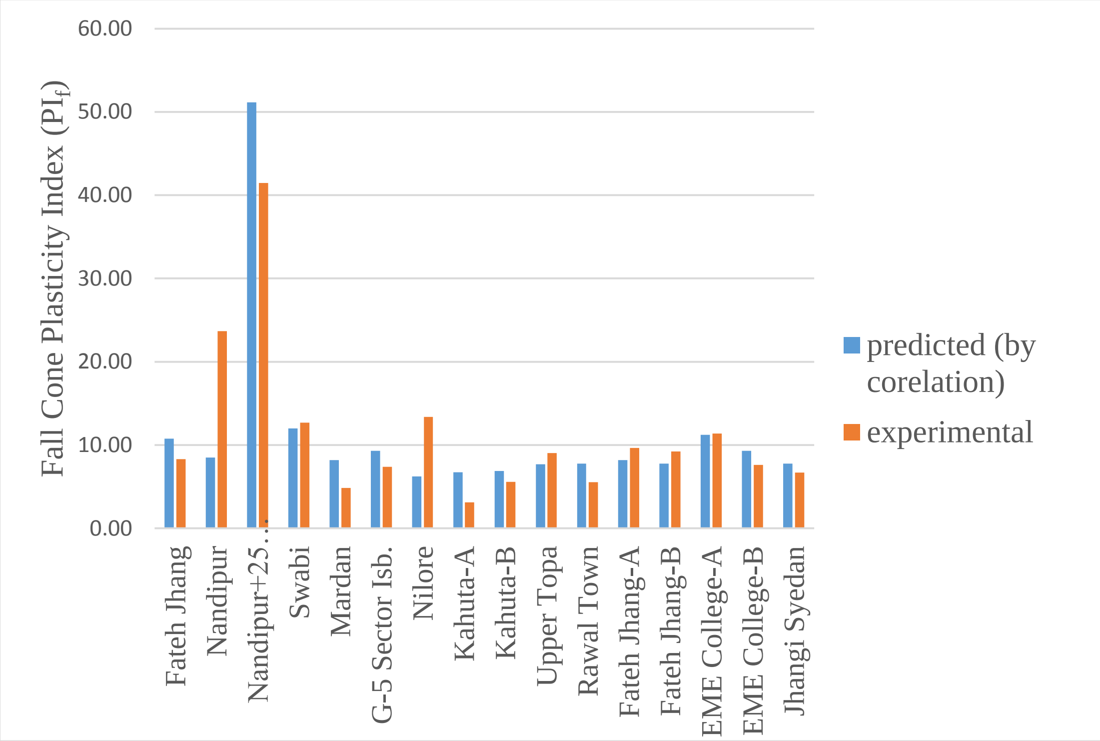

Figure 4.15: Comparison of Plasticity Index values (predicted by co-relation (linear) vs experimental)

4.6.4 Undrained Shear Strength

The values of Undrained Shear strength from Unconfined Compression test and Fall Cone Penetrometer test were compared and following co-relations were established.

Table 4.20: Co relations of Undrained Shear strength

Type of Relation	Equation	R^2 Value
Exponential	$C_{u\ (Fall\ Cone)} = 745.67e^{0.0009\ Cu\ (Unconfined)}$	0.77
Linear	$C_{u\ (Fall\ Cone)} = 1.7567C_{u\ (Unconfined)} + 232.8$	0.76
Logarithmic	$C_{u\ (Fall\ Cone)} = 1658.9\ln(C_{u\ (Unconfined)}) - 9386.3$	0.77
Polynomial (2nd order)	$C_{u\ (Fall\ Cone)} = -0.0009\ C_{u\ (Unconfined)}^2 + 3.6613\ C_{u\ (Unconfined)} - 655.23$	0.79
Power	$C_{u\ (Fall\ Cone)} = 4.0345\ C_{u\ (Unconfined)}^{0.8972}$	0.81

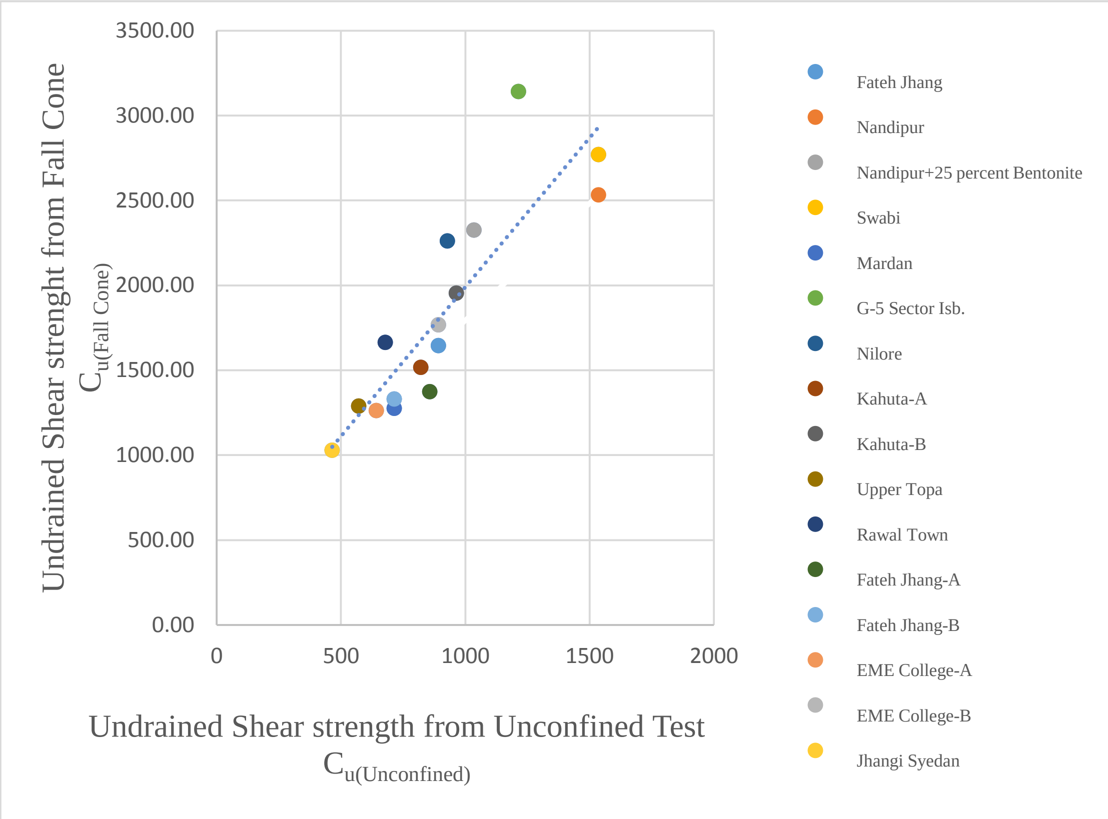

Figure 4.16: Graph showing values of Undrained Shear strength obtained from Fall Cone and Unconfined Compression test

It can be seen that the difference between Undrained Shear strength values obtained from both methods is very large. The average ratio (Cu (Unconfined)/Cu (Fall Cone)) is found to be 0.50. One possible reason for this large difference is that in Unconfined Compression test the sample is not confined while in case of Fall Cone test the sample is confined. According to Tanaka *et al*. (2012), one possible reason for the large value of this ratio is quality of sample. They further stated that this ratio and hence the difference between values of Undrained Shear strength can be decreased by improving quality of sample because unconfined compression test is directly related to sample quality. In his study, Tanaka *et al*. (2012) have observed the ratio (C_u (Unconfined)/C_u (Fall Cone)) as high as 0.85. Westerberg *et al*. (2015) suggested that a correction factor of 0.65 should be applied to the Undrained Shear strength values obtained from Fall Cone Method.

The comparison between the Undrained Shear strength values obtained from both methods in tabular form is given in table 4.17.

Table 4.21: Comparison of Undrained Shear strength values

S. No.	Name of Soil/Sample	Undrained shear strength using unconfined compressive strength (Psf)	Undrained shear strength using Fall Cone penetrometer (Psf)	Difference	Difference (percent)
1	Fateh Jhang	892.98	1644.76	751.78	45.71
2	Nandipur	1535.92	2532.55	996.63	39.35
3	Nandipur+25 percent Bentonite	1035.85	2324.49	1288.64	55.44
4	Swabi	1535.92	2769.86	1233.94	44.55
5	Mardan	714.38	1276.10	561.72	44.02
6	G-5 Sector Isb.	1214.45	3141.88	1927.43	61.35
7	Nilore	928.69	2260.81	1332.12	58.92
8	Kahuta-A	821.54	1517.24	695.70	45.85
9	Kahuta-B	964.41	1953.22	988.81	50.62
10	Upper Topa	571.5	1289.43	717.93	55.68
11	Rawal Town	678.66	1664.28	985.62	59.22
12	Fateh Jhang-A	857.26	1373.96	516.70	37.61
13	Fateh Jhang-B	714.38	1330.69	616.31	46.31
14	EME College-A	642.94	1262.98	620.04	49.09
15	EME College-B	892.98	1767.31	874.33	49.47
16	Jhangi Syedan	464.35	1028.31	563.96	54.84

The following figure shows the graphical comparison of Undrained Shear strength values predicted using the co-relation (linear) established vs actual values of Undrained Shear strength obtained using Unconfined Compression test.

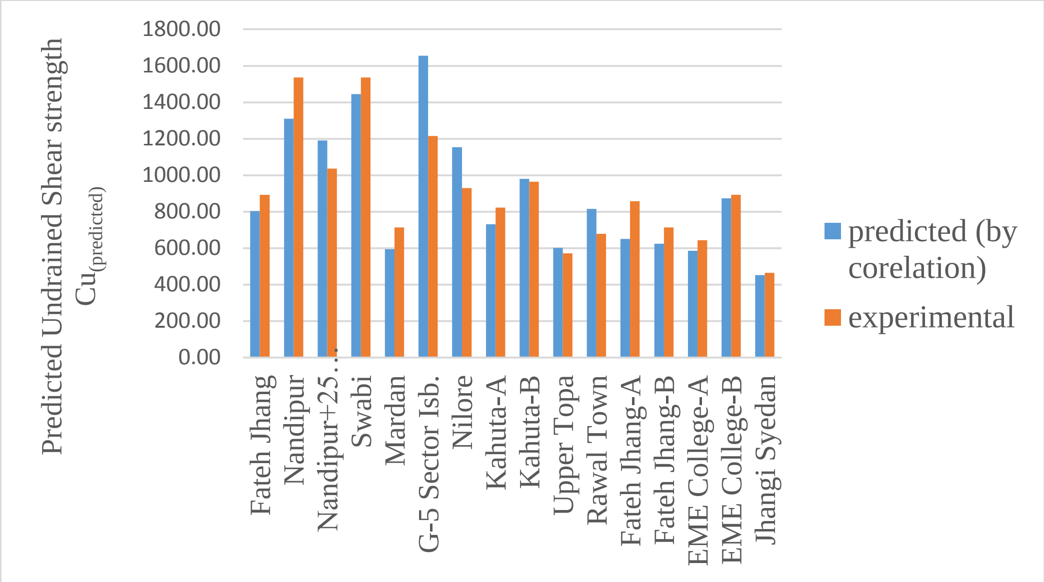

Figure 4.17: Comparison of Undrained Shear strength values (predicted by co relation (linear) vs experimental)

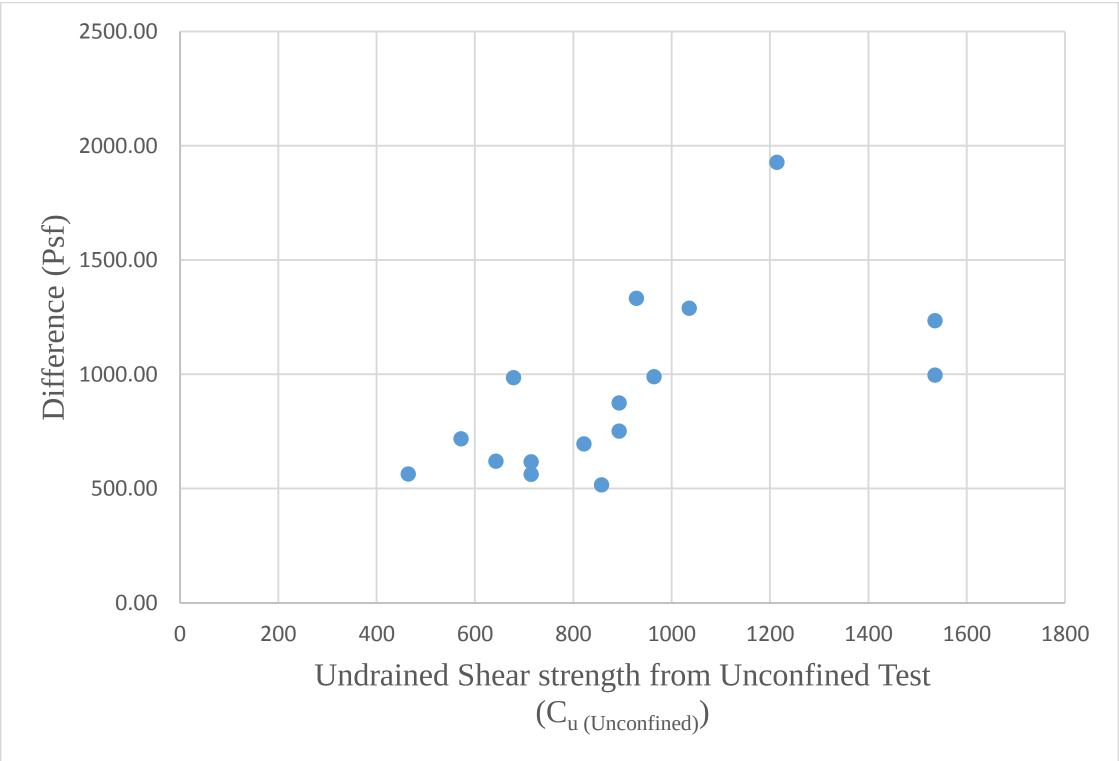

Figure 4.18: Difference between Undrained Shear strength values using both methods

Table 4.22: Values of Undrained Shear strength (predicted by co-relation (linear) vs experimental)

S. No.	Name of Soil/Sample	Undrained Shear Strength Values		Difference (percent)
		Predicted by co-relation ($Cu_{(predicted)}$)	Experimental ($C_{u(Unconfined)}$)	
1	Fateh Jhang	803.76	892.98	9.99
2	Nandipur	1309.13	1535.92	14.77
3	Nandipur+25 percent Bentonite	1190.69	1035.85	-14.95
4	Swabi	1444.22	1535.92	5.97
5	Mardan	593.90	714.38	16.87
6	G-5 Sector Isb.	1655.99	1214.45	-36.36
7	Nilore	1154.44	928.69	-24.31
8	Kahuta-A	731.16	821.54	11.00
9	Kahuta-B	979.35	964.41	-1.55
10	Upper Topa	601.48	571.5	-5.25
11	Rawal Town	814.87	678.66	-20.07
12	Fateh Jhang-A	649.60	857.26	24.22
13	Fateh Jhang-B	624.97	714.38	12.52
14	EME College-A	586.43	642.94	8.79
15	EME College-B	873.52	892.98	2.18
16	Jhangi Syedan	452.84	464.35	2.48

4.7 ESTABLISHED CO-RELATIONS IN PREVIOUS STUDIES

4.7.1 Co-relations of Liquid Limit

Several authors have published co-relations between Liquid Limit determined from Fall Cone and Casagrande Method (Campbell, 1975; Belviso *et al.*, 1985; Wasti and Bezirci, 1986; Feng, 2001; Dragoni *et al.*, 2008; Fojtova *et al.*, 2009; Ozer, 2009). The results are shown below:

Table 4.23: Empirical co-relations from literature between Liquid Limit determined from Casagrande's Method and Fall Cone Method

Reference	No. of Samples	Location of Soil Samples	Empirical Relationship
Belviso *et al.* (1985)	16	Southern Italian, natural soils	$LL_{cone} = 0.97\,LL_{cup} + 1.19$
Wasti and Bezirci (1986)	15	Various locations in Turkey, natural soils	$LL_{cone} = 1.01\,LL_{cup} + 4.92$
Feng (2001)	70	Various locations in Taiwan, natural soils.	$LL_{cone} = 0.94\,LL_{cup} + 2.6$
Dragoni *et al.* (2008)	41	Clayey soils from Central Italy	$LL_{cone} = 1.02\,LL_{cup} + 2.87$
Ozer (2009)	32	Various locations in Turkey, natural soils	$LL_{cone} = 0.90\,LL_{cup} + 6.04$
Fojtova´ *et al.* (2009)	52	Ostrava Basin, Czek Republic	$LL_{cone} = 1.00\,LL_{cup} + 2.44$
Di Matteo (2012)	6 + data base from other researches.	South Italy, natural soils.	$LL_{cone} = 1.00\,LL_{cup} + 2.20$

In order to compare the results of present study with the already developed co relations in literature and to verify the results of this study, the Liquid Limit values obtained by using above co relations and co relation developed in this study were compared. It can be observed that except for sample No.2 and 3 which have Liquid Limit values near and above 50 percent all other values are in good agreement with previous studies. The reason for deviation of sample number 2 and sample number 3 can be linked with their high swell potential and type of mineral present in them. The comparison is shown in table 4.20.

Table 4.24: Values of Liquid Limit obtained using co relations from current study and previous studies

S. No.	Name of Soil/Sample	Liquid Limit Values (LL_c)	Liquid Limit Values (LL_f)							
			Belviso et al. (1985)	Wasti & Bezirci (1986)	Feng (2001)	Dragoni et al. (2008)	Ozer (2009)	Fojtova´ et al. (2009)	Di Matteo (2012)	Current study
1	Fateh Jhang	32.4	32.6	37.6	33.1	35.9	35.2	34.8	34.6	45.0
2	Nandipur	47.2	47.0	52.6	47.0	51.0	48.5	49.6	49.4	76.4
3	Nandipur+25 percent Bentonite	64.9	64.1	70.5	63.6	69.1	64.5	67.3	67.1	113
4	Swabi	47.7	47.5	53.1	47.4	51.5	49.0	50.1	49.9	77.4
5	Mardan	24.2	24.7	29.4	25.3	27.6	27.8	26.6	26.4	27.7
6	G-5 Sector Isb.	27.4	27.8	32.6	28.4	30.8	30.7	29.8	29.6	34.5
7	Nilore	21	21.6	26.1	22.3	24.3	24.9	23.4	23.2	20.9
8	Kahuta-A	22.3	22.8	27.4	23.6	25.6	26.1	24.7	24.5	23.7
9	Kahuta-B	21.8	22.3	26.9	23.1	25.1	25.7	24.2	24.0	22.6
10	Upper Topa	26.2	26.6	31.4	27.2	29.6	29.6	28.6	28.4	31.9
11	Rawal Town	24.3	24.8	29.5	25.4	27.7	27.9	26.7	26.5	27.9
12	Fateh Jhang-A	25.9	26.3	31.1	26.9	29.3	29.4	28.3	28.1	31.3
13	Fateh Jhang-B	26.1	26.5	31.3	27.1	29.5	29.5	28.5	28.3	31.7
14	EME College-A	30.5	30.8	35.7	31.3	34.0	33.5	32.9	32.7	41.0
15	EME College-B	26.6	27.0	31.8	27.6	30.0	30.0	29.0	28.8	32.8
16	Jhangi Syedan	23	23.5	28.2	24.2	26.3	26.7	25.4	25.2	25.2

As discussed earlier, it can be observed from above table that the Liquid Limit values obtained from Fall Cone Method are always higher as compared to Liquid Limit values obtained from Casagrande's Method. The values obtained from different co-relations from literature and co-relation established in this study are comparable, except for the soils having Liquid Limit above 30, indicating the validity of co-relation established for soils having Liquid Limit less than and equal to 30.

The results of the above table are shown graphically in the following figure:

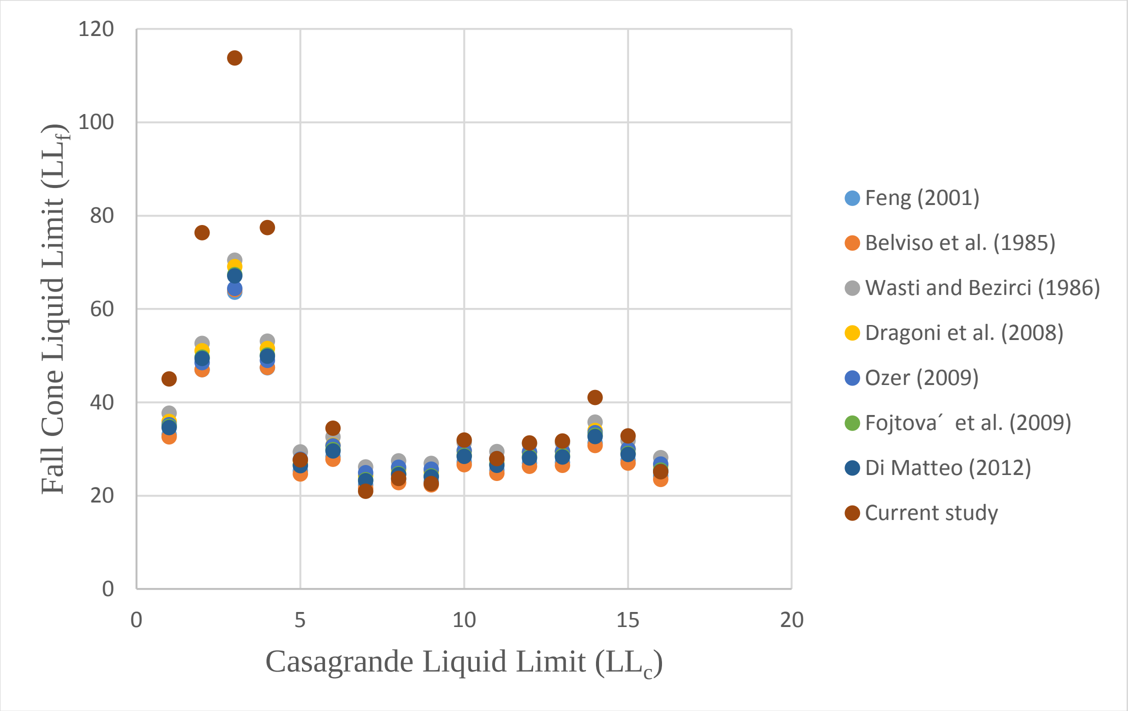

Figure 4.19: Comparison of Liquid Limit values using previous co-relations and current study

4.7.2 Co-relations of Plastic Limit

Yildiz Wasti (1987) studied 15 natural soils from different sites in Turkey and l0 artificial soil samples that were obtained by mixing bentonite and natural soils in various proportions. He presented the following co relation between plastic limits obtained from Fall Cone Method and conventional method of Thread formation.

$$PL_f = 0.765\ PL_c + 6.73 \quad (5.5)$$

Similarly Belviso *et al.* (1985) presented the following co relation between the Plastic Limits using both methods.

$$PL_f = 0.815\ PL_c + 6.42\ 9 \qquad (5.6)$$

Table 4.25: Values showing the Plastic Limit values from co relations from previous studies and current study

S. No.	Name of Soil/Sample	Plastic Limit Values (PL_c)	Plastic Limit Values (PL_f)		
			Belviso et al. (1985)	Yildiz Wasti (1987)	Current study
1	Fateh Jhang	24.1	25.17	26.06	27.72
2	Nandipur	23.53	24.73	25.60	27.21
3	Nandipur+25 percent Bentonite	23.44	24.66	25.52	27.12
4	Swabi	35	33.51	34.95	37.62
5	Mardan	19.35	21.53	22.19	23.41
6	G-5 Sector Isb.	20	22.03	22.72	24.00
7	Nilore	7.61	12.55	12.62	12.74
8	Kahuta-A	19.18	21.40	22.05	23.25
9	Kahuta-B	16.22	19.14	19.64	20.56
10	Upper Topa	17.17	19.87	20.41	21.43
11	Rawal Town	18.75	21.07	21.70	22.86
12	Fateh Jhang-A	16.25	19.16	19.66	20.59
13	Fateh Jhang-B	16.88	19.64	20.18	21.16
14	EME College-A	19.12	21.36	22.00	23.20
15	EME College-B	18.99	21.26	21.90	23.08
16	Jhangi Syedan	16.3	19.20	19.70	20.64

The graphical representation of above data is shown in following figure.

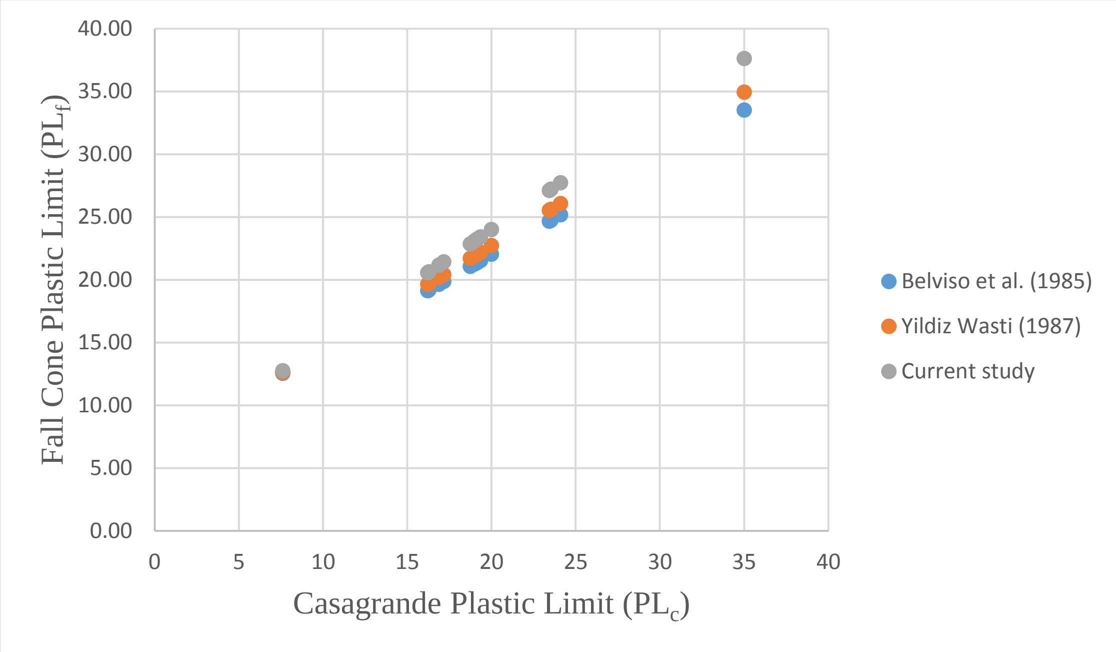

Figure 4.20: Comparison of Plastic Limit values (current study vs previous studies)

It can be seen that values obtained by co relation developed in this study are quite close to the already developed co relations.

4.8 SUMMARY

The Atterburg's limits and Undrained Shear strength were measured using conventional methods (Casagrande and Thread Rolling Method) and Unconfined Compression test. The co-relations then established are closely linked with already established co-relations in the literature. Using Fall Cone apparatus Liquid and Plastic limit, both, can be determined by performing single test and hence can save time and economy and gives more reliable values. For classification and other purposes corresponding values of Liquid and Plastic limit with conventional methods can be obtained using these co-relations, as many other co-relations and classification systems still base on Liquid and Plastic limit values obtained with conventional methods. The use of LL_f instead of LL_c in soil classifications for earthworks changes the suitability of that same soil, due to one of its conventional index properties. Alternatively, the LL_f

values should be converted to LL_c by using the appropriate equation (depending on the soil type) among those reported in the literature (Matteo *et al.*, 2015). Moreover Fall Cone apparatus can also be used to get a quick and reliable estimate of Undrained Shear strength, cheaply and quickly, which can be used for preliminary design purposes. But this Undrained Shear strength is no replacement of shear strength obtained from Triaxial or any other method.

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL

A comparative study was carried out to find the relation between Liquid Limit, Plastic Limit, Plastic Index and Undrained Shear strength determined using conventional methods and Fall Cone Method. After comparing the results critically with the previous studies following conclusions and recommendations are made:

5.2 CONCLUSIONS

Major conclusions drawn from the present research study have been listed below:

1. The computed Liquid Limits and Plastic Limits are comparable with those determined from the conventional methods. Therefore, it is concluded that the Fall Cone Method can provide an alternative for a simple approach to determine both the Liquid Limit and Plastic Limit.
2. Canadian, British, Indian and Swedish standards have included Fall Cone Method for determination of the Liquid Limit. In Pakistan the use of Fall Cone Method is not widely used, especially for commercial purposes. The use of Fall Cone Method is hence appreciated.
3. It is also possible to determine both limits (Liquid and Plastic) from the same Fall Cone test. The Atterberg limits determined by two entirely different methods are not expected to correspond precisely but the existence of good correlations between the old and new methods is desirable from the practical

point of view, and the available experimental results suggest that this aspect is satisfied.

4. This study compared Liquid Limit values determined by Casagrande apparatus with those obtained with Fall Cone apparatus based on 16 natural soil samples from various localities. The results indicate that data from different sources may be compared consistently.
5. The Fall Cone apparatus presents a quick and economic way of determining the Atterberg limits.

5.3 RECOMMENDATIONS

Some of the recommendations for future research are as under:

1. Because of the time and scope constraints the number of samples is restricted to 16. The no. of samples tested should be increased to make a better comparison and to make stronger co-relation.
2. Because of unavailability of field density and field moisture content, remolded samples were made at 95 percent of optimum moisture content and max dry density values obtained from literature. It is recommended that actual field values should be used to obtain more precise results.
3. The Undrained Shear strength values are compared with values obtained from Unconfined Compression test. For better results it can be compared with the Undrained Shear strength obtained from Triaxial test.
4. For determination of Liquid Limit hand operated Casagrande apparatus was used. Similarly manually operated Fall Cone apparatus was used. For better results automatic and motorized apparatus can be used in further research.

5. There was no soil sample with plasticity index greater than 30. So it was not possible to compare the co relation of Undrained Shear strength obtained from this study with the co relation in literature. It is suggested to include soils with plasticity index greater than 30, so that comparison can be made.

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APPENDIX A

The results of Casagrande Liquid limit, Plastic limit and Plasticity Index are as follow:

Fateh Jhang Soil

No of blows	34	23	12	P.L
Can No	112	79	85	73
wt of empty can	12.1	11.4	11.8	12.1
wt of wet soil+ can	34.2	35.7	52.3	22.4
wt of dry can + soil	29.2	29.7	40.6	20.4
wt of soil	17.1	18.3	28.8	8.3
wt of water	5	6	11.7	2
Moisture Content	29.24	32.79	40.63	24.10
Liquid Limit LL	32.4			
Plastic Limit PL	24.10			
PI	8.3			

Nandipur Soil

No of blows	34	24	14	P.L
Can No	113	63	32	64
wt of empty can	14.1	12.7	11	12.9
wt of wet soil+ can	24.7	26.6	20.3	23.2
wt of dry can + soil	21.4	22.1	17.2	21.2
wt of soil	7.3	9.4	6.2	8.3
wt of water	3.3	4.5	3.1	2
Moisture Content	45.21	47.87	50.00	24.10
Liquid Limit LL	47.2			
Plastic Limit PL	24.10			
PI	23.1			

Nandipur+25 percent Bentonite

No of blows	31	22	17	P.L
Can No	111	136	135	140
wt of empty can	11.1	14.1	11.6	11.4
wt of wet soil+ can	39.2	44	55.8	19.3
wt of dry can + soil	28.5	32	37.5	17.8
wt of soil	17.4	17.9	25.9	6.4
wt of water	10.7	12	18.3	1.5
Moisture Content	61.49	67.04	70.66	23.44
Liquid Limit LL	64.9			
Plastic Limit PL	23.44			
PI	41.46			

Swabi Soil

No of blows	56	32	18	P.L
Can No	67	115	79	95
wt of empty can	11.4	13.1	11.3	12.3
wt of wet soil+ can	19.4	24.7	30.4	15
wt of dry can + soil	17	21	24.1	14.3
wt of soil	5.6	7.9	12.8	2
wt of water	2.4	3.7	6.3	0.7
Moisture Content	42.86	46.84	49.22	35.00
Liquid Limit LL	47.7			
Plastic Limit PL	35.00			
PI	12.7			

Mardan Soil

No of blows	41	24	10	P.L
Can No	85	119	86	120
wt of empty can	12	11.5	10.3	12.7
wt of wet soil+ can	42.79	40.51	53.28	27.5
wt of dry can + soil	38.39	34.21	42.48	25.1
wt of soil	26.39	22.71	32.18	12.4
wt of water	4.4	6.3	10.8	2.4
Moisture Content	16.67	27.74	33.56	19.35
Liquid Limit LL	24.2			
Plastic Limit PL	19.35			
PI	4.8			

G-5 Sector Isb

No of blows	37	26	17	P.L
Can No	11	25	10	28
wt of empty can	31.9	30.7	30.4	32.2
wt of wet soil+ can	46.25	58.13	74.35	40
wt of dry can + soil	43.25	52.23	64.65	38.7
wt of soil	11.35	21.53	34.25	6.5
wt of water	3	5.9	9.7	1.3
Moisture Content	26.43	27.40	28.32	20.00
Liquid Limit LL	27.4			
Plastic Limit PL	20.00			
PI	7.4			

Nilore Soil

No of blows	38	23	14	P.L
Can No	137	117	139	102
wt of empty can	11.6	12.4	12.8	11.2
wt of wet soil+ can	32.5	32.8	35.4	21.1
wt of dry can + soil	29.1	29.2	31.2	20.4
wt of soil	17.5	16.8	18.4	9.2
wt of water	3.4	3.6	4.2	0.7
Moisture Content	19.43	21.43	22.83	7.61
Liquid Limit LL	21			
Plastic Limit PL	7.61			
PI	13.4			

Kahuta-A

No of blows	39	26	11	P.L
Can No	71	100	82	84
wt of empty can	11.4	13.4	11.3	11.5
wt of wet soil+ can	26.1	29.4	47.7	20.2
wt of dry can + soil	23.6	26.6	40	18.8
wt of soil	12.2	13.2	28.7	7.3
wt of water	2.5	2.8	7.7	1.4
Moisture Content	20.49	21.21	26.83	19.18
Liquid Limit LL	22.3			
Plastic Limit PL	19.18			
PI	3.1			

Kahuta-B

No of blows	37	26	13	P.L
Can No	90	73	119	120
wt of empty can	13.2	12.2	11.4	12.6
wt of wet soil+ can	32.1	30.1	39.2	25.5
wt of dry can + soil	28.9	26.9	33.8	23.7
wt of soil	15.7	14.7	22.4	11.1
wt of water	3.2	3.2	5.4	1.8
Moisture Content	20.38	21.77	24.11	16.22
Liquid Limit LL	21.8			
Plastic Limit PL	16.22			
PI	5.6			

Upper Topa Soil

No of blows	38	26	14	P.L
Can No	64	114	104	110
wt of empty can	11.1	14.3	13.1	12.4
wt of wet soil+ can	30.1	32.7	37.5	24
wt of dry can + soil	26.4	28.8	32.2	22.3
wt of soil	15.3	14.5	19.1	9.9
wt of water	3.7	3.9	5.3	1.7
Moisture Content	24.18	26.90	27.75	17.17
Liquid Limit LL	26.2			
Plastic Limit PL	17.17			
PI	9.0			

Rawal Town Soil

No of blows	36	24	13	P.L
Can No	97	87	65	109
wt of empty can	12.6	12.3	11.6	16.3
wt of wet soil+ can	31.1	34.5	40	23.9
wt of dry can + soil	27.7	30.1	33.9	22.7
wt of soil	15.1	17.8	22.3	6.4
wt of water	3.4	4.4	6.1	1.2
Moisture Content	22.52	24.72	27.35	18.75
Liquid Limit LL	24.3			
Plastic Limit PL	18.75			
PI	5.6			

Fateh Jhang Soil-A

No of blows	37	25	12	P.L
Can No	67	94	96	132
wt of empty can	11.4	9.8	13.1	11.2
wt of wet soil+ can	32.7	27.7	33.4	20.5
wt of dry can + soil	28.6	24	28.8	19.2
wt of soil	17.2	14.2	15.7	8
wt of water	4.1	3.7	4.6	1.3
Moisture Content	23.84	26.06	29.30	16.25
Liquid Limit LL	25.9			
Plastic Limit PL	16.25			
PI	9.6			

Fateh Jhang Soil-B

No of blows	39	23	11	P.L
Can No	62	63	88	89
wt of empty can	11.2	12	12.7	12.8
wt of wet soil+ can	29.7	30.3	45.3	21.8
wt of dry can + soil	26.3	26.3	37.7	20.5
wt of soil	15.1	14.3	25	7.7
wt of water	3.4	4	7.6	1.3
Moisture Content	22.52	27.97	30.40	16.88
Liquid Limit LL	26.1			
Plastic Limit PL	16.88			
PI	9.2			

EME College-A

No of blows	36	22	11	P.L
Can No	118	101	92	141
wt of empty can	10.6	13.4	9.9	12.2
wt of wet soil+ can	33.9	37.2	26.4	20.3
wt of dry can + soil	28.7	31.6	22.1	19
wt of soil	18.1	18.2	12.2	6.8
wt of water	5.2	5.6	4.3	1.3
Moisture Content	28.73	30.77	35.25	19.12
Liquid Limit LL	30.5			
Plastic Limit PL	19.12			
PI	11.4			

EME College-B

No of blows	34	23	15	P.L
Can No	76	1	145	70
wt of empty can	11.8	11.5	12.4	10.6
wt of wet soil+ can	30.8	34.1	47.2	20
wt of dry can + soil	27.3	29	39	18.5
wt of soil	15.5	17.5	26.6	7.9
wt of water	3.5	5.1	8.2	1.5
Moisture Content	22.58	29.14	30.83	18.99
Liquid Limit LL	26.6			
Plastic Limit PL	18.99			
PI	7.6			

Jhangi Syedan

No of blows	34	24	11	P.L
Can No	123	135	133	111
wt of empty can	11.5	11.9	11.1	11.1
wt of wet soil+ can	32.2	31	43.5	21.8
wt of dry can + soil	28.5	27.4	36.8	20.3
wt of soil	17	15.5	25.7	9.2
wt of water	3.7	3.6	6.7	1.5
Moisture Content	21.76	23.23	26.07	16.30
Liquid Limit LL	23			
Plastic Limit PL	16.30			
PI	6.7			

APPENDIX B

The results of Fall Cone test are as follow:

Fateh Jhang Soil

Trial No.	1	2	3
Initial reading	292	295	295
Final Reading	358	415	529
Penetration(mm)	6.6	12	23.4
Can No	85	79	73
wt of empty can	12	11.5	12.1
wt of wet soil+ can	33	39.8	53.2
wt of dry can + soil	27.6	31	39.6
wt of soil	15.6	19.5	27.5
wt of water	5.4	8.8	13.6
Moisture Content	34.62	45.13	49.45
Liquid Limit LL	47.9		
Plastic Limit PL	31		
PI	16.9		

Nandipur Soil

Trial No.	1	2	3
Initial reading	391	28	35
Final Reading	450	220	330
Penetration	5.9	19.2	29.5
Can No	123	83	119
wt of empty can	11.5	12.1	11.5
wt of wet soil+ can	24.6	28	27.1
wt of dry can + soil	20.3	22.5	20.9
wt of soil	8.8	10.4	9.4
wt of water	4.3	5.5	6.2
Moisture Content	48.86	52.88	65.96
Liquid Limit LL	53.7		
Plastic Limit PL	42		
PI	11.7		

Nandipur+ 25 percent Bentonite

Trial No.	1	2	3
Initial reading	29	290	317
Final Reading	66	430	560
Penetration(mm)	3.7	14	24.3
Can No	103	120	81
wt of empty can	12.4	12.7	11.9
wt of wet soil+ can	27.5	29	30
wt of dry can + soil	22	21.9	18.1
wt of soil	9.6	9.2	6.2
wt of water	5.5	7.1	11.9
Moisture Content	57.29	77.17	191.94
Liquid Limit LL	140		
Plastic Limit PL	30		
PI	110		

Swabi Soil

Trial No.	1	2	3
Initial reading	267	265	283
Final Reading	297	430	497
Penetration(mm)	3	16.5	21.4
Can No	104	68	93
wt of empty can	13.2	11.4	10.7
wt of wet soil+ can	26.7	39	28.9
wt of dry can + soil	23	29.6	22.3
wt of soil	9.8	18.2	11.6
wt of water	3.7	9.4	6.6
Moisture Content	37.76	51.65	56.90
Liquid Limit LL	55.7		
Plastic Limit PL	36		
PI	19.7		

Mardan Soil

Trial No.	1	2	3
Initial reading	255	280	300
Final Reading	310	460	520
Penetration(mm)	5.5	18	22
Can No	71	86	73
wt of empty can	11.4	10.3	12.1
wt of wet soil+ can	25.6	29.2	35.1
wt of dry can + soil	23.1	25.3	29.3
wt of soil	11.7	15	17.2
wt of water	2.5	3.9	5.8
Moisture Content	21.37	26.00	33.72
Liquid Limit LL	29		
Plastic Limit PL	18		
PI	11		

G-5 Sector Isb.

Trial No.	1	2	3
Initial reading	230	270	260
Final Reading	310	420	520
Penetration(mm)	8	15	26
Can No	96	142	110
wt of empty can	13.1	11.8	12.5
wt of wet soil+ can	25	29.8	29.6
wt of dry can + soil	22.9	25.8	25.2
wt of soil	9.8	14	12.7
wt of water	2.1	4	4.4
Moisture Content	21.43	28.57	34.65
Liquid Limit LL	31.5		
Plastic Limit PL	18		
PI	13.5		

Nilore Soil

Trial No.	1	2	3
Initial reading	310	290	325
Final Reading	390	430	565
Penetration(mm)	8	14	24
Can No	140	133	137
wt of empty can	11.4	11.1	10.7
wt of wet soil+ can	39.5	45.2	42
wt of dry can + soil	34.5	38.6	35.3
wt of soil	23.1	27.5	24.6
wt of water	5	6.6	6.7
Moisture Content	21.65	24.00	27.24
Liquid Limit LL	26		
Plastic Limit PL	19.5		
PI	6.5		

Kahuta Soil-A

Trial No.	1	2	3
Initial reading	285	315	325
Final Reading	357	490	565
Penetration(mm)	7.2	17.5	24
Can No	103	83	79
wt of empty can	12.3	12.1	11.4
wt of wet soil+ can	30.8	29.3	36.8
wt of dry can + soil	27.5	25.8	31.1
wt of soil	15.2	13.7	19.7
wt of water	3.3	3.5	5.7
Moisture Content	21.71	25.55	28.93
Liquid Limit LL	27		
Plastic Limit PL	19.4		
PI	7.6		

Kahuta Soil-B

Trial No.	1	2	3
Initial reading	283	295	325
Final Reading	339	445	592
Penetration(mm)	5.6	15	26.7
Can No	99	105	135
wt of empty can	11.8	12.5	11.8
wt of wet soil+ can	27.2	28.3	37.8
wt of dry can + soil	24.5	24.9	31.9
wt of soil	12.7	12.4	20.1
wt of water	2.7	3.4	5.9
Moisture Content	21.26	27.42	29.35
Liquid Limit LL	29		
Plastic Limit PL	21		
PI	8		

Upper Topa Soil

Trial No.	1	2	3
Initial reading	305	310	295
Final Reading	385	495	555
Penetration(mm)	8	18.5	26
Can No	134	69	90
wt of empty can	13.7	11.9	13.1
wt of wet soil+ can	31.8	37.4	32.4
wt of dry can + soil	28.4	31.6	27.7
wt of soil	14.7	19.7	14.6
wt of water	3.4	5.8	4.7
Moisture Content	23.13	29.44	32.19
Liquid Limit LL	30		
Plastic Limit PL	20.2		
PI	9.8		

Rawal Town Soil

Trial No.	1	2	3
Initial reading	295	300	310
Final Reading	335	430	551
Penetration(mm)	4	13	24.1
Can No	118	107	46
wt of empty can	10.6	11.6	11.1
wt of wet soil+ can	24.8	34.7	39.5
wt of dry can + soil	22.4	30.1	32.8
wt of soil	11.8	18.5	21.7
wt of water	2.4	4.6	6.7
Moisture Content	20.34	24.86	30.88
Liquid Limit LL	29		
Plastic Limit PL	19		
PI	10		

Fateh Jhang Soil-A

Trial No.	1	2	3
Initial reading	290	290	305
Final Reading	325	465	565
Penetration(mm)	3.5	17.5	26
Can No	93	142	115
wt of empty can	10.7	11.6	12.8
wt of wet soil+ can	28.2	43.3	29.7
wt of dry can + soil	25.2	35.7	25.6
wt of soil	14.5	24.1	12.8
wt of water	3	7.6	4.1
Moisture Content	20.69	31.54	32.03
Liquid Limit LL	32		
Plastic Limit PL	21		
PI	11		

Fateh Jhang Soil-B

Trial No.	1	2	3
Initial reading	278	305	315
Final Reading	322	490	585
Penetration(mm)	4.4	18.5	27
Can No	100	116	136
wt of empty can	13.5	10	14
wt of wet soil+ can	26.9	27.7	30.7
wt of dry can + soil	24.7	23.8	26.8
wt of soil	11.2	13.8	12.8
wt of water	2.2	3.9	3.9
Moisture Content	19.64	28.26	30.47
Liquid Limit LL	29		
Plastic Limit PL	19		
PI	10		

EME College Soil-A

Trial No.	1	2	3
Initial reading	314	290	340
Final Reading	355	402	570
Penetration(mm)	4.1	11.2	23
Can No	118	136	93
wt of empty can	10.6	14	10.7
wt of wet soil+ can	23.2	31.4	43.4
wt of dry can + soil	21	27	34
wt of soil	10.4	13	23.3
wt of water	2.2	4.4	9.4
Moisture Content	21.15	33.85	40.34
Liquid Limit LL	39		
Plastic Limit PL	21		
PI	18		

EME College Soil-B

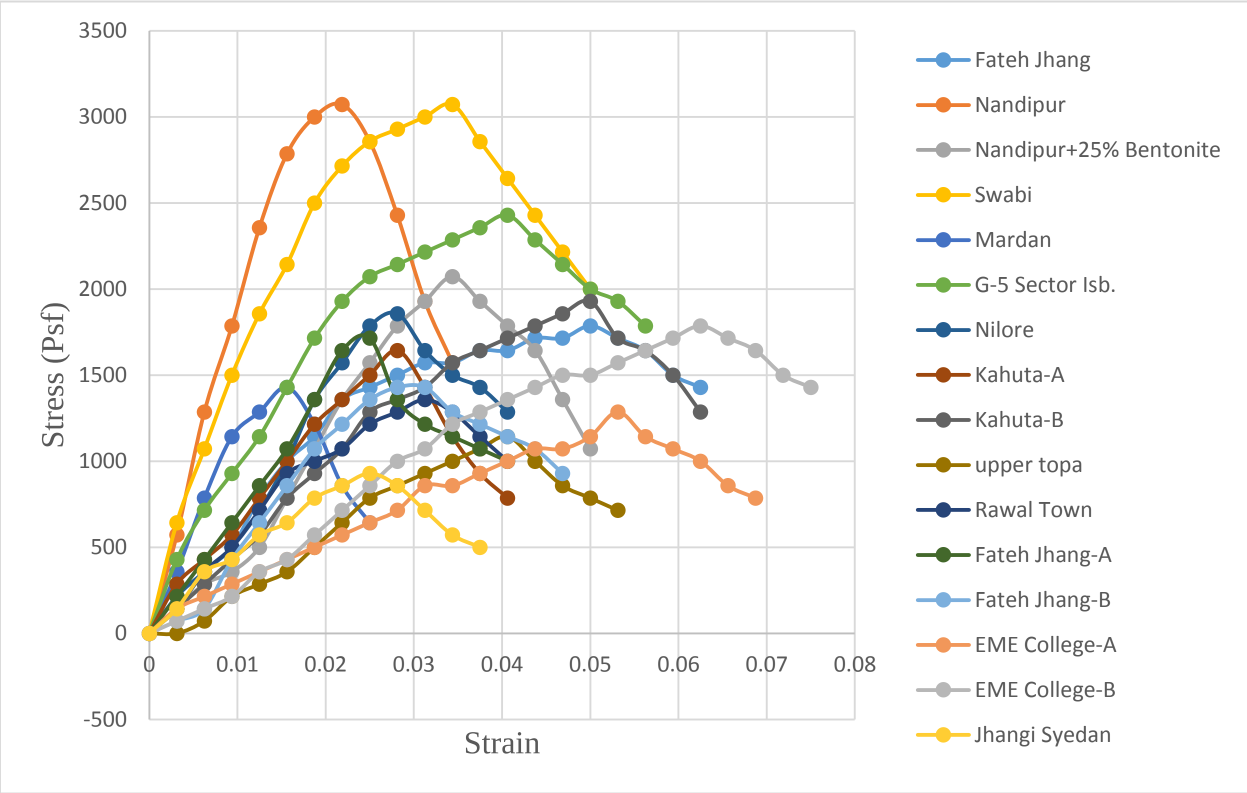
Trial No.	1	2	3
Initial reading	270	302	300
Final Reading	320	447	542
Penetration(mm)	5	14.5	24.2
Can No	134	96	40
wt of empty can	13.8	13.1	11.4
wt of wet soil+ can	35.4	29.1	43.5
wt of dry can + soil	31	25	34.5
wt of soil	17.2	11.9	23.1
wt of water	4.4	4.1	9
Moisture Content	25.58	34.45	38.96
Liquid Limit LL	38		
Plastic Limit PL	24.5		
PI	13.5		

Jhangi Syedan Soil

Trial No.	1	2	3
Initial reading	300	325	325
Final Reading	335	473	585
Penetration(mm)	3.5	14.8	26
Can No	124	133	204
wt of empty can	11.5	11.1	12.5
wt of wet soil+ can	35.5	43.4	32.6
wt of dry can + soil	31.9	37.1	28.1
wt of soil	20.4	26	15.6
wt of water	3.6	6.3	4.5
Moisture Content	17.65	24.23	28.85
Liquid Limit LL	27		
Plastic Limit PL	17		
PI	10		

APPENDIX C

Following are the results of the Unconfined Compression test.



ANNEX