ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY

DEPARTMENT OF CIVIL ENGINEERING

PREDICTION OF COMPACTION CHARACTERISTICS FROM ATTERBERG LIMITS FOR FINE-GRAINED SOILS

A thesis submitted to School of Graduate Studies of Addis Ababa University
in partial fulfillment of the requirements for the Degree of Master of Science
in Civil Engineering under Geotechnical Engineering

BY: ATSBEHA NEREA

ADVISOR: Dr. HADUSH SEGED

May, 2012

ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF GRADUATE STUDIES

PREDICTION OF COMPACTION CHARACTERISTICS FROM ATTERBERG LIMITS FOR FINE-GRAINED SOILS

BY
ATSBEHA NEREA

Approved By Board of Examiners

1. Dr. Hadush Seged ____________ ____________
   Advisor Signature Date

2. Dr. Samuel Tadesse ____________ ____________
   External Examiner Signature Date

3. Prof. Alemayehu Teferra ____________ ____________
   Internal Examiner Signature Date

4. Ato Yared Ashenafi ____________ ____________
   Chair Man Signature Date

Abstract

Compaction is one of the most important and routine engineering techniques, performed to assure the safety and stability of soils. However, in some situations such as large scale projects, obtaining the desired compaction characteristics, namely optimum moisture content (OMC) and maximum dry unit weight ($\boldsymbol{\gamma}_{\mathrm{dmax}}$), becomes time consuming and impracticable. In this case, predicting the compaction characteristics from correlation equations of index properties that involves simpler and quicker method of testing becomes vital task.

In this thesis, attempts have been made to obtain valid correlations between compaction characteristics of fine-grained soils with their Atterberg limits. For this purpose, 110 laboratory test data has been collected from different Governmental organizations. In addition, 20 samples were collected and a series of laboratory tests conducted as a primary data for this work. The total data used in this study is, therefore, 130.

In the analysis part, both the MS excel spreadsheet and the SPSS software have been used for the scatter plot, correlation, and regression analysis. Attempts were made to obtain the relationships of all the parameters (liquid limit, plastic limit, plasticity index, optimum moisture content, and maximum dry unit weight).

Results of the analyses reveal that both OMC and $\boldsymbol{\gamma}_{\mathrm{dmax}}$ have strong correlation with the PL than the other Atterberg limits. The OMC is particularly found to be about 90% of the PL. Therefore, it can be suggested that during prediction of OMC and $\boldsymbol{\gamma}_{\mathrm{dmax}}$ from Atterberg limit, the plastic limit should be used rather than other Atterberg limits. However, it shall be noted that $\boldsymbol{\gamma}_{\mathrm{dmax}}$ has better correlation with OMC than the PL.

The outcome of this thesis may be applicable in different civil Engineering sectors, especially for preliminary investigations and prefeasibility study of Civil Engineering works such as Construction of Roads, Earth dams, Earth fills, and other works that involve soils.

ACKNOWLEDGEMENTS

First, I want to address my appreciable gratitude to my advisor **Dr. Hadush Seged** for his precious assistance in all of this research work. I am thankful for his valuable encouragement, direction, advice, and helpful contribution during the preparation of this work.

My worthy gratitude extends to Geotechnical Engineering staffs: **Professor Alemayehu Teferra, Dr. Samuel Tadesse**, and **Dr. Messele Haile** for their arrangement of double presentation for thesis progress, and their important comments.

I am also pleased to say thanks to my sociable classmates for their positive responses whenever I need help from them. I am thankful for the Geotechnical laboratory staffs for their guidance and facilitation during sample testing program, and for the Governmental Organizations: Ministry of Water and Energy, Addis Ababa City Road Authority, Tigray Water and Energy Bureau, and Transport Construction Design Enterprise for their providing me the required secondary data.

Finally yet importantly, I want to express my lovely appreciation to my family and my friends for their endless support in every aspect during the preparation of this work.

Table of Contents

List of Tables

List of Figures

List of Appendixes

Abbreviations and Symbols

AAiT	Addis Ababa Institute of Technology
AAU	Addis Ababa University
AASHTO	American Association of Highway and Transportation Officials
ASTM	American Society of Testing and Materials
CH	Inorganic clays of high plasticity
CL	Inorganic cays of low to medium plasticity
FC	Fine content (percentage of soil passing No. 200 sieve)
FS	Free Swell
Gs	Specific gravity
LL	Liquid Limit
MDD	Maximum Dry Density
ML	Inorganic silts of low plasticity
MH	Inorganic silts of high plasticity
N	Number of sample
OH	Organic clays of medium of high plasticity.
OL	Organic silts of low plasticity
OMC	Optimum Moisture Content
PI	Plastic Index
PL	Plastic Limit
R^2	Correlation Coefficient
SE	Standard error of the estimate
USCS	Unified Soil Classification System
γ_{dmax}	Maximum dry unit weight

1. INTRODUCTION

1.1. General

Every man made structure resting on the ground needs safe and stable soil. To attain this safety and stability requirements the engineering properties of the soil beneath the structure or on the structure must be identified. However, obtaining these engineering properties of soils requires relatively more time and money. On the other hand investigating the index properties of a soil is much easier than investigating other engineering properties; in terms of time, money, and effort. More ever, most engineering properties of soils depend up on their index properties. Therefore, by obtaining the index property of soils that involves simpler and quicker method of testing, the engineering properties can be predicted satisfactorily from empirical correlations.

Soil compaction is one of the most important engineering techniques commonly performed in engineering projects such as highways, railway sub-grades, airfield pavements, earth dams, landfill, and foundations. The main aim of soil compaction is to improve engineering properties of soils such as increase density, reduction in compressibility leading to reduction in settlement, reduction in permeability, increase in shear strength, and increase in bearing capacity.

Compaction is the process of mechanically pressing the soil particles together into a close state of contact with air being expelled from the soil. In this process, both the number and size of voids in a given soil mass will be reduced, and therefore, the density of the soil increases, and the engineering property changes significantly.

Compaction characteristics of soils is expressed in terms of Maximum dry unit weight ($\boldsymbol{\gamma}_{\text{dmax}}$) and Optimum moisture content (OMC). Determining $\boldsymbol{\gamma}_{\text{dmax}}$ and OMC, especially in large scale projects, is both time consuming and costly. Hence, predicting $\boldsymbol{\gamma}_{\text{dmax}}$ and OMC from index properties becomes important.

1.2 Importance

Correlations are important to estimate engineering properties of soils particularly for project where there is a financial limitation, lack of test equipment or limited time, and correlations are commonly used in the preliminary stage of any project [12]. Many attempts have been made to obtain the optimum water content and maximum dry unit weight of compacted fine-grained soils. The correlation equations for fine-grained soils relate optimum moisture content (OMC) and maximum dry unit weight (γ_{dmax}) with index properties [11, 13, 16, 17, 18, 21].

1.3. Statement of the Problem

Compaction characteristics of soil are usually determined by conducting specified method of testing (eg. standard Procter test) in the laboratory, and the test results are utilized in the field to ensure the quality of construction for the desired purposes. However, when the extent of construction is very large (such as construction of long roads and large embankment dams that require massive materials), number of compaction tests are to be performed. Obtaining this compaction achievement requires relatively elaborated laboratory procedures and is time consuming. Thus, it is very important to obtain the index property parameters that involve simpler, quicker, and cheaper method of testing and the compaction characteristics can be predicted satisfactorily from empirical correlations.

1.4. Objective

General Objective

The objective of this work is to obtain applicable relationship between Atterberg limits and compaction characteristics of fine grained soils from laboratory experimental data (primary data) and other data collected from different organizations (secondary data) in Ethiopia.

Specific Objective

1. To establish relevant relationships between compaction characteristics and Atterber limits of fine grained soils, and to develop appropriate empirical correlations among the corresponding soil parameters.
2. To examine the validity of the correlations, and to draw appropriate conclusions on the relationships of each empirical equations.

1.5. Methodology

Sample Collection: For this work as primary data, eleven (11) sites were selected within Addis Ababa and 20 different samples were collected and brought to the Geotechnical Engineering Laboratory of Addis Ababa University. About 50 kg disturbed samples were collected from each pit at a depth ranging from 1.00m to 3.00m and transported to the laboratory. Once in the laboratory the soil was allowed to be air dried and each soil sample was mechanically pulverized over 4.75mm sieve before testing and was stored in covered plastic containers until needed for testing.

Grain Size Analysis: The amount of soil materials finer than 0.075mm was determined using ASTM D-1140 (Standard Test Method for Amount of Material in the Soil Finer than the No. 200 Sieve).

Atterberg Limits: The liquid limit, plastic limit, and plasticity index for each type of soil was determined according to ASTM D-4318 (Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils). The standard four-point method for determining the liquid limit was used for all tests.

Specific Gravity: The specific gravity of each type of soil was determined according to ASTM D-854 (Standard Test Method for Specific Gravity of Soils). The precision and bias of each pair of tests were investigated and all are within the ASTM accepted range.

Moisture-Density Relationships: Each sample extracted from the different sites was sieved over a 4.75mm sieve for testing and compacted in a 101.6-mm diameter mold as described in

Procedure “A” of the ASTM D-698. Each sample was immediately tested for water content according to ASTM D-2166 and the moisture content obtained in this procedure was used for generation of a compaction curve according to ASTM D-698. Finally the maximum dry unit weight ($\boldsymbol{\gamma}_{dmax}$) and corresponding optimum moisture content (OMC) were computed using spread sheet and chart plots.

1.6. Organization of the Thesis

In the first Chapter background, general objective, materials and methods were discussed as an introduction. In second Chapter, review of the literatures has been done for studying the accepted theories and practices in the related topics. In Chapter three site selection for sampling, visual soil identification procedures and sampling methods are included. Chapter four illustrates the laboratory examination, results and interpretations. The secondary data collected from different organizations are also included in this Chapter.

In Chapter five, statistical analysis has been executed using both the MS excel spread sheet and SPSS software. The scatter plot, correlation, and regression methods have been used to evaluate the validity of the relationships among the required variables. In this Chapter, discussions have been drawn based on the analytical and graphical results. At the end, Chapter six, final conclusions and recommendations are presented.

2. LITERATURE REVIEW

2.1. Properties of Fine grained soils

Fine-grained soils exhibit considerable changes in physical properties with change of water content. Dry clay may be suitable as a foundation for heavy loads as long as it remains dry, but may turn into swamp when wet [14]. Many of the fine soils shrink on drying and expand on wetting, which may adversely affect structures founded on them. Even when moisture content does not change, the properties of fine grained soils may vary considerably between their natural condition in the ground and their state after being disturbed [14].

Silts are different from clays in many important respects, but because of their similarity in appearance, they often have been mistaken to distinguish one from the other, but they are easily identified by their behavior in the presence of water [14].

(i) Silts

Silts are the non-plastic fine grained soils. They are unstable in the presence of water and have a tendency to become quick when saturated. Silts are fairly impervious, difficult to compact, and are highly susceptible to frost heaving [14].

Thus, silts have relatively low plasticity compared with clays. In terms of the classification chart they plot below the `A' line. The dilatancy property of silts, together with the quick reaction to vibration, affords a means of identifying typical silt in the loose wet state. When dry, silt can be pulverized easily under finger pressure and will have a smooth feel between the fingers in contrast to the grittiness of fine sand. For similar conditions of previous loading, the higher liquid limit of silt the more compressible it is [14].

(ii) Clays

Clays are the plastic fines. Thus, they plot above the `A' line on the plasticity chart. They have low resistance to deformation when wet, but become hard cohesive masses when they dry. Clays are virtually impervious, difficult to compact when wet, and impossible to drain by ordinary means. Large expansion and contraction with changes in water content are characteristics of clays. The higher the liquid limit of a clay, the more compressible it will be, and hence, in the most cases the liquid limit is used to distinguish between clays of high compressibility (H) and those of low compressibility (L) [14].

In general, the higher the liquid limit and thus the plasticity index the more cohesive is the clay. Field differentiation among clays is accomplished by the toughness test in which the moist soil is molded and rolled into threads until crumbling occurs and by the dry strength test which measures the resistance of the clay to breaking and pulverizing [14].

(iii) Organic Matter

Organic matter in the form of partly decomposed vegetation is the primary constituent of peaty soils. Thus, we have organic silts of low plasticity and organic clays of medium to high plasticity. Organic soils are dark grey or black in color, and usually have a characteristic odor of decay. Organic clays feel spongy in the plastic range as compared to inorganic clays. Soils containing organic matter are significantly more compressible and less stable than inorganic soils and they are undesirable for engineering uses [14].

2.2. Soil Compaction

2.2.1. General

Naturally occurring soils often do not have desirable engineering properties. More often soils must be improved in order to perform as required by the project. The most common type of soil improvement is soil compaction [10]. Soil compaction is one of the most significant components in the construction of roads, airfields, embankments, and foundations. The durability and stability of most structures depends up on the achievement of proper soil compaction [1, 8].

2.2.2 Background

There are four major groups of soil modification techniques used in construction today: mechanical, hydraulic, chemical, and confinement [15]. The most common technique is mechanical modification of the soil by increasing its unit weight with mechanical force applied using compaction equipment.

The importance of compaction as a practical means of achieving the desired strength, compressibility and permeability characteristics of fine-grained soils has been appreciated since the time as early as earth structures were built [13].

The theory of why compaction results in a denser material and why there is a limit to the moisture content has been studied since Proctor first introduced his findings [15].

Proctor recognized that moisture content affects the compaction process. He believed the reason why a moisture-density curve “breaks over” at optimum moisture content was related to capillarity and frictional forces. He also believed that the force of the compactive effort was applied to overcoming the inter-particle friction of the clay particles. As the water content increased from dry of optimum to wet of optimum he believed that the water acted as a lubricant between the soil particles.

The next compaction theory can be illustrated as: Compaction along the moisture density curve from dry to wet has four-step process [15]. First, the soil particles become hydrated as water is absorbed. Second, the water begins to act as a lubricant helping to rearrange the soil particles into a denser and denser state until optimum moisture content is reached. Third, the addition of water causes the soil to swell because the soil now has excess water. Finally, the soil approaches saturation as more water is added.

In 1956 another theory presented by Hilf [15] about the compaction phenomenon is based on pore water pressures in unsaturated soils. He developed a curve based on void ratio. The curve developed based on void ratio looks similar to a typical moisture-density curve because the minimum void ratio is also the maximum density at optimum moisture content. The decrease in density after optimum moisture content is due to buildup of pore pressure lowering the effectiveness of compaction [15].

Some of the studies attempted to correlate optimum water content and maximum dry unit weight to liquid limit alone [17], and others correlated optimum water content and maximum dry unit weight to liquid limits and plastic limits.

Recent studies [18] show that the compaction characteristics of fine-grained soils can be estimated well from Atterberg limits for a given compactive energy.

2.2.3 Purpose of Soil Compaction

Compaction increases the strength characteristics of soils, which in turn increases the bearing capacity of foundations, decreases the amount of excessive settlement of structures, increases the stability of slopes of embankments. Generally, compaction is used as practical means of achieving the following characteristics of soils [3, 8, 18].

- Reduce excessive settlement.
- Increase shear strength
- Increase bearing capacity
- Reduce permeability and seepage
- Reduce compressibility
- Optimizes swelling and shrinkage characteristics

Reduce excessive settlement and compressibility

The primary advantage resulting from the compaction of soils used in embankments is that it reduces settlement that might be caused by consolidation of the soil within the body of the embankment. This is true because compaction and consolidation both bring about closer arrangement of soil particles. Densification by compaction prevents later consolidation and settlement of a structure [8].

Increase shear strength

The increase in density by compaction usually increases shearing resistance [1]. This effect is highly desirable that it may allow the use of thinner pavement structure over a compacted sub-grade or the use of steeper side slopes for an embankment. For the same density, the highest strengths are frequently obtained by using greater compactive efforts. Large-scale experiments have indicated that the unconfined compressive strength of clayey sand could be doubled by compaction [8].

Reduce permeability and seepage

When soil particles are forced together by compaction, both the number of voids contained in the soil mass and the size of the individual void spaces are reduced [8]. This change in voids has an obvious effect on the movement of water through the soil. One effect is to reduce the permeability, thus reducing the seepage of water in earth dams, road embankments and water loss in reservoirs through deep percolation.

Optimizes swelling and shrinkage characteristics

Swelling characteristics is an important soil property. For expansive clay soils, the greater the density the greater the potential volume change due to swelling unless the soil is restrained [2]. An expansive clay soil should be compacted at moisture content at which swelling will not be excessive. Although the conditions corresponding to a minimum swell and minimum shrinkage may not be exactly the same, soils generally may be compacted so that these effects are minimized [2].

2.3. Factors Affecting Compaction Characteristics

Compaction characteristics of soils depend up on many factors such as water content of the soils, amount of compaction energy, soil type, method of compaction, and admixtures [1, 19].

2.3.1. Moisture Content in the Soil

The moisture content of a soil affects its dry density [1]. A soil with very low water content is difficult to compress into close state of particles. This results in higher void ratio and hence lower dry density for the same compaction effort. On the other hand when the water content increases excessively, the soil grain tends to move apart and the total void ratio continues to increase where as the dry density falls. However, if the moisture content of the soil is of some intermediate specific value, the water acts as lubricant causing the soil to soften and become more workable. In this case the soil grains are close packed thus lowering the void content and increasing the dry density [1]. This specific value of moisture is called **optimum water content** and the corresponding dry density termed as **maximum dry density**.

2.3.2. Amount of Compaction Energy

The compactive effort is the amount of energy applied on the soil [1]. With a soil of given moisture content, if the amount of compaction energy increases, the soils particles will be packed so that the dry unit weight increases. For a given compactive effort, there is only one moisture content which gives the maximum dry unit weight. If the compactive effort is increased the maximum dry unit weight also increases, but the optimum moisture content decreases.

2.3.3. Soil Type

The nature of a soil itself has a great effect on its response to a given compactive effort. Compaction characteristics of soils are divided in to three groups, Compaction of cohesionless soils, Compaction of sandy or silty soils with moderate cohesion, and compaction of clay [19].

In general, coarse grained soils can be compacted to higher dry density than fine grained soils[3]. In Coarse grained soils, when the amount of fines and the voids of the coarse grained soils are about the same highest dry density can be achieved [3]. In sand, the well graded sand attains higher dry density than poorly graded sand. Cohesive soils with high plasticity have, generally, low dry density and high optimum moisture content.

2.4. Method of Soil Compaction

2.4.1. Laboratory Compaction Methods

To attain the required maximum dry unit weight in the field, first appropriate tests are determined in the laboratory and this laboratory results must be confirmed in the field. The following tests are normally carried out in a laboratory [4].

Standard Proctor Compaction Test (ASTM D-698)

Proctor developed this test in connection with the construction of earth fill dams in California in 1933 [10]. It gives the standard specifications for conducting the test. A soil at a selected water content is placed in three layers into a mold of 101.6mm diameter, with each layer compacted by 25 blows of a 2.5 kg hammer dropped from a height of 305 mm, subjecting the soil to a total compactive effort of about 600 kN /m^2, so that the resulting dry unit weight at optimum water content is determined [10].

Modified Proctor Compaction Test (ASTM D-1557)

This test method covers laboratory compaction procedures used to determine the relationship between water content and dry unit weight of soils, compacted in 5-layers by 101.6mm diameter mold with a 4.5kg hammer dropped from a height of 457mm producing a compactive effort of 2,700 kN/m^2 [10].

2.4.2 Field Compaction Methods

Several methods are used for compaction of soils in the field. The choice of these methods depends up on the soil type, the maximum dry density required and economic considerations [5]. The four major types of compaction processes currently in use by modern construction equipment are:

a) Impact
b) Manipulation
c) Pressure
d) Vibration

Impact compaction involves dropping a weight on the soil during compaction [5]. This compaction equipment subjects the soil to a series of blows until the desired density is reached. In order to effectively compact the soil with an impact, it must be placed in multiple lifts so that the stress of the blow is distributed through the entire lift. Another form of impact compaction is known as deep dynamic compaction [5]. This type of compaction uses crane and very large mass to compact the soil to significant depth below the surface.

Compaction performed by manipulation is accomplished by introducing kneading force to the soil during compaction [5]. The construction equipment manipulates the soil over a series of passes until the desired level of compaction is achieved. The Proctor test does not accurately model the manipulation mechanisms of this type of compaction. The most common type of manipulation compaction test is typically referred to as the Miniature Harvard Compaction Test. Neither ASTM nor AASHTO currently has a recommended procedure for use of the Harvard Miniature Mold apparatus for compaction testing [5]; it is commonly used for research purposes.

During pressure compaction, called static compaction, usually consolidation apparatus is used, in laboratory, to compress the soil into a ring of known volume [5]. Static compaction is useful research method but the researcher must realize that in the field it may not have the same level of control.

Vibratory compaction is used to shake the soil into more dense state [5]. The compaction equipment induces strong vibrations in the soil to the desired level of compaction.

In general, modern compaction equipment typically incorporates more than one type of compaction mechanism at a time to accomplish compaction of the soil. Selection of the proper compaction method depends on the type of soil, the size of the project, final compaction requirements, rate of production, and economic factors.

The necessary compaction for sub-grades of roads, earth fills, and embankments may be obtained by mechanical means [10]. Some of the equipments that are normally used for compaction are as follows.

a) Smooth wheel rollers
b) Rubber tired rollers
c) Sheep foot rollers
d) Vibratory rollers

The choice of roller for a given job depends on the type of soil to be compacted and percentage of compaction to be obtained. For cohesive soil Sheep's foot roller, or Rubber tired roller, and for cohesionless soils Rubber-tired roller or Vibratory roller are suggested [10].

2.5. Water Content Dry-Density Relationships

When some moisture is added to dry soil, the soil grains are surrounded by a film of adsorbed water. If more water is added, the film of water becomes thicker and the soil particle surrounded by this film of water slide over each other more easily. At this condition, when some specified compactive effort is applied, the soil particles becomes close together easily. The water in this process acts as **lubricant** and the soil particles become so closely packed together by the expulsion of air from the voids [9].

If we continue to add still more water into the soil, the water occupies the space that could have been occupying by the soil particles during compaction. Thus, the soils are not dense under the given effort because the water hinders the soil grains from being close packed together. This condition leads to the conclusion that[9] "there must be most appropriate water content that the water could provide maximum benefit of lubrication without occupying a space that could have been occupied by the soil grains with a given compaction effort". Such moisture content at which the unit weight of compacted soil becomes maximum is called **Optimum Moister Content (OMC)** and the corresponding density is called **Maximum Dry Density (MDD)**[9].

Most soils exhibit similar relationship between moisture content and dry density when subjected to a given compactive effort [8]. For each soil, maximum dry density develops at its OMC for a given compactive effort. Beyond OMC, the air content of most soils remains essentially the same even though the moisture content is increased [8].

2.6. Atterberg Limits

The Swedish soil scientist Albert Atterberg originally defined six ‘Limits of consistency’ to classify fine-grained soils, but in current engineering practice only three of the limits, i.e. liquid, plastic and shrinkage limits are used [6]. In fact, he was able to define several limits of consistency and he has developed simple laboratory tests to define these limits. They are:

a) Upper limits of viscous flow.
b) Liquid limit – lower limit of viscous flow.
c) Sticky limit – clay loses its adhesion to a metal blade.
d) Cohesion limit – grains cease to cohere to each other.
e) Plastic limit – lower limit of the plastic state.
f) Shrinkage limit – lower limit of volume change.

He also defined the plasticity index, which is the range of water content where the soil is plastic, and he was the first to suggest it for soil classification. Later in the late 1920’s Terzaghi and Casagrande working for the U.S. Bureau of public Roads, standardized the Atterberg limits so that they could be readily used for soil classification purposes. In present geotechnical engineering practice one usually uses the liquid limit (LL), the plastic limit (PL), and the shrinkage limit (SL). The sticky and the cohesion limits are more useful in ceramics and agriculture [3, 10].

2.6.1. The Liquid Limit

The liquid limit of a soil is defined as the water content above which the soil behaves as a viscous liquid with little measurable shear strength. The liquid limit corresponds approximately to a water content at which the soil has shear strength of about 2.5 kPa**.** However, subsequent studies have indicated that the liquid limit for all fine-grained soils corresponds to shearing resistance of about 1.7-2.0 kPa [11]. In this test, the liquid limit is defined as the moisture content at which 2 mm wide groove closes over base distance of 13mm under 25 standard blows as standardize by ASTM.

Currently two methods are popular in practice for the determination of the liquid limit of fine-grained soils [11], they are: the percussion cup method and the cone penetration method.

In this study, the percussion cup method standardize by ASTM D 4318-98 is used to obtain the liquid limits of all the samples.

2.6.2. Plastic Limit and Plasticity Index

When the water content of a soil is at its plastic limit, the particles will slide one another on application of force, but there is sufficient cohesion to allow them to retain shape [11]. The range of water content from the liquid limit to plastic limit is known as the plasticity of the soil. Plasticity is represented by plasticity index PI which is numerically equal to the difference between the liquid limit and the plastic limit water contents of the soil.

Plasticity index is used in the classification of fine-grained soils, through the plasticity chart. The plasticity chart is widely used to differentiate between clays and Silts and further, to subgroup them according to the degree of their compressibility [11].

The plasticity index is used in a good number of correlations with many engineering properties such as the compression index, the coefficient of consolidation, swelling potential, the friction, the coefficient of earth pressure at rest, the un drained shear strength etc [11].

2.7. Previously Established Correlation Equations

Correlations are very important to estimate engineering property of soils, especially for preliminary investigation of projects. Correlations may be also used for projects where there is financial limitation, lack of test equipments and limited time [16].

Many attempts have been made to obtain the correlation equations for fine-grained soils that relate OMC and $\boldsymbol{\gamma}_{dmax}$ with index properties [16, 17, 18, 21]. The earliest author may be

McRae who studied the effect of compaction effort on determination of maximum dry unit weight of soils [21] in1958.

Later, Pandian *et al*. [13] and Blotz *et al*. [12] have proposed a method to predict the compaction characteristics in terms of the liquid limit, using the data from Proctor compaction tests at different compaction energies for fine grained soils.

Recently, considerable equations are proposed by different authors to predict the compaction characteristics from Atterberg limits, of which, some of them are summarized as follows:

Based on both primary and secondary data, Gurtug and Sridharan [21] obtained the following relationships using 86 data to estimate the standard Proctor compaction characteristics.

$$\begin{aligned} &OMC = 0.92 \times PL, \qquad R = 0.98 \\ &\gamma_d = 21.61 - 0.26 \times OMC, \quad R = 0.98 \\ &N = 86 \end{aligned} \qquad \text{------------------------- (2.1)}$$

Based on their own study and data from the literature, Sridharan and Nagaraj [18], proposed the following correlation equations to predict the compaction characteristics from plastic limit and liquid limit using 64 standard proctor compaction test data.

$$\begin{aligned} &OMC = 0.92 \times PL, \qquad R = 0.99 \\ &OMC = 0.37 \times LL + 4.61, \quad R = 0.80 \\ &\gamma_{d\max} = 21.46 - 0.23 \times PL, \quad R = 0.93 \\ &\gamma_{d\max} = 19.62 - 0.09LL, \quad R = 0.80 \\ &N = 64 \end{aligned} \qquad \text{---------------------- (2.2)}$$

Sivrikaya et.al. [17] also developed correlations with standard proctor compaction test data, and concluded that optimum water content has considerably good correlation with plastic limit in comparison with liquid limit and plasticity index.

$$OMC = 0.94 \times PL, \qquad R = 0.99, \qquad SE = 3.35\%$$
$$\gamma_{d\max} = 21.97 - 0.27 \times OMC, \qquad R = 0.97, \qquad SE = 0.64\%$$
$$N = 130 \qquad \text{---------------}(2.3)$$

Sivrikaya's work as summarized by Sivrikaya and Soycan [16], show the following correlations using standard Proctor data with index properties of fine-grained soils

$$OMC = 0.92 \times PL, \qquad R = 0.99, \qquad SE = 3.10$$
$$\gamma_{d\max} = 20.90 - 0.21 \times PL, \qquad R = 0.84, \qquad SE = 0.79$$
$$\gamma_{d\max} = 21.84 - 0.27 \times OMC, \qquad R = 0.97, \qquad SE = 0.45$$
$$N = 156 \qquad \text{------------------------ } (2.4)$$

Where:

OMC = Optimum moisture content

γ_{dmax} = Maximum dry unit weight

PL = Plastic limit

R = Correlation coefficient

SE = Standard error of the estimate

N = Number of sample (data)

3. FIELD INVESTIGATION AND SOIL SAMPLING

3.1 Area of Study and Soil Sampling

The samples used to obtain primary data for this work are taken from Addis Ababa, which is dominantly covered by red fine grained soils in the northern and western part and with black expansive soils in the eastern and southern parts. Eleven (11) sites are selected for sampling within Addis Ababa city and 20 disturbed samples from red, black, and grey types of soils are collected. These sites are:

a) Northern part, Gulele Sub-City: Addisu- Gebeya, Awelya, and Shegole sites.
b) Eastern part, Bole Sub-City: Megenagna, Millennium Hall, Imperial Hotel, and Summit.
c) Western part, Kolfe Keranio Sub-City: Kolfe and Atari sites.
d) Southern part, Nifas Silk Lafto Sub-City and Akaki klity Sub-City: Gofa and Gelan sites.

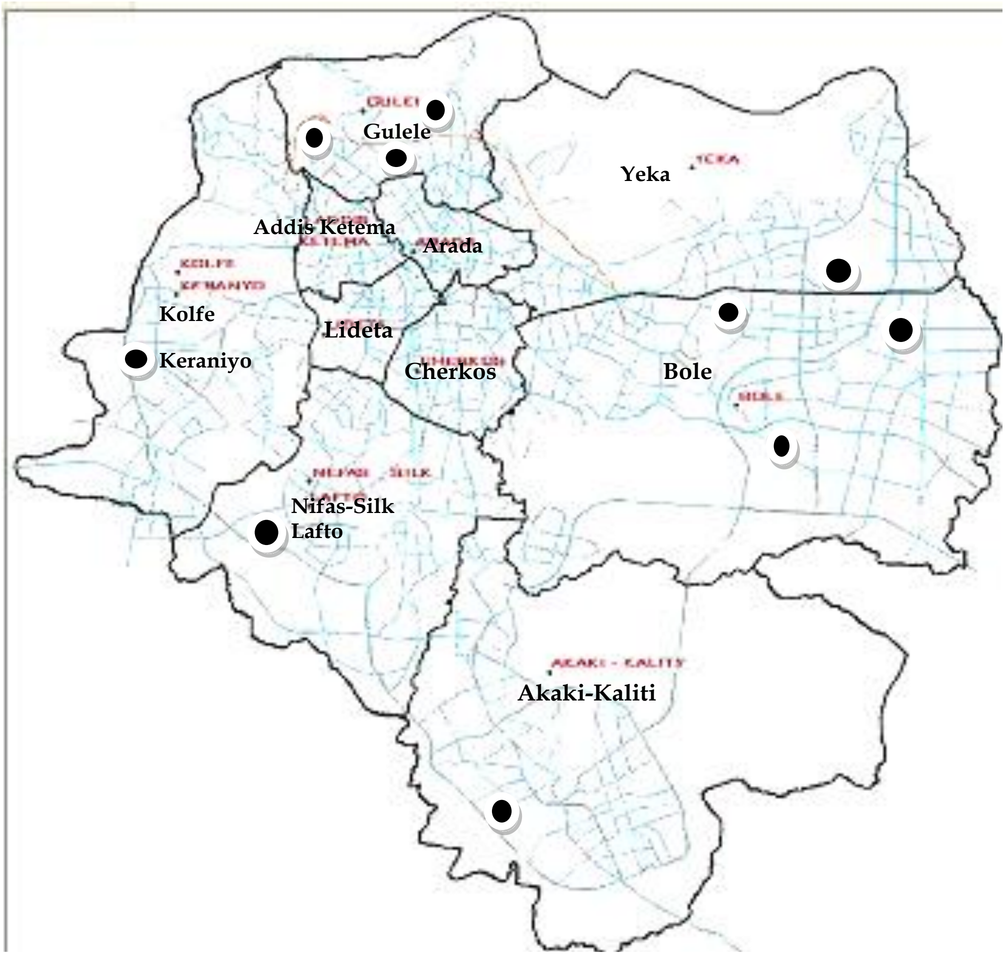


Figure 3.1. Location of the sampling area in the map of Addis Ababa city.

These samples include 10 red clay soils obtained from Addisu Gebeya, Kolfe, Attary, and Shegole areas and the remaining 10 expansive samples were obtained from Bole, Megenagna, Summit, Gelan, and Gofa areas. The samples were taken from a depth ranging from 1.00 m to 3.00m below the ground surface, and two samples were taken from each test pit at each site.

3.2. Visual Identification of Soils in the Field

Field identification of soils was carried out according to the ASTM D-2488 “Standard Practice for Description and Identification of Soils”.

The field description and classification of soil were based on the size and distribution of coarse-grained particles and on the behavior of fine-grained particles. The first step used in describing soil under the visual-manual method was to determine whether the soil is fine-grained or coarse-grained by visually observing the soil sample to be taken.

3.3. Sampling Methods and Sample Preservation

Clear and accurate data are required to describe the soil profile and sample locations [20]. Test pits were excavated using hand tools with plan area of 1.5m by 1.5m and representative disturbed samples were taken. The disturbed samples had been handled and preserved to prevent contamination by foreign material and to ensure that the in situ soil conditions are preserved.

An attempt was made to collect samples that should be representative of the in situ soil at the depth from which the sample was taken. The preserving and transporting of the samples were done according to ASTM D-4220-95 (standard Practice for Preserving and Transporting of Soil samples).

Identification: All soil samples were properly marked to accurately identify the origin of the sample. The name of the sampling area and the depth of sampling were written on each sampling container with waterproof permanent marker.

Packing of samples: In general, disturbed samples do not require special transport precautions [20]. However, the sample containers were protected from breakage and exposure to excessive moisture, which may cause deterioration of the labels and the sampling bags.

Methods of transportation: The most satisfactory method of sample transportation is vehicle that can be loaded at the exploration site and driven directly to the testing laboratory [20]. Since the sampling area was here in Addis Ababa, sample transportation was not any problem because it requires not more than an hour for transporting samples from the sampling area to the Geotechnical laboratory of Addis Ababa University (AAiT). Thus, there was no fear of exposing the sample to excessive heat, cold, or contaminants.

3.4. Sample Size and Preparations

For fine-grained soils that may contain high fraction of clay soils, it was necessary to soak the soil prior to washing in order to keep the fine material from adhering to larger particles[4]. In preparation of the sample to determine fine content of the soil, the soil sample to be tested was first air dried. Then sample was thoroughly pulverized with fingers and with wood hammer. Representative sample 250gram air dried sample was taken, and net100gram oven dried soil pulverized on 4.75mm (No.4) sieve is soaked in secured contained and waited for 24hours before wet sieving. This specimen is then to be tested for fine content according to ASTM D1440-97.

For the compaction characteristics test, the required sample mass for procedures “A” of ASTM D 698 – 91 (Laboratory Compaction Characteristics of Soil Using Standard Effort) is approximately 16kg. However about 20kg of representative soil sample pulverized on 4.75mm (No.4) sieve air-dried soil was prepared for each full test. Therefore, about 30kg field sample was collected for compaction characteristics, and about 50kg sample for all other tests was brought from each sampling depth.

In preparation of sample for Atterberg limit tests, attempts have been made to keep all samples to be the same as that of the samples used in compaction and other tests. The amount of material used for sampling was taken 200gm passing 0.425mm (No.40) sieve and it was kept air dried. Considerable amount of water was added to the soil sample and kept in closed container for 16 hours before testing which is used to moist the soil grains thoroughly so that to be tested according to ASTM D 4318-98 (Standard Test Method for Liquid Limit, Plastic Limit and Plasticity Index of Soils) was used.

4. LABORATORY SOIL TESTING

4.1. Introduction

This chapter presents the methods of soil investigations to determine soil index properties and compaction characteristics of 20 soil samples. The laboratory testing program includes: determination of grain size, Atterberg limits, compaction characteristics, free swell, and specific gravity. All laboratory tests were performed at Addis Ababa Institute of Technology (Addis Ababa University) Geotechnical Engineering Laboratory.

In this Chapter, details of test procedures to determine the Atterberg limits and compaction characteristics are presented. The validity of the correlations depends on the accuracy of the test procedures used. To improve the reliability of such correlations, careful understanding of test procedures and practice are required. In this case, attempt was made to obtain accurate laboratory results by careful following of proper testing procedures as described by ASTM standards.

4.2. Grain Size Distribution

Grain size analysis is a process in which the proportion of material of each grain size present in a given soil is determined. The grain- size distribution of coarse –grained soils is determined directly by sieve analysis, while that of fine-grained soils is determined indirectly by hydrometer analysis [4]. However, determination of amount of materials finer than No. 200(0.075mm) sieve can be separated from coarser particles much more efficiently and completely by wet sieving method than through the use of the dry sieving [4].

In this particular study, the wet sieving method is used in the laboratory to determine the fine content of the soil samples. Representative sample was obtained by using the quartering method, and representative 100gram of oven dried soils was taken, socked in water and it was washed over 0.075mm sieve. The amount of material passing 0.075mm during washing process was obtained and recorded. Finally the percentage of fine content was computed.

The test was performed according to the procedure described by ASTM D1140-97, Standard Test Method for Amount of Material in the Soils Finer than the No. 200 (0.075mm) Sieve.

4.3. Free Swell Test

This test has not been standardized by ASTM [7]. The method was suggested, in 1956, by Holtz and Gibbs to measure the expansive potential of cohesive soils [7], and it gives fair approximation of the degree of expansiveness of the soil sample. The procedure consists of pouring very slowly of 10 cubic centimeters of oven dry soil passing No.40 sieve in to a 100 cubic centimeters, full of water, graduated measuring cylinder and letting the content stand for approximately twenty four hours until all the soil completely settles on the bottom of the graduating cylinder.

4.4. Specific Gravity

The specific gravity of selected samples was measured in accordance with ASTM D 854-98 (Standard Test Method for Specific Gravity of Soils). The mass of a clean dry pycnometer was obtained. The pycnometer was filled with clean water, weighed, and the temperature was measured. The water was then poured out until the flask was half-full and oven-dried soil of a known mass was carefully placed in the pycnometer. The contents were allowed to be free from any trapped air. After removing all the air, distilled water was carefully added making sure that no air was reintroduced to the contents. Finally, computation to determine the specific gravity was done in spreadsheet as shown in Table 4.1 below.

Table 4.1 Typical steps for specific gravity computations

Specific Gravity Determination	
Date Tested	13/02/2011
Sample Designation	Addisu Gebeya 1.5m
Sample Location	Addis Ababa, Gullele Sub City
Sample Description	Dark Red, Fine Grained soils
Method of Test Procedures	ASTM D854-98

Description	**Test Trials**	
	1	**2**
Pycnometer bottle number	P4	P41
Weight empty Pycnometer, Wp (g)	54.72	49.81
Weight Pycnometer and dry soil, W_1 (g)	81.79	74.67
Weight of Pycnometer, soil & water, W_2 (g)	171.87	165.45
Weight of Pycnometer full of water, W_3 (g)	154.66	149.51
Weigh dry soil, Ws = W_1-Wp (g)	27.07	24.86
Weigh of equal volume of displaced water Ww = (W_1-Wp)-(W_2-W_3) (g)	9.86	8.92
Specific Gravity Gs = (Ws/Ww)	2.78	2.79
Average Specific Gravity Gs	**2.79**	

4.5. Atterberg Limits

This test was performed to determine the plastic limit and liquid limit of the soil samples. This experiment was performed using ASTM D4318 -98 (Standard Test Method for Liquid Limit, Plastic Limit, and Plasticity Index of Soils).

Approximately 200 grams of soil passing No.40 (0.425mm) sieve are needed to complete the Atterberg limits test. Water was added to the soil samples and the soil sample was covered and placed for 16 hours. The sample was split into two areas. Approximately 20 grams was set aside for the plastic limit determination and the rest was used for determining the liquid limit.

Four separate water content determinations were done between 15 and 35 blows using the Casagrande apparatus. Once these data were plotted, the liquid limit was determined by locating the water content at 25 blows.

For plastic limit determination, 1/3 of the 20 grams was taken and rolled into 3mm thread on the glass plate. This step was repeated until the soil crumbled when the thread is reached 3mm diameter. A water content determination was then performed. Two steps were performed and the water content determinations for each step were conducted. The average of the two water contents was taken as the plastic limit. The procedure of computation for plastic limit and liquid limit is illustrated in Table 4.2 below.

Table 4.2 Typical steps for Atterberg limit calculations

Determination of Atterberg Limits

Date Tested	24/01/2011
Sample designation	Awelya Site at 3.00m depth
Sample Location	Addis Ababa, Gullele Sub City
Sample Description	Dark Red, Fine Grained Soils (Clay)
Method of Test procedures	ASTM D4318-98

Plastic Limit Determination

	Test Trials			
Description	**1**	**2**	**PI**	**Remark**
Container number	35	107		
Weight of container, Wc (g)	15.63	15.82		
Weight of container & wet soil, W1 (g)	25.72	24.59		
Weight of container & dray soil, W2 (g)	23.40	22.60		
Weigh of water, Ww = W1-W2 (g)	2.32	1.99		
Weigh of dry soil, Ws = W2-Wc (g)	7.77	6.78		
Water content (%) = (Ww/Ws)*100	30.86	31.35		
Average Plastic Limit (%)	31		**33.50**	

Liquid Limit Determination

Description	**Test Trials**			
	1	**2**	**3**	**4**
Number of blows, N	15	24	28	32
Container number	46	A19	10*	A10
Weight of container, Wc (g)	15.7	15.6	15.8	15.57
Weight of container & wet soil, W1 (g)	45.58	48.82	37.35	42.54
Weight of container & dray soil. W2 (g)	33.57	35.8	29.1	32.25
Weigh of water, Ww = W1-W2 (g)	12.01	13.02	8.25	10.29
Weigh of dry Soil, Ws = W2-Wc (g)	17.87	20.2	13.3	16.68
Water content (%) = (Ww/Ws)*100	67.21	64.46	62.03	61.69
From Curve, Liquid Limit (%)	63.50			

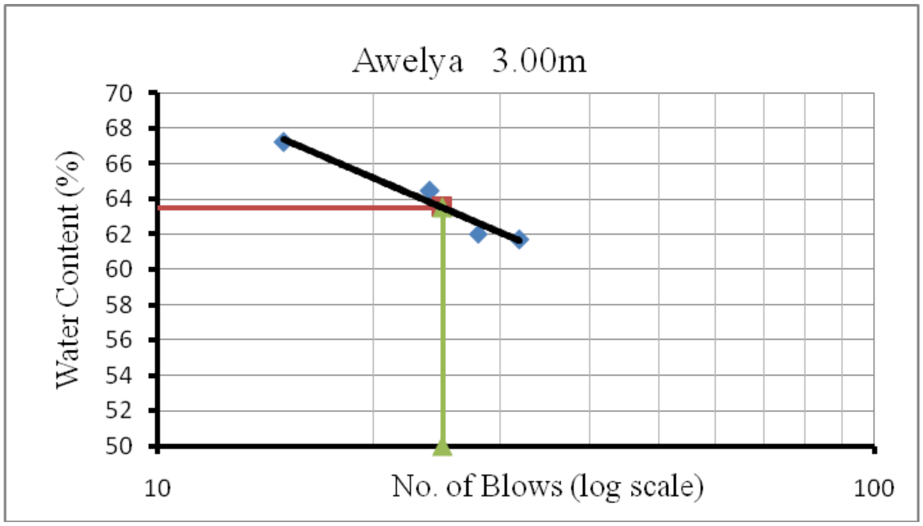


Figure 4.1 Illustration for liquid limit determination from laboratory experiments

4.6. Compaction

Laboratory compaction tests provide the basis for determining the percent compaction and water content needed to achieve the required engineering properties, and for controlling construction to assure the required compaction and water contents. The testing procedure according to ASTM D698-98 is summarized as follows:

A soil at a selected water content was placed in three layers into a mold of given dimensions, with each layer compacted by 25 blows of 24.4kN rammer dropped from a distance of 305mm, subjecting the soil to a total compactive effort of about 600 kN/m^2. The resulting dry unit weight is determined. The procedure was repeated for sufficient number of water contents to establish a relationship between the dry unit weight and the water content.

The values of optimum water content and maximum dry unit weight were determined from the compaction curve. The procedure of computation is illustrated in Table 4.3 as follows.

Table 4.3 Typical steps for calculations of OMC and MDD

Sample Location	Addis Ababa, Shegole site @ 1.50m depth
Sample Description	Red, Fine Grained Soil
Method Test Procedures	ASTM D-698-91
Date Tested	04/04/2011

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of mould & compacted soil (g)	**6910**	**7152**	**7328**	**7315**	**7264**
Weight of compacted soil(g)	1280	1522	1698	1685	1634
Bulk density of compacted soil, ρ_b (g/cc)	1.356	1.612	1.799	1.785	1.731
Container # (for water content)	77	CMC5	22	44	31
Weigh of container, Wc(g)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Weight of container & wet soil, W1(g)	**186.00**	**216.00**	**176.00**	**206.00**	**223.00**
Weigh of container & dry soil, W2(g)	**167.00**	**179.00**	**138.00**	**149.00**	**154.00**
Weight of water Ww = W1-W2(g)	19.00	37.00	38.00	57.00	69.00
Weight of dry soils, Ws = W2-Wc(g)	162.00	174.00	133.00	144.00	149.00
Water Content, w(%) = (Ww/Ws)	11.73	21.26	28.57	39.58	46.31
Dry density, ρ_d (g/cc) = (ρ_b)/(1+w)	1.214	1.330	1.399	1.279	1.183
From Curve, MDD (g/cc)	1.4				
From Curve, OMC (%)	29				

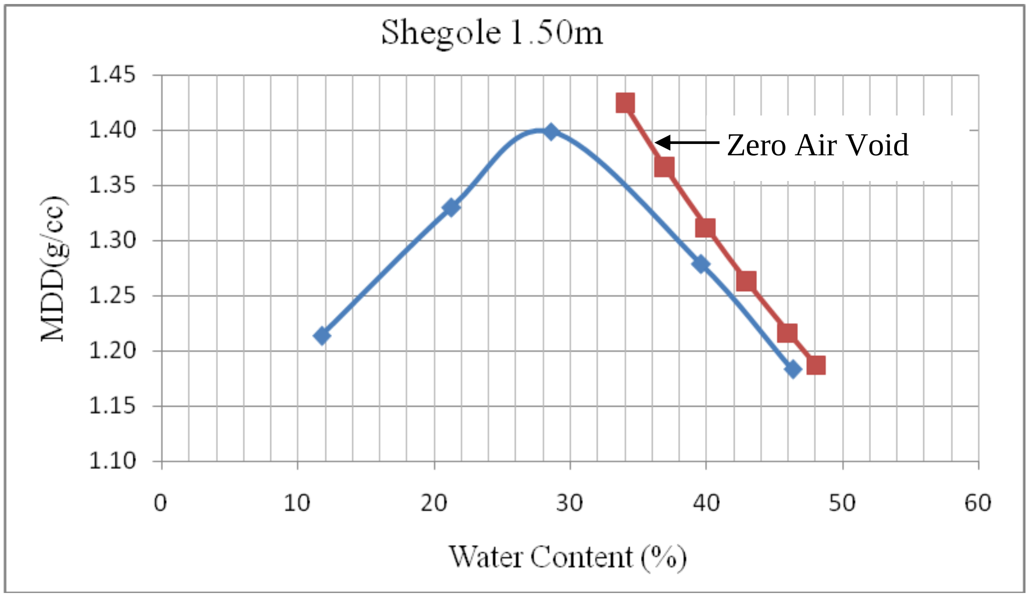


Figure 4.2 Illustration of determination of value of MDD and OMC

These test procedures are only for illustration purpose. All the other results of the laboratory test were performed accordingly. The detail calculations of the other tests are illustrated in appendixes A, B, and C.

4.7. Data Collection

In this study, besides the 20 primary data 110 secondary data were collected and tabulated in Table 4.4 to Table 4.6. The secondary data were collected from different organizations namely: Ministry of water resource and energy (71 data), Addis Ababa City Road Authority (16 data), and Tigray Water Resource and Energy Bureau (23 data). Totally 130 laboratory data were collected and analysis is made to obtain the relationship between Atterberg limits and compaction characteristics.

Both the primary and secondary data are plotted on plasticity chart as shown on Fig. 4.3 and 4.4. The primary data include the laboratory tests such as: Atterberg limits, compaction characteristics, specific gravity, grain size, and free swell. All tests were performed according to the procedures described by ASTM. All tests used in this study are performed on fine-grained soils that encompass Red, Black, Brown, and Grey soils.

Table 4.4 Data obtained from Ministry of Water Resource and Energy

S/N	Grain Size Distribution					Atterberg Limits			Compaction		
	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	FC (%)	LL (%)	PL (%)	PI (%)	MDD (g/cc)	γ_d (kN/m^3)	OMC (%)
1	5.8	33.7	24.6	36.0	60.5	83	46	37	1.115	10.94	42
2		0.9	4.8	94.3	99.1	104	41	64	1.305	12.80	37
3		25.1	5.0	70.0	75.0	54	32	22	1.525	14.96	27
4		16.1	18.9	65.0	83.9	48	31	17	1.530	15.01	25
5		6.8	18.2	75.0	93.2	102	40	62	1.310	12.85	38
6		30.1	7.4	62.5	69.9	46	28	18	1.625	15.94	23
7		6.8	46.7	46.5	93.2	56	29	27	1.495	14.67	28
8		3.4	14.1	82.5	96.6	78	30	48	1.532	15.03	27
9		4.0	39.8	56.2	96.0	68	38	26	1.398	13.71	35
10		1.2	19.8	79.0	98.8	69	39	26	1.405	13.78	37
11	0.9	13.0	44.1	42.0	86.1	74	38	31	1.269	12.45	36
12		3.8	44.2	52.0	96.2	53	32	21	1.420	13.93	30
13		4.7	31.3	64.0	95.3	47	27	20	1.514	14.85	26
14		7.3	5.5	87.2	92.7	93	38	55	1.337	13.12	36
15		5.9	4.0	90.1	94.1	92	41	50	1.259	12.35	37
16		4.0	6.8	89.2	96.0	86	36	49	1.325	13.00	33
17		5.0	75.0	20.0	95.0	33	20	14	1.739	17.06	18
18		5.0	76.1	18.9	95.0	40	21	19	1.697	16.65	20
19	0.0	5.0	75.8	19.2	95.0	34	20	14	1.765	17.31	17
20	0.0	5.0	84.2	10.8	95.0	30	20	10	1.836	18.01	17
21		17.4	64.3	18.3	82.6	34	22	13	1.728	16.95	19
22		22.1	59.3	18.7	78.0	39	26	14	1.510	14.81	25
23		6.3	60.2	33.6	93.7	45	23	21	1.542	15.13	24
24		7.4	59.5	33.1	92.6	49	29	20	1.545	15.16	25
25		12.9	75.3	11.9	87.1	42	27	14	1.477	14.49	26
26		20.8	63.1	16.2	79.2	33	22	11	1.640	16.09	20
27		10.1	42.2	47.7	89.9	51	31	21	1.479	14.51	28
28		1.9	24.5	73.6	98.1	61	36	25	1.383	13.57	32
29		12.3	25.3	62.4	87.7	56	27	28	1.513	14.84	26
30		6.3	53.8	40.0	93.8	51	33	18	1.395	13.68	32
31		5.6	34.4	60.0	94.4	69	30	39	1.480	14.52	26
32		6.1	22.9	71.0	93.9	92	31	61	1.376	13.50	31
33		13.9	48.9	37.3	86.2	45	25	20	1.550	15.21	24
34		7.4	51.9	40.8	92.6	53	28	25	1.458	14.30	28
35		33.0	59.2	7.9	67.0	34	24	10	1.628	15.97	23
36		14.9	52.0	33.1	85.1	50	30	20	1.459	14.31	29
37		6.8	79.2	14.0	93.2	80	41	39	1.248	12.24	39
38		26.2	72.3	1.5	73.8	49	31	18	1.408	13.81	30

Note: LL = Liquid limit, PL = Plastic Limit, PI = plasticity Index, MDD = Maximum Dry Density, γ_d = Maximum Dry Unit weight, OMC = Optimum Moisture Content, FC = Fine Content (passing # 200 sieve)

(Contd…) Data obtained from ministry of water and Energy

	Grain Size Distribution					Atterberg Limits			Compaction		
S/N	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	FC (%)	LL (%)	PL (%)	PI (%)	MDD (gm/cc)	γ_d (kN/m^3)	OMC (%)
39		9.1	76.4	14.5	90.9	52	31	21	1.583	15.53	29
40	17.4	7.4	26.7	48.5	75.2	72	32	38	1.422	13.95	27
41		5.6	70.0	24.5	94.5	70	41	29	1.298	12.73	36
42	9.2	8.0	58.8	24.0	82.8	68	35	33	1.342	13.17	34
43		1.8	19.2	79.0	98.2	84	34	50	1.383	13.57	30
44		1.6	31.7	66.8	98.4	83	38	45	1.298	12.73	32
45		24.8	45.0	30.2	75.2	44	25	19	1.695	16.63	21
46		47.0	30.6	22.5	53.1	46	28	18	1.533	15.04	27
47		11.7	29.8	58.5	88.3	70	31	35	1.376	13.50	28
48		30.6	47.0	22.4	69.4	43	30	13	1.374	13.48	29
49	23.3	8.7	48.1	20.0	68.0	50	29	21	1.488	14.60	27
50		34.1	50.7	15.3	65.9	45	24	21	1.670	16.38	22
51		36.9	51.7	11.4	63.1	59	29	27	1.572	15.42	26
52		17.4	52.2	30.4	82.6	60	36	25	1.343	13.17	33
53	19.4	25.7	35.9	19.0	54.9	43	21	21	1.735	17.02	18
54		5.0	58.0	37.0	95.0	36	21	15	1.728	16.95	18
55	11.0	11.3	45.5	32.3	77.7	78	36	41	1.425	13.98	31
56	8.6	18.6	56.5	16.4	72.9	53	30	23	1.490	14.62	29
57		7.6	53.4	39.0	92.4	63	35	27	1.433	14.06	31
58		5.6	30.7	63.8	94.4	63	36	27	1.413	13.86	33
59		4.0	82.0	14.0	96.0	56	30	26	1.410	13.83	28
60		10.0	76.0	14.0	90.0	46	29	17	1.400	13.73	27
61		15.0	61.0	24.0	85.0	51	28	23	1.480	14.52	28
62		5.0	86.0	9.0	95.0	41	28	13	1.510	14.81	25
63		3.0	62.0	35.0	97.0	79	34	45	1.340	13.15	31
64		11.0	77.0	12.0	89.0	33	23	10	1.570	15.40	21
65		8.0	79.0	13.0	92.0	45	28	17	1.420	13.93	26
66		3.0	76.0	21.0	97.0	76	32	44	1.300	12.75	27
67		4.0	71.0	25.0	96.0	47	27	20	1.410	13.83	26
68		3.0	56.0	41.0	97.0	63	30	33	1.390	13.64	26
69		6.0	76.0	18.0	94.0	57	30	27	1.400	13.73	27
70		6.0	65.0	29.0	94.0	61	30	31	1.350	13.24	29
71		8.0	59.0	33.0	92.0	58	29	29	1.430	14.03	28

Note: LL = Liquid limit, PL = Plastic Limit, PI = plasticity Index, MDD = Maximum Dry Density, γ_d = Maximum Dry Unit weight, OMC = Optimum Moisture Content, FC = Fine Content (passing # 200 sieve)

Table 4.5 Data obtained from Addis Ababa City Road Authority (AACRA)

		Grain Size Distribution			**Atterberg Limit**			**Compaction**		
S/N.	**Area of Sampling**	**<2mm (%)**	**Passing #4 (%)**	**FC (%)**	**LL (%)**	**PL (%)**	**PI (%)**	**MDD (gm/cc)**	**γ_d (kN/m^3)**	**OMC (%)**
1	Terhailoch-Keran.	87	85	82	81	42	39	1.396	13.69	34
2	Jima Ber	98	95	92	53	26	27	1.558	15.28	24
3	Diaspora round	84	79	74	58	35	23	1.491	14.63	32
4	Gabon Embasi	87	85	82	81	42	39	1.396	13.69	34
5	Hana Mariam Br.	99	98	93	74	29	45	1.510	14.81	28
6	Besrate Gebreal	87	83	79	65	33	32	1.473	14.45	29
7	Kazanchese-Gereda	92	89	85	67	34	33	1.463	14.35	29
8	Gerji, Unity University				106	40	52	1.390	13.64	37
9	CMS, Civil Service college				82	36	46	1.435	14.08	33
10	Bole high school				98	44	54	1.264	12.40	40
11	Abware English. Embasy				71	34	37	1.463	14.35	32
12	Repi Quary				33	22	11	1.976	19.38	17
13	Emperial, Gergi	98	85	59	47	25	22	1.520	14.91	23
14	Emperial, Gergi	97	65	34	34	21	13	1.796	17.62	17
15	Asko Sanusi				52	29	23	1.548	15.19	28
16	Asko Sanusi				60	28	32	1.520	14.91	26

Note: LL = Liquid limit, PL = Plastic Limit, PI = plasticity Index, MDD = Maximum Dry Density, γ_d = Maximum Dry Unit weight, OMC = Optimum Moisture Content, FC = Fine Content (passing # 200 sieve),

Table 4.6 Data obtained from Tigray Water Resource and Energy Bureau

S/N.	Fines Cont. (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	OMC (%)	MDD (g/cc)	γ_d (kN/m3)
1	61	32	16	16	14.0	1.89	18.54
2	57	24	18	6	14.0	1.89	18.54
3	80	42	21	21	20.5	1.67	16.38
4	82	51	34	17	30.0	1.39	13.64
5	53	39	18	21	14.0	1.73	16.97
6	60	40	22	18	20.0	1.63	15.99
7	81	41	27	14	23.0	1.46	14.32
8	71	29	18	11	16.0	1.69	16.58
9	75	26	16	10	14.5	1.84	18.05
10	75	32	18	14	16.0	1.70	16.68
11	54	33	17	16	15.5	1.79	17.56
12	52	31	15	16	14.5	1.84	18.05
13	68	40	18	22	17.0	1.86	18.25
14	57	39	17	22	16.5	1.79	17.56
15	79	40	18	22	16.0	1.74	17.07
16	78	64	34	30	32.7	1.30	12.75
17	95	84	37	47	36.2	1.21	11.87
18	96	89	32	57	31.1	1.25	12.26
19	94	68	33	35	29.8	1.36	13.34
20	84	62	29	33	22.7	1.39	13.64
21	50	40	24	16	18.0	1.75	17.17
22	93	77	27	50	24.8	1.41	13.83
23	87	58	31	27	32.8	1.36	13.34

Note: MDD = Maximum Dry Density, γ_d = Maximum Dry Unit weight , OMC = Optimum Moisture Content,

Table 4.7 Data obtained from laboratory soil testing (part of the study)

			Atterberg Lim.			Compaction				
S/N.	Area of Sampling	FC (%)	LL (%)	PL (%)	PI (%)	OMC (%)	MDD (g/cc)	γ_{dmax} (kN/m^3)	G_S	FS (%)
1	Addisu Gebeya, at 1.50m depth	98	72	31	41	30	1.42	13.93	2.79	45
2	Addisu Gebeya, at 3.00m depth	91	63	29	34	28	1.43	13.98	2.78	40
3	Awelya, 1.50m	94	67	29	39	26	1.53	15.01	2.82	42
4	Awelya, 3.00m	90	64	31	32	29	1.40	13.73	2.80	40
5	Gelan 1.50m	98	98	45	53	40	1.14	11.18	2.66	65
6	Gofa 1.50m	97	80	38	41	35	1.33	12.85	2.77	55
7	Megenagna 1.00m	99	84	40	45	35	1.25	12.26	2.63	140
8	Megenagna 2.00m	98	84	38	46	34	1.28	12.56	2.65	150
9	Kolfe 1.50m	86	62	34	28	30	1.41	13.83	2.68	45
10	Kolfe 3.00m	85	57	34	23	31	1.43	14.03	2.71	40
11	Bole, Imperial Hotel, at 1.50m	99	91	41	50	36	1.23	12.07	2.69	130
12	Bole, Imperial Hotel, 3.00m	99	92	39	53	35	1.24	12.12	2.68	120
13	Shegole, 1.50m	92	62	31	31	29	1.40	13.76	2.76	35
14	Shegole, 3.00m	95	70	30	40	28	1.38	13.54	2.79	30
15	Atari 1.50m	93	68	36	33	33	1.35	13.19	2.87	55
16	Atari 3.00m	96	71	35	37	31	1.34	13.17	2.83	50
17	Summit, soft drink 1.5m	93	92	30	62	29	1.41	13.83	2.69	120
18	Summit, soft drink, at 2.5m depth	99	106	35	71	32	1.36	13.34	2.65	160
19	Bole Millennium Hall, 1.5m depth	97	94	34	60	33	1.31	12.85	2.71	170
20	Bole Millennium Hall, 2.5m dept	98	89	32	57	30	1.39	13.64	2.75	130

Note: LL = Liquid limit, PL = Plastic Limit, PI = plasticity Index, MDD = Maximum Dry Density, γ_d = Maximum Dry Unit weight, OMC = Optimum Moisture Content, G_S = Specific Gravity, FS = Free Swell FC = Fine Content (passing # 200 sieve),

The plasticity Chart

The plasticity chart is a plot of PI and LL (in the ordinate and abscissa respectively) that describes the properties of clay and silt soils in terms of Atterberg limits [10].Thesis chart consist of two lines namely A-line and U-line as shown below. The A-line is assumed to be a boundary between clay and silt soils, whereas the U-line is assumed to be the upper limit of the relationship between PI and LL of fine grained soils, and no soil has so far been found above this line [10].

The chart is also divided in to six regions, three above and three below A-line namely: CL = inorganic Clay of low plasticity, ML = inorganic Silt of low plasticity, OL = Organic clay or silt of low plasticity, CH = inorganic clay of high plasticity, MH = inorganic silt of high plasticity, OH = organic clay or silt of high plasticity.

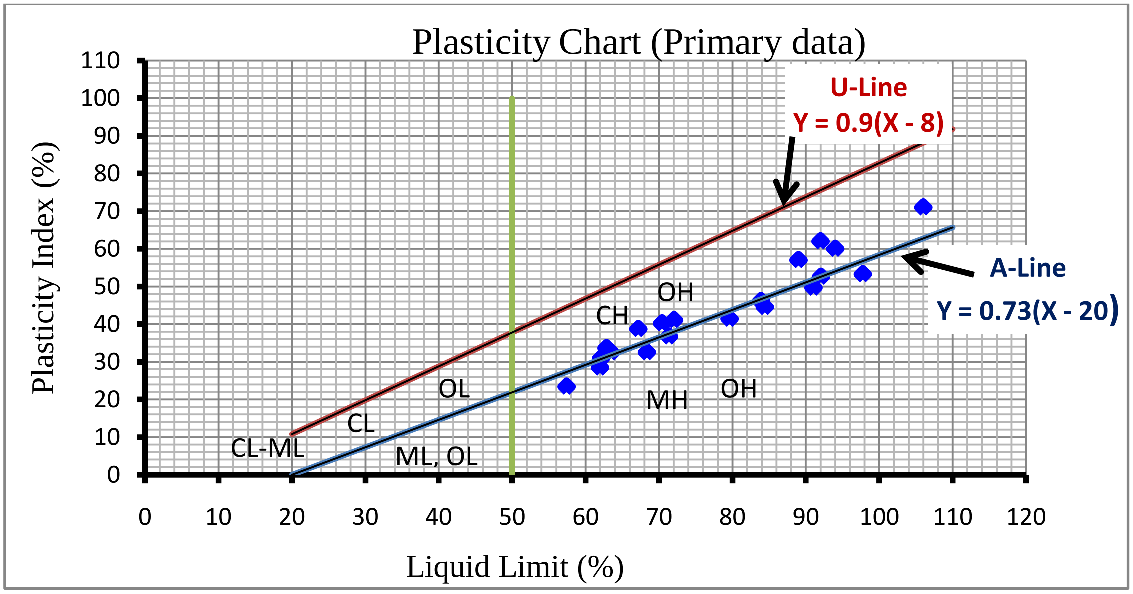


Figure 4.3 Plot of primary data on the plasticity chart

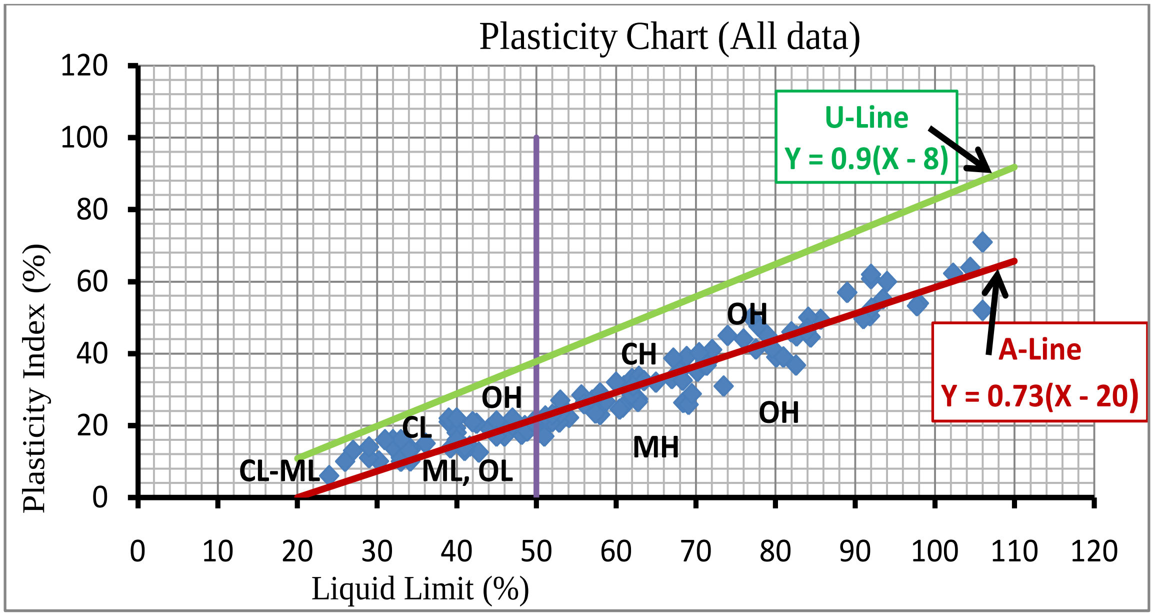


Figure 4.4 Plot of both primary and secondary data on the plasticity chart

Note: CL = inorganic Clay of low plasticity, ML = inorganic Silt of low plasticity, OL = Organic clay or silt of low plasticity, CH = inorganic clay of high plasticity, MH = inorganic silt of high plasticity, OH = organic clay or silt of high plasticity.

As shown in the plasticity chart (Fig. 4.4) for the primary data, most soils are classified as CH or OH, which is high plasticity clay with or without organic content. The remaining other soils are classified as MH or OH which is high plasticity silty soil with or without organic content. On the other hand for all available data (primary and secondary), we can observe that the soil samples cover all types of fine grained soils namely: CL, ML, OL, CH, MH, OH, and CL-ML.

More than half of the soils lie above A-line in the plasticity chart that indicates clay soils, and others lie blew A-line that show silt soils. Considerable amount of soil lie along the A-line which is the boundary of clay and silty soil. In the same way, more than half of the soils have liquid limit value more that 50% that indicate high plasticity soils and the remaining soils have liquid limit value of less than 50% that show low plasticity soils.

5. DATA ANALYSIS, RESULTS AND DISCUSSIONS

5.1. Introduction

The relationship of two or more variables can be expressed in mathematical form by determining an equation connecting the two variables **[22]**. Before obtaining the relations between two or more variables, valid data must be collected that may be obtaining from experiment (primary data) or may be collected from known sources (secondary data). In this work both primary data (20 samples) and secondary data (110 samples) are collected as tabulated in the previous section. In this Chapter analysis have been done to develop possible relationships among the parameters.

5.2. Data Analysis Methods

There are many methods that we can use to check the validity of the relationships between two or more variables **[22]**. However, in this study the two common methods are used, namely: scatter plot and linear regression analysis. Before the application of the analysis methods some important terms are discussed below.

1. **Level of significance:** The probability of making an error to reject a hypothesis while it happens to be true is called the level of significance. In practice it is customary to use 5% level of significance **[22]**. This means that we are 95% confident that we could make the right decision and we could wrong with probability of 5%.

2. **One tailed and two tailed Tests:** When a hypothesis is tested assuming that one process is better or worse than the other, then it is called one tailed or one sided test. However, if the hypothesis is tested assuming that the extreme values of the statistics score on both sides of the mean in both tails of the distribution, the tests are called two tailed or two sided tests.

3. **Standard error:** standard error is the average measure of error of each sample points about the best-fit line. Out of all curves, the best-fit curve has the smallest standard error.

4. **Correlation coefficient(R):** the coefficient of correlation (sometimes called coefficient of regression) is the measures of how well the least-square regression line (best fit line) fits the sample data. Value of R= 1 or -1 (R^2=1) shows that there is a perfect linear correlation and also perfect linear regression. On the other hand R = 0 or approaches to zero shows no valid relationship can be obtained between the variables **[22].**

5.2.1. Scatter Plot and Best-Fit Curve

Generally in analysis procedures, in this work, the value of OMC and γ_{dmax} were considered as the dependent variable where as the Atterberg values (LL, PL, and PI) are the independent (Predictor) variables.

In carrying out the statistical analysis, both the statistical software program called SPSS and MS excel spreadsheet are used to determine the scatter plot, correlation and regression. The MS excel spread sheet is found to be the most powerful and manageable tool for scatter plot analysis and determination of correlation between two variables

However, when determination of the relationships among more than two variables are required (the dependent variable requires two or more independent variables) regression analysis is used and the SPSS software is found to be the most powerful and descriptive tool.

The relationship between the dependent and independent variables are examined separately for the primary data as presented in Figs. 5.1 to 5.6. In addition, Figs. 5.7 to 5.2 show that the scatter plots of the combined secondary and primary data.

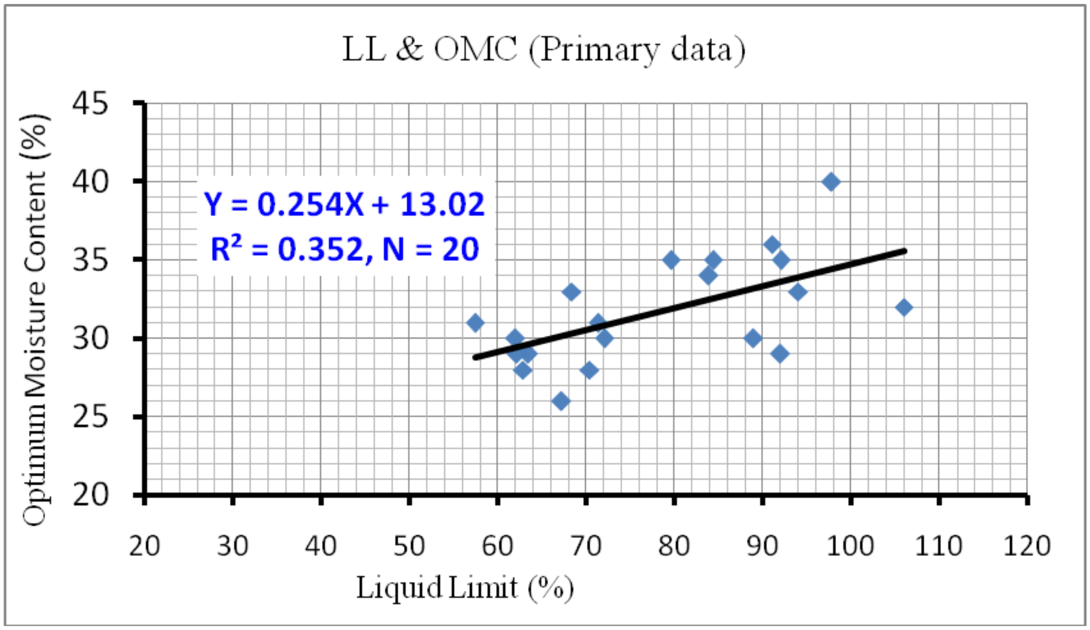


Figure 5.1 Scatter plot and best-fit curve of liquid limit and OMC

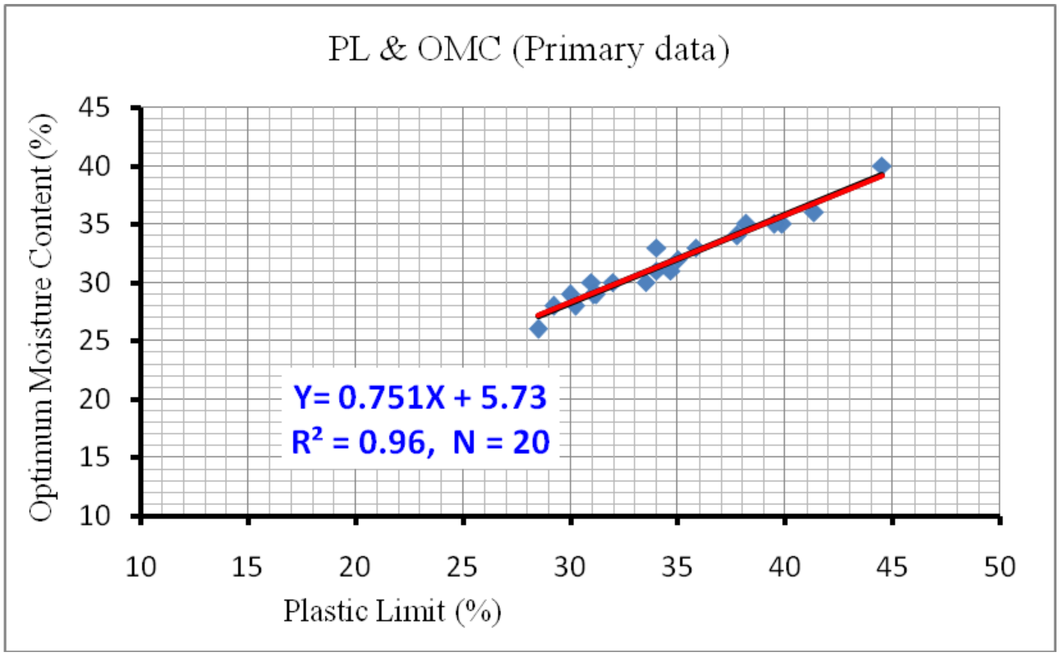


Figure 5.2 Scatter plot and best-fit curve of plastic limit and OMC

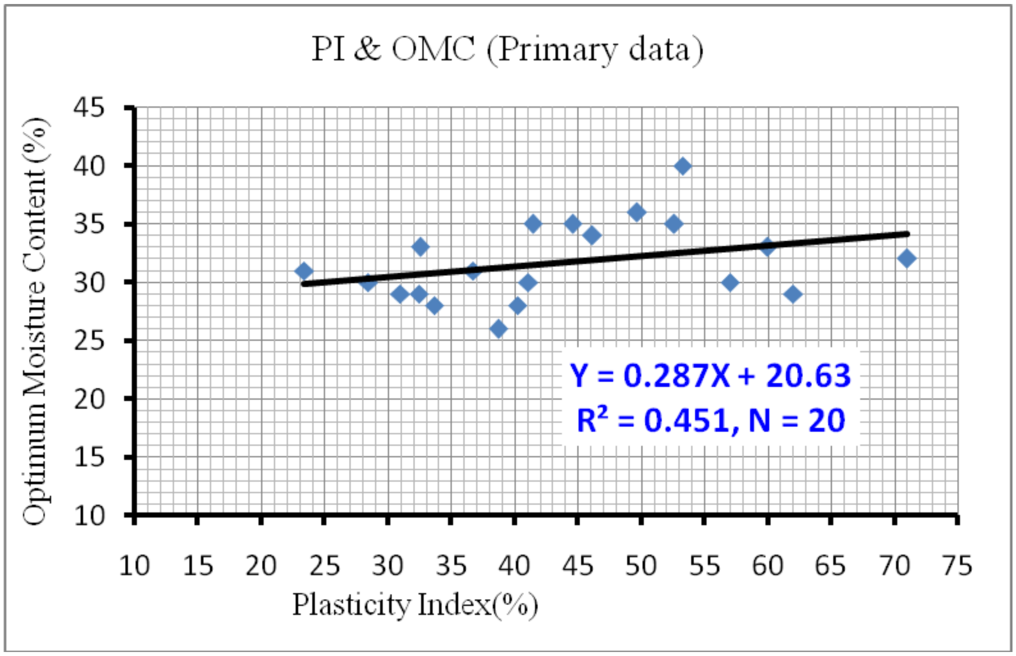


Figure 5.3 Scatter plot and best-fit curve of plasticity index and OMC

In Figure 5.1 to 5.3, the dependent variable is optimum moisture content, and the independent variables are: liquid limit, plastic limit, and plasticity index. Note that in predicting the dependent variable in the regression analysis more than one independent variable may be involved at a time. However in the scatter plot (Figs. 5.1to 5.3), only one independent variable is involved to predict one dependent variable.

The optimum moisture content has strong correlation with plastic limit than the liquid limit and plasticity index. On the other hand, as shown in Fig. 5.3, the relationship between OMC and plasticity index is the weakest of all of the Atterberg limits.

In general, it can be concluded that for preliminary soil investigation the optimum moisture content of fine grained soils, in standard proctor compaction, can be predicted from plastic limits without significant errors.

In the same way, Figure 5.4 and 5.5 also show the scatter plot and the corresponding best fit curve for predicting maximum dry unit weight. In these Figures the dependent variable is the maximum dry unit weight (γ_{dmax}), and the independent variables are liquid limit, plastic limit, and optimum moisture content.

It can be also seen in Fig.5.5 that the plastic limit has good relationship with maximum dry unit weight. Therefore both OMC and γ_{dmax} could be predicted from plastic limit alone with acceptable accuracy, especially for preliminary stage of projects. In addition, γ_{dmax} has the best correlation with OMC than all other parameters. Therefore, γ_{dmax} can be also predicted from OMC more accurately than predicting γ_{dmax} from PL, if incase, value of OMC is available.

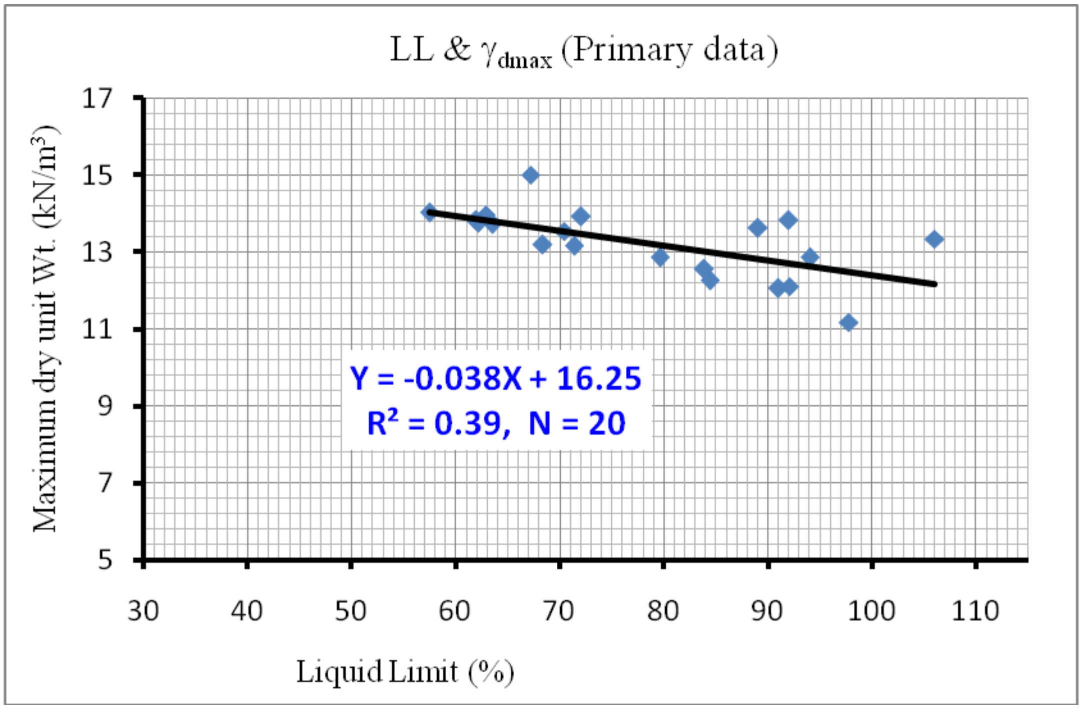


Figure 5.4 Scatter plot and best-fit curve for liquid limit and $\boldsymbol{\gamma}_{dmax}$

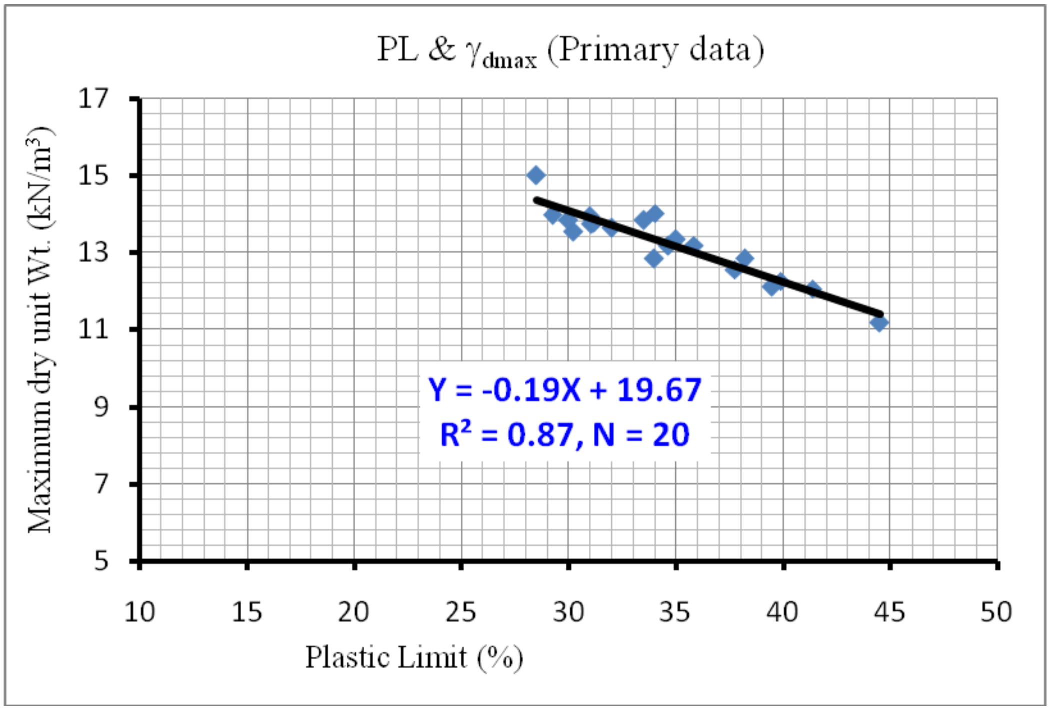


Figure 5.5 Scatter plot and best-fit curve for plasticity limit and γ_{dmax}

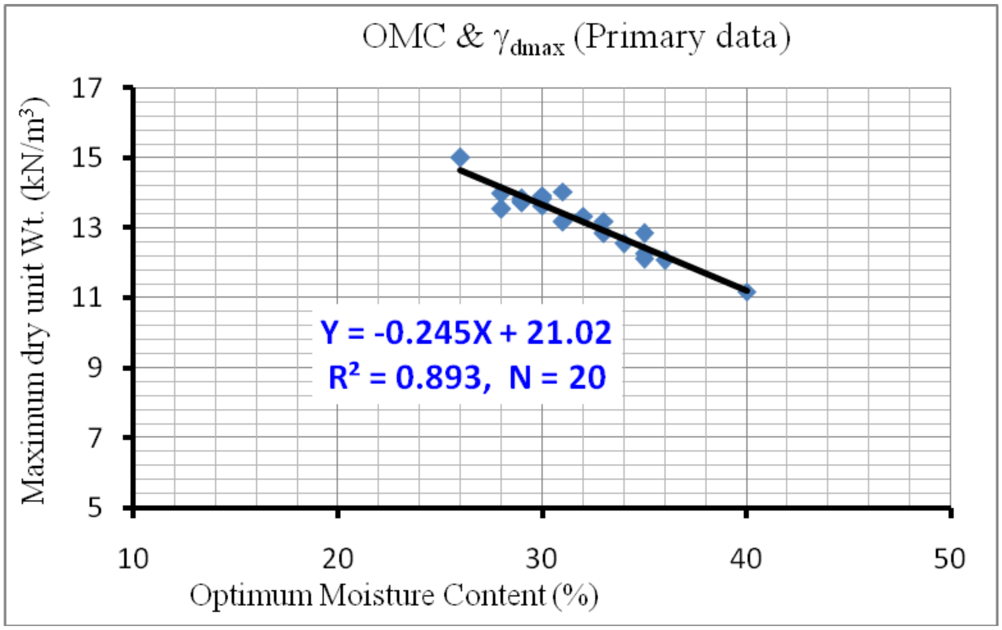


Figure 5.6 Scatter plot and best-fit curve for OMC and γ_{dmax}

The scatter plot and best fit-curve shown in Fig. 5.7 to 5.12 are essentially the same as these plots described in the Fig. 5.1 to 5.6, except the amount of data involved, which are 130 data and 20 data respectively.

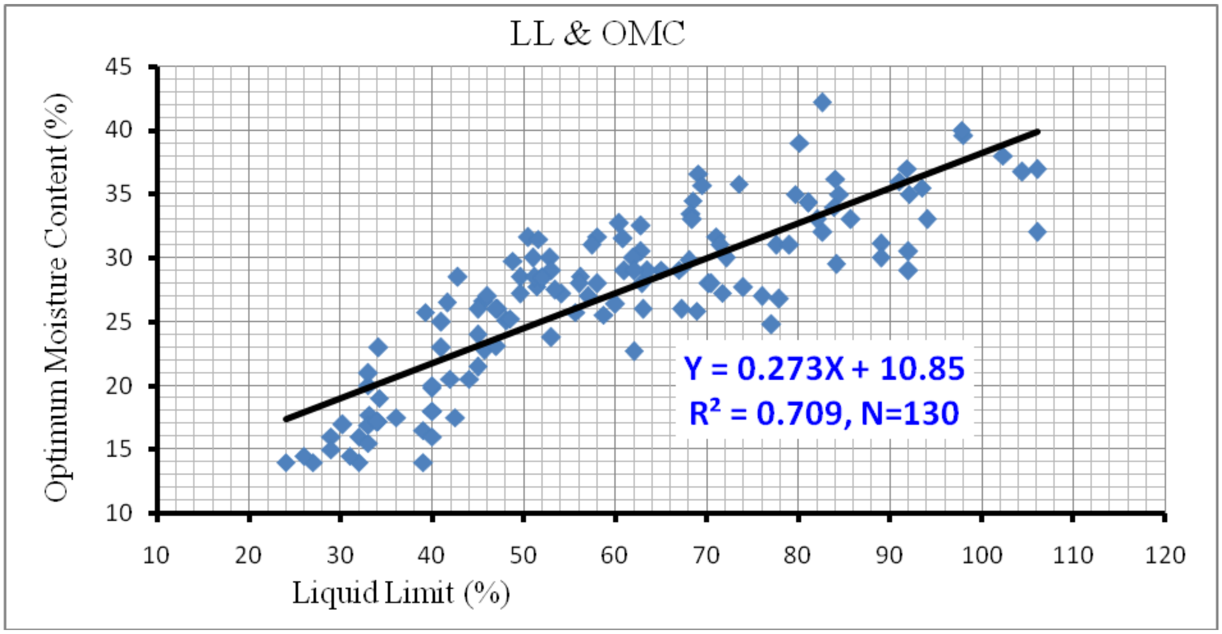


Figure 5.7 Scatter plot and best-fit line for liquid limit and OMC

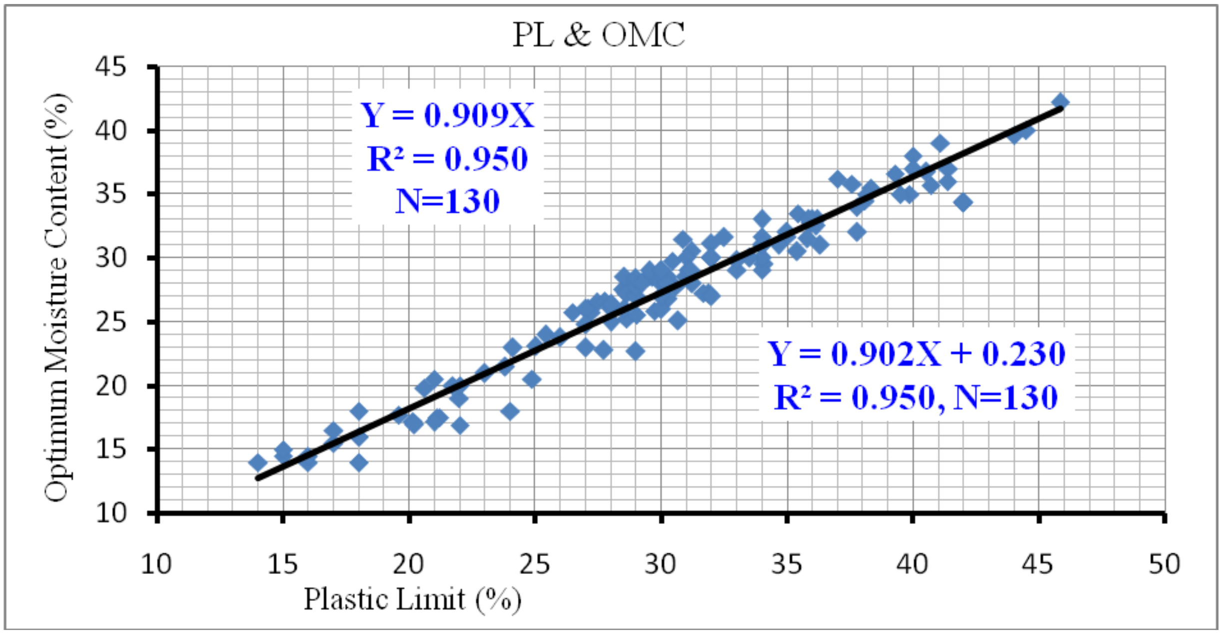


Figure 5.8 Scatter plot and best-fit curve for plastic limit and OMC

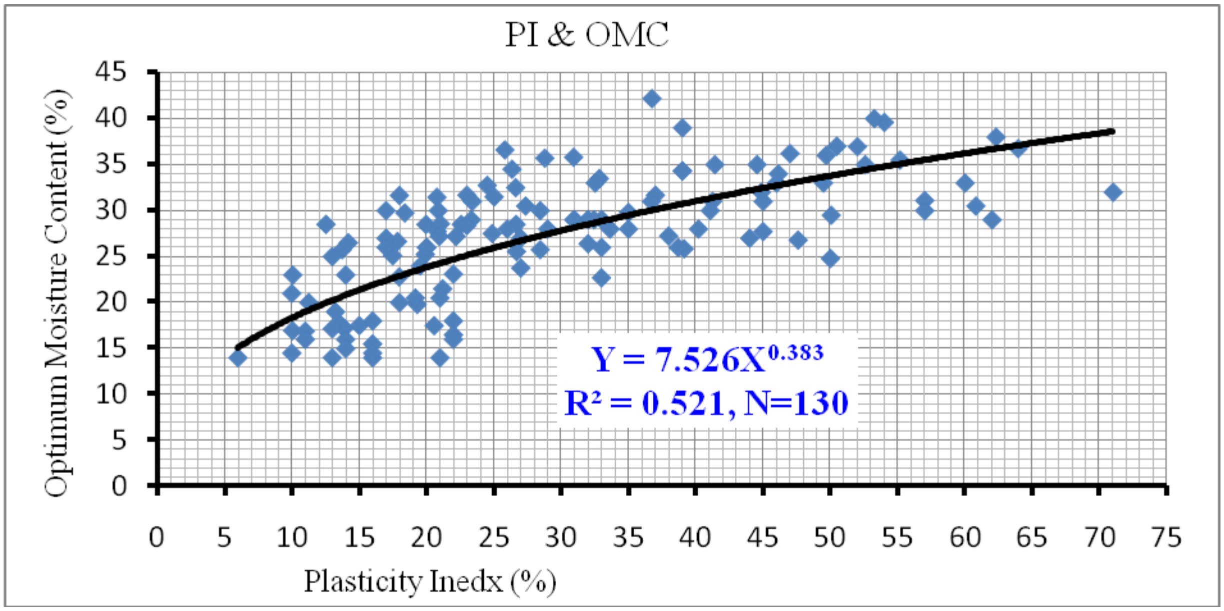


Figure 5.9 Scatter plot and best-fit curve for plasticity index and OMC

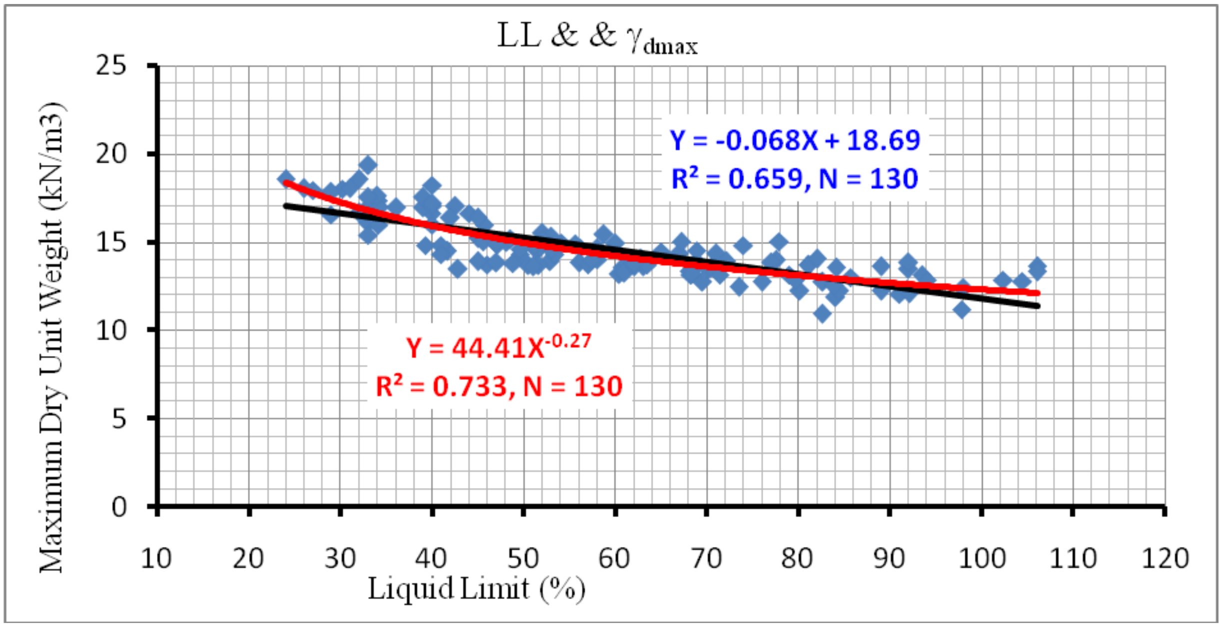


Figure 5.10 Scatter plot and best-fit curve for liquid limit and $\boldsymbol{\gamma}_{\text{dmax}}$

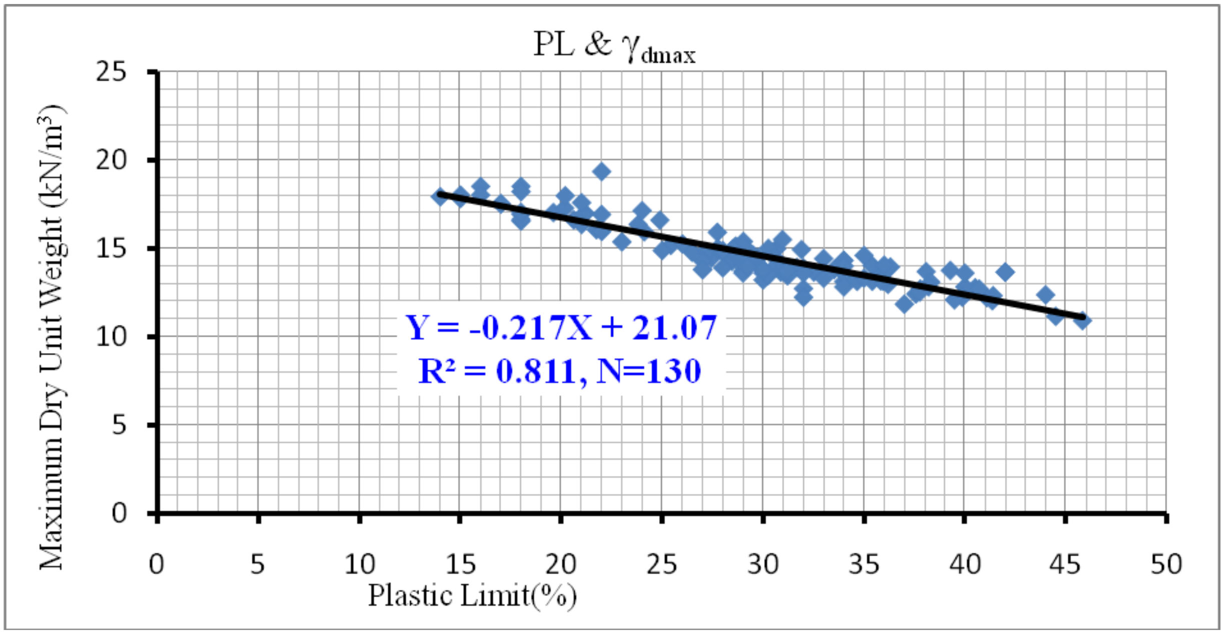


Figure 5.11 Scatter plot and best-fit curve for plastic limit and γ_{dmax}

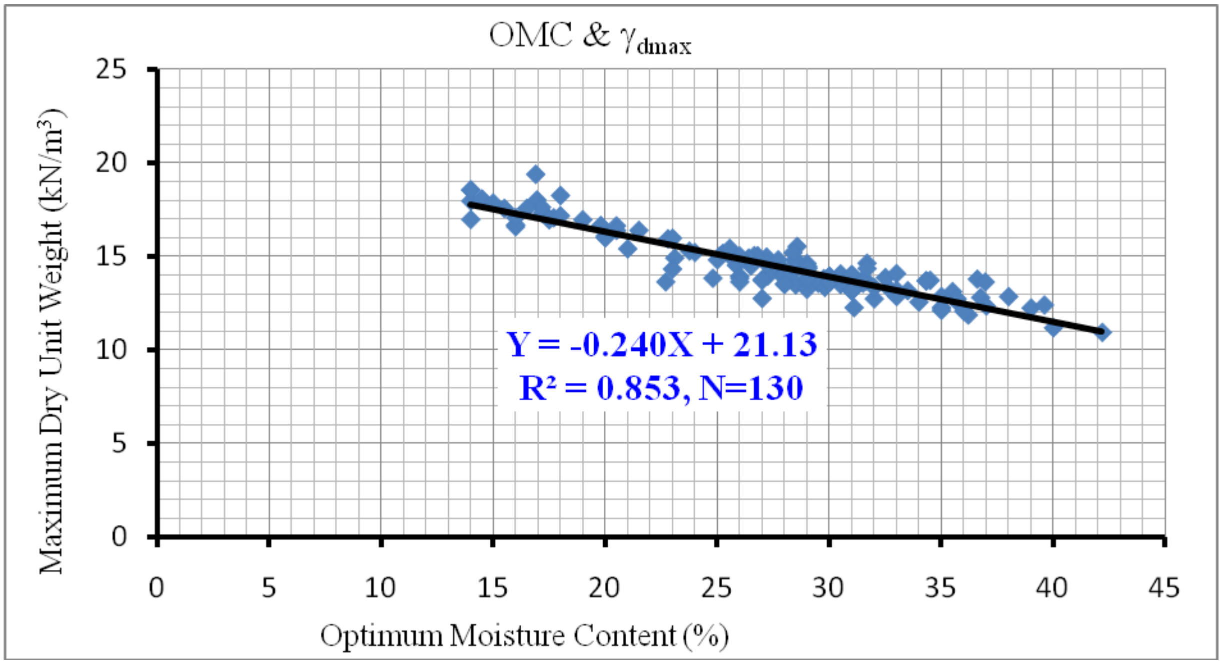


Figure 5.12 Scatter plot and best-fit curve for OMC and γ_{dmax}

From the above scatter plot, it can be clearly seen that the plastic limit (PL) has strong correlation with both OMC and γ_{dmax}. Thus, both OMC and γ_{dmax} could be estimated from PL using the correlation equation. On the other hand PI has the weakest relationship with both OMC and γ_{dmax}.

5.2.2. Regression analysis

Regression analysis is a statistical technique for modeling and investigating the relationship between two or more variables [22]. A variable whose value is predicted is called dependent variable or response. A variable used to predict the value of dependent variable is termed independent or predictor variable. A regression model that contains more than one predictor variable is called multiple regression models. Alternatively, Regression model containing one independent variable is termed as simple regression model.

A number of techniques can be used to indicate the adequacy of a multiple regression model; some of these are standard error and the coefficient of regression (R^2) values. The standard error of a statistic gives some idea about the precision of an estimate.

5.2.3.1 Regression analysis for 20 primary data

In the same way, all the regression analysis have been done and the outputs are tabulated in table form as follows:

i) Prediction of OMC from LL, PL, and PI

- Variable entered: Liquid Limit, Plastic Limit, Plasticity Index, OMC
- Predictors: : Liquid Limit, Plastic Limit, Plasticity Index, & Constant
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient , $R^2 = 0.959$
- Standard Error of the estimates (SE) = 0.686
- Proposed equation:

$$OMC = 0.61LL + 0.12PL - 0.59PI + 5.38 --------- (5.1)$$

Table 5.1 Summary of coefficients in predicting OMC from LL, PL, and PI

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	5.378	1.260		4.268	0.001
LL	0.613	0.286	2.594	2.147	0.047
PL	0.119	0.286	0.155	0.415	0.684
PI	-0.589	0.287	-2.180	-2.054	0.057

ii) Prediction of OMC from LL and PL

- Variable entered: Liquid Limit, Plastic Limit, OMC
- Variables Removed: No variable is removed
- Predictors: : Liquid Limit, Plastic Limit, & Constant
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient , $R^2 = 0.952$
- Standard Error of the estimates (SE): = 0.748
- Linear Equation:

$$OMC = 0.027\,LL + 0.70\,PL + 5.38 ----------(5.2)$$

Table 5.2 Summary of coefficients in predicting OMC from LL & PL

Predictors	Un standardized Coefficients B	Un standardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	5.362	1.374		3.902	0.001
LL	0.027	0.014	0.115	1.941	0.069
PL	0.700	0.045	0.913	15.410	0.000

iii) Prediction of OMC from PL

- Variable entered: Plastic Limit, & OMC
- Predictors: Plastic Limit & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson correlation coefficient , $R^2 = 0.945$
- Standard Error of the estimates (SE): = 0.803
- Linear Equation:

$$OMC = 0.75\,PL + 5.89 -------------(5.3)$$

Table 5.3 Summary of coefficients in predicting OMC from PL

Predictors	Un standardized Coefficients B	Un standardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
(Constant)	5.888	1.447		4.069	0.001
PL	0.746	0.042	0.973	17.976	0.000

iv) Prediction of OMC from LL

- Variable entered: Liquid Limit, & OMC
- Predictors: Liquid Limit & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient , $R^2 = 0.318$
- Standard Error of the estimates (SE): = 2.812
- **Linear Equation:**

$$OMC = 0.14LL + 20.69 \qquad - - - - - - - - - - - - - (5.4)$$

Table 5.4 Summary of coefficients in predicting OMC from LL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	20.695	3.564		5.807	0.000
LL	0.141	0.045	0.595	3.137	0.006

v) Prediction of γ_{dmax} from LL, PL, PI and OMC

- Variable entered: Liquid Limit, Plastic Limit, Plasticity Index, OMC & γ_{dmax}
- Predictors: Liquid Limit, Plastic Limit, Plasticity Index, OMC & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight
- Pearson Correlation coefficient (R) = 0.950, $R^2 = 0.903$
- Standard Error of the estimates (SE): = 0.313
- **Linear Equation:**

$$\gamma_{dmax} = 20.85 - 0.02LL - 0.014PL + 0.015PI - 0.19OMC - - - (5.5)$$

Table 5.5 Summary of coefficients in predicting γ_{dmax} from LL, PL, PI, & OMC

Predictors		Un standardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
	(Constant)	20.847	0.841		24.774	0.000
	LL	-0.021	0.148	-0.347	-0.144	0.888
	PL	-0.014	0.131	-0.073	-0.110	0.914
	PI	0.015	0.147	0.209	0.100	0.922
	OMC	-0.192	0.114	-0.739	-1.680	0.114

vi) Prediction of γ_{dmax} from LL, PL, and OMC

- Variable entered: Liquid Limit, Plastic Limit , OMC & γ_{dmax}
- Predictors: Liquid Limit, Plastic Limit , OMC, & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight
- Pearson Correlation coefficient (R) = 0.950, R^2 = 0.901
- Standard Error of the estimates (SE): = 0.303
- **Linear Equation:**

$$\gamma_{dmax} = 20.70 - 0.007LL - 0.057PL - 0.155OMC \text{ ------}(5.6)$$

Table 5.6 Summary of coefficients in predicting γ_{dmax} from LL, PL & OMC

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	20.696	0.774		26.724	0.000
Liquid Limit	-0.007	0.006	-0.117	-1.168	0.260
Plastic Limit	-0.057	0.075	-0.285	-.755	0.461
OMC	-0.155	0.103	-0.598	-1.508	0.151

vii) Prediction of γ_{dmax} from PL and OMC

- Variable entered Plastic Limit , OMC & γ_{dmax}
- Variables Removed: No variable is removed.
- Predictors: Plastic Limit , OMC, & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight
- Pearson Correlation coefficient (R) = 0.946, R^2 = 0.900
- Standard Error of the estimates (SE): = 0.304
- **Linear Equation:**

$$\gamma_{dmax} = 20.84 - 0.033PL - 0.200MC \text{ ---------}(5.7)$$

Table 5.7 Summary of coefficients in predicting γ_{dmax} from PL & OMC

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	20.837	0.773		26.948	0.000
Plastic Limit	-0.033	0.073	-0.167	-0.455	0.655
OMC	-0.203	0.095	-0.782	-2.129	0.048

viii) Prediction of γ_{dmax} from OMC

- Variable entered OMC & γ_{dmax}
- Predictors: OMC, & Constant (C)
- Dependent Variable: Maximum dry unit Weight (γ_{dmax})
- Pearson Correlation coefficient (R) = 0.945, R^2 = 0.894
- Standard Error of the estimates (SE): = 0.300
- **Linear Equation:**

$$\gamma_{dmax} = 21.03 - 0.25\text{OMC} \quad ------------- (5.8)$$

Table 5.8 Summary of coefficients in predicting γ_{dmax} from OMC

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	21.026	0.636		33.036	0.000
OMC	-0.246	0.020	-0.945	-12.295	0.000

ix) Prediction of γ_{dmax} from PL and LL

- Variable entered: LL, PL & γ_{dmax}
- Predictors: LL, PL, & Constant (C)
- Dependent Variable: Maximum dry unit weight (γ_{dmax})
- Pearson Correlation coefficient (R) = 0.943, R^2 = 0.876

- Standard Error of the estimates (SE): = 0.329
- **Linear Equation:**

$$\gamma_{dmax} = 19.88 - 0.011LL - 0.17PL \quad --------(5.9)$$

Table 5.9 Summary of coefficients in predicting γ_{dmax} from LL & PL

predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	19.876	0.572		34.754	0.000
Plastic Limit	-0.167	0.019	-0.836	-8.766	0.000
Liquid Limit	-0.011	0.006	-0.178	-1.861	0.080

x) Prediction of γ_{dmax} from PL

- Variable entered: PL & γ_{dmax}
- Predictors: PL & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight
- Pearson Correlation coefficient (R) = 0.931, R^2 = 0.849
- Standard Error of the estimates (SE): = 0.353
- **Linear Equation:**

$$\gamma_{dmax} = 19.67 - 0.186PL \quad -----------(5.10)$$

Table 5.10 Summary of coefficients in predicting γ_{dmax} from PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
Constant	19.673	0.599		32.865	0.000
Plastic Limit	-0.186	0.017	-0.931	-10.825	0.000

xi) Prediction of γ_{dmax} from LL

- Variable entered: LL & γ_{dmax}
- Predictors: LL & Constant (C)
- Dependent Variable: Maximum dry unit weight (γ_{dmax})

- Pearson Correlation coefficient (R) = 0.624, R^2 = 0.389
- Standard Error of the estimates (SE): = 0.71
- **Linear Equation:**

$$\gamma_{dmax} = 16.26 - 0.038LL \qquad - - - - - - - - - - - -(5.11)$$

Table 5.11 Summary of coefficients in predicting γ_{dmax} from LL

	Un standardized Coefficients		Standardized Coefficients	
Predictors	B	Std. Error	Beta	t
Constant	16.257	0.904		17.992
Liquid Limit	-0.038	0.011	-0.624	-3.388

Summary of regression analysis (for primary data)

Table 5.12 Summary linear equations and their corresponding R^2 in predicting OMC

S/N	Coefficients of Predictors				Output Equation	R^2	SE
	LL	PL	PI	C			
1	0.614	0.119	-0.59	5.38	OMC = 0.0.614LL+0.119PL - 0.59PI+5.38	0.959	0.686
2	0.027	0.70	-	5.36	OMC = 0.027LL+0.70PL+5.36	0.952	0.748
3	-	0.75	-	5.89	OMC = 0.75PL+5.89	0.945	0.803
4	0.14	-	-	20.69	OMC = 0.14LL+20.69	0.318	2.812

Note: LL = Liquid limit, PL = Plastic Limit, PI = Plasticity index, OMC = Optimum Moisture Content, γ_{dmax} = Maximum dry Unit Weight, C = Constant, R^2 = Coefficient of regression SE = Standard error of estimate

Table 5.13 Linear equations and their corresponding R^2 in predicting $\boldsymbol{\gamma}_{dmax}$

S/N	Coefficients of Predictors					Output Equation (γ_{dmax})	R^2	SE
	LL	PL	PI	OMC	C			
1	-0.02	-0.014	0.015	-0.19	20.85	γ_d = 20.85-(0.02LL+0.014PL +0.19OMC)+ 0.015PI	0.903	0.313
2	-0.007	-0.057	------	-0.155	20.70	γ_d = 20.70-(0.057PL+ 0.007LL+0.155OMC)	0.901	0.303
3	-----	-0.033	---	-0.200	20.84	γ_d = 20.84- (0.033PL+ 0.200OMC)	0.900	0.304
4	-------	------	-----	-0.25	21.03	γ_d = 21.03-0.25OMC	0.894	0.300
5	-0.11	-0.17	-----	-----	19.88	γ_d = 19.88-(0.11LL+0.17PL)	0.876	0.329
6	-------	-0.186	------	-----	19.67	γ_d = 19.88-0.186PL	0.850	0.353
7	-0.038	-----	-----	-----	16.26	γ_d = 16.26-0.038LL	0.389	0.71

Note: LL, PL, PI,OMC, γ_{dmax} , C, R^2, & SE have the same definition as above

5.2.3.2 Regression analysis for all available data (primary and secondary)

a) Prediction of OMC from LL, PL, & PI

- Variable entered: LL, PL, PI & OMC
- Predictors: LL, PL, PI & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient, R^2 = 0.945
- Standard Error of the estimate (SE): = 1.55
- **Linear Equation:**

$$\boldsymbol{OMC = 0.07PL + 0.80LL - 0.05PI + 0.77} \quad ------(5.12)$$

Table 5.14 Summary of coefficients in predicting OMC from LL, PL, & PI

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.766	0.608		1.260	0.210
LL	0.070	0.092	0.215	0.759	0.449
PL	0.798	0.099	0.865	8.040	0.000
PI	-0.051	0.093	-0.111	-0.545	0.587

b) Prediction of OMC from LL and PL

- Variable entered: LL, PL, & OMC
- Variables Removed: No variable is removed.
- Predictors: LL, PL, & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient , $R^2 = 0.946$
- Standard Error of the estimate (SE): = 1.545
- **Linear Equation:**

$$OMC = 0.02\mathrm{LL} + 0.85\mathrm{PL} + 0.73 \quad ---------(5.13)$$

Table 5.15 Summary of coefficients in predicting OMC from LL & PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.731	0.603		1.212	0.228
LL	0.020	0.013	0.062	1.611	0.110
PL	0.849	0.036	0.920	23.817	0.000

c) Prediction of OMC from PL

- Variable entered: PL & OMC
- Predictors: PL & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient, 0.945
- Standard Error of the estimate (SE): = 1.555
- **Linear Equation:**

$$OMC = 0.90\mathrm{PL} + 0.48 \quad -------------(5.14)$$

Table 5.16 Summary of coefficients in predicting OMC from PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	0.483	0.587		0.823	0.412
PL	0.897	0.019	0.972	47.029	0.000

d) Prediction of OMC from LL

- Variable entered: LL & OMC
- Predictors: LL & Constant (C)
- Dependent Variable: Optimum Moisture Content (OMC)
- Pearson Correlation coefficient, $R^2 = 0.705$
- Standard Error of the estimate (SE): = 3.600
- **Linear Equation:**

$$\boldsymbol{OMC = 0.27LL + 11.02 \qquad - - - - - - - - - - - - - - (5.15)}$$

Table 5.17 Summary of coefficients in predicting OMC from PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	11.018	0.980		11.245	0.000
LL	0.273	0.016	0.841	17.571	0.000

e) Prediction of γ_{dmax} from LL, PL, PI, and OMC

- Variable entered: LL, PL, PI, OMC, and (γ_{dmax})
- Predictors: LL, PL, PI, OMC & Constant (C)
- Dependent Variable: Maximum dry unit weight (γ_{dmax})
- Pearson correlation coefficient, $R^2 = 0.856$
- Standard error of the estimate (SE): = 0.656
- **Linear Equation:**

$$\boldsymbol{\gamma_{dmax} = 21.11 + 0.086LL - 0.09PL - 0.10PI - \ 0.22OMC - - - - (5.16)}$$

Table 5.18 Summary of coefficients in predicting γ_{dmax} from LL, PL, PI, &OMC

	Un standardized Coefficients		Standardized Coefficients		
Predictors	B	Std. Error	Beta	t	Sig.
(Constant)	21.105	0.259		81.455	0.000
LL	0.086	0.039	1.016	2.202	0.030
PL	-0.094	0.052	-0.391	-1.822	0.071
PI	-0.099	0.039	-0.833	-2.509	0.013
OMC	-0.217	0.038	-0.830	-5.751	0.000

f) Prediction of γ_{dmax} from LL, PL, and OMC

- Variable entered: LL, PL, OMC & γ_{dmax}
- Predictors: LL, PL, OMC & Constant (C)
- Dependent Variable: maximum dry unit weight (γ_{dmax})
- Pearson correlation coefficient, $R^2 = 0.850$
- Standard error of the estimate (SE): = 0.670
- **Linear Equation:**

$$\gamma_{dmax} = 21.03 - 0.01LL - 0.002PL - 0.21OMC \quad ------(5.17)$$

Table 5.19 Summary of coefficients in predicting γ_{dmax} from LL, PL & OMC

	Un standardized Coefficients		Standardized Coefficients		
Predictors	B	Std. Error	Beta	t	Sig.
(Constant)	21.032	0.263		80.023	0.000
LL	-0.010	0.005	-0.131	-2.018	0.046
PL	-0.002	0.036	0.002	0.010	0.992
OMC	-0.211	0.038	-0.813	-5.521	0.000

g) Prediction of γ_{dmax} from PL and OMC

- Variable entered: PL, OMC & γ_{dmax}
- Predictors: PL, OMC & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight (γ_{dmax})
- Pearson Correlation coefficient, $R^2 = 0.846$
- Standard Error of the estimate (SE): = 0.678

- **Linear Equation:**

$$\gamma_{dmax} = 21.17 - 0.016PL - 0.220MC \quad ------(5.18)$$

Table 5.20 Summary of coefficients in predicting γ_{dmax} from PL & OMC

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	21.173	0.256		82.580	0.000
PL	-0.016	0.036	-0.068	-0.462	0.645
OMC	-0.223	0.039	-0.855	-5.796	0.000

h) Prediction of γ_{dmax} from OMC

- Variable entered: OMC & γ_{dmax}
- Predictors: OMC & Constant (C)
- Dependent Variable: Maximum dry unit weight (γ_{dmax})
- Pearson correlation coefficient, $R^2 = 0.847$
- Standard error of the estimate (SE): = 0.676
- **Linear Equation:**

$$\gamma_{dmax} = 21.16 - 0.240MC \quad ------------(5.19)$$

Table 5.21 Summary of coefficients in predicting γ_{dmax} from OMC

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	21.155	0.252		83.793	0.000
OMC	-0.241	0.009	-0.921	-26.783	0.000

i) Prediction of γ_{dmax} from LL and PL

- Variable entered: LL, PL & γ_{dmax}
- Predictors: LL, PL & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight (γ_{dmax})
- Pearson correlation coefficient, $R^2 = 0.815$
- Standard error of the estimate (SE): = 0.744
- **Linear Equation:**

$$\gamma_{dmax} = \mathbf{20.87 - 0.015LL - 0.18PL} --------(5.20)$$

Table 5.22 Summary of coefficients in predicting γ_{dmax} from LL & PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	20.877	0.290		71.972	0.000
PL	-0.180	0.017	-0.746	-10.490	0.000
LL	-0.015	0.006	-0.181	-2.548	0.012

j) Prediction of γ_{dmax} from PL

- Variable entered: PL & γ_{dmax}
- Predictors: PL & Constant (C)
- Dependent Variable: Maximum Dry Unit Weight (γ_{dmax})
- Pearson correlation coefficient (R) = 0.881, R^2 = 0.807
- Standard error of the estimate (SE): = 0.759
- **Linear Equation:**

$$\gamma_{dmax} = \mathbf{21.10 - 0.22PL} ------------(5.29)$$

Table 5.23 Summary of coefficients in predicting γ_{dmax} from PL

Predictors	Un standardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	21.066	0.286		73.544	0.000
PL	-0.217	0.009	-0.899	-23.273	0.000

Summary of regression analysis (for all primary and secondary data)

Table 5.24 Summary linear equations and their corresponding R^2 in predicting OMC

S.No.	**Coefficients of Predictors**				**Output Equation**	**R^2**	**SE**
	LL	**PL**	**PI**	**C**			
1	-0.19	0.90	0.033	1.09	OMC = 0.90PL-0.19LL+0.033PI+1.09	0.913	1.93
2	0.014	-0.86	-----	1.11	OMC = 0.014LL-0.86PL+1.11	0.913	1.92
3	-----	0.895	-----	0.968	OMC = 0.895PL+0.968	0.913	1.92
4	0.27	-----	-----	11.55	OMC = 0.270LL+11.55	0.658	3.81

Note: LL = Liquid limit, PL = Plastic Limit, PI = Plasticity index, OMC = Optimum Moisture Content, γ_{dmax} = Maximum dry Unit Weight, C = Constant, R^2 = Coefficient of regression
SE = Standard error of estimate

Table 5.25 Summary of linear equations and their corresponding R^2 in predicting γ_{dmax}

S.No.	**Coefficients of Predictors**					**Output Equation, γ_{dmax} =**	**R^2**	**SE**
	LL	**PL**	**PI**	**OMC**	**C**			
1	0.086	-0.094	-0.10	-0.22	21.11	γ_{dmax} = 21.11+0.086LL-(0.094PL+ 0.10PI+0.22OMC)	0.847	0.655
2	-0.011	-0.002	-----	-0.21	21.03	γ_{dmax} = 21.03-(0.011LL+0.002PL +0.21OMC)	0.840	0.667
3	------	-0.016	------	-0.22	21.17	γ_{dmax} = 21.17-(0.016PL+0.22OMC)	0.831	0.685
4	------	------	------	-0.24	21.16	γ_{dmax} = 21.16-0.24OMC	0.830	0.686
5	-0.015	-0.018	-----	-----	20.87	γ_{dmax} = 20.87-(0.015LL+0.018PL)	0.790	0.763
6	-----	-0.22	-----	-----	21.10	γ_{dmax} = 21.10-0.22PL	0.777	0.784
7	-0.036	------	-----	------	16.54		0.36	1.92

Note: LL = Liquid limit, PL = Plastic Limit, PI = Plasticity index, OMC = Optimum Moisture Content, γ_{dmax} = Maximum dry Unit Weight, C = Constant, R^2 = Coefficient of regression
SE = Standard error of estimate

5.3. Discussions

Table 5.24 shows the summarized results of the regression analysis in predicting the optimum moisture content from the corresponding Atterberg limits. In the same way Table 5.25 shows the summarized results of regression analysis in predicting maximum dry unit weight from the Atterberg limits. An attempt is made to obtain which one of the predictors can be strongly related with dependent variables. This has been done in two options; the first option was to analyze the relationship between the predictors and the dependent variable one by one interchangeably. The second option was done to predict the OMC and γ_{dmax} from two or more independent variables.

In the first option it has been found that the OMC has a strong correlation with plastic limit and weakest correlation with plasticity index. In addition, the maximum dry unit weight has also has strong correlation with the plastic limit than the other Atterberg limits. Thus, both OMC and γ_{dmax} have good relationship with plastic limit that the liquid limit and plasticity index and, therefore, one can conclude that both OMC and γ_{dmax} can be predicted from the correlation equations without significant errors. However, it should be noted that the maximum dry unit weight has strongest correlation with optimum moisture content than all other parameters.

The result of the statistical analysis, in the second option, shows that as the number of predictor variable increases, the value of regression coefficient increases slightly. In the summary, Table 5.25, we can observe that if the number of independent variables decreases from four variables (LL, PL, PI, and OMC) in to two variables (PL & OMC), and then in to one variable (OMC) the value of regression coefficient decreases slightly from $R^2 = 0.847$ to $R^2 = 0.831$, and to $R^2 = 0.830$.

In this case, the output shows that the liquid limit and the plastic limits have strong correlations with both OMC and γ_{dmax}. However, γ_{dmax} has better correlation with the Plastic limit and OMC than LL & PL. Therefore, if one wants to predict the γ_{dmax} from two independent variables of Atterberg limits, first the OMC must be predicted from LL and PL, and then the γ_{dmax} should be computed from the known values of OMC & PL.

If the number of independent variables is further decreased to only one, the coefficient of regression (R^2) remains almost the same with very small changes from $R^2 = 0.831$ for two independent variables to $R^2 = 0.83$ for only one independent variable.

Therefore, it is recommended that both OMC and γ_{dmax} should be predicted from one independent variable (from plastic limit) without significant reduction in the correlation coefficient, instead of using two or more independent variable, since the value of regression coefficient is almost the same in both cases.

When soil is compaction at low water content, the soil is stiff and has more void space resulted in lower dry unit weight. If the water content is increases excessively, the space that might have been occupied by solid particles is occupied by water and also resulted in lower dry unit weight.

However, if the soil is compaction at OMC the soil particles get lubricated and move easily in to close state position and the corresponding dry unit weight is higher. This specific water content (OMC) of fine grained soil is very close to PL. in addition, as the fine content of soil increases, both OMC and PL are increased but γ_{dmax} is reduced. This condition might be the possible reason that the OMC and γ_{dmax} have good correlations with plastic limit.

6. CONCLUSIONS AND RECOMMENDATIONS

Based on the analysis of data obtained from laboratory soil testing and secondary data collection, the following Conclusions and Recommendations are drawn.

6.1. Conclusions

1. Both Optimum Moisture Content (OMC) and maximum dry unit weight (γ_{dmax}) of fine-grained soils have better correlations with plastic limit than with liquid limit and plasticity index of soils.

2. The maximum dry unit weight has satisfactory correlation with plastic limit and best relationship with optimum moisture content. Therefore, both OMC and γ_{dmax} of fine grained soils can be predicted from plastic limit especially for prefeasibility study of projects.

3. The main objective of this thesis was to obtain valid relationships between Atterberg limits and compaction characteristics of fine-grained soils. However, as additional information, a very strong correlation between liquid limit and plasticity index has been obtained. Therefore, plasticity index and then plastic limit can be computed from known value of liquid limit by the correlation equations.

6.2. Recommendations

The result of this study is limited to correlation of Atterberg limits with compaction characteristics for fine-grained soils at standard compactive energy. However, when soil is compacted at different applied energy the resulting correlation with Atterberg limits may vary greatly. For a given soil, as the compaction energy changes the OMC also changes, but the plastic limit remains the same. Thus, the correlation equation of OMC and PL varies.

Therefore, this work can farther be extended to correlate the Atterberg limits with different compaction energies such as modified Proctor test, reduced Proctor test, and modified reduced Proctor test.

7. LIST OF REFERENCES

1. Alemayehu, Teferra and Mesfin, Leikun (2009). Soil Mechanics. AAU press, 2nd ed. Addis Ababa
2. Amer Ali, Al-Rawas, and Mattheus, F.A.G.(2006). Expansive Soils. Taylor & Francis, London, UK
3. Arora, K.R. (2004). Soil Mechanics and Foundation Engineering. NAI SARAK, 6th ed.New Delhi
4. ASTM (1998). Annual Book of ASTM Standards on Soils and Rocks.
5. Aysen, A. (2002). Soil mechanics. The University of Queensland, Australia.
6. Dessalegn Sissay (2003). Compuation of Soil Compressibility using Tangent Modulus approach
7. Habtamu Kassahun, (2006). Examining Atterberg Limits for Expansive Soils. MSc Thesis, Addis Ababa University, Addis Ababa.
8. Military Soils Engineering, (1997). Field Manual 5-410, Department of the Army, Washington DC
9. Mittal,S. and Shukla, J.P, (2009). Soil Testing for Engineers, 5th ed. Khanna Publishers, New Delhi, india.
10. Murthy, V.N.S. (2007). Geotechnical Engineering, Principles and Practice of Soil Mechanics and Foundation Engineering. Marcel Dekker, INC, New York
11. Nagaraj H.B. (2000). Prediction of Engineering properties of Fine-Grained Soils from their index properties. PhD Thesis, Indian institute of Science, India.
12. Nigel, R .Wightman (2009) The State of Compaction: the Effect of Compaction on Soil Properties and Slope Fill Performance. Maunsell Geotechnical Services, Hong Kong
13. Pandian, N. S., Nagaraj, T. S. and Manoj, M. (1997). Re-examination of compaction characteristics of fine-grained soils. Indian Institute of Science, India.
14. Raymond, G.P. (1997). Geotechnical Engineering. Unified Soil Classification.
15. Robert, L., Parsons and Derek, H. Foster (2000), Compaction and Settlement of Existing Embankments. University of Kansas, Lawrence, Kansas
16. Sivrikaya, O. and Soycan, Y.T. (2009). Estimation of compaction parameters of fine-grained soils using Artificial Neural Networks. 2nd International Conference on New Developments in Soil Mechanics and Geotechnical Engineering. Near East University, Nicosia, North Cyprus.
17. Sivrikaya, O. Togrol, E. and Kayadelen, C. (2008). Estimating compaction behavior of fine-grained soils based on compaction energy, Canadian Geotechnical Journal.

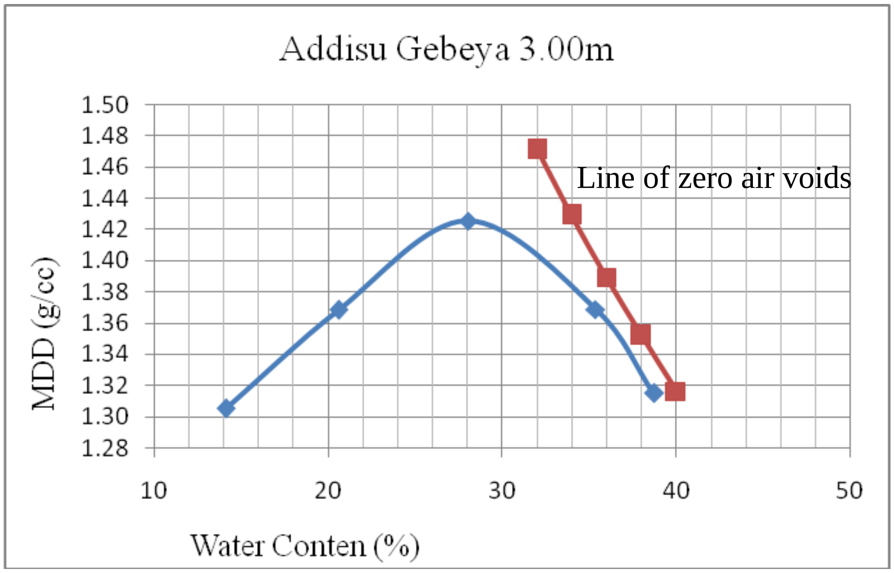
18. Sridharan, A. and Nagaraj, H.B. (2005). Plastic limit and compaction characteristics of fine-grained soils. Journal of Ground Improvement, Indian Institute of Science.
19. Terzaghi, K. (1943). Theoretical Soil Mechanics. John Wiley and Sons INK. London Uk
20. US Army Corps of Engineers (1970). Laboratory soils testing. Engineer Manual, Dept. of the Army, Washington, D.C.
21. Yesim Gurtugand Sridharan, A. (2004). Compaction Behavior and Prediction of its Characteristics of Fine Grained Soils with Particular Reference to Compaction Energy. Journal of Soil and Foundation, Japanese geotechnical Society.
22. Zelalem Worku (2010). Prediction of California Bearing Ratio (CBR) Value from Index Properties of Soil. MSC Thesis, Addis Ababa University, Addis Ababa.

8. LIST OF APPENDIXES

Appendix A: Method of Computation for Compaction Characteristics

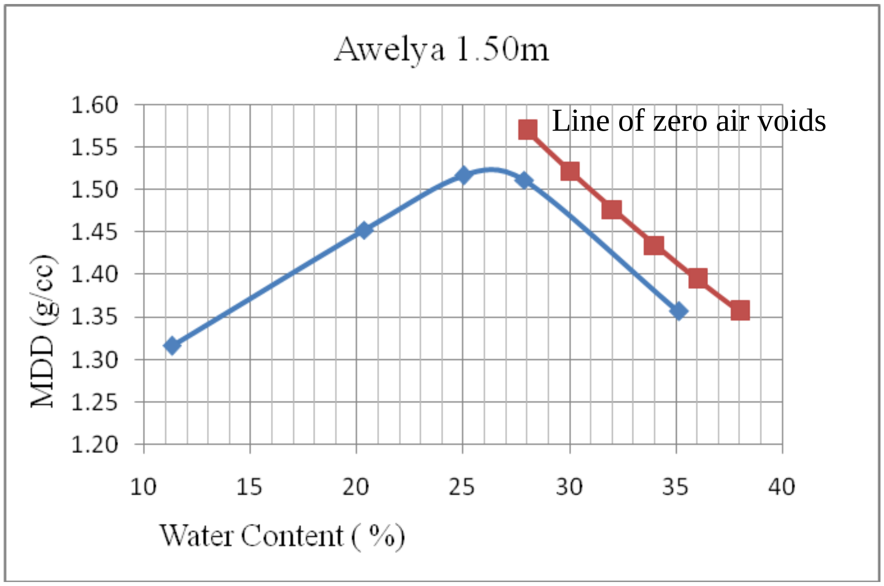
Sample Location	**Addis Ababa, Addisu Gebeya @ 3.00m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D-698-91**

	Test Trials				
Description	**1**	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	**7037**	**7189**	**7354**	**7380**	**7353**
Weight of Compacted soil (g)	1406	1558	1723	1749	1722
Bulk Unit wt. of Compacted soil (γ_b) (g/cc)	1.489	1.650	1.825	1.853	1.824
Container # (for water content)	77	CMC-5	100	34	15
Weigh of container, Wc (g)	5.00	5.00	5.00	5.00	5.00
Weight of container & wet soil, W_1 (g)	215.00	204.00	215.00	227.00	245.00
Weigh of container & dry soil, W_2 (g)	189.00	170.00	169.00	169.00	178.00
Weight of water $Ww = W1-W_2$ (g)	26.00	34.00	46.00	58.00	67.00
Weight of dry soils, $Ws = W_2-Wc$ (g)	184.00	165.00	164.00	164.00	173.00
Water Content, $w = (Ww/Ws)$ (%)	14.13	20.61	28.05	35.37	38.73
Dry Unit Weight $= (\gamma_b)/(1+w)$ (g/cc)	1.305	1.368	1.425	1.369	1.315
From Curve, MDD (g/cc)	1.43				
From Curve, OMC (%)	28				



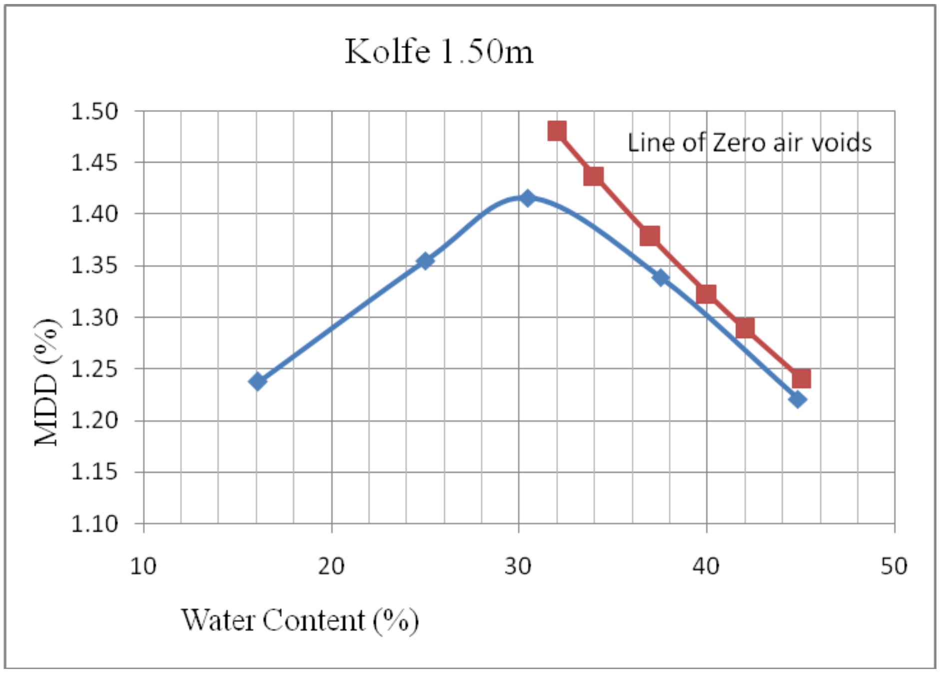
Sample Location	**Addis Ababa, Awelya site @ 1.50m depth**
Sample Description	**Bright-Red, Fine Grained Soil**
Method Test Procedures	**ASTM D-698-91**

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	**7014**	**7281**	**7421**	**7455**	**7362**
Weight of Compacted soil (g)	1383	1650	1790	1824	1731
Bulk Unit Wt. of Compacted soil (γ_b) g/cc)	1.465	1.748	1.896	1.932	1.834
Container # (for water content)	CMC-5	77	100	34	30
Weigh of container, Wc (g)	5.00	5.00	5.00	5.00	5.00
Weight of container & wet soil, W1 (g)	192.00	212.00	235.00	207.00	232.00
Weigh of container & dry soil, W2 (g)	173.00	177.00	189.00	163.00	173.00
Weight of water Ww = W1-W2 (g)	19.00	35.00	46.00	44.00	59.00
Weight of dry soils, Ws = W2-Wc (g)	168.00	172.00	184.00	158.00	168.00
Water Content, w = (Ww/Ws) (%)	11.31	20.35	25.00	27.85	35.12
Dry Unit Weight = (γ_b)/(1+w) (g/cc)	1.316	1.452	1.517	1.511	1.357
From Curve, MDD (g/cc)	1.53				
From Curve, OMC (%)	26				



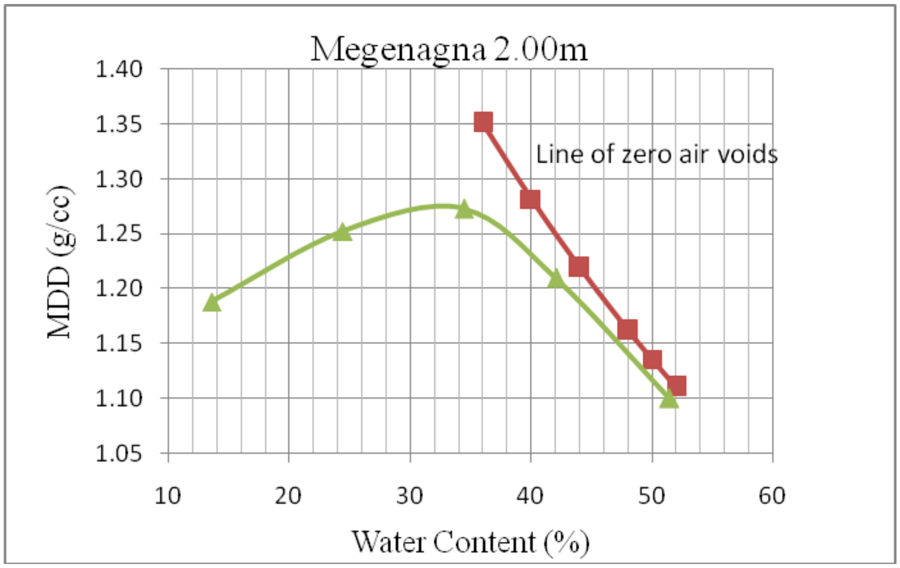
Sample Location	**Addis Ababa, Kolfe site @ 1.50m depth**
Sample Description	**Dark-Red, Fine Grained Soil**
Method Test Procedures	**ASTM D-698-91**

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	6987	7230	7375	7369	7300
Weight of Compacted soil (g)	1356	1599	1744	1738	1669
Bulk Unit weigh of Compacted soil (γ_b)	1.436	1.694	1.847	1.841	1.768
Container # (for water content)	CMC1	22	B3	40	44
Weigh of container, Wc (g)	5.00	5.00	5.00	5.00	5.00
Weight of container & wet soil, W1 (g)	207.00	220.00	220.00	181.00	215.00
Weigh of container & dry soil, W2 (g)	179.00	177.00	169.78	133.00	150.00
Weight of water Ww = W1-W2 (g)	28.00	43.00	50.22	48.00	65.00
Weight of dry soils, Ws = W2-Wc (g)	174.00	172.00	164.78	128.00	145.00
Water Content, w = (Ww/Ws) (%)	16.09	25.00	30.48	37.50	44.83
Dry Unit Weight = (γ_b)/(1+w) (g/cc)	1.237	1.355	1.416	1.339	1.221
From Curve, MDD (g/cc)	1.42				
From Curve, OMC (%)	30				



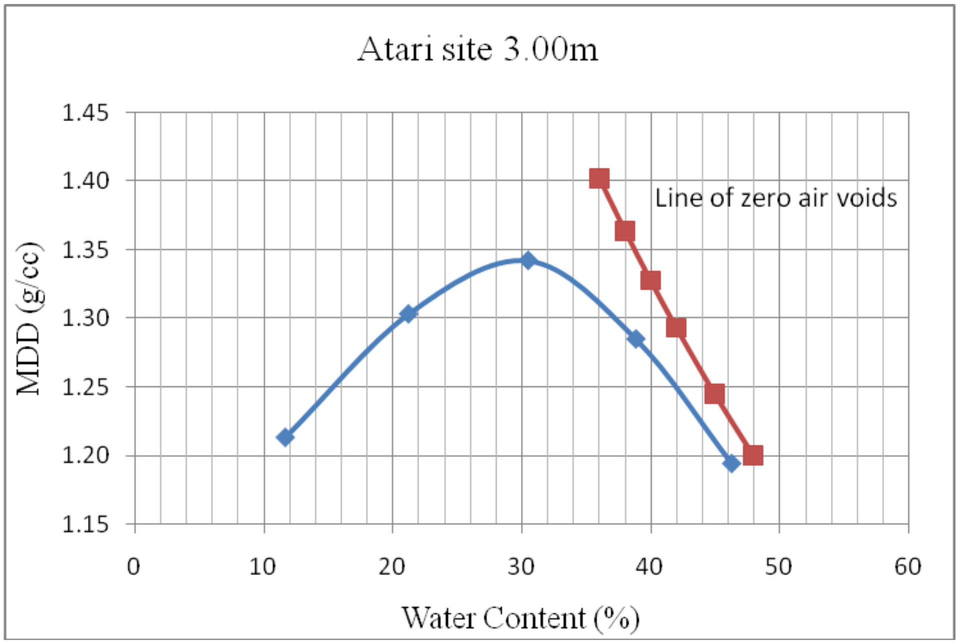
Sample Location	**Addis Ababa, Meganagna @ 2.00m depth**
Sample Description	**Black-Gray Soil**
Method Test Procedures	**ASTM D-698-91**

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	**6905**	**7102**	**7246**	**7253**	**7204**
Weight of Compacted soil (g)	1274	1471	1615	1622	1573
Bulk Unit weigh of Compacted soil (γ_b)	1.350	1.558	1.711	1.718	1.666
Container # (for water content)	36	22	CMC-3	16	78
Weigh of container, Wc (g)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Weight of container & wet soil, W1 (g)	**231.00**	**163.00**	**216.00**	**201.00**	**220.00**
Weigh of container & dry soil, W2 (g)	**204.00**	**132.00**	**162.00**	**143.00**	**147.00**
Weight of water Ww = W1-W2 (g)	27.00	31.00	54.00	58.00	73.00
Weight of dry soils, Ws = W2-Wc (g)	199.00	127.00	157.00	138.00	142.00
Water Content, w = (Ww/Ws) (%)	13.57	24.41	34.39	42.03	51.41
Dry Density = (γ_b)/(1+w) (g/cc)	1.188	1.253	1.273	1.210	1.101
From Curve, MDD (g/cc)	1.28				
From Curve, OMC (%)	34				



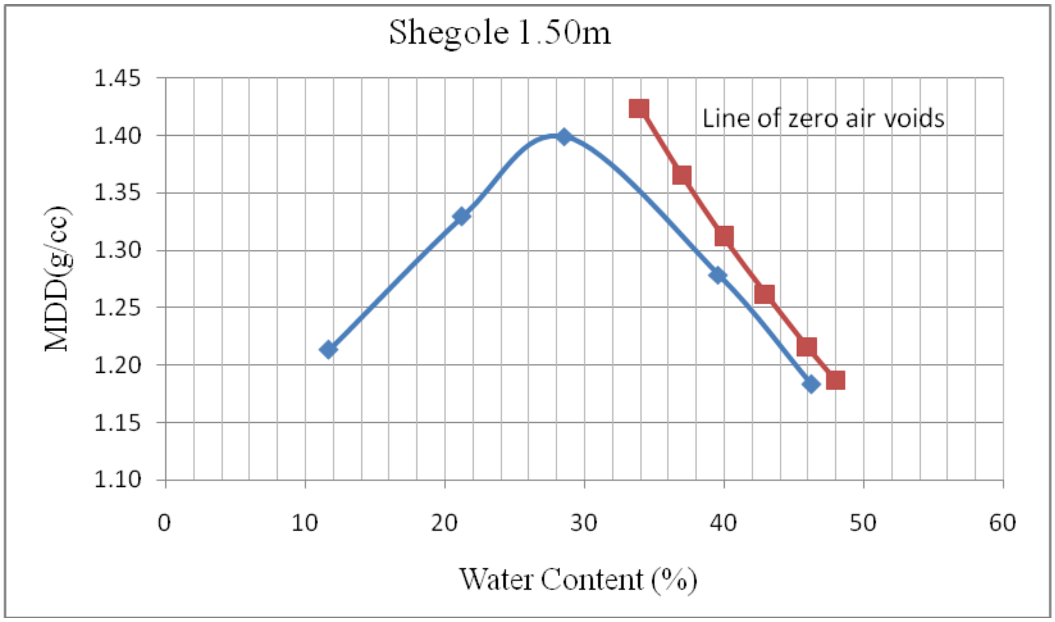
Tested date	04/04/2011
Sample Location	Addis Ababa, Atari @ 3.00m depth
Sample Description	Red, Fine Grained Soil
Method Test Procedures	ASTM D-698-91

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	6910	7122	7284	7315	7280
Weight of Compacted soil (g)	1280	1492	1654	1685	1650
Bulk Unit weigh of Compacted soil (γ_b)	1.356	1.581	1.752	1.785	1.748
Container # (for water content)	31	CMC5	44	22	77
Weigh of container, Wc (g)	5.00	5.00	5.00	5.00	5.00
Weight of container & wet soil, W1 (g)	186.00	216.00	176.00	205.00	223.00
Weigh of container & dry soil, W2 (g)	167.00	179.00	136.00	149.00	154.00
Weight of water Ww = W1-W2 (g)	19.00	37.00	40.00	56.00	69.00
Weight of dry soils, Ws = W2-Wc (g)	162.00	174.00	131.00	144.00	149.00
Water Content, w = (Ww/Ws) (%)	11.73	21.26	30.53	38.89	46.31
Dry Unit Weight = (γ_b)/(1+w) (g/cc)	1.214	1.303	1.342	1.285	1.195
From Curve, MDD (g/cc)	1.34				
From Curve, OMC (%)	31				



Sample Location	**Addis Ababa, Shegole site @ 1.50m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D-698-91**
Date Tested	**04/04/2011**

Description	**Test Trials**				
	1	**2**	**3**	**4**	**5**
Weight of Mould & Compacted soil (g)	**6910**	**7152**	**7328**	**7315**	**7264**
Weight of Compacted soil (g)	1280	1522	1698	1685	1634
Bulk Unit weigh of Compacted soil (γ_b)	1.356	1.612	1.799	1.785	1.731
Container # (for water content)	77	CMC5	22	44	31
Weigh of container, Wc (g)	**5.00**	**5.00**	**5.00**	**5.00**	**5.00**
Weight of container & wet soil, W1 (g)	**186.00**	**216.00**	**176.00**	**206.00**	**223.00**
Weigh of container & dry soil, W2 (g)	**167.00**	**179.00**	**138.00**	**149.00**	**154.00**
Weight of water Ww = W1-W2 (g)	19.00	37.00	38.00	57.00	69.00
Weight of dry soils, Ws = W2-Wc (g)	162.00	174.00	133.00	144.00	149.00
Water Content, w = (Ww/Ws) (%)	11.73	21.26	28.57	39.58	46.31
Dry Unit Weight = (γ_b)/(1+w) (g/cc)	1.214	1.330	1.399	1.279	1.183
From Curve, MDD (g/cc)	1.40				
From Curve, OMC (%)	29				



Appendix- B: Method of Computation for Atterberg Limits

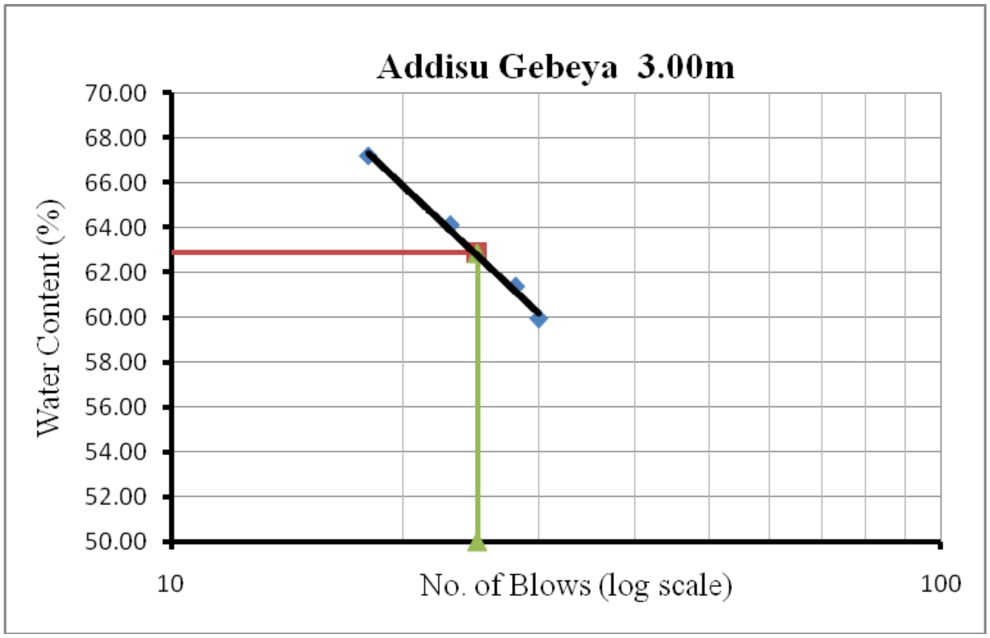
Testing date	**30/01/2011**
Sample Location	**Addis Ababa, Addisu Gebeya @ 3.00m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D 4318-98**

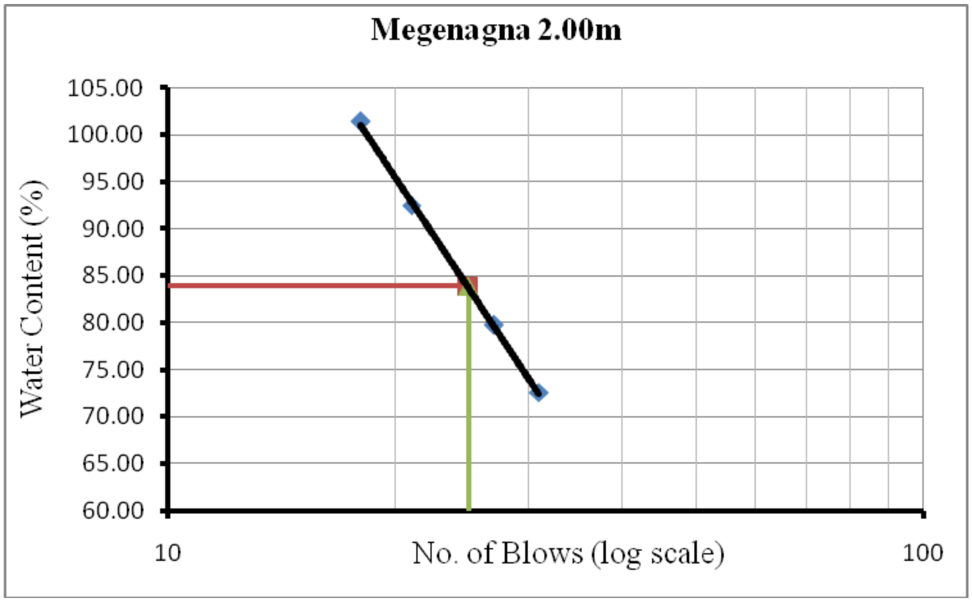
Plastic Limit Determination

	Test Trials		
Description	**1**	**2**	**PI**
Container Number	A-81	12	
Weight of Container, Wc (g)	15.75	15.86	
Weight of container & wet soil, W1 (g)	24.37	27.15	
Weight of Container & dray soil, W2 (g)	22.41	24.61	
Weigh of Water, Ww = W1-W2 (g)	1.96	2.54	
Weigh of dry Soil, Ws = W2-Wc (g)	6.66	8.75	
Water Content (%) = (Ww/Ws)	29.43	29.03	
Average Plastic Limit (%)	29.23		**33.63**

Liquid Limit Determination

	Test Trials			
Description	**1**	**2**	**3**	4
Number of blows, N	23	18	28	30
Container Number,	B-15	C-21	D-18	B-11
Weight of Container, Wc (g)	15.51	14.18	15.67	15.5
Weight of container & wet soil, W_1(g)	37.76	43.86	41.05	40.34
Weight of Container & dray soil. W_2(g)	29.07	31.93	31.4	31.03
Weigh of Water, Ww = W_1-W_2 (g)	8.69	11.93	9.65	9.31
Weigh of dry Soil, Ws = W_2-Wc (g)	13.56	17.75	15.73	15.53
Water Content (%) = (Ww/Ws)	64.09	67.21	61.35	59.95
From Curve, Liquid Limit (%)	**62.86**			





Testing Date	**02/02/2011**
Sample Location	**Addis Ababa, Meganagna @ 2.00m depth**
Sample Description	**Black-Gray Soil**
Method Test Procedures	**ASTM D 4318-98**

Plastic Limit Determination

Description	Test Trials		
	1	2	PI
Container Number	A19	A70	
Weight of Container, Wc (g)	15.66	15.74	
Weight of container & wet soil, W1 (g)	30.52	28.25	
Weight of Container & dray soil, W2 (g)	26.46	24.81	
Weigh of Water, Ww = W1-W2 (g)	4.06	3.44	
Weigh of dry Soil, Ws = W2-Wc (g)	10.80	9.07	
Water Content (%) = (Ww/Ws)	37.59	37.93	
Average Plastic Limit (%)	37.76		**46.13**

Liquid Limit Determination

	Test Trials			
Description	**1**	**2**	**3**	4
Number of blows, N	18	21	27	31
Container Number,	10*	A18	D24	B-15
Weight of Container, Wc (g)	15.77	15.7	15.54	15.54
Weight of container & wet soil, W1 (g)	43.12	44.63	45.3	45.62
Weight of Container & dray soil. W2 (g)	29.35	30.73	32.1	32.97
Weigh of Water, Ww = W1-W2 (g)	13.77	13.9	13.2	12.65
Weigh of dry Soil, Ws = W2-Wc (g)	13.58	15.03	16.56	17.43
Water Content (%) = (Ww/Ws)	101.40	92.48	79.71	72.58
From Curve, Liquid Limit (%)	**83.89**			

Testing date	**26/03/2011**
Sample Location	**Addis Ababa, Shegole @ 1.50m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D 4318-98**

Plastic Limit Determination

Description	Test Trials		
	1	2	PI
Container Number	**22**	**Y3**	
Weight of Container, Wc (g)	**21.34**	**15.70**	
Weight of container & wet soil, W1 (g)	**27.02**	**20.39**	
Weight of Container & dray soil, W2 (g)	**25.67**	**19.27**	
Weigh of Water, Ww = W1-W2 (g)	1.35	1.12	
Weigh of dry Soil, Ws = W2-Wc (g)	4.33	3.58	
Water Content (%) = (Ww/Ws)	31.21	31.16	
Average Plastic Limit (%)	**31.18**		**30.94**

Liquid Limit Determination

Description	Test Trials			
	1	2	3	4
Number of blows, N	26	30	22	16
Container Number,	DEF	A34	53	28
Weight of Container, Wc (g)	15.64	15.63	15.56	15.55
Weight of container & wet soil, W1 (g)	46.71	53.75	42.04	43.67
Weight of Container & dray soil. W2 (g)	34.97	39.77	31.70	31.67
Weigh of Water, Ww = W1-W2 (g)	11.7424	13.9787	10.337	12
Weigh of dry Soil, Ws = W2-Wc (g)	19.3271	24.1409	16.143	16.12
Water Content (%) = (Ww/Ws)	60.76	57.90	64.03	74.44
From Curve, Liquid Limit (%)	**62.12**			

Appendix- C: Method of Computation for Specific Gravity

Testing date	**13/02/2011**
Sample Location	**Addis Ababa, Adisu Gebeyaa @ 3.00m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D 4318-98**

Description	**Test Trials**	
	1	**2**
Pycnometer Bottle Number	P9	Px
Weight empty Pycnometer, Wp (g)	49.45	49.9
Weight Pycnometer and dry soil, W1 (g)	76.27	74.67
Weight of Pycnometer, Soil & water,W2 (g)	166.35	165.45
Weight of Pycnometer full of water, W3 (g)	149.22	149.51
Weigh dry soil, Ws = W1-Wp (g)	26.82	24.77
Weigh of equal volume of displaced water Ww = (W1-Wp)-(W2-W3) (g)	9.69	8.83
Specifig Gravity Gs = (Ws/Ww)	2.77	2.81
Average Specific Gravity Gs	2.79	

Testing date	**13/03/2011**
Sample Location	**Addis Ababa, Awelya @ 1.50m depth**
Sample Description	**Red, Fine Grained Soil**
Method Test Procedures	**ASTM D 4318-98**

Description	**Test Trials**	
	1	**2**
Pycnometer Bottle Number	P13	P32
Weight empty Pycnometer, Wp (g)	49.01	49.62
Weight Pycnometer and dry soil, W1 (g)	76.33	78.1
Weight of Pycnometer, Soil & water,W2 (g)	166.08	167.7
Weight of Pycnometer full of water, W3 (g)	148.54	149.26
Weigh dry soil, Ws = W1-Wp (g)	27.32	28.48
Weight of equal volume of displaced water Ww = (W1-Wp)-(W2-W3) (g)	9.78	10.04
Specifig Gravity Gs = (Ws/Ww)	2.79	2.84
Average Specific Gravity Gs	**2.82**	

Declaration

I, the undersigned, hereby declare that this thesis is my original work and has not been presented for a degree in any other university, and that all sources of material used for this thesis have been duly acknowledged.

Name: Atsbeha Nerea

Signature: ________________

Date: ________________

Advisor: Dr. Hadush Seged