**SCHOOL OF GRADUATE STUDIES**

**JIMMA INSTITUTE OF TECHNOLOGY**

**FACULTY OF CIVIL AND ENVIRONMENTAL ENGINEERING**

**GEOTECHNICAL ENGINEERING STREAM**


# Developing Correlation between Index Properties and Swelling Pressure of Expansive Soils Case of Bishoftu Town

*A Thesis Submitted to Jimma University, School of Graduate Studies in Partial Fulfillment for Degree of Masters of Science in Civil Engineering (Geotechnical Engineering)*


**By: Tigist Mergia**



**June, 2019**

**Jimma, Ethiopia**

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**Advisor: Dr. Ing Samuel Tadesse.**

**Co Advisor: Mohammed Yassin (MSc.)**

**BY:**

**Tigist Mergia**

**June, 2019**

**Jimma, Ethiopia**

# DECLARATION

This thesis titled, **Developing Correlation between Index Properties and Swelling Pressure of Expansive Soils Case of Bishoftu Town** is an original work of mine and has not been presented for a degree in any University. All references used for this research are accredited for and duly acknowledged.

Tigist Mergia

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Approved by:

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Co- advisor: Mohammed Yassin (MSc.)

Signature _________________ date __________________

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*This Academic scholarship would not have been possible without the financial support of Ethiopian Road Authorities for this I also want to extend my gratitude for the program and at last but not least I want to thank all JIT geotechnical engineering stream staff members.*

# ABSTRACT

*When an expansive soil is subjected to moisture increment it will exert an uplift pressure on the structure resting on it. Expansive soil covers an appreciable part of Ethiopia. The study area, Bishoftu is one of the places where expansive soils are found in abundance and present a significant structural and geotechnical challenge, especially to light weight structures. Crucial factors that require identification when dealing with expansive soils are the swelling characteristics. Swelling pressure predictions via laboratory testing of samples is the most acceptable approach to estimate swelling pressure, but it is expensive and time taking, therefore empirical equations developed from correlations with index properties are an alternative means to predict swelling pressure. This study aims* to *correlate index properties and swelling pressure of expansive soils found in Bishoftu town.*

*A total of 24 disturbed and 22 undisturbed representative samples were collected from 12 test pits, at a depth of 1.5m and 3.0m and the necessary laboratory tests were conducted to find out the index property and swelling pressure for all samples. The soil in the study area is classified as CH as per USCS and A-7-5 as per AASHTO soil classifications. The results were analyzed using MS-EXCEL and SPSS computer programs, taking swelling pressure as the dependent variable and results of index property test as predictors.*

*The results of the single linear regression analysis showed that the swelling pressure, Ps of the study area could be best estimated from its dry density with* $R^2$*=0.9172 and* $P_s$*= 785.24ρd-744.82. Besides dry density; the correlations with water content, Free Swell Index and Linear Shrinkage yielded an acceptable estimations of Ps with* $R^2$ *values of 0.8976, 0.7888 & 0.6902 respectively.*

*The results of multiple linear regression indicated that the regression analysis that included dry density and water content have better predictions of swelling pressure. The empirical equations that could best predict swelling pressure are*

$Ps = -24.790\omega + 400.977\rho dry + 737.845$ with $R^2$=0.946 and

$Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$ With $R^2$=0.925.

Key words: Swelling Pressure, Index Properties, Expansive Soils of Bishoftu, Regression Analysis

# TABLE OF CONTENTS

**CONTENTS** **PAGE**

**DECLARATION** .......... I
**ACKNOWLEDMENT** .......... II
**ABSTRACT** .......... III
**TABLE OF CONTENTS** .......... IV
**LIST OF TABLES** .......... VIII
**LIST OF FIGURES** .......... IX
**ACRONYMS** .......... XI
**CHAPTER ONE** .......... 1
**INTRODUCTION** .......... 1
1.1. Introduction .......... 1
1.2. Background of the Study Area .......... 1
1.3. Statement of the Problem .......... 1
1.4. Research Questions .......... 2
1.5. Objectives .......... 3
1.5.1. General Objective .......... 3
1.5.2. Specific Objectives .......... 3
1.6. Significance of the Study .......... 3
1.7. Scope of the Study .......... 4
1.8. Limitations of the Study .......... 4
1.9. Organization of Paper .......... 4
**CHAPTER TWO** .......... 5
**LITERATURE REVIEW** .......... 5
2.1. Introduction .......... 5
2.2. Origin of Expansive Soil .......... 5
2.3. Mineralogical Structure .......... 6
2.3.1. Smectite Mineral .......... 6
2.3.3. Illite Mineral .......... 7
2.3.4. Vermiculite Mineral .......... 8
2.3.5. Kaolinite Mineral .......... 8
2.3.6. Comparison of Clay Mineral Properties .......... 9

2.4. Identification of Expansive Soils ........ 9
2.4.1. Visual Identification ........ 10
2.4.2. Experimental Identification ........ 11
2.5. Soil Classification ........ 11
2.5.1. USCS Classification ........ 12
2.5.2. AASHTO Classification ........ 12
2.5.3. The British Standard System ........ 13
2.5.4. Other Classification Systems ........ 14
2.6. Swelling Pressure ........ 16
2.6.1. Factors Affecting Swelling Pressure of Expansive Soils ........ 16
2.7. Swelling Pressure Measurement ........ 18
2.7.1. Oedometer Tests ........ 18
2.7.2. Soil Suction Test ........ 20
2.7.3. Empirical Equations ........ 20
**CHAPTER THREE** ........ 23
**METHDOLOGY** ........ 23
3.1. Introduction ........ 23
3.2. Location of the Study Area ........ 23
3.2.1. Background of the Study Area ........ 24
3.2.2. Land Cover and Land use ........ 25
3.2.3. Land uses around Lakes ........ 26
3.2.4. Topographic Features /Landscape ........ 26
3.3. Climatic Condition ........ 27
3.3.1. Temperature and Precipitation ........ 27
3.3.2. Elevation / Altitude/ ........ 28
3.3.3. Drainage ........ 28
3.4. Sampling and Testing ........ 28
3.4.1. Sampling Technique ........ 28
3.4.2. Selection of Sampling Sites ........ 29
3.5. Laboratory Testing ........ 31
3.5.1. Index Properties ........ 31
3.5.2. Swelling Characteristics ........ 36
3.6. Data Analysis ........ 37

3.6.1. Linear Regression Analysis ........ 37
3.6.2. Multiple Linear Regression Analysis ........ 39
**CHAPTER FOUR** ........ 40
**RESULTS AND DISCUSSION** ........ 40
4.1. Sampling Area ........ 40
4.2. Results of Moisture Content ........ 40
4.3. Results of Atterberg Limit Test ........ 41
4.4. Results of Linear Shrinkage ........ 41
4.5. Results of Specific Gravity ........ 41
4.6. Result of Liquidity Index ........ 43
4.7. Results of Grain Size Analysis ........ 44
4.8. Results of Free Swell test ........ 47
4.9. Results of Swelling Pressure ........ 47
4.10. Results Comparison with Expansive Soils Found in Ethiopia ........ 48
4.11. Soil Classification of the Study Area ........ 50
4.11.1. USCS Classification ........ 50
4.11.2. AASHTO Classification ........ 51
4.11.3. Other Classification Systems ........ 53
4.12. Empirical Correlations ........ 55
4.13. Regression Analysis ........ 56
4.13.1. Linear Regression Analysis ........ 56
4.13.2. Multiple Linear Regression Analysis ........ 63
4.13.4. Comparison of Measured Ps with Previously Developed Empirical Equations ........ 74
4.13.5. Comparison of Calculated Ps with Previously Developed Empirical Equations ........ 75
4.14. Discussion ........ 77
**CHAPTER FIVE** ........ 79
**CONCLUSION AND RECOMMENDATION** ........ 79
5.1. Conclusion ........ 79
5.2. Recommendation ........ 80
**REFERENCES** ........ 82
**APPENDIX A** ........ 84
**REPRESENTATIVE LABORATORY TEST RESULTS** ........ 84
Moisture Content Test Results ........ 84

Representative Atterberg Limit Test Results ........ 85
Representative Linear Shrinkage Test Result ........ 89
Representative Specific Gravity Test Results ........ 90
Representative Sieve and Hydrometer Analysis ........ 95
Wet Sieve Analysis ........ 95
Hydrometer Analysis ........ 95
Representative Free Swell Test Results ........ 106
Representative Swelling Pressure Test Results ........ 108
**APPENDIX B** ........ 121
**MULTIPLE LINEAR REGRESSION** ........ 121
SPSS 20 Linear Regression Outputs ........ 121

# LIST OF TABLES

**PAGE**

Table 1 Index properties and characteristics of clay minerals (Deliktaş 2016) .......... 9
Table 2 Skempton's activity range and potential for expansion .......... 14
Table 3 Values of activity for different clay minerals Skempton (1953).......... 14
Table 4 Burmister (1949) Soil classifications based on Plasticity Index .......... 15
Table 5 Seed, Woodward and Lundgreen classification based on PI .......... 16
Table 6 Empirical equations (Sapaz, 2004) .......... 21
Table 7 Developed empirical equations for soils found in Ethiopia(Kemal, 2015).......... 22
Table 8 shows Bishoftu city Administration land use .......... 26
Table 9 The location of test pits and color of the soil sample.......... 40
Table 10 Summary of laboratory test results .......... 42
Table 11 Liquidity Index Vs Soil Consistency .......... 43
Table 12 Liquidity Index result.......... 43
Table 13 Grain size distribution of the study area .......... 46
Table 14 Expansiveness based on FSI .......... 47
Table 15 Results of dry density and swelling pressure tests .......... 47
Table 16 Comparison of Property ranges of Bishoftu Expansive soil with other expansive soils found in Ethiopia .......... 49
Table 17 USCS soil classification of the study area .......... 51
Table 18 AASHTO classification of the study area.......... 52
Table 19 Activity of the study area.......... 54
Table 20 Plasticity Index Vs Swelling Potential.......... 55
Table 21 Input data for multiple regressions .......... 63
Table 22 Input data for control samples.......... 63
Table 23 Developed empirical equations.......... 64
Table 24 Selected Possible Empirical Equations .......... 65
Table 25 Predicted Swelling Pressure values.......... 67
Table 26 Predicted Swelling Pressure values for the control sample .......... 67
Table 27 Empirical Equation to be used .......... 69
Table 28 Comparison with Previously developed equations .......... 75
Table 29 Comparison of calculated values .......... 76

# LIST OF FIGURES

**PAGE**

Figure 1 Problems that occurred due to expansive soils in Bishoftu .......... 2
Figure 2 Smectite mineral structure (Source:(Deliktaş, 2016)) .......... 7
Figure 3 Structure of Montmorillonite(Source:(Deliktaş, 2016)) .......... 7
Figure 4 Structure of Illite group (Source:(Deliktaş, 2016)).......... 8
Figure 5 Structure of kaolinite group (Source: (Deliktaş, 2016)) .......... 9
Figure 6 Wet slippery expansive soil sample and Desiccation cracks( Source; Photos taken while sampling and visual identification) .......... 10
Figure 7 Plasticity chart for the USCS/ ASTM soil classification system (Source: Carter, 2016) .......... 12
Figure 8 Plasticity chart for the AASHTO soil classification system (Source: Carter, 2016) .......... 13
Figure 9 Plasticity chart for the BS soil classification system (Source: Carter, 2016) .......... 13
Figure 10 Activity chart by Skempton (1953) .......... 15
Figure 11 An illustration of free swell test result(Jones and Jefferson, 2012) .......... 19
Figure 12 An illustration of constant volume test result(Jones and Jefferson, 2012) .......... 19
Figure 13 Location of Bishoftu in Map of Ethiopia .......... 23
Figure 14 Map of Bishoftu .......... 24
Figure 15 Relief map of Bishoftu .......... 27
Figure 16 Location of test pits in the master plan .......... 29
Figure 17 Excavation of test pits during sampling (Source: photos taken during test pit excavation) .......... 30
Figure 18 Disturbed samples and undisturbed samples (Source: photos taken of the samples in the laboratory) .......... 31
Figure 19 Specific gravity test in the laboratory (Source: photos taken during Specific gravity test) .......... 32
Figure 20 Liquid Limit test (Source: photos taken during Liquid Limit test) .......... 33
Figure 21 Plastic Limit test and Samples of LL, PL and Ls test during oven drying (Source: photos taken during Plastic Limit test and samples of LL, PL & Ls inside an oven) .......... 34
Figure 22 Linear shrinkage soil sample after oven drying (Source: photos taken After Ls test conducted) .......... 34
Figure 23 wet sieve analysis result and Hydrometer Analysis (Source: photos taken after wet Sieve and during hydrometer analysis) .......... 35
Figure 24 Free swell test (Source: photos taken during FS test) .......... 36
Figure 25 Swell-Consolidation test (Source: photos taken during swell-consolidation test) .......... 37
Figure 26 Grain size distribution curve .......... 45
Figure 27 USCS soil classification of the study area .......... 50
Figure 28 AASHTO classification of the study area .......... 52
Figure 29 Activity of the Chart of the study area .......... 53
Figure 30 Water content Vs Swelling pressure .......... 57
Figure 31 Liquid Limit Vs Swelling pressure .......... 58
Figure 32 Plastic Limit Vs Swelling pressure .......... 58
Figure 33 Plasticity Index Vs Swelling pressure .......... 59
Figure 34 Linear shrinkage Vs Swelling pressure .......... 60
Figure 35 Liquidity Index Vs Swelling pressure .......... 60
Figure 36 Dry density Vs Swelling pressure .......... 61

Figure 37 Free swell Index Vs Swelling pressure........................................................................................62
Figure 38 Clay fraction Vs Swelling pressure ..............................................................................................62
Figure 39 Measured Vs calculated values Eqn-1 Figure 40 Measured Vs calculated values Eqn-2 ..........68
Figure 41 Measured Vs calculated values Eqn-10    Figure 42Measured Vs calculated values Eqn-11 ....68
Figure 43 Measured Vs calculated values for Eqn-16 and Eqn-15.............................................................68

# ACRONYMS

| | |
|---|---|
| AASHTO | American Association of State Highway and Transportation Officials |
| ASTM | American Society of Testing and Materials |
| BS | British Standard |
| CEC | Cation Exchange Capacity |
| DEC | Defense Engineering Collage |
| Eqn | Equation |
| FS | Free Swell |
| FSI- | Free Swell Index |
| Gs | Specific Gravity of Solids |
| LI | Liquidity Index |
| LL | Liquid Limit |
| Ls | Linear Shrinkage |
| N | Number of sample |
| NMC | Natural Moisture Content |
| PI | Plasticity Index |
| PL | Plastic Limit |
| Ps | Swelling Pressure |
| PVC | Potential Volume Change |
| $R^2$ | Correlation Coefficient |
| SP | Swelling Potential |
| SPSS | Statistical Package for Social Science |
| SSR | Sum Squares of Regression |
| SST | Total Sum Squares |
| TP | Test Pit |
| USCS | Unified Soil Classification System |
| $\omega$ | Natural Moisture Content |
| $\rho$dry | Dry Density |

# CHAPTER ONE

# INTRODUCTION

## 1.1. Introduction

Expansive soil is a term generally applied to any soil or rock material that has a potential for shrinkage or swelling under changing moisture content. Some partially saturated clay soils are very sensitive to variations in water content and show excessive volume changes (Das, 2013). Such soils, when they increase in volume under applied loads because of an increase in their water contents, are classified as expansive soils. Here the focus is on soils that exhibit significant swell and shrink potential. Swelling pressures can cause heaving, or lifting, of structures whilst shrinkage can cause differential settlement. Failure results when the volume changes are unevenly distributed beneath the foundation(Jones and Jefferson 2012). Expansive soils are causing damage to structures all over the world especially in arid and semi-arid areas. Ethiopia is one of the places where expansive soils are found abundantly especially in the central part of the country (Kemal, 2015), where Bishoftu is located.

## 1.2. Background of the Study Area

Bishoftu formerly known as Dbere Ziet is a town located 47 kilometers southeast of the capital Addis Ababa. The town has got a first rank urban grade level as per the classification of urban grade levels of Oromia Region urban centers, Bishoftu is situated between Dukem and Mojo towns along Addis Ababa-Djibouti road (Abebe, 2015). Bishoftu is one of the vastly developing towns especially in the infrastructure sector and also the town is well known for its natural water sources. There are 7 lakes in Bishoftu which cover a large area and also contribute to the GDP of the town and the country in general.

## 1.3. Statement of the Problem

Expansive soils are clay soils with high tendency to expand and contract upon changes in moisture content. Foundations constructed on these soils are subjected to Large up lifting forces caused by swelling. These forces will induce heaving, differential settlement, cracking, and disruptions of different structures (Rogers, Olshansky et al., 1993).

Expansive soils cause major problems all over the world and in our country Ethiopia substantial damage has been occurring on buildings and roads that are constructed on expansive soils with severe economic consequences, psychological effects and loss of proper functioning of structures (Kemal, 2015). Bishoftu is one of the cities in Ethiopia covered with expansive soils and is facing major problems because of it. This is what raises the need for geotechnical investigation and quantifying the swelling pressure of expansive soils in the study area. In this study an attempt is made to come up with a relationship that can estimate swelling pressure from index properties for expansive soils in Bishoftu town.

Figure 1 Problems that occurred due to expansive soils in Bishoftu

## 1.4. Research Questions

I. What are the range of values of index properties of expansive soils found in Bishoftu town?

II. Which index property affects swelling pressure of expansive soils found in Bishoftu town to the highest degree?

III. What is the relationship between index properties and swelling pressure of expansive soils found in Bishoftu town?

## 1.5. Objectives

### 1.5.1. General Objective

The general objective of this study is to correlate index properties and swelling pressure of expansive soils found in Bishoftu town.

### 1.5.2. Specific Objectives

The specific objectives of this study are:

- To determine the range of values of index properties and swelling pressure of expansive soils in Bishoftu town.
- To determine the index property that significantly affects swelling pressure of expansive soils found in Bishoftu town.
- To study the relationship between index properties and swelling pressure of expansive soils found in Bishoftu town.

## 1.6. Significance of the Study

The problems associated with expansive soil are related to bearing capacity and cracking, breaking up of pavements, and various other building foundation problems. This kind of soils are wide spread all over the world and believed to be the major economic disasters of the construction sector (Assefa, Lin et al., 2016). The structures most susceptible to damage caused by expansive soils are usually lightweight structures such as small story buildings and pavements because they are less able to suppress differential movements than heavier multi-story structures, this light weight structures are rapidly increasing in Bishoftu which raises the need for geotechnical investigation of the swelling pressure of the expansive soils. The odometer swell- consolidation test is used to determine the swelling pressure of a soil. It also provides some important compressibility indices such as compression index and the coefficient of volume compressibility to describe the consolidation of soil.(Ameta, Purohit et al. 2007) However, odometer test is a complex, time consuming and expensive test as compared to index property tests. It needs to be fully equipped in order to run the test. A large number of undisturbed samples are needed to acquire reliable data and it consumes approximately two weeks to obtain the data. Index properties tests are simple test as it needs only a short time to obtain the results. Hence, the aim of this study is to establish a correlation between index properties and swelling pressure that could be used to estimate swelling pressure. If an empirical relationship is established between the aforementioned characteristics, the swelling pressure value can be predicted from the measured values of the index properties test.

## 1.7. Scope of the Study

This study is conducted in Bishoftu town and is limited to areas with expansive soils. This study is based on the laboratory test results of 24 disturbed and 22 undisturbed samples that were collected from 12 test pits. The aim of this study is to correlate index properties and swelling pressure of expansive soil found in Bishoftu, in order to do that the required laboratory tests were conducted on both samples and the results are correlated using Linear regression analysis This study will only discuss the case of the expansive soils found in Bishoftu town considering the moisture condition during the study period.

## 1.8. Limitations of the Study

The study area Bishoftu is covered with different types of soils and there is insufficiency of documented soil data on the type and distribution of soil, there is no documented data on the depth and type of expansive soils present and the problems encountered due to expansive soil in the city administration and also for the most part different types of buildings and road infrastructures are built and are currently being built in areas that are covered with expansive soils that made the sampling area in close proximity.

## 1.9. Organization of Paper

This paper comprises of five chapters. The first chapter presented what expansive soils are and how it causes problems, background of the study area, statement of the problem, research questions, objective of the study, significance of the study, scope, limitations and organization of the study. The second chapter covers literature reviews on the topic to be studied. The third chapter covers study area and research methodology, sample preparation for laboratory tests, laboratory testing of index properties and swelling pressure and methods of data analysis. The Forth chapter discusses results of laboratory tests, regression analysis and discussions of developed empirical equations. The Fifth chapter covers summary, conclusion and recommendations finally; the last pages cover references and relevant annexes.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1. Introduction

Expansive soils are clay soils that exhibit a large volume change when exposed to moisture variations. The moisture variation causes shrinkage and swelling, shrink when dry and swell when wet (Deliktaş, 2016). This continuous volume change in expansive soils is a major problem in the construction industry reported all over the world, including Ethiopia (Debelo, 2015) and costs millions each year. Damage to structure due to expansive soils is intensified on light weight structures such as pavements and small story buildings because the soil underneath the foundation may expand in a larger volume and the superstructure load won't be able to suppress it due to this crack, differential settlement and even collapse of the entire structure may encounter. Basically through investigation of the nature and amount of expansiveness has to be done and this could be done by determining the swelling characteristics of the expansive soil along with its index properties via laboratory tests (Mitchell and Soga, 2005, Chen, 2012).

## 2.2. Origin of Expansive Soil

A reactive soil is one that exhibits a reasonable tendency to volume changes (shrinkage and swelling) in response to a variation in moisture content within the soil mass. Occasionally, soils that exhibit such behavior are referred to as expansive soils or swelling soils. Most clay soils are reactive to a greater or lesser degree depending on the type, amount and mineralogical properties of clay particles present within the soil mass, the intensity of the moisture variation the soil deposit is expected to undergo and possible variations of soil suction characteristics (Ameta, Purohit et al., 2007, Chen, 2012). The parent materials associated with expansive soils are classified into two. The first group comprises of the sedimentary rocks that contain montmorillonite as constituent including shale and clay stones. Limestone and marls, rich in magnesium. These constituents of the shale and clay stones contain varying amount of volcanic ash and glass, which were subsequently weathered to montmorillonite. Some of the fine grained sediments which accumulated to form these rocks also contain montmorillonite derived from weathering of continental igneous rocks and from ash, which fell on the continental areas as clouds of ash from volcanic eruptions can fall on continents and sea (Jones, 2012). Montmorillonite minerals are the most expansive of all the clay minerals because of the weak Van der Waals forces that exist between the tetrahedral sheets which can be easily broken by water or other molecules which makes it susceptible to large volume variations even with small change in the moisture content (Debelo, 2015 ,Ameta, 2007 ). The second group comprises of the basic igneous rocks, which are comparatively low in silica, generally about 45% to 52%. Rocks which are rich in metallic base such as the pyroxenes, amphiboles, biotitic and olivine fall within this category. Such rocks include the gabbro's, basalts and volcanic glass.(Mitchell and Soga, 2005, Chen, 2012)

## 2.3. Mineralogical Structure

Expansive soils owe their characteristics to the presence of swelling clay minerals; the minerals of clays are formed by weathering of rocks. According to ASTM the term clay is applied to the fraction of grains whose equivalent diameter is less than 0.005mm. The individual grains are fragments of a single mineral i.e. A solid compound with a definite chemical composition and unique crystalline structure(Chen, 2012).All clays consist of mineral sheets packaged into layers, and can be classified as either 1:1 or 2:1. These ratios refer to the proportion of tetrahedral sheets to octahedral sheets. Octahedral sheets are sandwiched between two tetrahedral sheets in 2:1 clays, while 1:1 clays have sheets in matched pairs (Harishkumar and Muthukkumaran, 2011).

### 2.3.1. Smectite Mineral

Smectite mineral has 2:1 layer in which octahedral sheet between two silica tetrahedral. Smectite minerals are bonded to each other with Van der Waals forces. Water molecules and exchangeable cations such as sodium, calcium and magnesium present at interlayer spacing in order to balance the charge deficiencies(Harishkumar and Muthukkumaran, 2011, Jones and Jefferson, 2012). Since bonds formed by Van der Waals forces can be easily separated with polar liquids and water, Smectite mineral shows very high swelling property (Harishkumar and Muthukkumaran, 2011).The most abundant Smectite type is calcium montmorillonite.

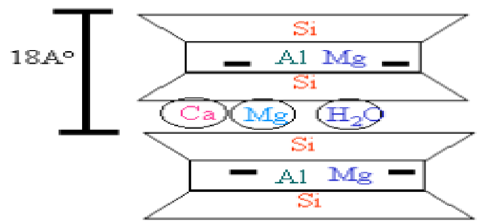



Figure 2 Smectite mineral structure (Source:(Deliktaş, 2016))

2.3.1.1. Montmorillonite Mineral

Montmorillonites are formed in poorly draining soils so that a wide variety of atomic species are available for recrystallization. Montmorillonites are made up of sheet like unit comprising an alumna octahedral sheet between two silica tetrahedral sheets held by Van der Waals forces. In Montmorillonite the layers are separated by loosely held water and exchangeable metallic ions. The basic montmorillonite units are stacked one on top of the other but the bond between the individual units is relatively weak and water is easily able to penetrate between the sheets and cause their separation and hence swelling. Therefore, montmorillonite has very high degree of expansiveness (Harishkumar and Muthukkumaran, 2011).

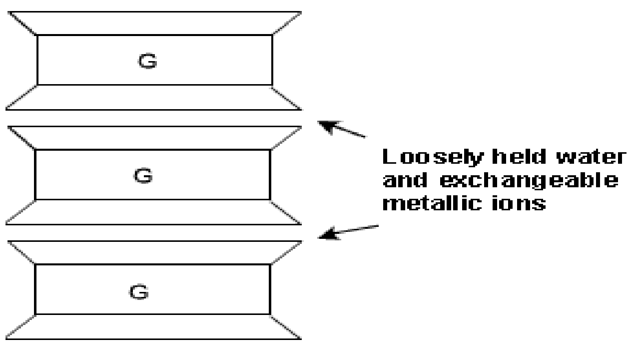



Figure 3 Structure of Montmorillonite(Source:(Deliktaş, 2016))

2.3.3. Illite Mineral

Illite has a basic structure similar to that of montmorillonite. By contrast, the basic Illite units are bonded non-exchangeable potassium ions. Unlike Montmorillonite particles, which are extremely small and have a great affinity for water, the Illite particles will normally aggregate and there by develop less affinity for water than Montmorillonites.

Correspondingly, their expansion properties are less.  The Cation Exchange Capacity of Illite is less than that of Montmorillonite (Harishkumar and Muthukkumaran 2011).

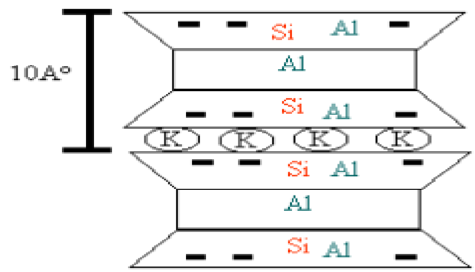



Figure 4 Structure of Illite group (Source:(Deliktaş, 2016))

2.3.4. Vermiculite Mineral

Structure of vermiculite mineral is similar to Illlite's mineral pattern. The only difference between these two minerals is the interlayer bonding material. In vermiculite mineral, potassium, which stacks the Illite mineral layers, is replaced with hydrated magnesium. The reason behind potassium loss is weathering.  Since unit block structure of vermiculate is very parallel to Illite, it also has limited swelling capacity (DELİKTAŞ, 2016).

2.3.5. Kaolinite Mineral

Kaolinites are formed in well drained soils, with an abundance of Oxygen, Silicon and Aluminum. Kaolinite has a structure that consists of one silica sheet and one alumna sheet bonded together in to a layer about 0.72mm thick and stacked repeatedly(Chen, 2012). The layers are held together by hydrogen bonds. The bond that exists between layers is tight and hence it is difficult to separate the layers. As a result, kaolinite is relatively stable and water is unable to penetrate between the layers. Which results in, kaolinite having low degree of expansiveness (DELİKTAŞ, 2016).

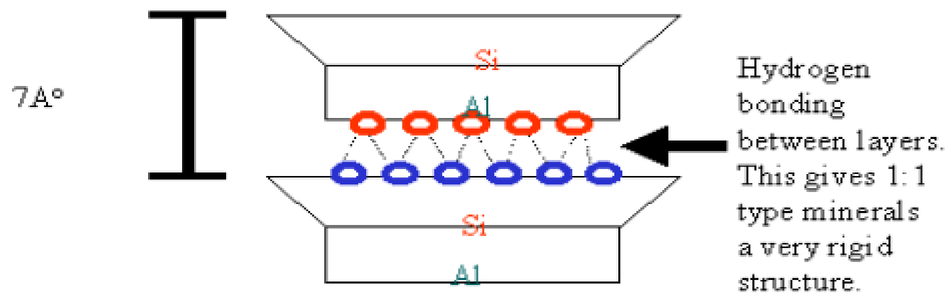



Figure 5 Structure of kaolinite group (Source: (Deliktaş, 2016))

2.3.6. Comparison of Clay Mineral Properties

The clay mineral is composed of different minerals which governs its index properties and also its cation exchange capacity. Cation exchange capacity (CEC) is defined as the mineral ability to absorb an external cation. The following comparisons is based on the index properties like liquid limit(LL) and plastic limit(PL) and cation exchange capacity, which shows the Illite mineral which has the lowest CEC, LL and PL has the lowest degree of volume change and montmorillonite mineral having the highest CEC, LL and PL has the highest degree of volume change (Deliktaş, 2016)

Table 1 Index properties and characteristics of clay minerals (Deliktaş 2016)

| Clay mineral | CEC Meq/100g | Specific gravity | Specific surfacem$^2$/g | LL% | PL% | Swell potential |
|---|---|---|---|---|---|---|
| Illite | 3-5 | 2.6-2.68 | 10-20 | 30-60 | 25-35 | Low |
| Sodium (Na) | | | | 53 | 21 | |
| Calcium(Ca) | | | | 38 | 11 | |
| Kaolinite | 10-40 | 2.6-3.0 | 65-100 | 60-120 | 35-60 | Medium |
| Sodium (Na) | | | | 61 | 34 | |
| Calcium(Ca) | | | | 90 | 40 | |
| Montmorillonite | 80-150 | 2.35-2.7 | 700-840 | 100-900 | 50-100 | High |
| Sodium (Na) | | | | 700 | 97 | |
| Calcium(Ca) | | | | 177 | 63 | |

## 2.4. Identification of Expansive Soils

Expansive soils in many parts of the United States pose a significant hazard to foundations for light buildings (Ameta, Purohit et al. 2007).Expansive soils owe their characteristics to the presence of swelling clay minerals. As they get wet, the clay minerals absorb water molecules and expand; conversely, as they dry they shrink, leaving large voids in the soil. Swelling clays can control the behavior of virtually any type of soil if the percentage of clay is more than about 5 percent by weight. Soils with Smectite clay minerals, such as montmorillonite, exhibit the most profound swelling properties. Identification of potential swelling or shrinking of subsoil problems is an important tool for selection of appropriate foundation.

2.4.1. Visual Identification

Field identification of expansiveness can be made by observing desiccation cracks. Great potential swell is indicated by large and more frequent polygon arrangements of cracks while low shrink/swell means that potential for shrinkage cracks developing is low (Earl, 2005). Expansive soils are often clay like, becoming very sticky when wet and hard and brittle when dry (Deliktaş, 2016) in addition, the following characteristics are indicators of expansive soil.

- It becomes adhesive when wet and is difficult to wash off.
- Are usually black and gray in color.
- In areas with high expansive soils cracks will develop in nearby structures.
- When the surface is polished with an object like pocket knife it gives shinny surface.
- Are very hard when dry.

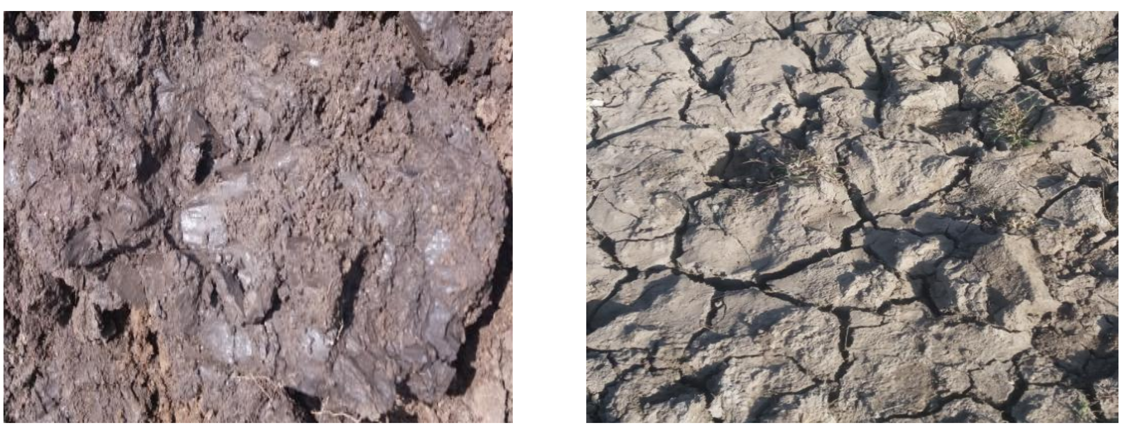


Figure 6 Wet slippery expansive soil sample and Desiccation cracks( Source; Photos taken while sampling and visual identification)

#### 2.4.2. Experimental Identification

In the laboratory we can use three methods to identify expansive soils.

##### 2.4.2.1. Direct Measurement

This is the most reliable method of determining the swelling pressure of expansive soil. This method gives the exact value of swelling pressure for a given expansive soil sample. It is done using the odometer consolidation test apparatus, which measures the one dimensional consolidation of the given sample and it gives information on the possible in-situ response of the soil at different moisture conditions (Deliktaş, 2016).

##### 2.4.2.2. Mineralogical Methods

The swelling of an expansive soil is to a greater extent dependent on the mineralogical composition of the sample under consideration. The type of clay mineral present in the soil governs the shrink-swell characteristics of the soil for example if the montmorillonite clay constitutes the large part of the sample then it will have higher tendency to swelling (Deliktaş, 2016, King, 2016). There are a lot of factors that contribute to swelling of clay soil such as the negative electric charges on the surface of clay mineral, the strength of the interlayer bonding, and the cation exchange capacity. Due to this it is acknowledged that swelling of any expansive soil can be evaluated by identifying of the constituent mineral through the following methods (King, 2016).

- X-ray Diffraction
- Differential Thermal Analysis
- Dye Adsorption
- Chemical Analysis and
- Electron Microscope Resolution.

## 2.5. Soil Classification

The purpose of a soil classification is to group together soils with similar properties or attributes. The first step in classifying a soil is to identify it. To be of practical value, a classification system should permit identification by either inspection or testing, and tests should be as simple as possible. There are different soil classification methods. The most widely used soil classification systems are The Unified Soil Classification System (USCS), The American Association for Testing and Materials (ASTM), The British

Standard Classification system and American Association of State Highway and Transportation Officials (AASHTO) system (Carter and Bentley, 2016).

2.5.1. USCS Classification

The Unified system is the oldest system to be widely adopted, and variations of this system still represent probably the most widely used form of soil classification. It was developed from a system proposed by Casagrande (1948) and referred to as the Airfield Classification System. Coarse-grained soils (sands and gravels) are classified according to their grading, and fine-grained soils (silts and clays) and organic soils are classified according to their plasticity.(Morsi,2010).

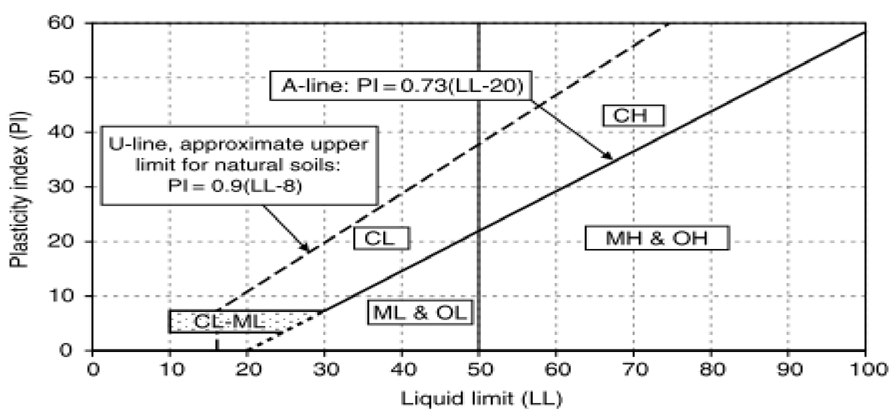



Figure 7 Plasticity chart for the USCS/ ASTM soil classification system (Source: Carter, 2016)

2.5.2. AASHTO Classification

Unified system and its derivatives classify soil by type rather than by engineering suitability for specific uses, although they can nevertheless be used to infer suitability. By contrast, the system defined by the American Association of State Highway and Transportation Officials (AASHTO 2012) does not classify soils by type (e.g. Sands, clays) but simply divides them into seven major groups, essentially classifying soils according to their suitability as subgrades (Morsi, 2010). Soils classified under groups A-1, A-2 and A-3 are granular materials with 35% or less passing through a No. 200 sieve but A-1 & A-3 non-plastic. Soils with more than 35% passing a No. 200 sieve are classified under groups A-4, A-5, A-6 and A-7. These soils are mostly silt and clay type materials. Unlike the USCS system the plasticity chart for the AASHTO classification is based on PI= LL-30 (Ameratunga, Sivakugan et al., 2016)

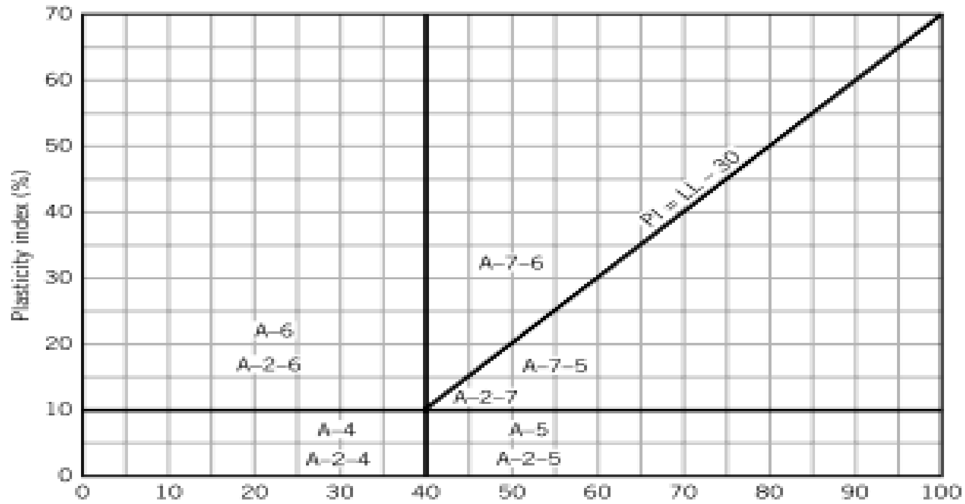



Figure 8 Plasticity chart for the AASHTO soil classification system (Source: Carter, 2016)

2.5.3. The British Standard System

This system of classification is also based on the Casagrande classification except the definitions of sand and gravel are slightly different also the fine-grained soils are divided into five plasticity ranges rather than the simple ‘low’ and ‘high’ divisions of the USCS and the original Casagrande systems. In addition, a considerable number of sub-groups have been introduced (Carter and Bentley, 2016).

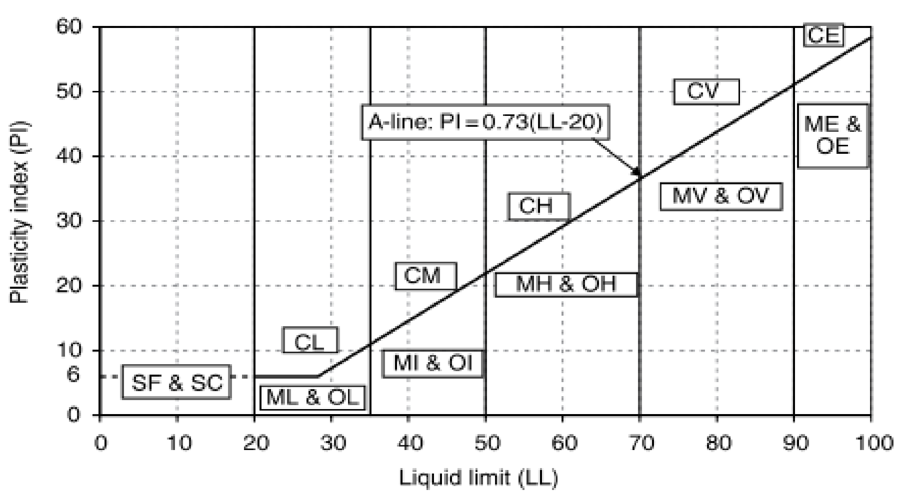



Figure 9 Plasticity chart for the BS soil classification system (Source: Carter, 2016)

2.5.4. Other Classification Systems

For expansive soils different scholars have established different classification schemes based on factors that are associated with the nature of soil under consideration either directly or indirectly.

2.5.4.1. Skempton's Method

According to Skempton's method expansive soils can be classified based on their activity, which is a characteristic that accounts for amount of clay fraction in the soil and plasticity index of the soil.

$$\text{Activity}=\frac{\textit{Plasticity Index}}{\textit{Percentage of Clay}}$$

Plastic limit and liquid limit tests are generally carried out on the soil fraction passing No.40 (0.425 mm) sieve. This fraction can contain clays, silts and some fine sands. Two clays having the same plasticity index can have quite different behavior depending on their mineralogical characteristics and the clay content. Activity is a good measure of the potential swell problems in clays (Ameratunga, Sivakugan et al.,2016).

Table 2 Skempton's activity range and potential for expansion

| Activity | Potential of Expansion |
|---|---|
| Ac < 0.75 | Low (Inactive) |
| 0.75 < Ac<1.25 | Medium (Normal) |
| Ac > 1.25 | High (Active) |

Table 3 Values of activity for different clay minerals Skempton (1953)

| Clay Mineral | Activity |
|---|---|
| Kaolinite | 0.33-0.46 |
| Illite | 0.9 |
| Montmorillonite(Ca) | 1.5 |
| Montmorillonite(Na) | 7.2 |

An activity chart that classifies soils based on their activity value has been developed by Skempton.

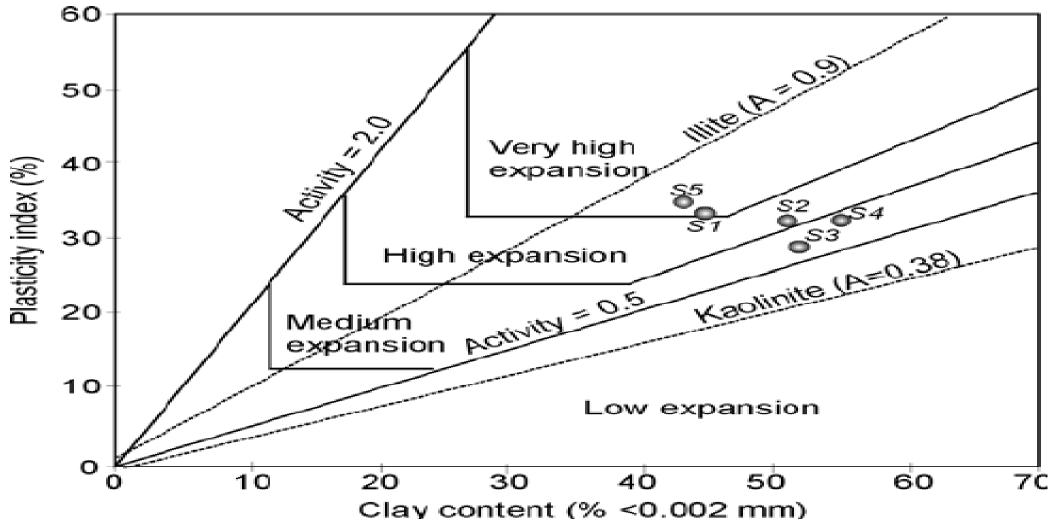



Figure 10 Activity chart by Skempton (1953)

2.5.4.2. Burmister's Method

Plasticity is a term that is associated with clays. The mineralogy of the clay grains, their grain shapes resembling flakes and needles with large surface area per unit mass and the charge imbalance make them cohesive and plastic. Plasticity index indicates the degree of plasticity of a soil. The greater the difference between liquid and plastic limits, the greater is the plasticity of the soil. (Ameratunga, Sivakugan et al.,2016) According to Burmister (1949) Soil classifications based on Plasticity Index:

Table 4 Burmister (1949) Soil classifications based on Plasticity Index

| **Plasticity Index(PI)** | **Description** |
|---|---|
| 0 | Non-plastic |
| 1-5 | Slightly plastic |
| 5-10 | Low plasticity |
| 10-20 | Medium plasticity |
| 20-40 | High plasticity |
| >40 | Very high plasticity |

2.5.4.3. Seed, Woodward and Lundgreen

Taking plasticity index as a means to assess the swelling potential of expansive soils Seed, Woodward and Lundgreen have categorized it in four classes. Seed, Woodward and Lundgreen have proposed the following relationship between swell potential and PI;(Ameratunga, Sivakugan et al.)

$SP=60K\ (PI)^{2.44}$

Where SP= Swelling potential (%)

PI = Plasticity index (%)

K= a Constant=$3.6*10^{-5}$

Table 5 Seed, Woodward and Lundgreen classification based on PI

| **Plasticity Index** | **Swell Potential** |
|---|---|
| 0-10 | Low |
| 10-35 | Medium |
| 20-55 | High |
| 55 and above | Very High |

The classification systems developed based on a single property alone such as activity and plasticity index are difficult to use alone as a classification system because it may lead to wrong conclusions.

## 2.6. Swelling Pressure

Definition: the swelling pressure is defined as the vertical pressure required to prevent volume change of laterally confined sample when it is allowed to take in water. In other words, the swelling pressure is the load at which the void ratio is equal to the initial void ratio. Swelling pressure of a soil is the amount of vertical swell obtained under a particular surcharge load of 7Kpa. Most of the structural damages occur when the swelling pressure is greater than the foundation pressure, assessing the swelling pressure is an important task in dealing with expansive soil, because absorption of water by clay leads to swelling.

### 2.6.1. Factors Affecting Swelling Pressure of Expansive Soils

Swelling of an expansive soil can be influenced by different factors. Expansion is a change in particle spacing and this is a result of change in the soil water system that disturbs the internal stress equilibrium (Sapaz, 2004) Factors that influence the swelling pressure of an expansive soil also affect or are affected by the physical properties of that soil, such as moisture content, plasticity and density. The factors that affect swelling of expansive soils can be grouped in three major groups which can further be subdivided (Harishkumar and Muthukkumaran, 2011).

1. Environmental factors
2. Soil properties and
3. State of stress

2.6.1.1. Environmental Factors

- Initial moisture content- An expansive soil with lower moisture content has higher affinity for water and suction than the one at higher moisture content.
- Permeability- Higher permeability of soil especially due to cracks and fissures let water mitigate faster. This induces higher rate of swell.

2.6.1.2. Soil Properties

- Mineral Composition- Clays which contain montmorillonite, vermiculite and some mixed layer minerals own larger volume changes than the ones whose mineralogy is consists of Illite and kaolinite minerals.
- Plasticity- High liquid limit and plasticity over a wide range of moisture content cause high swelling potential.
- Dry Density- Higher densities mean closer particle spacing and greater repulsive forces between particles, which causes higher swelling pressure.
- Soil- Water Chemistry- One of the main roles in swelling belongs to cations. Increase in cation concentration and valence results in less expansiveness.
- Soil Structure and Fabric- Cemented particles and dispersed structure reduce swell. Compaction at higher water content or remolding change fabric and structure. Additionally, kneading compaction has shown to cause soil samples with lower swell potential than statically compacted soils at lower moisture contents. The reason of this situation is creating dispersed structure of soil with kneading compaction (Sridharan and Prakash, 2000).

2.6.1.3. State of Stress

- Loading- The amount of swell for given moisture content depends on magnitude of surcharge load. In order to balance inter-particle repulsive forces and reduce swell, an external load is applied.

- Soil Suction- Soil suction is represented by negative pore pressure in unsaturated soils. Pore size and shape, surface tension, saturation, gravity, electrochemical properties of soil and water relates to soil suction (Morsi, 2010).

## 2.7. Swelling Pressure Measurement

Swelling pressure of an expansive soil can be measured or predicted using different techniques (Ameratunga, Sivakugan et al.,2016).

- Oedometer tests
- Soil suction tests and
- Empirical methodology

### 2.7.1. Oedometer Tests

The swelling characteristics of expansive soils can be measured using the one dimensional consolidation apparatus, Oedometer. The Oedometer tests consider moisture as well as volume change in one dimension only. However, the in-situ condition of the soil is that's volumetric expansion and contraction takes place in three directions, the above changes take place in three directions. Even with its limitations the one dimensional consolidation test is used extensively to estimate swelling pressure. There are various methods of estimating swelling pressure using the Oedometer apparatus (Teferra and Leikun. 1999).

#### 2.7.1.1. Swell Consolidation Method

An undisturbed sample is allowed to absorb water under 7Kpa surcharge, and is left until maximum equilibrium expansion is reached. Then it is consolidated by increasing the applied pressure in intervals following the conventional consolidation test procedure. The load increment is continued until the sample reaches its initial volume (zero volume change). The load correspond to zero volume change is taken as swelling pressure. The swell pressure is then defined as the pressure required re-compressing the swollen sample to its pre-swelling volume.

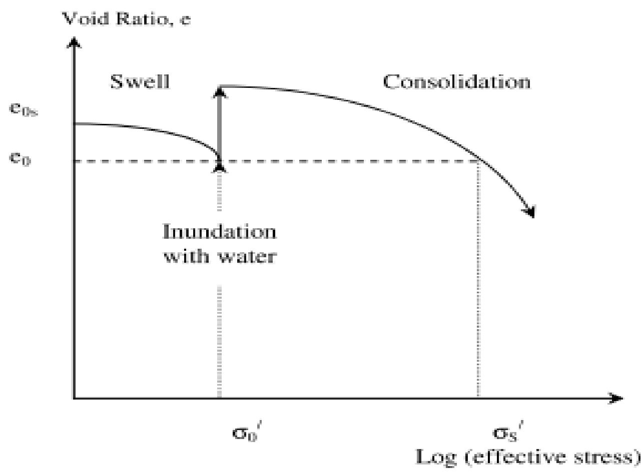



Figure 11 An illustration of free swell test result(Jones and Jefferson, 2012)

2.7.1.2. Constant Volume Method

During constant volume swell test, the specimen is placed in to the odometer ring and will be soaked with water, in order for the sample to develop vertical deformations but those deformations are suppressed by applying small load increments of vertical pressure while the specimen is still soaked. The aim of this is to arrive at a load where there is neither swelling nor shrinkage by maintaining the specimen at its original volume. After this stage the rebound curve is obtained by consecutive load decrements (Guggenheim and Martin, 1995).

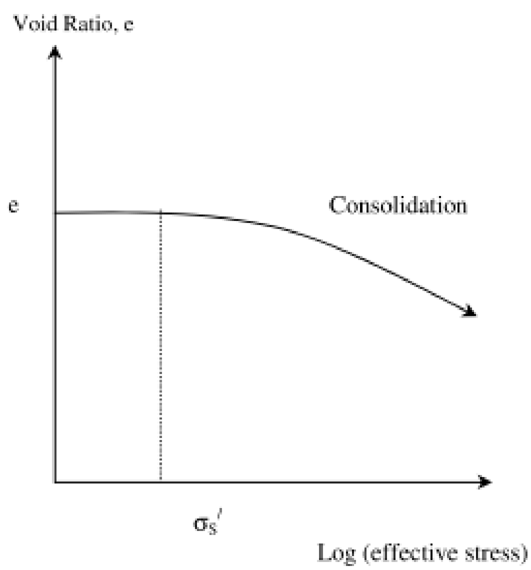



Figure 12 An illustration of constant volume test result(Jones and Jefferson, 2012)

### 2.7.1.3. Swell Overburden Test

An undisturbed sample is loaded 7Kpa surcharge in its initial moisture condition, and is left until maximum equilibrium expansion is reached. Then the sample is inundated with water and is allowed to swell until primary swell is completed, the specimen is then loaded until it reaches its original height i.e. Zero swell. After this stage the rebound curve is obtained by consecutive load decrements (Sapaz, 2004).

### 2.7.1.4. Double Odometer Test

In the double odometer test method two identical samples will be tested, the first sample is consolidated being in its initial state of moisture while the second sample will be loaded in an initial setting load while being soaked in water, and consolidation is carried out after the swelling is done. After both tests are completed the e-logP curve of both tests will be plotted in a single diagram and the pressure corresponding to the intersection of the curves will be the swelling pressure. This method was first suggested by Jennings and Knight. The swelling pressure results of this test are higher than the actual swelling pressure because the pressure taken as the swelling pressure is not that required to bring the sample to its initial volume, but to its volume after being compressed in the dry state to a pressure equal to the swelling pressure (Jones and Jefferson, 2012).

### 2.7.2. Soil Suction Test

Soil suction describes the interaction between soil particles and water which determines the physical behavior of the soil mass (Morsi, 2010). In suction test method negative pore pressure is measured. For this test Thermocouple psychrometer test set-up or pressure plate can be used. The relative humidity of soil can be measured using the psychrometer. The soil suction which is assumed to be equivalent to the swelling pressure of the soil, will be determined from the relative humidity using the principles of thermodynamics. Then e- log soil suction curve will be plotted and the swelling pressure is equivalent to the determined soil suction from the curve. The gentler the curve the higher the swelling pressure. This method takes less time than that of Oedometer techniques.

### 2.7.3. Empirical Equations

This method is used to predict the swelling pressure and swelling potential of an expansive soil by examining other parameters and correlating them with swelling pressure. These parameters include Index Property Tests (consist of Grain Size Analysis, Atterberg Limit, Linear Shrinkage and Free Swell); Cation Exchange Capacity (CEC), and Potential Volume Change (PVC) tests. Different scholars formulated various empirical equations to predict swelling pressure and swelling potential some of which are given below.

Table 6 Empirical equations (Sapaz, 2004)

| | Reference | Description |
|---|---|---|
| 1 | Seed et al | $Sp=0.00216PI^{2.44}$ |
| 2 | Van der Merve | $\Delta H=Fe^{-0.377D}(e^{-0.377H}-1)$ |
| 3 | Vijayvergia et al | 1. $\text{Log } Sp=(0.44LL-\omega_o+5.5)/12$<br>2. $\text{Log } Sp=(6.24*g_d+0.65LL-100)/19.5$ |
| 4 | Nayak et al | $Sp=(0.00229PI)(F-45C)/\omega_o+6.38$ |
| 5 | Johnson | $Sp=23.82+0.73PI-0.145BH-1.7\omega_o+0.00225pi\omega_o-0.0098PIH$ |
| 6 | Komornik et al | $\text{Log } Ps=0.132+0.0208LL+0.0006688g_d-0.0269\omega_o$<br>Note: $g_d$ is in $Kg/m^3$ |
| 7 | Schnider et al | $\text{Log } Sp=0.9(PI/\omega_o-1.19)$ |

Where Sp, PI, LL, $\Delta H$, F, D, H, $\omega_o$, $g_d$ and C, are percent swell, plasticity index, liquid limit, total heave, correction factor for degree of expansiveness, thickness of non-expansive layer, thickness of expansive layer, initial water content, dry unit weight and clay percent respectively.

The problem with empirical equations is that the equations formulated in one area may or may not work in another because swelling pressure is affected by environmental factors.

2.7.3.1. Correlations Between Index Properties and Swelling Pressure in Ethiopia

Empirical correlations to determine swelling pressure from index properties have been developed by different researchers in different parts of the country, and even though the studies were conducted to develop equations of swelling pressure from index properties the results of the study vary from place to place.

Table 7 Developed empirical equations for soils found in Ethiopia(Kemal, 2015)

| Researcher | N | Study Area | Developed Equation |
| --- | --- | --- | --- |
| Daniel Telku | 17 | Addis Abeba | 1. Log Ps = -5.00 - 0.0002064*LL + 0.003477*PI + 0.005827* $\gamma d$ <br> 2. Log Ps = -9.384 + 0.02748*$\omega$ + 0.006307*PI + 0.008359* $\gamma d$ |
| Dagmawi Negussie | 21 | Bahirdar | Log Ps = 7.018 – 1.924*$\gamma d$ - 0.042*$\omega$ - 0.008* LL + 0.003*CEC, where CEC is cation exchange capacity |
| Ashenafi Tamrat | 15 | Dukem | P s = 1.639* $\gamma d$ +32.676* PL-3110.94 |
| Abdishkur Kemal | 19 | Koye Area | Ps=965.22+38.53 $\gamma d$/ $\gamma$’-26.99$\omega$+8.68PL |
| Asamnew Gullat | 19 | Woliso | SP= 0.2769PI-0.335$\omega$+2.3114 where SP is swelling potential |

Where Ps, PI, LL, PL, $\omega$, $g_d$, $\gamma$’ and SP are Swelling pressure, plasticity index, liquid limit, plastic limit, water content, dry density, effective density and swelling potential respectively.

# CHAPTER THREE

# METHDOLOGY

## 3.1. Introduction

In dealing with different types of soil the following factors play a vital role in their formation. This includes the parent material, time, climatic conditions, topography, relief and organisms. The combination of the aforementioned factors will govern the type of soil but how much one factor contributes for the formation of soil varies from one location to the other. In engineering works the presence of expansive soils plays a crucial role in the design of the intended structure. Since, a considerable part of Bishoftu town is covered with expansive soil careful investigation and design is required for sustainability of the structure.

## 3.2. Location of the Study Area

The city is located between $8^{0}45^{'}$- $8^{0}47^{'}$ North latitudes and $38^{0}56^{'}$-$39^{0}$ East longitudes and has an altitude that ranges from 1746m to 1995m. It is situated at a distance of 47 km South East of Addis Ababa, and 52 Km from Adama. In the North the city is bordered with Yerer Silassie, in the south with Wedo and Keta Jara, in East with Kaliti and in the West with Dire town and Peasant Association. Formerly known by the name Debre Ziet Bishoftu city is found in east shoa zonal administration.


Figure 13 Location of Bishoftu in Map of Ethiopia (Source: Google Map)

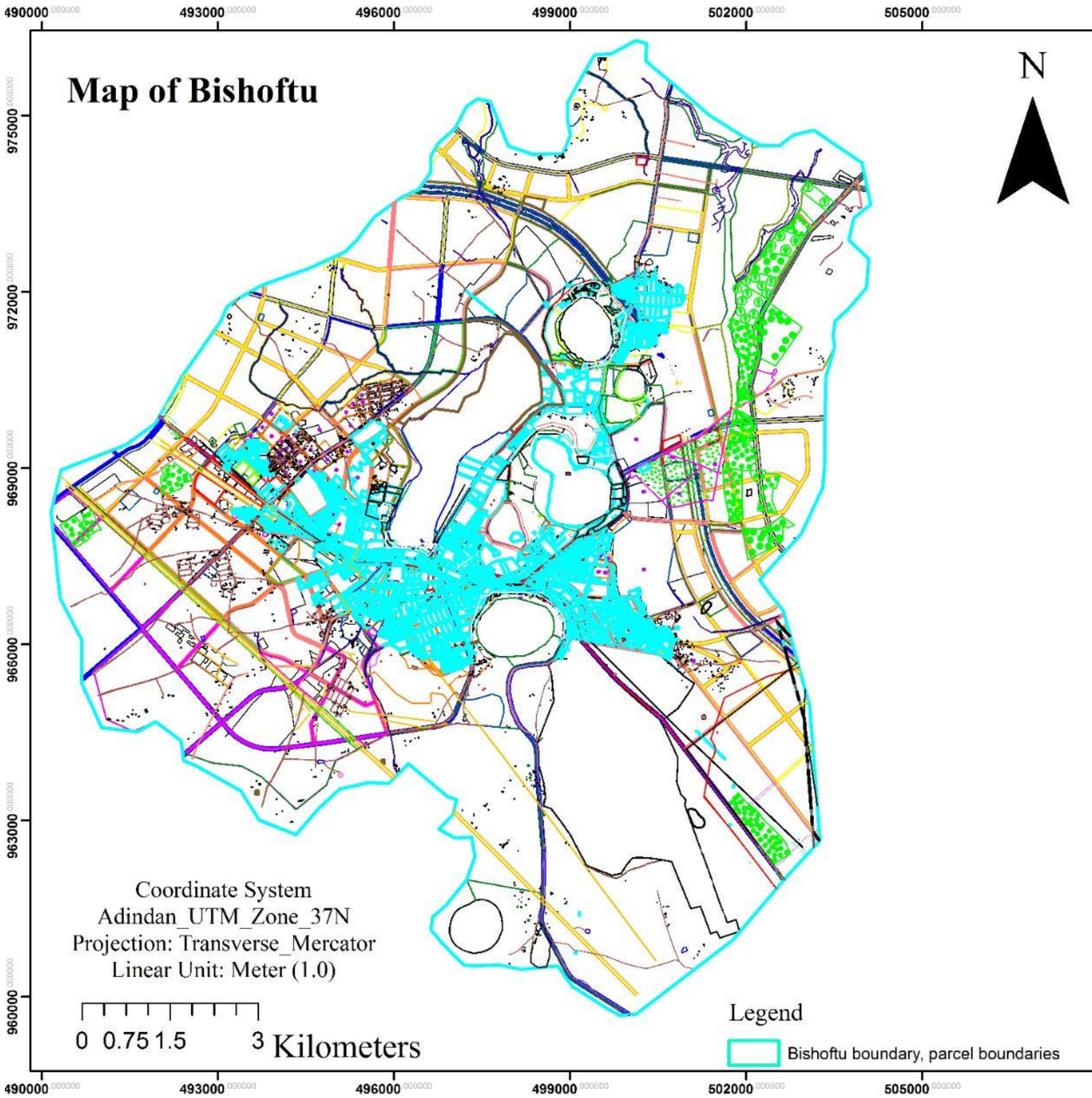



Figure 14 Map of Bishoftu

3.2.1. Background of the Study Area

The most remarkable year for the development of small towns was 1889. The factors to change the status of urbanization during this period were the development of new system of administration, development of communication and flourishing of commerce. In addition to these the most important reasons for the emergence of urbanization in larger parts of the country in general and in the region in particular was mainly attributed to three major historical events which are southward expansion, introduction of Djibouti-

Finfinne rail way line and the Italian occupation/1936-1941/ of the country. The period was the completion of Ethio- Djibouti railway. The railway provided an easy and effective means of contact with the outside world. Along the railway a number of small towns were developed: Metahara, Adama, Modjo, Bishoftu, Dukem and Akaki were direct products of the railway line. Based on the above details Bishoftu city is found in east shoa zonal administration and it was found in1917 with the coming of Ethio – Djibouti railway. The name Bishoftu comes from the Afan Oromo language called "Bishanoftu" which refers to "water bodies". From the existing of volcanic crater lakes named as, horaarsade, Babogaya. Bishoftu, Cheleleka /seasonal/, Kilole, Kuriftu and Green lake. On the topic of its growth from 1983-1994 E.C. it was the political center of Adea District. Beginning from 1995 it renamed as first level city with Mayor, Municipality Administer, city Council's and city cabinet members. Gradually the city had developed from a station center to a large and big city. The Municipality of the city was founded around 1943 E.C. The Municipality has expanded its horizon to reach out to the people and provide diversified socio-Economic services including the provision of infrastructure development, affordable housing and sanitation, public parks development, fire and emergency services. For administrative simplicity in real circumstances the city is divided in to 14 Kebeles. The city also hosts large institutions such as the Great Ethiopian Air Force, different higher institutions, Agricultural research centers, galleries and the likes. Bishoftu is a rapidly growing urban city both in terms of population and economy. One can also see the dynamisms of the city in various aspects. The city has been experiencing a high population growth compared to other cities of the region. Various studies have indicated that rural-urban migration accounts to the high increase in population of the city.

### 3.2.2. Land Cover and Land use

Since the first master plan of the city was made in 1961 and revised in 1978, 1992, 2001, and 2004 E.C. In 2001 E.C., the city had area of 14,500 ha. Now a day, the total area of the city incorporated under the master plan is enlarged to 18,278 hectors. According to the master plan of 2004/2011/12 the land use of the city administration is summarized as follows.

Table 8 shows Bishoftu city Administration land use

| | Land use type | Area Covered In Hectare | Percentage /%/ |
|---|---|---|---|
| 1 | Open space | 4,467 | 24.44 |
| 2 | Recreation | 3,115 | 17.04 |
| 3 | Residence | 2,826 | 15.46 |
| 4 | Social service | 2,553 | 13.90 |
| 5 | Transport and street network | 2,309 | 12.33 |
| 6 | Manufacturing and storage | 1,362 | 7.45 |
| 7 | Special function | 828 | 4.53 |
| 8 | Agriculture | 486 | 3.02 |
| 9 | Commerce | 303 | 1.66 |
| 10 | Administration | 31 | 0.17 |
| | Total | 18,278 | 100 |

### 3.2.3. Land uses around Lakes

In Bishoftu, different types of land use occupy the sites around the lakes. But land uses around lakes are characterized by specialization. In this regard, urban agriculture is dominant around Lake Cheleleka occupying 28.2%. Social service around Lake Kuriftu, Real estate around Lake Hora Arsede (55.1%), residence around lake Bishoftu (55.9%) and resort/recreation around Lake Babogaya (19.9%).

### 3.2.4. Topographic Features /Landscape

The natural topography of Bishoftu city with buffer zones has been characterized in the north and east by flat land, which is broken by the swampy, express road, rail way and lakes. In the south by undulating land that is dominated by hills, in general, the topography of the city is undulating, that is dominated by hills. It is very important to note here that the city is part of the rift valley.

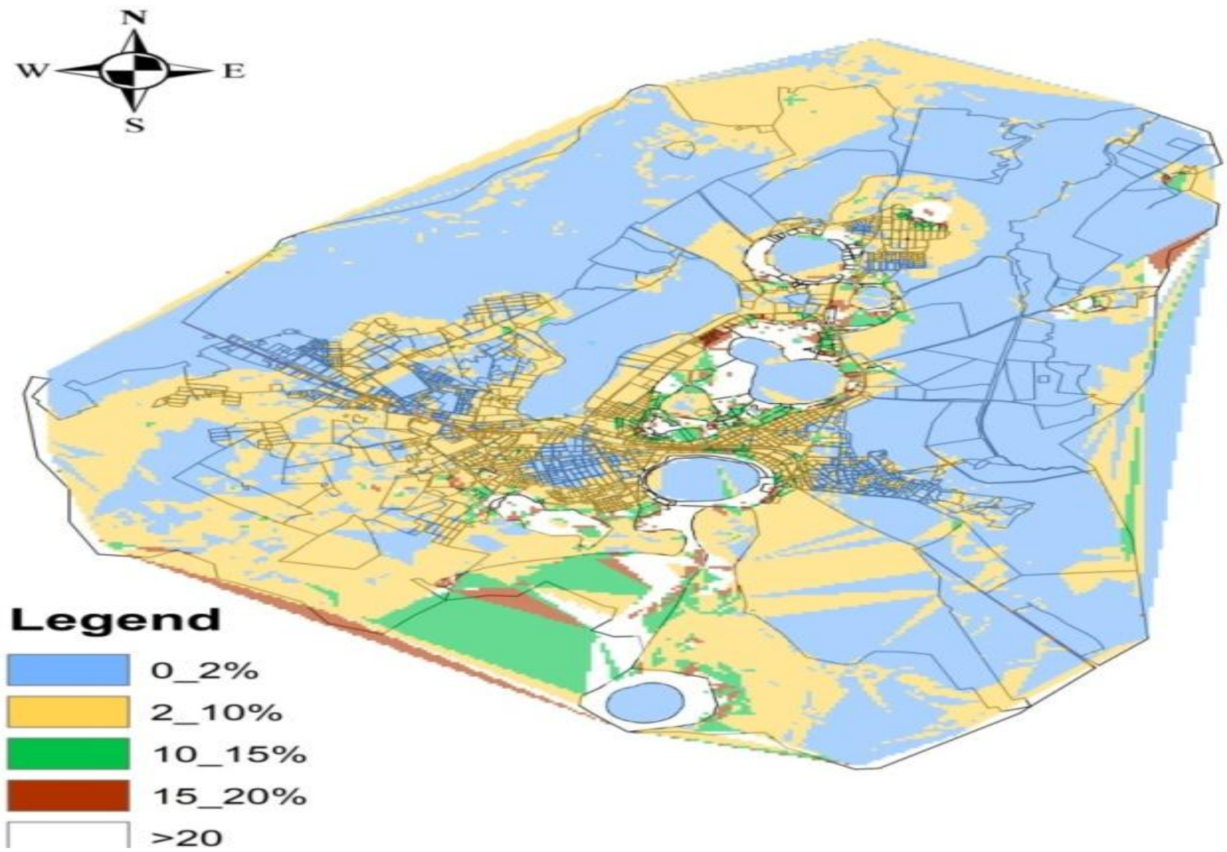



Figure 15 Relief map of Bishoftu

The above topographic map shows types of slope in the city administration; based on the above map Places with a slope below 2% are considered as swampy and are not recommended for heavy developments as they are flood hazard prone areas. Slope of greater than 10% are not considered for general developments as they are undulating, steep and very steep areas.

## 3.3. Climatic Condition

### 3.3.1. Temperature and Precipitation

The climate of the city in general belongs to woina dega (Agro climatic zone). The Maximum annual temperature is 29.8 $^{0}$c and the Minimum is 4.9. Annual average rainfall of the city is 797.2 mm. April is the hottest month of the year (29.3$^{0}$C), December is the coldest month (4.9 $^{0}$C) and July is the rainy month (225.3 mm) of the year (Bishoftu city of Lakes,2019). The highest wind speed is registered in May (2.91m/s) and the most common wind direction seen in the city is easterlies (Bishoftu city of Lakes,2019).

### 3.3.2. Elevation / Altitude/

The general elevation of the town ranges from 1746m to 1995m. The altitude is generally higher in the southwestern part of the town and gradually declines to east directions for few distances and then increases again in the same direction. Altitude declines gradually from north to south direction for few distances and then increases again from north to south direction. The greatest proportion of the altitude of the town ranges between 1893 to 1930 meters and almost covers western, northern, and southwestern parts of the town. The central part of the town where the lakes are found is surrounded by higher elevations ranging from 1856-1893m with few lower altitudes to access the lakes.

### 3.3.3. Drainage

Surface flow direction is determined by topographic features, nature of soil, vegetation cover and human impacts. Based on the topography of the city, Seasonal streams flow from northern direction to the central part of the town (some draining to the lakes) and then flow to southeast direction. On the other hand, Surface run off from southwestern parts of the town flows to southeast direction. At the same time, Surface runoff from northeast direction also flows to southwest until it is blocked by the upland areas Located around and near the Lakes. Thus, appropriate watershed management should be carried out to reduce risks of siltation and hence increase the volume of Lakes by timely supervising the watershed and diversion channels.

## 3.4. Sampling and Testing

With the objective of correlating index properties and swelling pressure of expansive soils found in Bishoftu town, in this study both disturbed and un disturbed samples were taken from different locations with potential expansive soils and the required laboratory test to determine index properties and swelling pressure were conducted.

### 3.4.1. Sampling Technique

In this study the study populations were selected using non probability sampling technique from which purposive sampling is used. Purposive sampling is a type of sampling where the members of the sample are selected according to the purpose of the study.

### 3.4.2. Selection of Sampling Sites

Wide variety of soils is available in the study area, from which the areas that contain expansive soils were selected. During the selection of sampling sites, the sites with soils that exhibit expansive nature where identified by visual identification, in the identification processes of the areas with expansive soils the physical characteristics of expansive soils stated in Chapter two were taken into consideration.

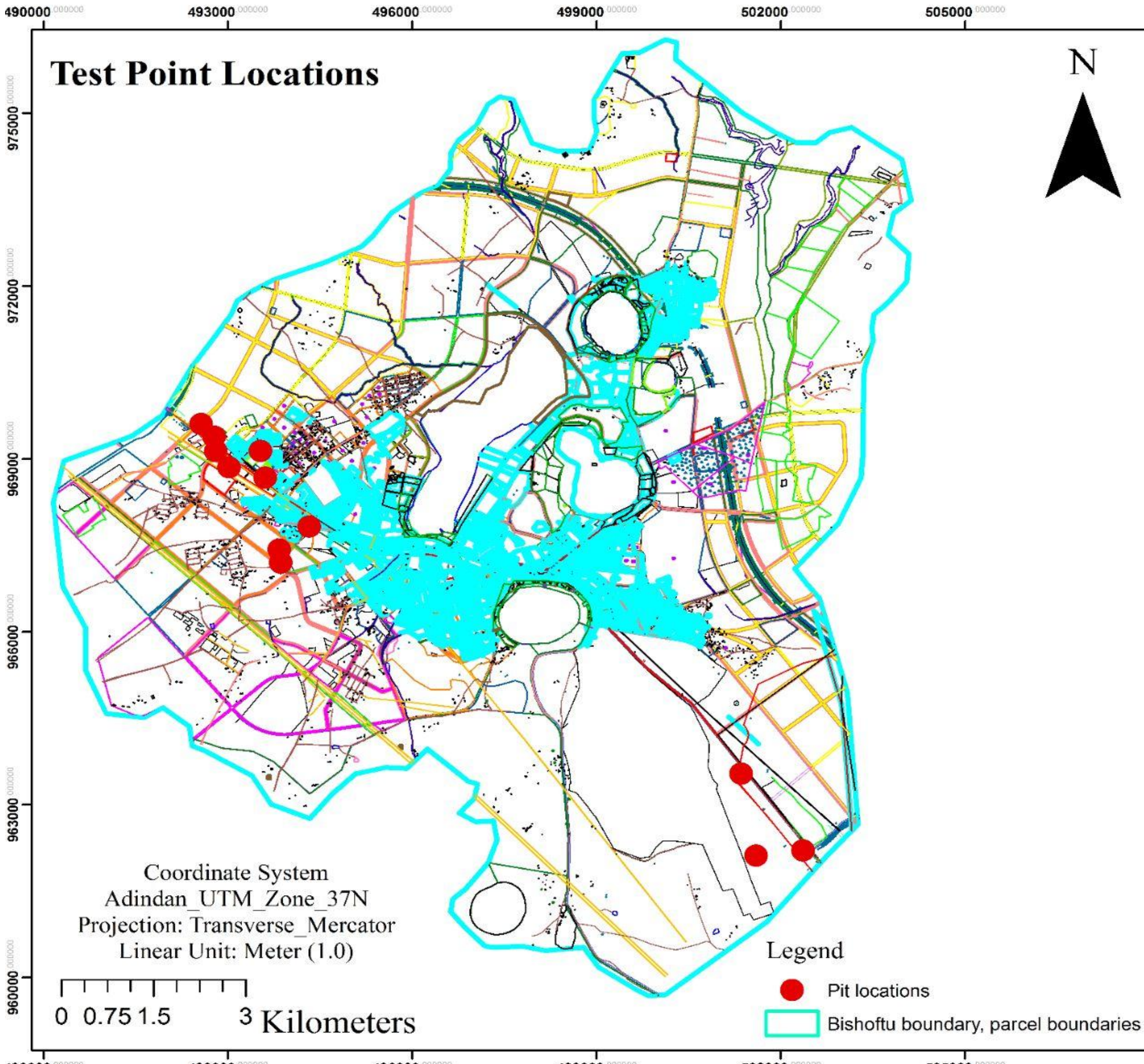



Figure 16 Location of test pits in the master plan

A Pit is dug manually in order to reveal the sub surface conditions to the desired depth. Sampling was done during three intervals. The first period was from July-August 2018 where eight samples were collected from four test pits the second period is from September-November 2018 where 10 samples were collected from Six test pits and the last was from December of 2018-January 2019 where four samples were collected from two test pits. Samples were taken at depth of 1.5m and 3.0m.

Figure 17 Excavation of test pits during sampling (Source: photos taken during test pit excavation)

A total of 24 disturbed and 22 undisturbed representative samples were collected from 12 test pits. The disturbed soil sample were collected from their respective sites at a depth of 1.5m and 3.0m below ground surface using tight plastic bag with a reference tag to describe the location, color and depth of sample from which it was taken. The Undisturbed soil samples for the swell consolidation test were recovered by applying static force pressing the Shelby sampler into the ground using hydraulic jack after leveling the surface and also using the rings of the odometer. The sampling tube was then removed from the hole and the ends of the sampler were immediately sealed with aluminum foil in order to sustain the in-situ condition of the samples, and labeled with necessary information for subsequent laboratory testing.

Figure 18 Disturbed samples and undisturbed samples (Source: photos taken of the samples in the laboratory)

## 3.5. Laboratory Testing

To determine index properties of expansive soils found in Bishoftu town, the samples were collected, the next step is conducting the required laboratory tests. All the necessary laboratory tests were conducted at Defense Engineering Collage (DEC) and Core Consulting Engineers PLC, soil laboratories. The following laboratory tests were conducted:

### 3.5.1. Index Properties

#### 3.5.1.1. Determination of water content

Initial moisture content refers to the water content of the soil under field or natural condition. The value of natural field moisture ω will vary depending on the location of the soil sample, i.e. at or near ground surface, deep in the ground and depending on the type of soil and climatic conditions. Moisture content of a soil is the ratio of weight water present to weight of dry soil in a given soil mass. It is usually expressed as percentage of the dry mass. The water content, which is usually expressed as a percentage, can range from zero (dry soil) to several hundred percent. For many soils, the water content may be an extremely important index used for establishing the relationship between the way a soil behaves and its properties. The consistency of a fine-grained soil largely depends on its water content. The water content is also used in expressing the phase relationships of air, water, and solids in a given volume of soil. The standard laboratory procedure is by oven drying a specimen of about 30 g fine-grained soils in an open tin or tray at 105-110 °C for 18-24hours. To investigate the effect of moisture variation on expansive soils found in Bishoftu town during laboratory testing AASHTO T-265 and ASTM D-2216 manuals were used.

$\omega = \frac{w_w - w_d}{w_d} * 100(\%)$, where $w_w$ – weight of water

$w_d$ -weight of dry soil sample

3.5.1.2. Determination of Specific Gravity

Specific Gravity**:-**of soil is the ratio of weight of a given volume of soil particles in air at a stated temperature to the weight of an equal volume of distilled water at a stated temperature. The specific gravity of a soil is often used in relating a weight of soil to its volume.

Mathematically, it is expressed as

$G_s = \frac{Ms}{M_2 + M_s - M_1}$ Where,

$M_S$ = mass of dry soil (g)

$M_1$ = mass of pycnometer + soil + water (g)

$M_2$ = mass of pycnometer full of water (g)

Figure 19 Specific gravity test in the laboratory (Source: photos taken during Specific gravity test)

3.5.1.3. Atterberg Limit Tests (Liquid Limit and Plastic Limit Test)

The behavior of all the soils and especially clays considerably varies with the presence of water. The Atterberg limit tests also known as consistency test are types of index property tests and it is used to determine the degree of firmness of the soil. Based on their mode of formation and mineralogical composition, different soils respond differently for the same moisture content. Atterburg limits are empirical formulas developed to determine the soil consistency. These tests are mostly used for cohesive soils by which their strength is highly dependent on the amount of water they have in their voids. The gradual increase of water in a dry cohesive soil sample for example will change the sample from solid to a semi solid state, to a plastic state and finally by adding more water the sample will be changed into a liquid state. Based on the above Atterberg put limits for the above mentioned states of the soil at different water contents. The states are shrinkage limit, plastic limit and liquid limit. The tests are carried out only on the fine fraction of a soil, which is normally material passing the 425 μm sieve, and about 200-gram soil sample are taken. Laboratory test were performed following AASHTO T89-90 and ASTM D-4318 test procedures.

Figure 20 Liquid Limit test (Source: photos taken during Liquid Limit test)

Figure 21 Plastic Limit test and Samples of LL, PL and Ls test during oven drying (Source: photos taken during Plastic Limit test and samples of LL, PL & Ls inside an oven)

3.5.1.4. Linear Shrinkage

Linear shrinkage of a soil is a measure of its horizontal shrinkage. This test was conducted on the soil at its liquid limit, on the sample that was tested for liquid limit, additional (2-3) % water was added and thoroughly mixed to a uniform consistency, it was then placed in a lightly greased shrinkage mold the mold was filled in three steps and the voids were removed by tapping the mold in a hard surface finally the sample in the mold was filled properly and was levelled off. Prior to oven drying the sample was left to dry at a room temperature and then placed in an oven of temperature 105$^{o}$c-110$^{o}$c for 16-24 hours. To calculate the linear shrinkage of the specimen it is required to divide the longitudinal shrinkage of the specimen by the length of the mould and convert this result to a percentage.

$Ls = (1 - \frac{Ld}{L})$ *100, where Ls is linear shrinkage in percent, $L_d$ is oven dried length and L is total length of the Mould.

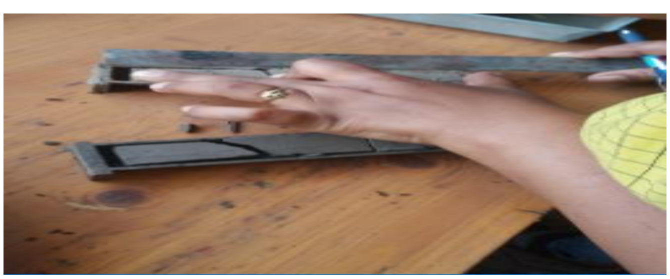


Figure 22 Linear shrinkage soil sample after oven drying (Source: photos taken After Ls test conducted)

3.5.1.5. Grain Size Distribution Analysis

Knowledge of particle size distribution of a soil is very useful in the present geotechnical world. The result of this analysis are widely used for soil classification, design of filters, construction of earth dams, highway embankments and determining the mode of bearing capacity computations. Hence grain size analysis tests are conducted on almost every soil investigation project.

This test method covers the quantitative determination of the distribution of particle sizes in soils. For fine-grained soils wet sieve analysis was performed by soaking the soil prior to washing in order to avoid the soil particles coherency then the samples were washed through the 75µm sieve. After washing, the material which has been retained on 75µm sieve is oven dried and mechanical sieve is conducted. While the distribution of particle sizes smaller than 75 µm is determined by a sedimentation process. A 50g of sample passing No 200 sieve was placed in to a beaker and 125ml dispersant agent of Sodium hexametphosphate was added, stirred and soaked for 16hours.

At the end of soaking period the sample was stirred by mechanical stirrer and transferred to the cylinder and was filled up to 1000ml, using a hydrometer analysis particle size determination was done. The grain size distribution analysis was done in accordance with AASHTO T-88 and ASTM D-421-22.

Figure 23 wet sieve analysis result and Hydrometer Analysis (Source: photos taken after wet Sieve and during hydrometer analysis)

3.5.2. Swelling Characteristics

3.5.2.1. Free Swell Test

Free Swell is the percentage heave, ($\Delta h/h$) *100, of soil following absorption of water at the seating pressure. This method is suggested by Holtz and Gibbs to measure the expansive potential of a soil. This is performed by pouring slowly 10 cc of dry soil passing 425 microns' sieve, into a 100 cc graduated cylinder filled with water. The volume of swelled soil is recorded after 24 hours, from the graduations of the cylinder. The free swell index in percent, is then determined. Free swell of the soil sample was determined using IS-2720.

Free Swell Index=$\frac{(Final\ Volume - Initial\ Volume)}{Initial\ Volume} * 100$

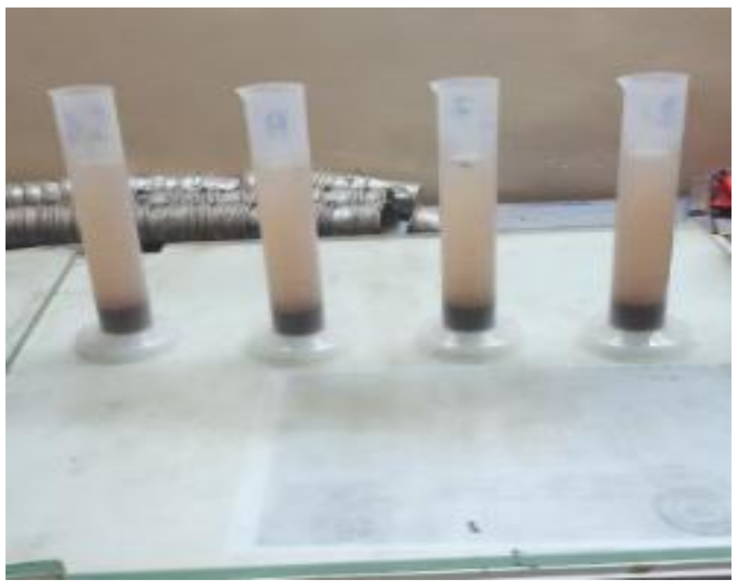


Figure 24 Free swell test (Source: photos taken during FS test)

3.5.2.2. Swelling Pressure Determination

When an expansive soil is subjected to moisture increment it will exert an uplift pressure on the structure resting on it. This pressure exerted is proportional to the swelling pressure of the soil. Hence swelling pressure of an expansive soil is the pressure required to prevent volume change of the soil during wetting. The swelling pressure is directly proportional to the initial dry density for constant moisture content. The relative swell/ settlement potential of soil determined from these test methods can be used to develop estimates of heave or settlement for given final moisture and loading condition. In order to determine the swelling pressure of the collected undisturbed samples ASTM D-2435 and D-4546 were used as a guideline.

Figure 25 Swell-Consolidation test (Source: photos taken during swell-consolidation test)

## 3.6. Data Analysis

### 3.6.1. Linear Regression Analysis

The method used to analyses the results to determine if there is a correlation Between Index properties and swelling pressure is Linear Regression Analysis. The process that was undertaken to carry out this analysis was for the results to be graphed using the computer program Microsoft Excel. To be able to achieve a graph from this program the results of swelling pressure were tabulated against the corresponding Index property test results. Once all the results were tabulated the results were then graphed as a 'XY' scatter plot. A scatter chart has two axes with the x–axis showing one set of numerical data and the other value along the y-axis. Scatter plots are frequently used for displaying and comparing numeric values, such as engineering, statistical, and scientific data. The advantage of a scatter plot for this situation is that this chart allows different comparisons to be made. A trend line is a graphical representation of the trend or direction of data in a series. Trend lines are used generally to predict a value on the y axis from data on the x axis. The data was tested for different trend lines which consisted of the following relationships: (Field, 2013)

- Linear
- Logarithmic
- Polynomial
- Power
- Exponential

For each trend line both the equation and $R^2$ value of the trend line was determined using the options provided in the Excel program. To determine the strength of each correlation the $R^2$ value for the trend line was calculated. $R^2$ is the square of the correlation between the response values and the predicted response values. $R^2$ is the relative predictive power of a model and is a descriptive measure between 0 and 1. The closer it is to one the greater the ability for the equation to predict an outcome. Overall the $R^2$ statistic indicates how much of the behavior of y is captured by the model. $R^2$ is defined as the ratio of the sum of squares of the regression (SSR) and the total sum of squares (SST) (Field ,2013).

SSR is defined as;

$$SSR = \sum_{n=0}^{n} wi(\hat{Y} - \bar{Y})^2$$

SST is also called the sum of squares about the mean, and is defined as;

$$SST = \sum_{n=0}^{n} wi(Yi - \bar{Y})^2$$

Given these definitions, $R^2$ is expressed as;

$$R^{2=} \frac{SSR}{SST} = \frac{\sum_{n=0}^{n} wi(\hat{Y} - \bar{Y})^2}{\sum_{n=0}^{n} wi(Yi - \bar{Y})^2}$$

For the single linear regression analysis done via MS-Excel the values of the index property tests were taken as independent variable and the measured values of swelling pressure were taken as the dependent variable. That is the values of LL, PL, PI, Ls, ω, LI, $\rho_{dry}$ and clay fraction were each correlated with swelling pressure Ps.

### 3.6.2. Multiple Linear Regression Analysis

Multiple Regression Analysis refers to a set of techniques for studying the straight-line relationships among two or more variables. Multiple regression estimates the b's in the equation

$$Y = b_1x_1 + b_2x_2 + \ldots\ldots\ldots\ldots\ldots + C$$

The X's are the independent variables (IV's). Y is the dependent variable. The b's are the regression coefficients, representing the amount the dependent variable changes when the independent changes a single unit. The C is the constant, where the regression line intercepts the Y axis, representing the amount the dependent Y will be when all the independent variables are 0 (Field, 2013). The computer program Statistical Package for Social Science (SPSS) is an efficacious tool that can be used to do multiple linear regression and it yields better regression coefficients $R^2$ values than other computer programs that can be used for multiple regression.

# CHAPTER FOUR

# RESULTS AND DISCUSSION

In order to determine index properties and swelling pressure of expansive soils in Bishoftu town, index property and swelling pressure tests were conducted at 12 test pits with potential expansive soils and the results of the laboratory tests and the regression analysis results will be discussed in this chapter.

## 4.1. Sampling Area

The test pits designation, location of test pits and color of the soil sample is shown below.

Table 9 The location of test pits and color of the soil sample

| **S/ No** | **Station** | Location | Color | Northing | Easting |
|---|---|---|---|---|---|
| 1 | TP 1 | 105 B4 | Dark Gray | 493834 | 967425 |
| 2 | TP 2 | Sunshine 1 | Black | 493632 | 968985 |
| 3 | TP 3 | Sunshine 2 | Black | 493606 | 968672 |
| 4 | TP 4 | M-A Exit | Dark Gray | 502364 | 962202 |
| 5 | TP 5 | SSP | Black | 492236 | 969874 |
| 6 | TP 6 | Near Air force | Black | 501365 | 962569 |
| 7 | TP 7 | Express way 1 | Black | 492565 | 969605 |
| 8 | TP 8 | NOC | Black | 493018 | 968851 |
| 9 | TP 9 | M-A Exit 2 | Black | 501354 | 963535 |
| 10 | TP 10 | Mekelakeya K01 | Dark Gray | 494325 | 967826 |
| 11 | TP 11 | Sunshine 3 | Black | 493530 | 969136 |
| 12 | TP 12 | Express way 2 | Black | 493124 | 969521 |

## 4.2. Results of Moisture Content

The natural moisture content of the collected samples ranges from (37-44.7%) and the results are summarized in the following table, detail laboratory NMC results are given in APPENDIX A.

## 4.3. Results of Atterberg Limit Test

In addition to soil classification Atterberg limit results are used for the following purpose.

- With natural water content is used determine the relative consistency or liquidity index.
- With the percentage finer 0.002 mm size is used to determine its activity number.
- Sometimes used to evaluate the weathering characteristics of clay-shale materials. When subjected to repeated wetting and drying cycles the liquid limits of these materials tend to increase. The amount of increase is considered to be a measure of shale susceptibility to weathering.
- Qualitatively measure of organic matter content of soil by comparing the liquid limit of sample before and after oven-drying can be used.
- Either individually or together with other soil properties to correlate with engineering behavior such as compressibility, permeability, compatibility, shrink, swell and shear strength

The results are summarized in the following table, detail laboratory Atterberg limit test results are given in APPENDIX A.

## 4.4. Results of Linear Shrinkage

Linear shrinkage is the decrease in length of soil sample when oven dried, starting with a moisture content of the sample at the liquid limit, the results are summarized in the following table, detail laboratory Ls results are given in APPENDIX A.

## 4.5. Results of Specific Gravity

Specific gravity test results are used:

- For determination of particle size in hydrometer,
- For solving phase relation such as void ratio, degree of saturation unit weight etc.
- For computing compression index in consolidation test,

- For computation of density corresponding to full saturation (zero void air curve) in compaction test.

The results are summarized in the following table, detail laboratory Specific gravity test results are given in APPENDIX A.

The laboratory results of ***Natural Moisture Content, Specific Gravity, Liquid Limit, Plastic Limit, Plasticity Index*** and ***Linear Shrinkage*** are summarized in the table given below.

Table 10 Summary of laboratory test results

| **S/ No** | **Station** | **Depth(m)** | **ω (%)** | **$G_S$** | **LL (%)** | **PL (%)** | **PI (%)** | **Ls (%)** |
|---|---|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 41.78 | 2.68 | 93 | 31 | 62 | 13.4 |
| 2 | TP 1 | 3.0 | 39.75 | 2.7 | 102 | 36 | 66 | 21.4 |
| 3 | TP 2 | 1.5 | 38.9 | 2.68 | 97 | 35 | 62 | 17.6 |
| 4 | TP 2 | 3.0 | 37.4 | 2.71 | 98 | 35 | 63 | 20.4 |
| 5 | TP 3 | 1.5 | 39.1 | 2.68 | 106 | 34 | 72 | 17.9 |
| 6 | TP 3 | 3.0 | 37.4 | 2.71 | 101 | 34 | 67 | 19.6 |
| 7 | TP 4 | 1.5 | 39.7 | 2.72 | 106 | 41 | 65 | 18.6 |
| 8 | TP 4 | 3.0 | 40.78 | 2.75 | 105 | 39 | 66 | 21.5 |
| 9 | TP 5 | 1.5 | 41.4 | 2.71 | 102 | 39 | 63 | 15.4 |
| 10 | TP 5 | 3.0 | 40.1 | 2.70 | 104 | 38 | 66 | 18.1 |
| 11 | TP 6 | 1.5 | 38.83 | 2.69 | 97 | 32 | 65 | 16.1 |
| 12 | TP 6 | 3.0 | 41.03 | 2.7 | 98 | 33 | 64 | 16.5 |
| 13 | TP 7 | 1.5 | 38.5 | 2.65 | 97 | 34 | 64 | 21.9 |
| 14 | TP 7 | 3.0 | 39.63 | 2.67 | 104 | 34 | 70 | 17.9 |
| 15 | TP 8 | 1.5 | 39.59 | 2.65 | 96 | 33 | 63 | 19.6 |
| 16 | TP 8 | 3.0 | 40.91 | 2.70 | 105 | 38 | 67 | 16.4 |
| 17 | TP 9 | 1.5 | 39.97 | 2.70 | 98 | 35 | 64 | 19.1 |
| 18 | TP 9 | 3.0 | 37.1 | 2.73 | 105 | 38 | 67 | 22.3 |
| 19 | TP 10 | 1.5 | 39.48 | 2.71 | 101 | 36 | 65 | 19.6 |
| 20 | TP 10 | 3.0 | 40.63 | 2.70 | 97 | 34 | 63 | 16.4 |
| 21 | TP 11 | 1.5 | 44.1 | 2.57 | 87 | 30 | 57 | 12.1 |
| 22 | TP 11 | 3.0 | 41.21 | 2.70 | 101 | 37 | 64 | 17.8 |
| 23 | TP 12 | 1.5 | 44.7 | 2.66 | 86 | 30 | 56 | 11.7 |
| 24 | TP 12 | 3.0 | 38.99 | 2.73 | 104 | 35 | 69 | 16.5 |

## 4.6. Result of Liquidity Index

LI is a measure of where the current water content (ω) lies with respect to the PL-LL range.

LI $=\frac{(\omega-PL)}{(LL-PL)}$ where ω is the water content at which LI is being determined.

The value of Liquidity Index (LI) varies according to the consistency of soils as follows:

Table 11 Liquidity Index Vs Soil Consistency

| Liquidity Index(LI) | Description of Strength |
|---|---|
| LI<0 | Semisolid state- High strength but brittle i.e. Sudden failure is expected |
| 0<LI<1 | Plastic state- Intermediate strength |
| LI>1 | Liquid state- Low strength |

The results of Liquidity Index for the soil samples are tabulated in the following table.

Table 12 Liquidity Index result

| **S/ No** | **Station** | **Depth (m)** | **Moisture content (%)** | **Plastic Limit(PL)** | **Plasticity Index(PI)** | **LIQUIDITY INDEX(LI)** | **REMARK** |
|---|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 41.78 | 31 | 62 | 0.173871 | Plastic state |
| 2 | TP 1 | 3.0 | 39.75 | 36 | 66 | 0.056818 | Plastic state |
| 3 | TP 2 | 1.5 | 38.9 | 35 | 62 | 0.062903 | Plastic state |
| 4 | TP 2 | 3.0 | 37.4 | 35 | 63 | 0.038095 | Plastic state |
| 5 | TP 3 | 1.5 | 39.1 | 34 | 72 | 0.070833 | Plastic state |
| 6 | TP 3 | 3.0 | 37.4 | 34 | 67 | 0.050746 | Plastic state |
| 7 | TP 4 | 1.5 | 39.7 | 41 | 65 | -0.02 | Semisolid state |
| 8 | TP 4 | 3.0 | 40.78 | 39 | 66 | 0.02697 | Plastic state |
| 9 | TP 5 | 1.5 | 41.4 | 39 | 63 | 0.038095 | Plastic state |
| 10 | TP 5 | 3.0 | 40.1 | 38 | 66 | 0.031818 | Plastic state |
| 11 | TP 6 | 1.5 | 38.83 | 32 | 65 | 0.105077 | Plastic state |
| 12 | TP 6 | 3.0 | 41.03 | 33 | 64 | 0.125469 | Plastic state |
| 13 | TP 7 | 1.5 | 38.5 | 33 | 64 | 0.087969 | Plastic state |
| 14 | TP 7 | 3.0 | 39.63 | 34 | 70 | 0.080 | Plastic state |
| 15 | TP 8 | 1.5 | 39.59 | 33 | 63 | 0.104603 | Plastic state |
| 16 | TP 8 | 3.0 | 40.91 | 38 | 67 | 0.043433 | Plastic state |
| 17 | TP 9 | 1.5 | 39.97 | 35 | 63 | 0.077656 | Plastic state |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 18 | TP 9 | 3.0 | 37.1 | 38 | 67 | -0.01343 | Semisolid state |
| 19 | TP 10 | 1.5 | 39.48 | 36 | 65 | 0.053538 | Plastic state |
| 20 | TP 10 | 3.0 | 40.63 | 34 | 63 | 0.105238 | Plastic state |
| 21 | TP 11 | 1.5 | 44.1 | 30 | 57 | 0.247368 | Plastic state |
| 22 | TP 11 | 3.0 | 41.21 | 37 | 64 | 0.065781 | Plastic state |
| 23 | TP 12 | 1.5 | 44.7 | 30 | 56 | 0.2625 | Plastic state |
| 24 | TP 12 | 3.0 | 38.99 | 35 | 69 | 0.057826 | Plastic state |

## 4.7. Results of Grain Size Analysis

The grading of a soil determines many of its characteristics. Since it is such an obvious property and easy to measure, it is plainly a suitable first choice as the most fundamental property to assess the characteristics of soil.

- Grading influences density of soil.
- Grading can be seen to influence permeability.
- Grading influences, the rate of consolidation.
- Shear strength is affected by grading since grading influences the amount of interlock between soil particles.
- Swelling property and frost susceptibility are influenced by grading.

In order to determine the types and amount of particles present in the soil samples both wet sieve and Hydrometer analysis were conducted and the results are presented in the following graph.

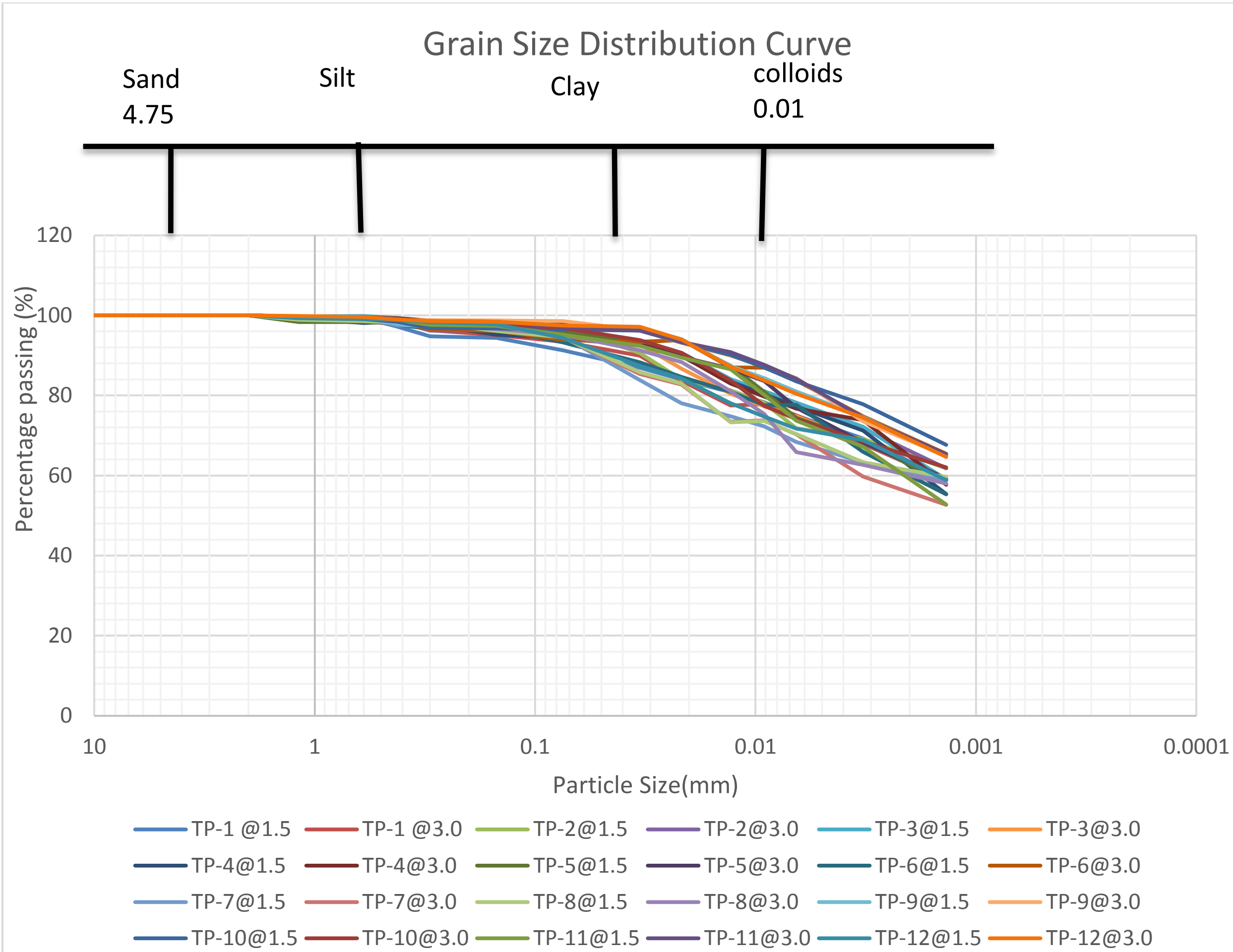



Figure 26 Grain size distribution curve

Different soil classification schemes are available based on particle size. The results are summarized in the following table, detail laboratory particle size distribution results are given in APPENDIX A.

Table 13 Grain size distribution of the study area

| S/ No | Station | Depth (m) | Sand (%) | Silt(%) | Clay(%) | Colloids(%) |
|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 8.74 | 19.17 | 64.11 | 7.97 |
| 2 | TP 1 | 3.0 | 6.6 | 22.49 | 63.34 | 7.57 |
| 3 | TP 2 | 1.5 | 2.58 | 18.68 | 65.50 | 1.24 |
| 4 | TP 2 | 3.0 | 4.28 | 16.55 | 66.72 | 12.45 |
| 5 | TP 3 | 1.5 | 4.74 | 15.94 | 65.61 | 13.71 |
| 6 | TP 3 | 3.0 | 4.8 | 19.61 | 63.73 | 11.86 |
| 7 | TP 4 | 1.5 | 5.56 | 16.6 | 63.32 | 14.51 |
| 8 | TP 4 | 3.0 | 2.06 | 17.03 | 65.75 | 15.61 |
| 9 | TP 5 | 1.5 | 4.4 | 12.59 | 63.34 | 19.67 |
| 10 | TP 5 | 3.0 | 5.78 | 13.34 | 63.81 | 17.08 |
| 11 | TP 6 | 1.5 | 6.7 | 19.07 | 60.03 | 13.60 |
| 12 | TP 6 | 3.0 | 6.1 | 12.96 | 70.12 | 10.81 |
| 13 | TP 7 | 1.5 | 5.24 | 25.17 | 61.02 | 8.57 |
| 14 | TP 7 | 3.0 | 5.46 | 26.52 | 56.23 | 11.79 |
| 15 | TP 8 | 1.5 | 5.5 | 26.71 | 61.47 | 6.31 |
| 16 | TP 8 | 3.0 | 4.78 | 18.93 | 60.31 | 15.98 |
| 17 | TP 9 | 1.5 | 3.14 | 12.69 | 69.85 | 14.32 |
| 18 | TP 9 | 3.0 | 1.44 | 10.03 | 69.21 | 19.32 |
| 19 | TP 10 | 1.5 | 3.6 | 9.93 | 72.73 | 13.74 |
| 20 | TP 10 | 3.0 | 3.2 | 16.24 | 65.27 | 15.29 |
| 21 | TP 11 | 1.5 | 4.78 | 13.51 | 59.96 | 21.76 |
| 22 | TP 11 | 3.0 | 2.9 | 9.17 | 69.88 | 18.04 |
| 23 | TP 12 | 1.5 | 5.6 | 21.98 | 63.86 | 8.56 |
| 24 | TP 12 | 3.0 | 2.56 | 12.87 | 69.56 | 15.01 |

## 4.8. Results of Free Swell test

One of the easiest ways to know whether a given soil type has potential for swell or not is to measure its free swell. The results are summarized in the following table, detail laboratory free swell test results are given in APPENDIX A.

According to Indian standard IS 2911 the degree of expansiveness is given below the soil in the study area is categorized under very high degree of expansiveness.

Table 14 Expansiveness based on FSI

| Degree of expansiveness | Percent swell |
|---|---|
| Low | Less than 20 |
| Medium | 20 to 35 |
| High | 35 to 50 |
| Very High | Greater than 50 |

## 4.9. Results of Swelling Pressure

In order to determine the swelling pressure for the collected undisturbed samples one dimensional swell-consolidation test was conducted using an odometer as per the ASTM standards. During this test dry density and moisture content were also measured for those undisturbed samples. The results are summarized in the following table, detail laboratory tests results are given in APPENDIX A.

Table 15 Results of dry density and swelling pressure tests

| **S/ No** | **Station** | **Depth (m)** | **FSI (%)** | **$\rho_{bulk}$** | **$\rho_{dry}$** | **$P_s$ (kPa)** |
|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 118 | 1.67 | 1.10 | 100 |
| 2 | TP 1 | 3.0 | 220 | 1.78 | 1.37 | 300 |
| 3 | TP 2 | 1.5 | 200 | 1.68 | 1.33 | 300 |
| 4 | TP 2 | 3.0 | 225 | 1.71 | 1.39 | 350 |
| 5 | TP 3 | 1.5 | 225 | 1.68 | 1.34 | 300 |
| 6 | TP 3 | 3.0 | 230 | 1.77 | 1.43 | 400 |
| 7 | TP 4 | 1.5 | 220 | 1.68 | 1.33 | 300 |
| 8 | TP-4 | 3 | 225 | 1.70 | 1.22 | 210 |
| 9 | TP 5 | 1.5 | 175 | 1.72 | 1.19 | 190 |
| 10 | TP 5 | 3.0 | 180 | 1.70 | 1.38 | 270 |
| 11 | TP 6 | 3.0 | 180 | 1.65 | 1.22 | 200 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 12 | TP 7 | 1.5 | 235 | 1.81 | 1.41 | 400 |
| 13 | TP 7 | 3.0 | 210 | 1.63 | 1.32 | 300 |
| 14 | TP 8 | 3.0 | 210 | 1.65 | 1.26 | 250 |
| 15 | TP 9 | 1.5 | 205 | 1.72 | 1.28 | 290 |
| 16 | TP 9 | 3.0 | 240 | 1.79 | 1.38 | 400 |
| 17 | TP 10 | 1.5 | 200 | 1.68 | 1.39 | 300 |
| 18 | TP 10 | 3.0 | 190 | 1.50 | 1.20 | 200 |
| 19 | TP 11 | 1.5 | 90 | 1.34 | 1.06 | 90 |
| 20 | TP 11 | 3.0 | 190 | 1.48 | 1.21 | 200 |
| 21 | TP 12 | 1.5 | 95 | 1.30 | 1.03 | 80 |
| 22 | TP 12 | 3.0 | 210 | 1.70 | 1.35 | 320 |

From the above result we can see that the higher the dry density the higher the swelling pressure. This means that as the grain to grain interaction increases the swelling pressure is higher.

## 4.10. Results Comparison with Expansive Soils Found in Ethiopia

Even though there is a limited amount of data on expansive soils found in Bishoftu studies are conducted on expansive soils in different parts of the country and the following table shows the comparisons of the laboratory results of the current study with studies on expansive soils found in other locations in Ethiopia.

Table 16 Comparison of Property ranges of Bishoftu Expansive soil with other expansive soils found in Ethiopia

| Property | Location | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Bishoftu (current Study) | Addis Abeba(Teklu,2003) | Bahir Dar (Gebrekrstos,2005) | Dukem (Tamrat,2013) | Jimma (Jibril,2014) | Koye Area A.A (Kemal,2015) | Mekelle (Nigussie,2007) | Woliso (Gulilat,2016) |
| %Gravel | | | | | | 0.1-1.6 | | 0.3-8.9 |
| %Sand | 1.44-8.74 | | 0.6-17.1 | 1.5-7.2 | 1-7 | 2.8-6.8 | 3.8-19.2 | 2.3-15.1 |
| %Silt | 9.17-26.71 | | 10.23-26.88 | 8.5-23.4 | 42-51 | 23.2-35.0 | 34.8-69.5 | 15.9-24.3 |
| %Clay | 56.23-72.73 | 50-81 | 58.1-87 | 26.4-70.4 | 40-59 | 56.6-71.8 | 20.8-60.2 | 62-76 |
| Liquid Limit(%) | 86-106 | 96-121 | 78.5-112.05 | 83.41-124.56 | 72-108 | 92.4-113.3 | 48.6-89.7 | 86-113 |
| Plasticity Index(%) | 56-70 | 54-84 | 46.46-64.2 | 32.2-79.49 | 36-68 | 56.2-70.3 | 25.1-70.6 | 45-68 |
| Specific Gravity | 2.5-2.75 | 2.77-2.85 | 2.55-2.81 | 2.61-2.74 | 2.58-2.72 | 2.67-2.84 | 2.4-2.78 | 2.6-2.81 |
| Free Swell Index(%) | 90-240 | 64-140 | 78-200 | 72-250 | 80-160 | 95-217.5 | 22-127 | 90-125 |
| Swelling Pressure(kPa) | 80-400 | 0-420 | 80-520 | 0-523.95 | 135-210 | 80-400 | 50.2-262.9 | 65.08-337.04 |

## 4.11. Soil Classification of the Study Area

There are different soil classification methods. The most widely used soil classification systems are the unified soil classification system (USCS), The American Association for Testing and Materials (ASTM), The British Standard Classification system (BS) and American Association of State Highway and Transportation Officials (AASHTO) system.

### 4.11.1. USCS Classification

The Unified system classifies fine-grained soils (silts and clays) and organic soils, according to their plasticity. As per the USCS classification system the soil in the study area is categorized under CH or OH region, and because the liquid limit of the samples was greater than 50 the soil is classified as clay soil with High plasticity (CH) or Fat Clay soil. The plasticity chart of the study area according to USCS is given below.

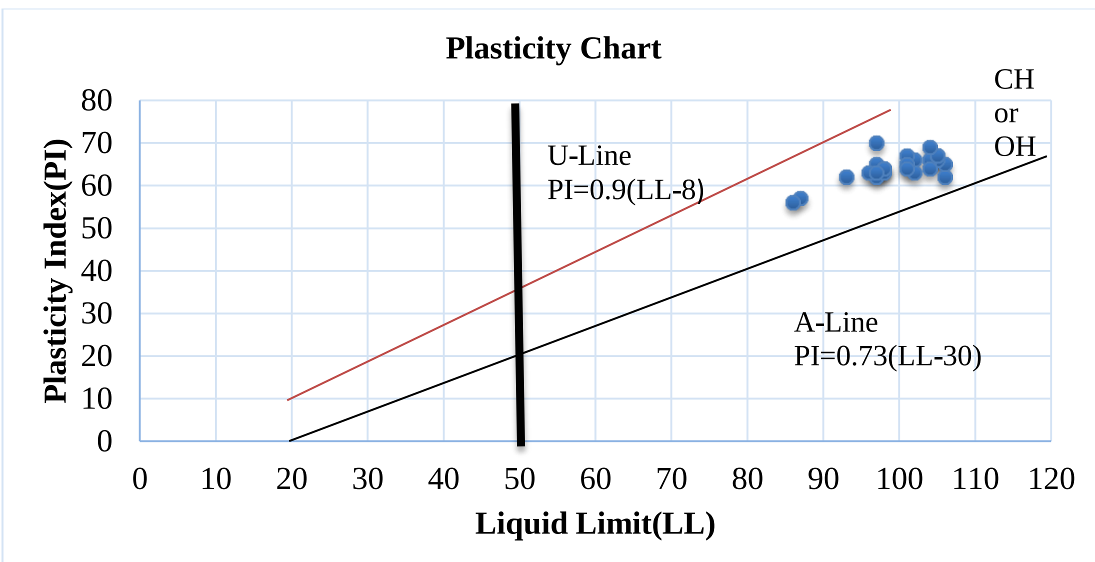



Figure 27 USCS soil classification of the study area

Table 17 USCS soil classification of the study area

| S/ No | Station(Km) | Depth(m) | Liquid Limit(LL) | Plasticity Index(PI) | %passing Sieve #200 | USCS |
|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 93 | 62 | 91.26 | CH |
| 2 | TP 1 | 3.0 | 102 | 66 | 93.40 | CH |
| 3 | TP 2 | 1.5 | 97 | 62 | 97.42 | CH |
| 4 | TP 2 | 3.0 | 98 | 63 | 95.72 | CH |
| 5 | TP 3 | 1.5 | 106 | 72 | 95.26 | CH |
| 6 | TP 3 | 3.0 | 101 | 67 | 95.20 | CH |
| 7 | TP 4 | 1.5 | 106 | 65 | 94.44 | CH |
| 8 | TP 4 | 3.0 | 105 | 66 | 97.94 | CH |
| 9 | TP 5 | 1.5 | 102 | 63 | 95.60 | CH |
| 10 | TP 5 | 3.0 | 104 | 66 | 94.22 | CH |
| 11 | TP 6 | 1.5 | 97 | 65 | 93.30 | CH |
| 12 | TP 6 | 3.0 | 98 | 64 | 93.90 | CH |
| 13 | TP 7 | 1.5 | 97 | 64 | 94.76 | CH |
| 14 | TP 7 | 3.0 | 104 | 70 | 94.54 | CH |
| 15 | TP 8 | 1.5 | 96 | 63 | 94.50 | CH |
| 16 | TP 8 | 3.0 | 105 | 67 | 95.22 | CH |
| 17 | TP 9 | 1.5 | 98 | 63 | 96.86 | CH |
| 18 | TP 9 | 3.0 | 105 | 67 | 98.56 | CH |
| 19 | TP 10 | 1.5 | 101 | 65 | 96.40 | CH |
| 20 | TP 10 | 3.0 | 97 | 63 | 96.80 | CH |
| 21 | TP 11 | 1.5 | 87 | 57 | 95.22 | CH |
| 22 | TP 11 | 3.0 | 101 | 64 | 97.10 | CH |
| 23 | TP 12 | 1.5 | 86 | 56 | 94.40 | CH |
| 24 | TP 12 | 3.0 | 104 | 69 | 97.44 | CH |

#### 4.11.2. AASHTO Classification

Essentially classifying soils according to their suitability as subgrades, based on this classification system the soil of the study area falls in the region of A-2-7 and A-7-5 but more than 35% passing No. 200 sieve it classified under groups A-7-5. Subgroup A-7-5 includes those materials with moderate plasticity index in relation to the liquid limit and which may be highly elastic as well as considerable volume change between wet and dry states. The plasticity chart as per AASHTO classification system is given below.

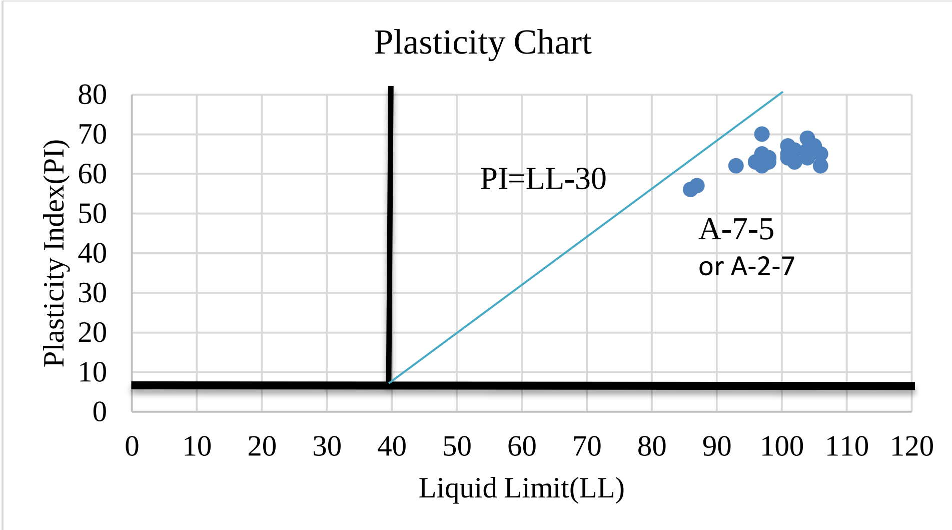



Figure 28 AASHTO classification of the study area

Table 18 AASHTO classification of the study area

| S/ No | Station(Km) | Depth(m) | Liquid Limit(LL) | Plasticity Index(PI) | %passing Sieve #200 | AASHTO |
|---|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 93 | 62 | 91.26 | A-7-5 |
| 2 | TP 1 | 3.0 | 102 | 66 | 93.40 | A-7-5 |
| 3 | TP 2 | 1.5 | 97 | 62 | 97.42 | A-7-5 |
| 4 | TP 2 | 3.0 | 98 | 63 | 95.72 | A-7-5 |
| 5 | TP 3 | 1.5 | 106 | 72 | 95.26 | A-7-5 |
| 6 | TP 3 | 3.0 | 101 | 67 | 95.20 | A-7-5 |
| 7 | TP 4 | 1.5 | 106 | 65 | 94.44 | A-7-5 |
| 8 | TP 4 | 3.0 | 105 | 66 | 97.94 | A-7-5 |
| 9 | TP 5 | 1.5 | 102 | 63 | 95.60 | A-7-5 |
| 10 | TP 5 | 3.0 | 104 | 66 | 94.22 | A-7-5 |
| 11 | TP 6 | 1.5 | 97 | 65 | 93.30 | A-7-5 |
| 12 | TP 6 | 3.0 | 98 | 64 | 93.90 | A-7-5 |
| 13 | TP 7 | 1.5 | 97 | 64 | 94.76 | A-7-5 |
| 14 | TP 7 | 3.0 | 104 | 70 | 94.54 | A-7-5 |
| 15 | TP 8 | 1.5 | 96 | 63 | 94.50 | A-7-5 |
| 16 | TP 8 | 3.0 | 105 | 67 | 95.22 | A-7-5 |
| 17 | TP 9 | 1.5 | 98 | 63 | 96.86 | A-7-5 |
| 18 | TP 9 | 3.0 | 105 | 67 | 98.56 | A-7-5 |
| 19 | TP 10 | 1.5 | 101 | 65 | 96.40 | A-7-5 |
| 20 | TP 10 | 3.0 | 97 | 63 | 96.80 | A-7-5 |
| 21 | TP 11 | 1.5 | 87 | 57 | 95.22 | A-7-5 |
| 22 | TP 11 | 3.0 | 101 | 64 | 97.10 | A-7-5 |
| 23 | TP 12 | 1.5 | 86 | 56 | 94.40 | A-7-5 |
| 24 | TP 12 | 3.0 | 104 | 69 | 97.44 | A-7-5 |

The BS classification system and the ASTM soil classification system are based on the Casagrande system and the soil in the study area is classified as fat clay soil (CH) in both classification schemes.

#### 4.11.3. Other Classification Systems

For expansive soils different scholars have established different classification schemes based on factors that are associated with the nature of soil under consideration either directly or indirectly.

##### 4.11.3.1. Skempton's Method

Skempton's classification technique is based on activity of clay which is given by:

$$\text{Activity} = \frac{Plasticity\ Index}{Clay\ percentage}$$

The soil in the study area has an activity that ranges from (0.8-1.2) which is in the normal activity region. Clays with activity larger than one may show very high swell potential. Such clays are known as expansive clays or reactive clays. Based on their activity value the Activity chart of the study area is given below.

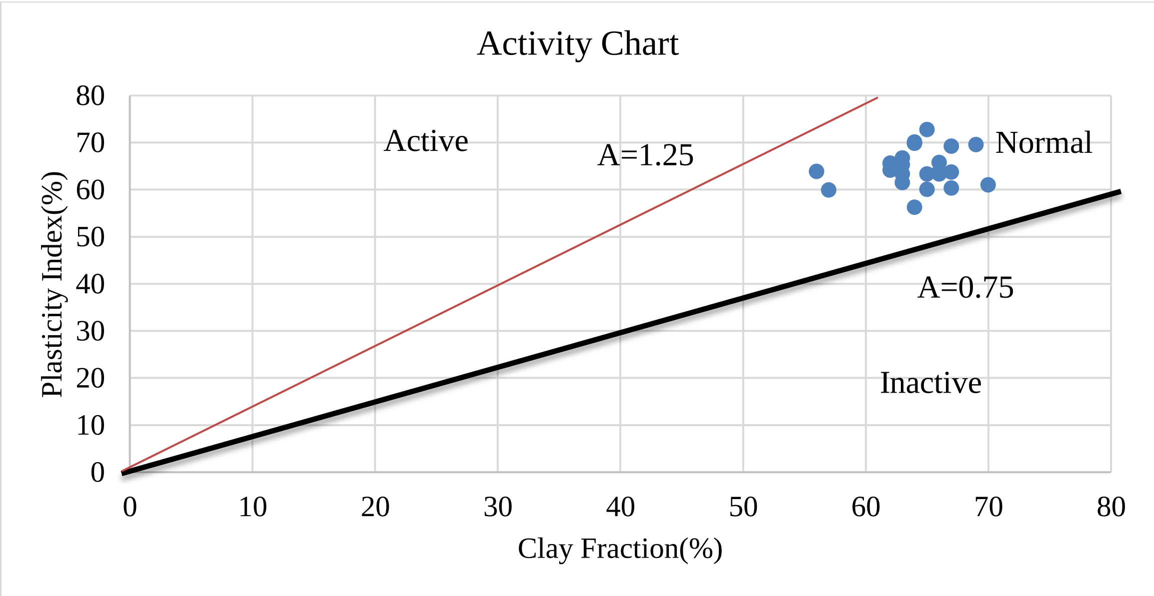



Figure 29 Activity of the Chart of the study area

Table 19 Activity of the study area

| S/ No | Station(Km) | Depth(m) | Plasticity Index(PI) | Clay(%) | Activity(A) |
|---|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 62 | 64.11 | 0.967087818 |
| 2 | TP 1 | 3.0 | 66 | 63.34 | 1.041995579 |
| 3 | TP 2 | 1.5 | 62 | 65.5 | 0.946564885 |
| 4 | TP 2 | 3.0 | 63 | 66.72 | 0.944244604 |
| 5 | TP 3 | 1.5 | 72 | 65.61 | 1.09739368 |
| 6 | TP 3 | 3.0 | 67 | 63.73 | 1.051310215 |
| 7 | TP 4 | 1.5 | 65 | 63.32 | 1.026531901 |
| 8 | TP 4 | 3.0 | 66 | 65.75 | 1.003802281 |
| 9 | TP 5 | 1.5 | 63 | 63.34 | 0.994632144 |
| 10 | TP 5 | 3.0 | 66 | 63.81 | 1.034320639 |
| 11 | TP 6 | 1.5 | 65 | 60.03 | 1.082791937 |
| 12 | TP 6 | 3.0 | 64 | 70.12 | 0.91272105 |
| 13 | TP 7 | 1.5 | 64 | 61.02 | 1.147164864 |
| 14 | TP 7 | 3.0 | 70 | 56.23 | 1.2448707 |
| 15 | TP 8 | 1.5 | 63 | 61.47 | 1.02489019 |
| 16 | TP 8 | 3.0 | 67 | 60.31 | 1.110926878 |
| 17 | TP 9 | 1.5 | 63 | 69.85 | 0.90193271 |
| 18 | TP 9 | 3.0 | 67 | 69.21 | 0.968068198 |
| 19 | TP 10 | 1.5 | 65 | 72.73 | 0.893716486 |
| 20 | TP 10 | 3.0 | 63 | 65.27 | 0.965221388 |
| 21 | TP 11 | 1.5 | 57 | 59.96 | 0.950633756 |
| 22 | TP 11 | 3.0 | 64 | 69.88 | 0.915855753 |
| 23 | TP 12 | 1.5 | 56 | 63.86 | 0.876918259 |
| 24 | TP 12 | 3.0 | 69 | 69.56 | 0.991949396 |

4.11.3.2. Burmister's Method

Plasticity index indicates the degree of plasticity of a soil. According to Burmister (1949) Soil classifications based on Plasticity Index. In this method of classification, the soil samples that were tested fall in the very high plasticity range.

4.11.3.3. Seed, Woodward and Lundgreen

Taking plasticity index as a means to assess the swelling potential of expansive soils Seed, Woodward and Lundgreen have categorized the soil in the study area has very high swelling potential.

Table 20 Plasticity Index Vs Swelling Potential

| S/ No | Station(Km) | Depth(m) | Plasticity Index(PI) | Swelling Potential |
|---|---|---|---|---|
| 1 | TP 1 | 1.5 | 62 | Very High |
| 2 | TP 1 | 3.0 | 66 | Very High |
| 3 | TP 2 | 1.5 | 62 | Very High |
| 4 | TP 2 | 3.0 | 63 | Very High |
| 5 | TP 3 | 1.5 | 72 | Very High |
| 6 | TP 3 | 3.0 | 67 | Very High |
| 7 | TP 4 | 1.5 | 65 | Very High |
| 8 | TP 4 | 3.0 | 66 | Very High |
| 9 | TP 5 | 1.5 | 63 | Very High |
| 10 | TP 5 | 3.0 | 66 | Very High |
| 11 | TP 6 | 1.5 | 65 | Very High |
| 12 | TP 6 | 3.0 | 64 | Very High |
| 13 | TP 7 | 1.5 | 64 | Very High |
| 14 | TP 7 | 3.0 | 70 | Very High |
| 15 | TP 8 | 1.5 | 63 | Very High |
| 16 | TP 8 | 3.0 | 67 | Very High |
| 17 | TP 9 | 1.5 | 63 | Very High |
| 18 | TP 9 | 3.0 | 67 | Very High |
| 19 | TP 10 | 1.5 | 65 | Very High |
| 20 | TP 10 | 3.0 | 63 | Very High |
| 21 | TP 11 | 1.5 | 57 | Very High |
| 22 | TP 11 | 3.0 | 64 | Very High |
| 23 | TP 12 | 1.5 | 56 | Very High |
| 24 | TP 12 | 3.0 | 69 | Very High |

## 4.12. Empirical Correlations

The swelling characteristics are the most fundamental characteristics that has to be investigated in dealing with expansive soils but the test methods used to investigate the swelling characteristics are costly and time taking thus an alternative approach has to be provided. Index properties are the widely used parameters in indicating the swelling behavior of a soil. Empirical correlations become very valuable for the purpose of determining one parameter based on the results of other parameters thus saving time and money (Carter, 2016). For example, from simple index properties tests, one can get a fair idea about the swelling characteristics for a given soil using empirical correlations between the two (Debelo, 2015). Swelling potential of a soil depends on environmental factors which vary from place to place thus relationships that have been developed in one area may or may not predict swelling potential of another place. This demands the need for specific correlations for specific location.

## 4.13. Regression Analysis

The regression model is a statistical procedure that allows a researcher to estimate the linear or straight line, relationship that relates two or more variables. This linear relationship summarizes the amount of change in one variable that is associated with change in another variable or variables. In the regression model, the independent variable is labeled the X variable, and the dependent variable the Y variable. In this study the results of ***Liquid Limit, Plastic Limit, Plasticity Index, Linear Shrinkage, Liquidity Index, Moisture Content and dry density*** are the independent variables from which ***Swelling Pressure***, the dependent variable is predicted.

### 4.13.1. Linear Regression Analysis

In single linear regression analysis one independent variable will be compared with the dependent variable and their linear relationship will be used to estimate the values of the dependent variable, to determine the index property that significantly affects swelling pressure single linear regression analysis was conducted taking the results of the index property tests as independent variables and swelling pressure as the dependent variable. For the purpose of estimating single linear regression MS-excel scatter plot was used for this study and different equations were developed.

4.13.1.1. Water Content Vs Swelling Pressure

Natural moisture content of a soil has an impact on its swelling pressure. On the preceding chapter we have observed that the wetter the sample the lower the swelling pressure i.e. as the water content of the samples are higher their swelling pressure decreases. The developed trend line for this relationship is $P_s$= -46.939*ω+2144.4. The developed equation has $R^2$ = 0.8976 which means the predictions of swelling pressure from moisture content are 89.76% accurate. The scatter plot of ω Vs $P_s$ is given in the figure below.

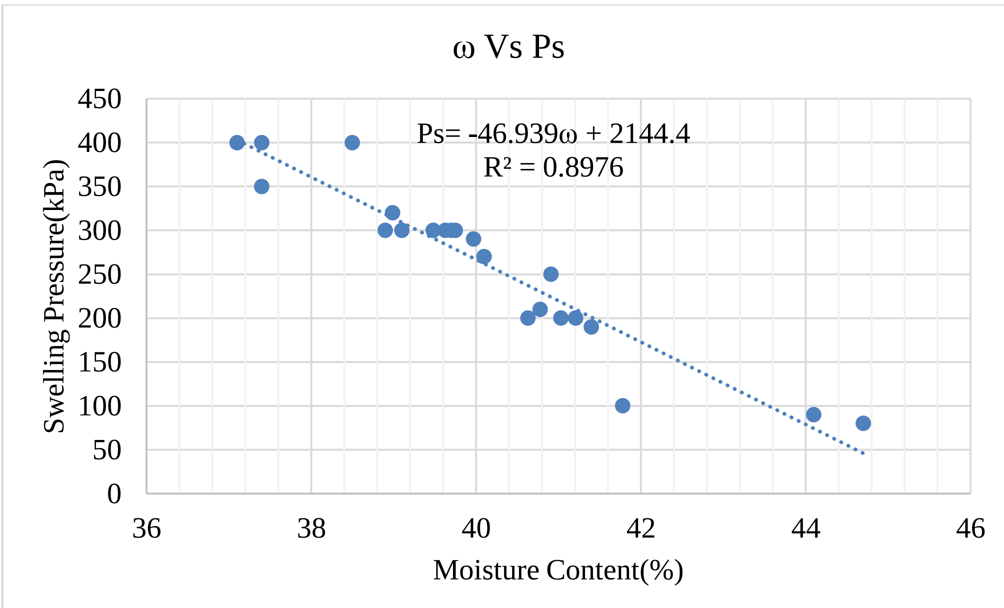



Figure 30 Water content Vs Swelling pressure

4.13.1.2. Liquid Limit Vs Swelling Pressure

The developed trend line for this relationship is $P_s$= 10.255LL-762.77. The developed equation has $R^2$ = 0.3719 which means the predictions of swelling pressure from Liquid Limit are 37.19% accurate, which indicates that predictions based on Liquid Limit alone will not suffice to properly predict swelling pressure. The scatter plot of LL Vs $P_s$ is given in the figure below.

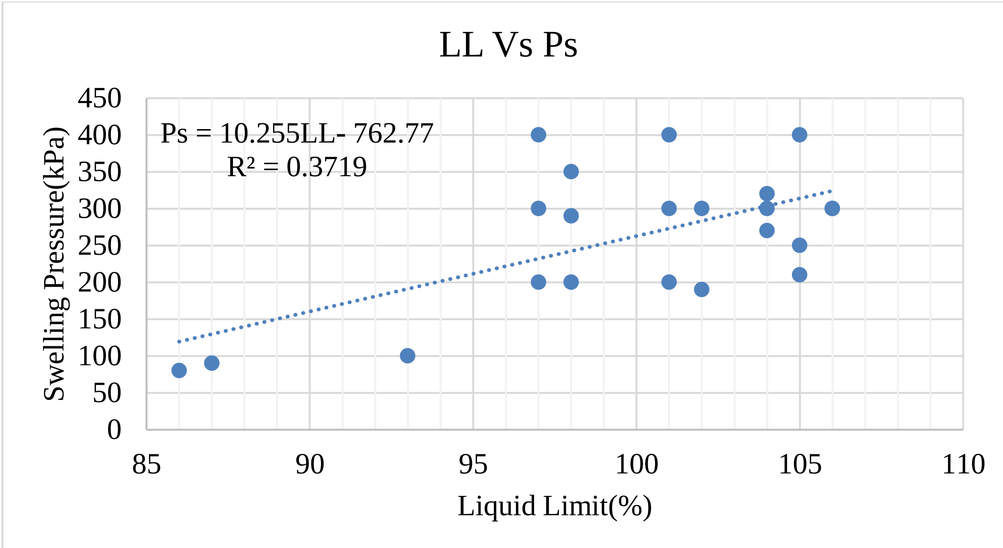



Figure 31 Liquid Limit Vs Swelling pressure

4.13.1.3. Plastic Limit Vs Swelling Pressure

The developed trend line for this relationship is $P_s$= 13.431PL-212.37. The developed equation has $R^2$ = 0.1689 which means the predictions of swelling pressure from Plastic Limit are 16.89% accurate, which indicates that predictions based on Plastic Limit alone will not suffice to properly predict swelling pressure. The scatter plot of PL Vs $P_s$ is given in the figure below.

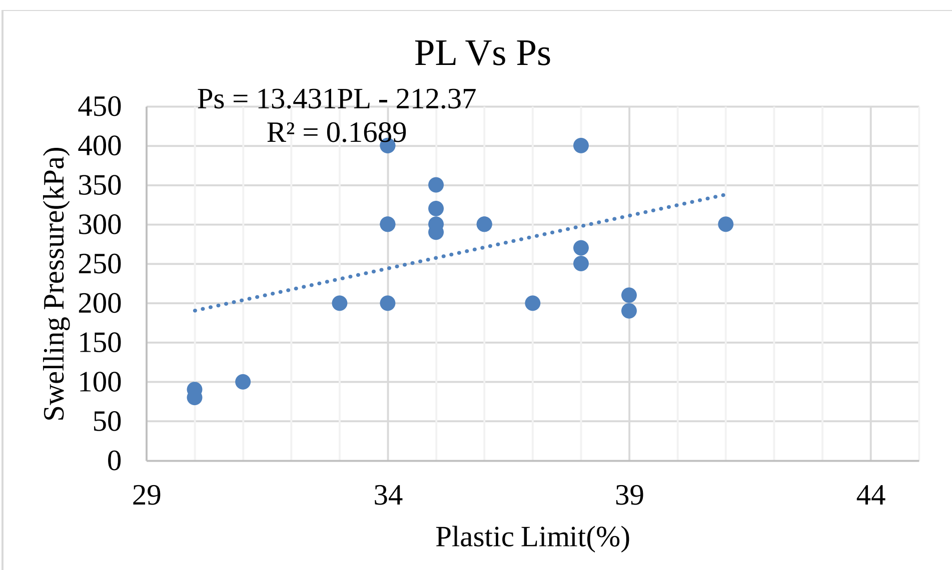



Figure 32 Plastic Limit Vs Swelling pressure

4.13.1.4. Plasticity Index Vs Swelling Pressure

The developed trend line for this relationship is $P_s$= 16.51PI-805.81. The developed equation has $R^2$ = 0.4114 which means the predictions of swelling pressure from moisture content are 41.14% accurate, which indicates that predictions based on Plasticity Index alone will not suffice to properly predict swelling pressure unless other properties are investigated. The scatter plot of PL Vs $P_s$ is given in the figure below.

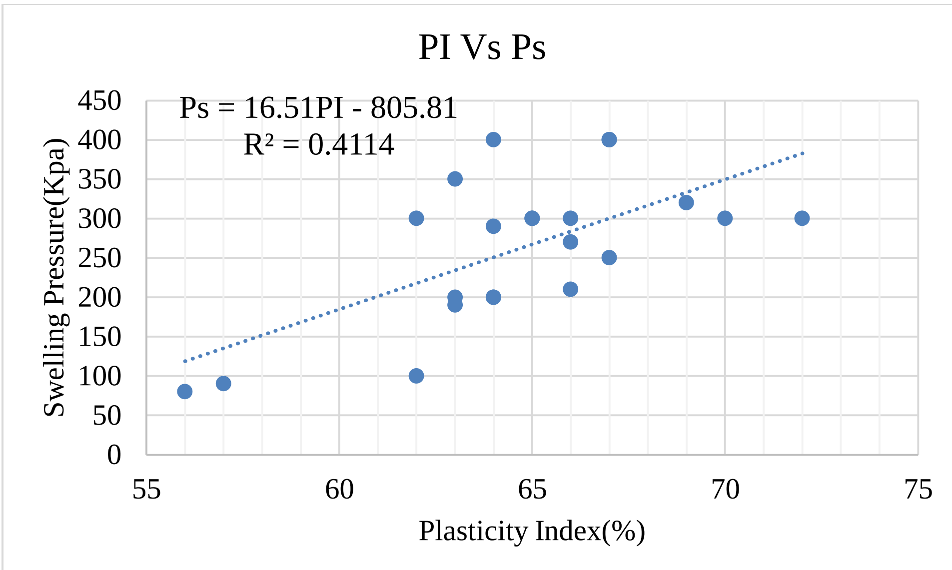



Figure 33 Plasticity Index Vs Swelling pressure

4.13.1.5. Linear Shrinkage Vs Swelling Pressure

The linear shrinkage (Ls) of a soil is the measure of the horizontal shrinkage of a soil at its liquid limit. The developed trend line for this relationship is $P_s$= 26.613PI-212.96. The developed equation has $R^2$ = 0.6903 which means the predictions of swelling pressure from Ls are 69.03% accurate, which indicates that predictions based on Linear Shrinkage can be used to predict swelling pressure considering all the factors that could influence swelling pressure. The scatter plot of Ls Vs $P_s$ is given in the figure below.

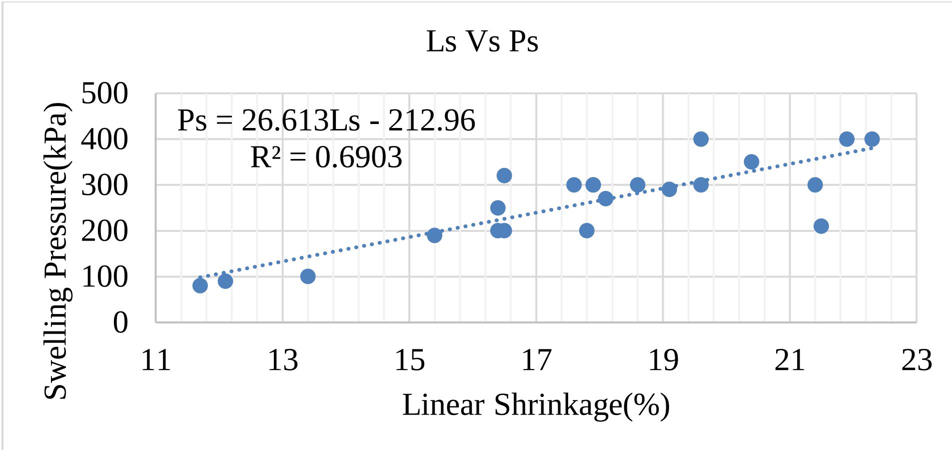



Figure 34 Linear shrinkage Vs Swelling pressure

4.13.1.6. Liquidity Index Vs Swelling Pressure

LI is a measure of where the current water content (w) lies with respect to the PL-LL range. The developed trend line for this relationship is $P_s$= -978.44LI+338.02. The developed equation has $R^2$ = 0.5382 which means the predictions of swelling pressure from Liquidity Index are 53.82% accurate, which indicates that predictions based on Liquidity Index will not suffice to properly predict swelling pressure because LI is not a measured parameter predictions of Ps from LI alone can't be used. The scatter plot of LI Vs $P_s$ is given in the figure below.

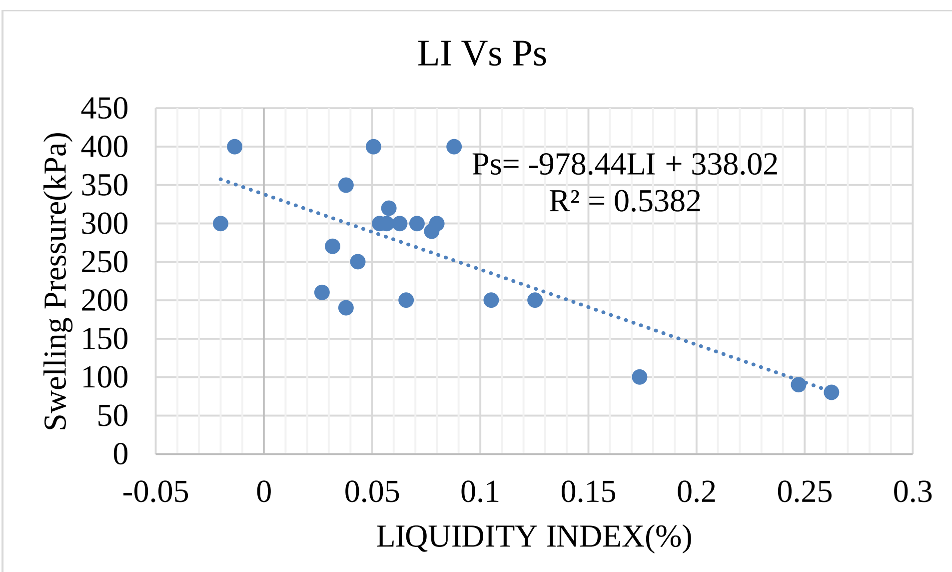



Figure 35 Liquidity Index Vs Swelling pressure

4.13.1.7. Dry Density Vs Swelling Pressure

Dry density, which is the weight of soil solids per unit volume, ignoring any water, is a Measure of how soil grains are spaced. The smaller the particle spacing the higher the dry density. The developed trend line for this relationship is $P_s$= 785.24ρd-744.82. The developed equation has $R^2$ = 0.9172 which means the predictions of swelling pressure from dry density are 91.72% accurate, which indicates that predictions based on dry density can be used to predict swelling pressure. The scatter plot of $\rho_d$ Vs $P_s$ is given in the figure below.

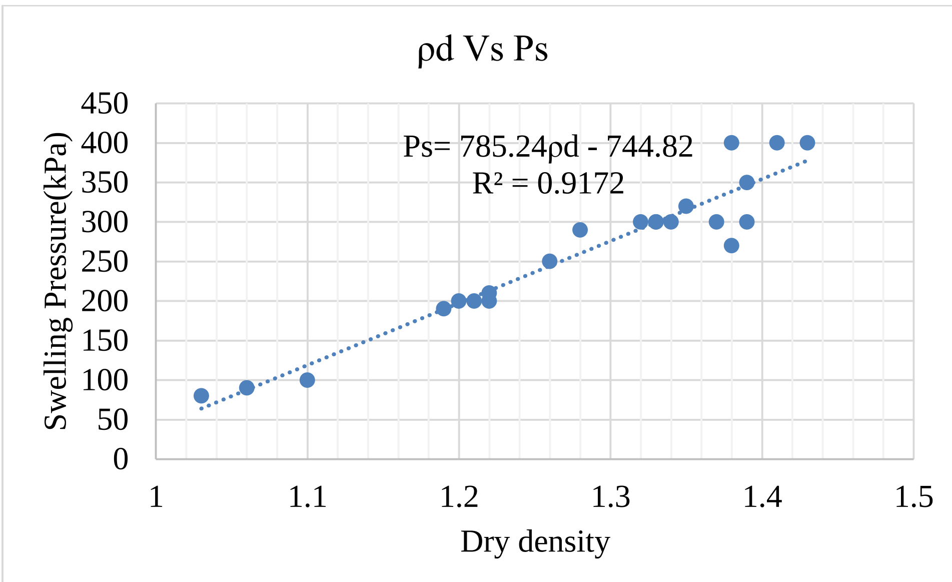



Figure 36 Dry density Vs Swelling pressure

4.13.1.8. Free Swell Vs Swelling Pressure

Free swell tests indicate the degree of expansiveness of a soil sample. The developed trend line for this relationship is $P_s$= 1.980FSI-123.26. The developed equation has $R^2$ = 0.7888 which means the predictions of swelling pressure from Free swell are 78.88% accurate, which indicates that the higher the tendency of a soil to swell the higher its swelling pressure. The scatter plot of FSI Vs $P_s$ is given in the figure below.

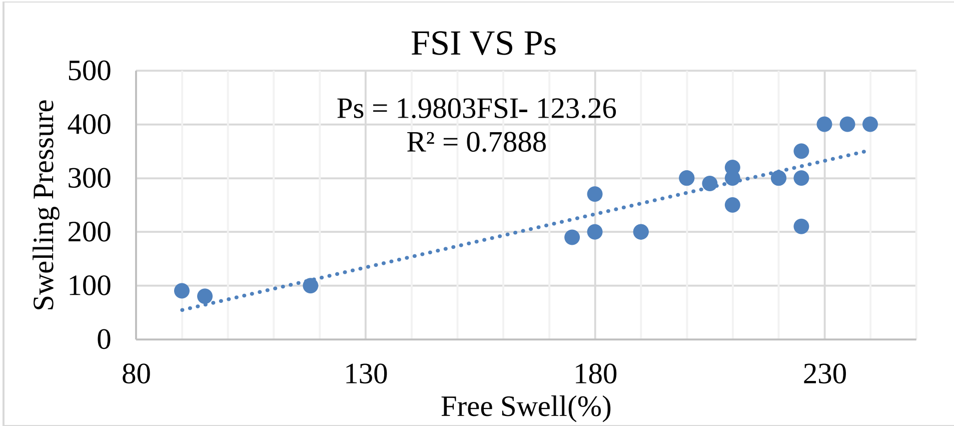



Figure 37 Free swell Index Vs Swelling pressure

4.13.1.9. Clay Fraction Vs Swelling Pressure

The amount and type of clay material in a given sample could estimate the swelling potential, clayey materials can undergo relatively large volume changes in response to fluctuations in water content. The developed trend line for this relationship is $P_s$= 3.0228%clay+64.441. The developed equation has $R^2$ = 0.0161 which means predictions of $P_s$ from amount of clay in a sample alone can't predict the swelling pressure. This shows that not only the amount of clay but also the type of clay mineral present affects swelling pressure. The scatter plot of %clay Vs $P_s$ is given in the figure below.

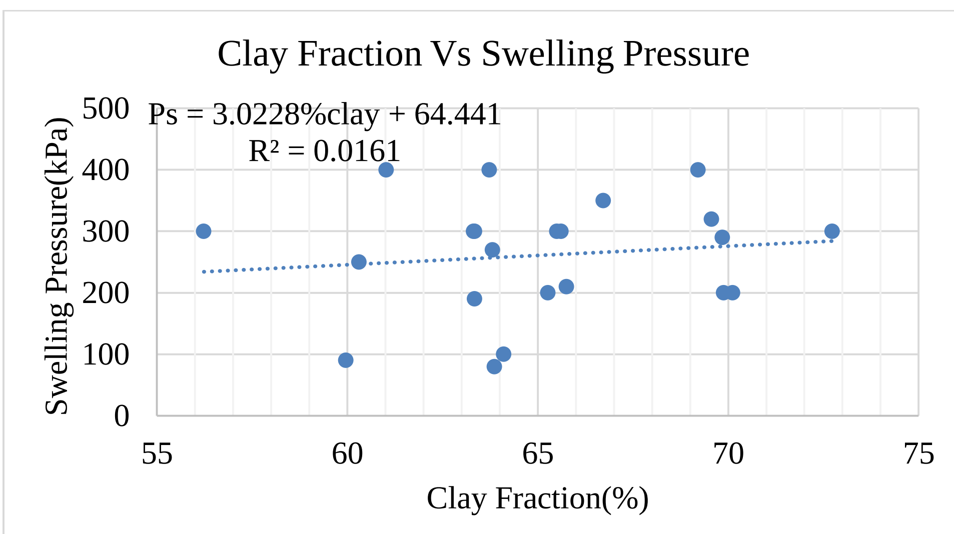



Figure 38 Clay fraction Vs Swelling pressure

### 4.13.2. Multiple Linear Regression Analysis

The general objective of this study is to be able to predict swelling pressure from index property tests and in order to do those correlations between swelling pressure and index property has to be developed and this is done by multiple linear regressions using SPSS 20. The multiple regression results with higher $R^2$ value are then used to predict the swelling pressure for the study area and the results of the regression analysis are compared to choose the best possible Empirical equation. Also, the developed equations were tested for three samples, which are used as a control sample to test the accuracy of the developed relationships. The input data for SPSS 20 computer program is given below.

Table 21 Input data for multiple regressions

| **Station(Km)** | **LL** | **PL** | **PI** | **LI** | **Ls** | **ω** | **ρdry** | **Ps** |
|---|---|---|---|---|---|---|---|---|
| TP 1@1.5 | 93 | 31 | 62 | 0.173871 | 13.4 | 41.78 | 1.10 | 100 |
| TP 1@3.0 | 102 | 36 | 66 | 0.056818 | 21.4 | 39.75 | 1.37 | 300 |
| TP 2@1.5 | 97 | 35 | 62 | 0.062903 | 17.6 | 38.9 | 1.33 | 300 |
| TP 2@3.0 | 98 | 35 | 63 | 0.038095 | 20.4 | 37.4 | 1.39 | 350 |
| TP 3@1.5 | 106 | 34 | 72 | 0.070833 | 17.9 | 39.1 | 1.34 | 300 |
| TP 3@3.0 | 101 | 34 | 67 | 0.050746 | 19.6 | 37.4 | 1.43 | 400 |
| TP 4@1.5 | 106 | 41 | 65 | -0.02 | 18.6 | 39.7 | 1.33 | 300 |
| TP 4@3.0 | 105 | 39 | 66 | 0.02697 | 21.5 | 40.78 | 1.22 | 210 |
| TP 5@1.5 | 102 | 39 | 63 | 0.038095 | 15.4 | 41.4 | 1.19 | 190 |
| TP 5@3.0 | 104 | 38 | 66 | 0.031818 | 18.1 | 40.1 | 1.38 | 270 |
| TP 6@3.0 | 98 | 33 | 64 | 0.125469 | 16.5 | 41.03 | 1.22 | 200 |
| TP 7@3.0 | 104 | 34 | 70 | 0.080 | 17.9 | 39.63 | 1.32 | 300 |
| TP 9@1.5 | 98 | 35 | 63 | 0.077656 | 19.1 | 39.97 | 1.28 | 290 |
| TP 9@3.0 | 105 | 38 | 67 | -0.01343 | 22.3 | 37.1 | 1.38 | 400 |
| TP 10@1.5 | 101 | 36 | 65 | 0.053538 | 19.6 | 39.48 | 1.39 | 300 |
| TP 10@3.0 | 97 | 34 | 63 | 0.105238 | 16.4 | 40.63 | 1.20 | 200 |
| TP 11@3.0 | 101 | 37 | 64 | 0.065781 | 17.8 | 41.21 | 1.21 | 200 |
| TP 12@1.5 | 86 | 30 | 56 | 0.2625 | 11.7 | 44.7 | 1.03 | 80 |
| TP 12@3.0 | 104 | 35 | 69 | 0.057826 | 16.5 | 38.99 | 1.35 | 320 |

Table 22 Input data for control samples

| **Station(Km)** | **LL** | **PL** | **PI** | **LI** | **Ls** | **Ω** | **ρdry** | **Ps** |
|---|---|---|---|---|---|---|---|---|
| TP 7@1.5 | 97 | 33 | 64 | 0.087969 | 21.9 | 38.5 | 1.41 | 400 |
| TP 8@3.0 | 105 | 38 | 67 | 0.043433 | 16.4 | 40.91 | 1.26 | 250 |
| TP 11@1.5 | 87 | 30 | 57 | 0.247368 | 12.1 | 44.1 | 1.06 | 90 |

Taking the above data as an input for the multiple regression analysis different empirical equations are developed but the most relevant predictions are taken considering their $R^2$ value and the empirical equations are given below.

Table 23 Developed empirical equations

| No | Developed Empirical Equations | $R^2$ |
|---|---|---|
| Eqn-1 | $Ps = 4.812LL + 44.375PL - 0.206PI + 3046.765LI + 1.264Ls - 76.878\omega + 358.950\rho dry + 540.437$ | 0.965 |
| Eqn-2 | $Ps = 6.266LL + 52.446PL + 0.760PI + 3576.057LI + 2.966Ls - 101.189\omega + 1460$ | 0.935 |
| Eqn-3 | $Ps = 13.780PL - 14.545LL + 14.698PI + 766.839\rho dry - 705.554$ | 0.901 |
| Eqn-4 | $Ps = 13.823\text{LL} - 6.854\text{PL} - 881.317$ | 0.419 |
| Eqn -5 | $Ps = 6.412LL + 7.730PI - 881.873$ | 0.424 |
| Eqn-6 | $Ps = -0.470LL - 512.956LI + 16.007Ls + 59.334$ | 0.642 |
| Eqn-7 | $Ps = 44.379PL - 38.451LL + 52.524PI - 857.877$ | 0.437 |
| Eqn-8 | $Ps = 1.041LL + 3.451Ls - 41.204\omega + 1743.212$ | 0.911 |
| Eqn-9 | $Ps = 3.541LL + 20.706Ls - 464.298$ | 0.620 |
| Eqn-10 | $Ps = -17.712LL + 0.307PL + 15.783PI - 1007.857LI + 2.871Ls + 479.434\rho dry + 409.668$ | 0.933 |
| Eqn-11 | $Ps = -0.466PI + 409.074\rho dry - 24.907\omega + 762.301$ | 0.947 |
| Eqn-12 | $Ps = 7.248PI - 787.200LI - 150.934$ | 0.609 |
| Eqn-13 | $Ps = 1.682LL - 44.051\omega + 1854.585$ | 0.907 |
| Eqn-14 | $Ps = 6.628PL + 14.046PI - 884.127$ | 0.428 |
| Eqn-15 | $Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$ | 0.925 |
| Eqn-16 | $Ps = -24.790\omega + 400.977\rho dry + 737.845$ | 0.946 |

Where Ps, LL, PL, PI, LI, Ls, ω and $\rho_{dry}$ are swelling pressure, liquid limit, plastic limit, plasticity index, liquidity index, linear shrinkage, moisture content and dry density respectively. Using the above equations swelling pressure is calculated.

From the developed empirical equation given above, based on their $R^2$ value the equations that could best estimate swelling pressure are:

Table 24 Selected Possible Empirical Equations

| No | Developed Empirical Equations | $R^2$ |
|---|---|---|
| Eqn-1 | $Ps = 4.812LL + 44.375PL - 0.206PI + 3046.765LI + 1.264Ls - 76.878\omega + 358.950\rho dry + 540.437$ | 0.965 |
| Eqn-2 | $Ps = 6.266LL + 52.446PL + 0.760PI + 3576.057LI + 2.966Ls - 101.189\omega + 1460$ | 0.935 |
| Eqn-10 | $Ps = -17.712LL + 0.307PL + 15.783PI - 1007.857LI + 2.871Ls + 479.434\rho dry + 409.668$ | 0.933 |
| Eqn-11 | $Ps = -0.466PI + 409.074\rho dry - 24.907\omega + 762.301$ | 0.947 |
| Eqn-15 | $Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$ | 0.925 |
| Eqn-16 | $Ps = -24.790\omega + 400.977\rho dry + 737.845$ | 0.946 |

The developed empirical equations show that one can determine the swelling pressure of expansive soils of Bishoftu town using laboratory tests conducted on index properties because the $R^2$ values show that there is an acceptable relationship between them. The accuracy of the developed equations varies and the precision of the predicted values from the measured values varies depending on the independent variables used for that particular regression analysis. In the above empirical relations, the equations that constitute water content and dry density with various combinations of Atterberg limit test results have given higher $R^2$ values than those that didn't include either moisture content or dry density. For example, in Eqn-7, $Ps = 44.379PL - 38.451LL + 52.524PI - 857.877$

swelling pressure is determined from PI, PL, LL and the $R^2$ value is 0.437 and when dry density is added to the above equation like in Eqn-3,

$Ps = 13.780PL - 14.545LL + 14.698PI + 766.839\rho dry - 705.554$ the accuracy of this relationship to predict swelling pressure is significantly higher, with $R^2$ =0.901. This is because dry density directly affects the swelling characteristics of expansive soils. Soils with high dry density values have high swelling pressure i.e. Do not swell easily because the soil particles grain to grain interaction is high which will prevent water to enter easily to cause swelling. In addition to this swelling pressure decreases with increasing water content, the wetter the soil sample the easier it is for it to swell upon minimum amount of added water. In the above empirical equations swelling pressure is predicted from water content and dry density alone as in Eqn-16, $Ps = -24.790\omega + 400.977\rho dry + 737.845$ with $R^2$ of 0.946 which indicates that predictions from this equation are 94.6% accurate and will be close with the measured results of Ps. When we compare Eqn-2 and Eqn-10 given by

$Ps = 6.266LL + 52.446PL + 0.760PI + 3576.057LI + 2.966Ls - 101.189\omega + 1460$ and

$Ps = -17.712LL + 0.307PL + 15.783PI - 1007.857LI + 2.871Ls + 479.434\rho dry + 409.668$ respectively have $R^2$=0.935 and $R^2$=0.933 with 93.5% 93.3% accuracy respectively indicates that predictions based on moisture content will be more suitable for expansive soils found in Bishoftu. The linear shrinkage of the soil is the study area can enhance predictions of swelling pressure, this can be seen in Eqn-8,

$Ps = 1.041LL + 3.451Ls - 41.204\omega + 1743.212$ Which has $R^2$=0.911 while Eqn-13, $Ps = 1.682LL - 44.051\omega + 1854.585$ which has $R^2$=0.907.Eqn-1 which has incorporated all the parameters selected for swelling pressure predictions given by, $Ps = 4.812LL + 44.375PL - 0.206PI + 3046.765LI + 1.264Ls - 76.878\omega + 358.950\rho dry + 540.437$ has $R^2$=0.965, which can be said it best predicts swelling pressure from index properties for expansive soils under consideration. The details of regression analysis and calculated swelling pressure values for all empirical equations are given in APPENDIX B.

Table 25 Predicted Swelling Pressure values

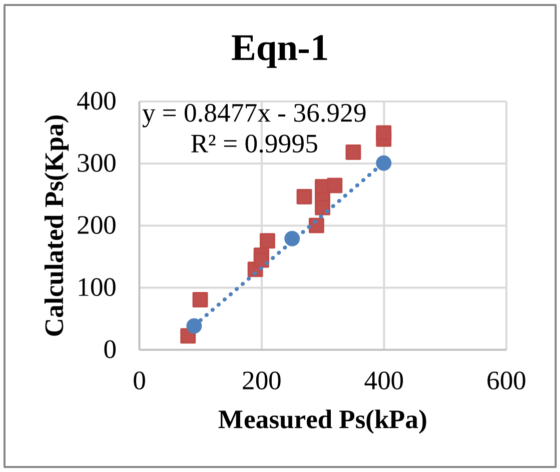
| Measured Ps(kPa) | Calculated values of Ps(kPa) | | | | | |
|---|---|---|---|---|---|---|
| **Ps** | **Eqn-1** | **Eqn-2** | **Eqn-10** | **Eqn-11** | **Eqn-15** | **Eqn-16** |
| 100 | 80.3698 | 150.285 | 141.127 | 142.776 | 140.258 | 143.194 |
| 300 | 251.187 | 282.502 | 316.774 | 301.923 | 310.453 | 301.781 |
| 300 | 248.3 | 292.186 | 305.675 | 308.595 | 299.918 | 306.813 |
| 350 | 317.715 | 370.586 | 365.553 | 370.034 | 353.695 | 368.057 |
| 300 | 257.927 | 312.744 | 301.453 | 303.044 | 312.813 | 305.865 |
| 400 | 338.844 | 382.846 | 379.373 | 384.533 | 377.215 | 384.096 |
| 300 | 244.416 | 291.085 | 281.883 | 287.272 | 286.316 | 286.981 |
| 210 | 174.907 | 247.972 | 223.013 | 214.908 | 217.089 | 216.101 |
| 190 | 128.841 | 185.848 | 185.692 | 188.591 | 191.415 | 188.702 |
| 270 | 245.903 | 265.321 | 302.48 | 297.296 | 308.453 | 297.114 |
| 200 | 149.949 | 200.025 | 199.961 | 209.613 | 215.881 | 209.903 |
| 300 | 228.721 | 277.844 | 286.483 | 282.594 | 294.035 | 284.707 |
| 290 | 199.544 | 248.147 | 269.211 | 261.025 | 260.727 | 260.239 |
| 400 | 348.591 | 426.561 | 358.213 | 371.551 | 351.424 | 371.484 |
| 300 | 262.248 | 285.729 | 326.429 | 317.296 | 323.64 | 316.494 |
| 200 | 151.525 | 213.276 | 212.711 | 211.86 | 209.632 | 211.8 |
| 200 | 144.246 | 200.801 | 207.148 | 201.039 | 205.973 | 201.431 |
| 80 | 21.8195 | 65.8449 | 42.3393 | 44.2083 | 36.224 | 42.7383 |
| 320 | 263.944 | 310.843 | 303.719 | 311.273 | 314.812 | 312.602 |

Table 26 Predicted Swelling Pressure values for the control sample

| Control Samples | | | | | | |
|---|---|---|---|---|---|---|
| Measured Ps(kPa) | Calculated values of Ps(kPa) | | | | | |
| **Ps** | **Eqn-1** | **Eqn-2** | **Eqn-10** | **Eqn-11** | **Eqn-15** | **Eqn-16** |
| 400 | 300.411 | 331.681 | 362.064 | 350.352 | 347.181 | 348.808 |
| 250 | 178.403 | 226.877 | 226.432 | 227.567 | 236.988 | 228.917 |
| 90 | 37.7228 | 80.6578 | 71.1926 | 70.9587 | 65.7032 | 69.6416 |

### 4.12.3. Comparisons of Measured Vs Predicted Values

The preciseness of the new empirical equations is verified by comparing the actual laboratory results of the soil with the calculated results of swelling pressure for the control samples. The regression analysis of the calculated and measured swelling pressure results with higher $R^2$ values, that could best predict swelling pressure are given below.



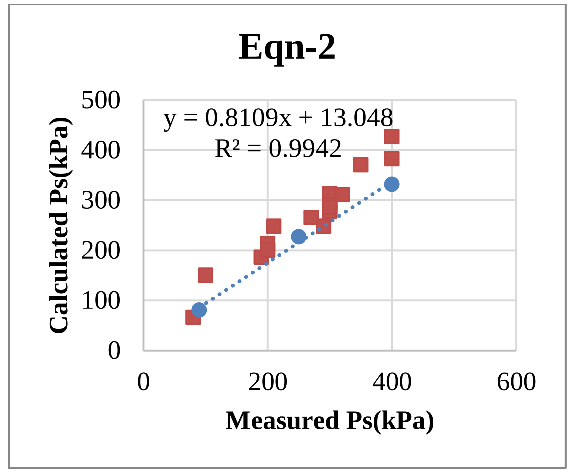
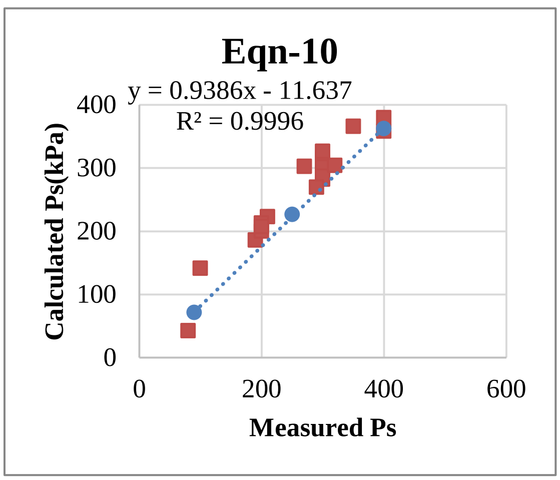




Figure 39 Measured Vs calculated values Eqn-1 Figure 40 Measured Vs calculated values Eqn-2



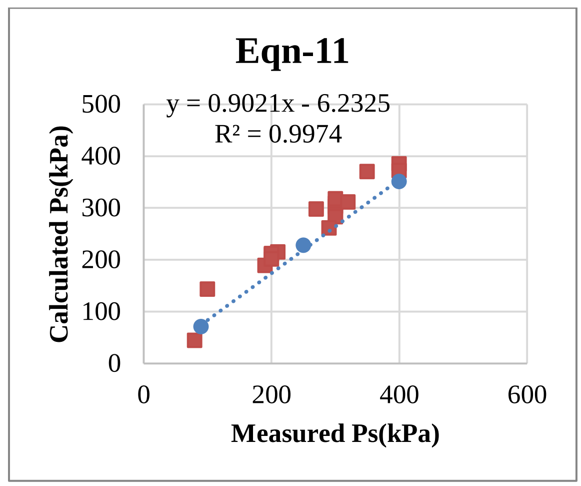
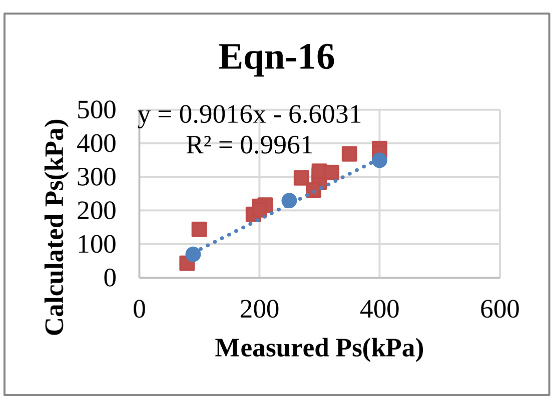




Figure 41 Measured Vs calculated values Eqn-10 Figure 42Measured Vs calculated values Eqn-11



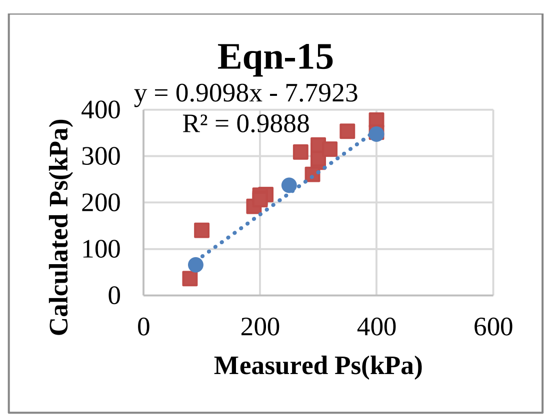




Figure 43 Measured Vs calculated values for Eqn-16 and Eqn-15

Choice of best possible empirical equation is founded on;

- $R^2$ value of the multiple linear regression analysis
- Significance of the developed equations (P-value)
- Significance of each parameter in the regression analysis (P-value of each parameter considered)
- $R^2$ value of the measured Vs predicted swelling pressure, considering the results of the control sample
- The accuracy of the parameters in predicting swelling pressure
- The simplicity of laboratory tests to be conducted for the correlation
- The slope of measured Vs predicted swelling pressure.

Contingent upon the above conditions the following equations are selected to be best fit empirical equations;

Table 27 Empirical Equation to be used

| No | Developed Empirical Equations | $R^2$ |
|---|---|---|
| Eqn-15 | $Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$ | 0.925 |
| Eqn-16 | $Ps = -24.790\omega + 400.977\rho dry + 737.845$ | 0.946 |

- Linear regression analysis output of **Eqn-15**
  - **Variables Entered/Removed[a]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | DD, PL, LI[b] | . | Enter |

a. Dependent Variable: Ps

b. All requested variables entered.

**Model Summary[b]**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .962[a] | .925 | .910 | 26.1788 |

a. Predictors: (Constant), DD, PL, LI

b. Dependent Variable: Ps

**ANOVA[a]**

| Model | | Sum of Squares | Df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 127162.140 | 3 | 42387.380 | 61.849 | .000[b] |
| | Residual | 10279.965 | 15 | 685.331 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps

b. Predictors: (Constant), DD, PL, LI

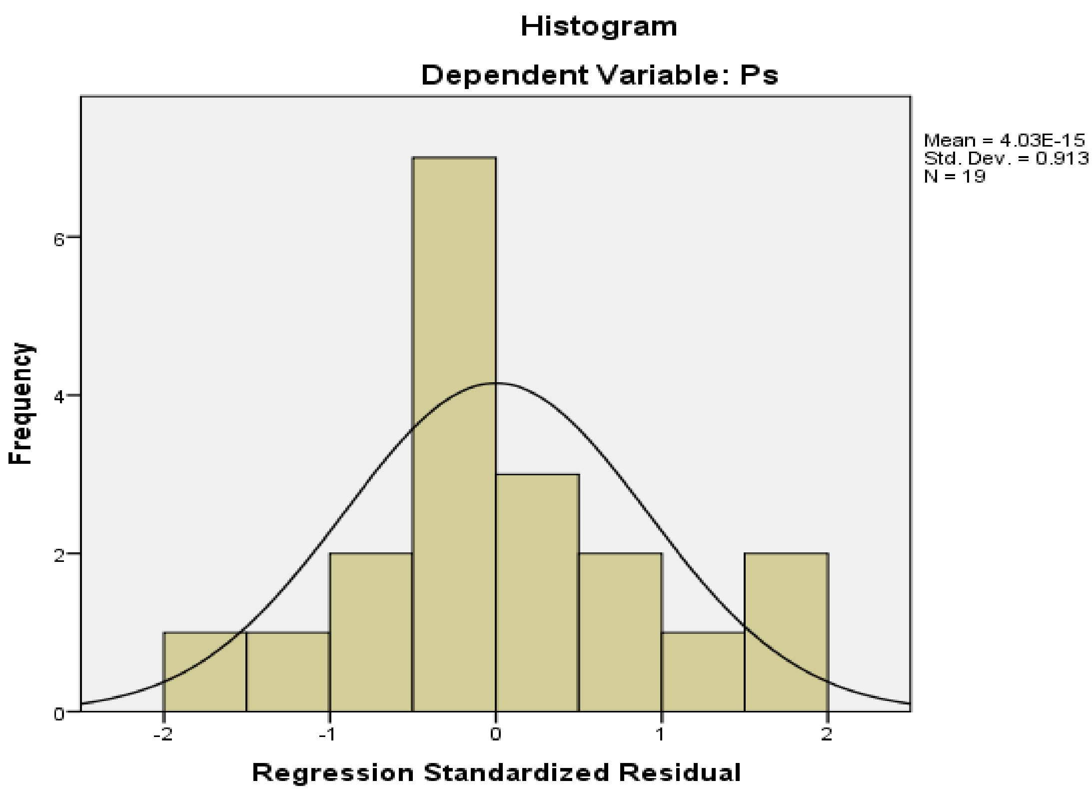
**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 228.458 | 427.219 | | .535 | .601 |
| | PL | -15.389 | 7.039 | -.485 | -2.186 | .045 |
| | LI | -949.682 | 421.596 | -.696 | -2.253 | .040 |
| | DD | 503.619 | 134.724 | .623 | 3.738 | .002 |

**Coefficients[a]**

| Model | | 95.0% Confidence Interval for B | |
|---|---|---|---|
| | | Lower Bound | Upper Bound |
| 1 | (Constant) | -682.138 | 1139.053 |
| | PL | -30.391 | -.386 |
| | LI | -1848.292 | -51.072 |
| | DD | 216.461 | 790.777 |

a. Dependent Variable: Ps



a. Dependent Variable: Ps

**Residuals Statistics[a]**

| | Minimum | Maximum | Mean | Std. Deviation | N |
|---|---|---|---|---|---|
| Predicted Value | 36.225 | 377.216 | 263.684 | 84.0510 | 19 |
| Std. Predicted Value | -2.706 | 1.351 | .000 | 1.000 | 19 |
| Standard Error of Predicted Value | 6.198 | 22.249 | 11.419 | 3.830 | 19 |
| Adjusted Predicted Value | -77.623 | 370.438 | 259.319 | 101.2723 | 19 |
| Residual | -40.2589 | 48.5740 | .0000 | 23.8979 | 19 |
| Std. Residual | -1.538 | 1.855 | .000 | .913 | 19 |
| Stud. Residual | -1.949 | 3.173 | .051 | 1.208 | 19 |
| Deleted Residual | -64.6585 | 157.6229 | 4.3650 | 46.8812 | 19 |
| Stud. Deleted Residual | -2.179 | 5.346 | .165 | 1.618 | 19 |
| Mahal. Distance | .061 | 12.054 | 2.842 | 2.761 | 19 |
| Cook's Distance | .000 | 6.546 | .420 | 1.491 | 19 |
| Centered Leverage Value | .003 | .670 | .158 | .153 | 19 |

- Linear regression analysis output of **Eqn-16**

**Variables Entered/Removed[a]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | DD, W[b] | . | Enter |

a. Dependent Variable: Ps

b. All requested variables entered.

**Model Summary[b]**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .973[a] | .946 | .940 | 21.4469 |

a. Predictors: (Constant), DD, W

b. Dependent Variable: Ps

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 130082.576 | 2 | 65041.288 | 141.403 | .000[b] |
| | Residual | 7359.529 | 16 | 459.971 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps
b. Predictors: (Constant), DD, W

**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 737.845 | 395.440 | | 1.866 | .080 |
| | W | -24.790 | 6.630 | -.501 | -3.739 | .002 |
| | DD | 400.977 | 108.412 | .496 | 3.699 | .002 |

**Coefficients[a]**

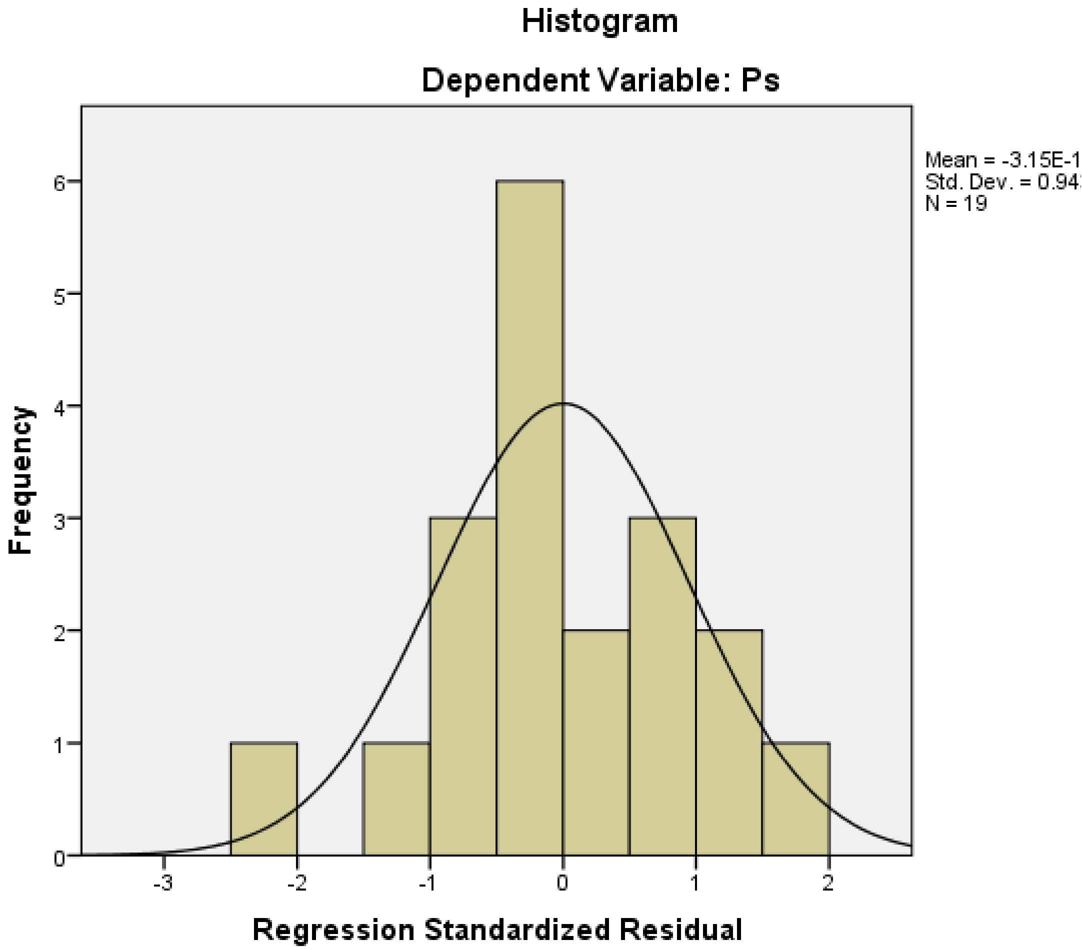
| Model | | 95.0% Confidence Interval for B | |
|---|---|---|---|
| | | Lower Bound | Upper Bound |
| 1 | (Constant) | -100.452 | 1576.141 |
| | W | -38.846 | -10.734 |
| | DD | 171.154 | 630.801 |

a. Dependent Variable: Ps

**Residuals Statistics[a]**

| | Minimum | Maximum | Mean | Std. Deviation | N |
|---|---|---|---|---|---|
| Predicted Value | 42.732 | 384.091 | 263.684 | 85.0106 | 19 |
| Std. Predicted Value | -2.599 | 1.416 | .000 | 1.000 | 19 |
| Standard Error of Predicted Value | 4.967 | 14.457 | 8.061 | 2.842 | 19 |
| Adjusted Predicted Value | 11.698 | 380.871 | 263.340 | 88.0118 | 19 |
| Residual | -43.1878 | 37.2679 | .0000 | 20.2204 | 19 |
| Std. Residual | -2.014 | 1.738 | .000 | .943 | 19 |
| Stud. Residual | -2.412 | 2.352 | .005 | 1.118 | 19 |
| Deleted Residual | -61.9528 | 68.3025 | .3439 | 28.8772 | 19 |
| Stud. Deleted Residual | -2.927 | 2.816 | .007 | 1.251 | 19 |
| Mahal. Distance | .018 | 7.231 | 1.895 | 2.049 | 19 |
| Cook's Distance | .000 | 1.536 | .178 | .390 | 19 |
| Centered Leverage Value | .001 | .402 | .105 | .114 | 19 |

a. Dependent Variable: Ps




Where Ps, LL, PL, PI, LI, Ls, ω and $\rho_{dry}$ are swelling pressure, liquid limit, plastic limit, plasticity index, liquidity index, linear shrinkage, moisture content and dry density respectively.

4.13.4. Comparison of Measured Ps with Previously Developed Empirical Equations

Empirical equations are being used to determine swelling pressure from simple index property tests in order to save time and money because swelling pressure tests are expensive also take weeks for completion. Different scholars and researchers have suggested various empirical equation to determine swelling pressure from index properties as discussed in chapter two. In the following table comparisons have been made between measured values and calculated values using their equation.

Table 28 Comparison with Previously developed equations

| Station(Km) | Measured Ps(kPa) | Calculated Ps(kPa) using previously developed equations for Expansive soils | | |
|---|---|---|---|---|
| | | Ashenafi Tamrat (Dukem) | Abdishkur Kemal (Koye Area, A.A) | Asamnew Gullat Swelling Potential, SP(%) |
| TP 1@1.5 | 100 | -295.084 | 169.916009 | 5.4829 |
| TP 1@3.0 | 300 | 310.826 | 272.5219872 | 7.27055 |
| TP 2@1.5 | 300 | 212.59 | 294.4691471 | 6.4477 |
| TP 2@3.0 | 350 | 310.93 | 335.0259718 | 7.2271 |
| TP 3@1.5 | 300 | 196.304 | 280.9577647 | 6.3807 |
| TP 3@3.0 | 400 | 343.814 | 322.4697143 | 8.3347 |
| TP 4@1.5 | 300 | 408.646 | 324.9571471 | 7.0104 |
| TP 4@3.0 | 210 | 163.004 | 270.2400857 | 6.9255 |
| TP 5@1.5 | 190 | 113.834 | 250.0355278 | 5.8871 |
| TP 5@3.0 | 270 | 392.568 | 288.7201429 | 7.1533 |
| TP 6@3.0 | 200 | -33.052 | 216.5781462 | 6.28795 |
| TP 7@3.0 | 300 | 163.524 | 271.4558238 | 6.75695 |
| TP 9@1.5 | 290 | 130.64 | 258.7274778 | 6.64305 |
| TP 9@3.0 | 400 | 392.568 | 361.0365696 | 8.4352 |
| TP 10@1.5 | 300 | 343.606 | 290.8946529 | 7.0841 |
| TP 10@3.0 | 200 | -33.156 | 256.2083 | 6.14505 |
| TP 11@3.0 | 200 | 81.262 | 271.2498083 | 6.22765 |
| TP 12@1.5 | 80 | -442.49 | 151.4533333 | 2.8433 |
| TP 12@3.0 | 320 | 245.37 | 290.9877571 | 8.35585 |
| Control sample | Measured Ps(kPa) | | | |
| TP 7@1.5 | 400 | 343.71 | 296.9757407 | 8.7969 |
| TP 8@3.0 | 250 | 195.888 | 265.5880231 | 7.15885 |
| TP 11@1.5 | 90 | -393.32 | 155.4839412 | 3.3212 |

4.13.5. Comparison of Calculated Ps with Previously Developed Empirical Equations

The calculated results computed from the developed empirical equations are compared with the swelling pressure values that are calculated using previously developed equations, and are given below

Table 29 Comparison of calculated values

| Station(Km) | Using previously developed equation | | | |
|---|---|---|---|---|
| | **Eqn-15** | **Eqn-16** | Ashenafi Tamrat | Abdishkur Kemal |
| TP 1@1.5 | 140.258 | 143.1935 | -295.084 | 169.916009 |
| TP 1@3.0 | 310.453 | 301.78099 | 310.826 | 272.5219872 |
| TP 2@1.5 | 299.918 | 306.81341 | 212.59 | 294.4691471 |
| TP 2@3.0 | 353.695 | 368.05703 | 310.93 | 335.0259718 |
| TP 3@1.5 | 312.813 | 305.86518 | 196.304 | 280.9577647 |
| TP 3@3.0 | 377.215 | 384.09611 | 343.814 | 322.4697143 |
| TP 4@1.5 | 286.316 | 286.98141 | 408.646 | 324.9571471 |
| TP 4@3.0 | 217.089 | 216.10074 | 163.004 | 270.2400857 |
| TP 5@1.5 | 191.415 | 188.70163 | 113.834 | 250.0355278 |
| TP 5@3.0 | 308.453 | 297.11426 | 392.568 | 288.7201429 |
| TP 6@3.0 | 215.881 | 209.90324 | -33.052 | 216.5781462 |
| TP 7@3.0 | 294.035 | 284.70694 | 163.524 | 271.4558238 |
| TP 9@1.5 | 260.727 | 260.23926 | 130.64 | 258.7274778 |
| TP 9@3.0 | 351.424 | 371.48426 | 392.568 | 361.0365696 |
| TP 10@1.5 | 323.64 | 316.49383 | 343.606 | 290.8946529 |
| TP 10@3.0 | 209.632 | 211.7997 | -33.156 | 256.2083 |
| TP 11@3.0 | 205.973 | 201.43127 | 81.262 | 271.2498083 |
| TP 12@1.5 | 36.224 | 42.73831 | -442.49 | 151.4533333 |
| TP 12@3.0 | 314.812 | 312.60185 | 245.37 | 290.9877571 |
| control sample | **Eqn-15** | **Eqn-16** | | |
| TP 7@1.5 | 347.181 | 348.80757 | 343.71 | 296.9757407 |
| TP 8@3.0 | 236.988 | 228.91712 | 195.888 | 265.5880231 |
| TP 11@1.5 | 65.7032 | 69.64162 | -393.32 | 155.4839412 |

The above comparisons with measured and calculated values show that in determining swelling pressure for expansive soils an Empirical formula developed for a particular situation in a given area will result in an over exaggerated estimation for another area, this divergence is due to variation of the nature of the soil, type and percent of clay material, environmental conditions, climatic condition, season of the study and geologic formation of the region. Consequently, developing empirical equations based on the conditions of the area under consideration will result in better swelling pressure predictions.

## 4.14. Discussion

Expansive soils found in Bishoftu town have LL range from (86-106) %, PL ranging from (30-41) % and PI ranging from (56-70) %. The soil in the study area has (37-45) % natural moisture content, specific gravity from (2.5-2.75), more than 91% of the soil in the study area passes through sieve #200, the clay fraction of the soil ranges from (56-70) %, the FSI of the soil ranges from (90-240), dry density ranges from (1.03-1.43) g/cm$^3$ and the swelling pressure of the study area falls in between (80-400) kPa. The soil in the study area is classified as CH as per USCS classification and A-7-5 according to AASHTO soil classification. The developed empirical equations show that one can determine the swelling pressure of expansive soils of Bishoftu town using laboratory tests conducted on index properties because the $R^2$ values show that there is an acceptable relationship between them. The accuracy of the developed equations varies and the precision of the predicted values from the measured values varies depending on the independent variables used for that particular regression analysis. In the above empirical relations, the equations that constitute water content and dry density with various combinations of Atterberg limit test results have given higher $R^2$ values than those that didn't include either moisture content or density. For example, in Eqn-7, $Ps = 44.379PL - 38.451LL + 52.524PI - 857.877$ swelling pressure is determined from PI, PL, LL and the $R^2$ value is 0.437 and when dry density is added to the above equation the like in Eqn-3, $Ps = 13.780PL - 14.545LL + 14.698PI + 766.839\rho dry - 705.554$ the accuracy of this relationship to predict swelling pressure is significantly higher, with $R^2$ =0.901. This is because dry density and water content directly affect the swelling characteristics of expansive soils. Soils with high dry density values have high swelling pressure i.e. Do not swell easily because the soil particles grain to grain interaction is high which will prevent water to enter easily to cause swelling. In addition to this swelling pressure decreases with increasing water content, the wetter the soil sample the easier it is for it to swell upon minimum amount of added water. In the above empirical equations swelling pressure is predicted from water content and dry density alone as in Eqn-16, $Ps = -24.790\omega + 400.977\rho dry + 737.845$ with $R^2$ of 0.946 which indicates that predictions from this equation are 94.6% accurate and will be close with the measured results of Ps. When we compare Eqn-2 and Eqn-10 given by:

$Ps = 6.266LL + 52.446PL + 0.760PI + 3576.057LI + 2.966Ls - 101.189\omega + 1460$ and

$Ps = -17.712LL + 0.307PL + 15.783PI - 1007.857LI + 2.871Ls + 479.434\rho dry + 409.668$ respectively have $R^2$=0.935 and $R^2$=0.933 with 93.5% 93.3% accuracy respectively indicates that predictions based on moisture content will be more suitable for expansive soils found in Bishoftu. The linear shrinkage of the soil is the study area can enhance predictions of swelling pressure, this can be seen in Eqn-8,

$Ps = 1.041LL + 3.451Ls - 41.204\omega + 1743.212$ Which has $R^2$=0.911 while Eqn-13, $Ps = 1.682LL - 44.051\omega + 1854.585$ which has $R^2$=0.907.Eqn-15 which has incorporated PL, LI and $\rho_{dry}$ for swelling pressure predictions given by

$Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$, has $R^2$=0.925 and Eqn-16 which has incorporated ω and $\rho_{dry}$ given by $Ps = -24.790\omega + 400.977\rho dry + 737.845$ with $R^2$ of 0.946 fulfilling all the aforementioned criteria can be said it best predicts swelling pressure from index properties for expansive soils found in Bishoftu town.

# CHAPTER FIVE

# CONCLUSION AND RECOMMENDATION

This chapter includes the discussion of the findings, the conclusion drawn by the researcher, recommendations made and areas for further research. All these are made in light of the study objectives.

## 5.1. Conclusion

Expansive soils are spread all over the world and are the primary causes of infrastructural impairment. The damage from expansive soils could be from small scale cracks & differential settlements which can lead to total collapse of the structure. The problem with expansive soils are intensified in light weight structures because the super structure load won't be able to suppress large expansions. Bishoftu is one of the rapidly developing cities in Ethiopia and has a variety of soil types, one of which is expansive soils. The problem with expansive soils is due to their shrink- swell properties, therefore proper investigation of the swelling pressure is essential. Direct measurement of swelling pressure in the laboratory gives the exact value of swelling potential but it is time taking and expensive process, for this reason indirect estimation of swelling pressure by developing empirical equation is an alternative approach. The aim of this study is to develop an empirical equation that could best predict swelling pressure from index property tests for expansive soils of Bishoftu city. Laboratory tests were conducted on 12 test pits on disturbed and undisturbed samples to determine index property and swelling pressure of the study area prior to linear regression analysis. Various scholars all over the world have studied the relationship between index properties and swelling pressure and have developed empirical equations but swelling characteristics of expansive soils are dependent on environmental, climate and geological conditions of the soil, this raises the need for developing empirical equations for particular study area.

- The first specific objective of this study is to determine index properties of expansive soils in Bishoftu town, in order to do that laboratory tests were conducted and the results show that expansive soils found in Bishoftu town are found to be expansive very high degree of expansiveness and has a swelling pressure that ranges from (80-400). The soil in the study area is classified as CH as per USCS classification and A-7-5 according to AASHTO soil classification.

- Apropos with the second specific objective which is to determine the index property that significantly affects swelling pressure of expansive soils found in Bishoftu town, different single linear regression analysis was conducted and the relationship between dry density and swelling pressure is found the most relevant to estimate swelling pressure from, with $P_s$= 785.24ρd-744.82 and $R^2$ = 0.9172. Also the regression analysis between water content and swelling pressure of the study area showed that swelling pressure estimations based on water content give relevant predictions of swelling pressure with $P_s$= -46.939*ω+2144.4 and $R^2$ = 0.8976.
- Different multiple regression analysis was conducted and the results showed that swelling pressure of the study area can be estimated from index property tests. From the regression analysis results the swelling pressure of expansive soils found in Bishoftu are dependent to a greater degree on properties like moisture content and dry density. The empirical equations that could best predict swelling pressure are Eqn-15, $Ps = -15.389PL - 949.682LI + 503.619\rho dry + 228.458$ with $R^2$=0.925and Eqn-16, $Ps = -24.790\omega + 400.977\rho dry + 737.845$ and $R^2$=0.946. For future investigations of the swelling characteristics, these empirical equations can be used if to determine swelling pressure for expansive soils found in Bishoftu.

## 5.2. Recommendation

1. This study is only concerned with areas covered with expansive soils in Bishoftu and Bishoftu is covered with different types of soils, therefore further investigation is required to know the type and engineering properties of the soil for the whole area.
2. The empirical equations developed for swelling pressure estimations are based on results of 12 test pits and the equations can be further improved by increasing the number of samples.
3. For shallow foundations or road projects to be designed and executed in this area, the estimation of swelling pressure using the developed empirical equations may

be used for preliminary design stages but the actual swelling pressure has to be measured.

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# APPENDIX A

# REPRESENTATIVE LABORATORY TEST RESULTS

## Moisture Content Test Results

$$\omega = \frac{(w_2 - w_3)}{(w_3 - w_1)} * 100$$

Moisture content test results

| Station | Depth | Container No. | Wt. of wet sample + Container ($w_2$) gm | Wt. of dry sample + Container ($w_3$) gm | Can Weight ($w_1$) gm | Weight of Water (Moisture) ($w_2$-$w_3$) gm | Wt of dry Sample ($w_3$-$w_1$) gm | Moisture Content (%) | Average |
|---|---|---|---|---|---|---|---|---|---|
| TP-1 | 1.5m | A-47 | 250.7 | 187.9 | 29.9 | 62.8 | 150.9 | 41.62 | |
| TP-1 | 1.5m | B-12 | 256.5 | 190.2 | 23.4 | 66.3 | 158.1 | 41.94 | 41.78 |
| TP-1 | 3m | L-33 | 281.1 | 211.6 | 36.4 | 69.5 | 174.9 | 39.74 | |
| TP-1 | 3m | J-1 | 100.5 | 76.2 | 18.2 | 24.3 | 61.1 | 39.77 | 39.75 |
| TP-2 | 1.5m | L-38 | 236.7 | 178.6 | 35.3 | 58.1 | 149.4 | 38.89 | |
| TP-2 | 1.5m | 11 | 247.8 | 179.5 | 13.1 | 68.3 | 175.6 | 38.90 | 38.89 |
| TP-2 | 3m | L-49 | 240.6 | 181.3 | 35.2 | 59.3 | 158.3 | 37.46 | |
| TP-2 | 3m | B-1 | 216.4 | 160.2 | 23.2 | 56.2 | 150.2 | 37.42 | 37.44 |
| TP-3 | 1.5m | 4 | 125.6 | 95.2 | 23.4 | 30.4 | 78.1 | 38.92 | |
| TP-3 | 1.5m | A-1 | 240.5 | 175.2 | 15.1 | 65.3 | 166.2 | 39.29 | 39.11 |
| TP-3 | 3m | 6 | 117.5 | 89.5 | 23.5 | 28 | 74.9 | 37.38 | |
| TP-3 | 3m | M-1 | 241.8 | 176.4 | 17.4 | 65.4 | 174.8 | 37.41 | 37.40 |
| TP-4 | 1.5m | L-10 | 89.9 | 70.6 | 23.5 | 19.3 | 48.7 | 39.63 | |
| TP-4 | 1.5m | V | 121.5 | 90.2 | 14 | 31.3 | 78.7 | 39.77 | 39.70 |
| TP-4 | 3m | 3A | 76.8 | 59 | 13.7 | 17.8 | 43.6 | 40.83 | |
| TP-4 | 3m | 3B | 99.8 | 75.2 | 13.6 | 24.6 | 60.4 | 40.73 | 40.78 |
| TP-5 | 1.5m | 7 | 100.1 | 78.4 | 18.1 | 21.7 | 52.6 | 41.25 | |
| TP-5 | 1.5m | J-5 | 134.7 | 103.5 | 17.7 | 31.2 | 75.1 | 41.54 | 41.40 |
| TP-5 | 3m | 5 | 88.7 | 70.1 | 23.1 | 18.6 | 46.4 | 40.09 | |
| TP-5 | 3m | A-2 | 204.2 | 152.9 | 22.8 | 51.3 | 127.9 | 40.11 | 40.10 |
| TP-6 | 1.5m | L-33 | 198.7 | 152.8 | 23.2 | 45.9 | 118.7 | 38.67 | |
| TP-6 | 1.5m | A-40 | 100.9 | 80.2 | 23.4 | 20.7 | 53.1 | 38.98 | 38.83 |
| TP-6 | 3m | J-1 | 97.9 | 74.2 | 15.1 | 23.7 | 57.8 | 41.00 | |
| TP-6 | 3m | C-4 | 214.8 | 160.9 | 17.4 | 53.9 | 131.3 | 41.05 | 41.03 |
| TP-7 | 1.5m | 3 | 244.3 | 178.9 | 22.9 | 65.4 | 169.7 | 38.54 | |
| TP-7 | 1.5m | 4 | 195.8 | 145.1 | 23.4 | 50.7 | 131.8 | 38.47 | 38.50 |
| TP-7 | 3m | 5 | 160.8 | 120.9 | 23 | 39.9 | 101.1 | 39.47 | |
| TP-7 | 3m | 6 | 248.7 | 183.9 | 23.5 | 64.8 | 162.8 | 39.80 | 39.63 |

Representative Atterberg Limit Test Results

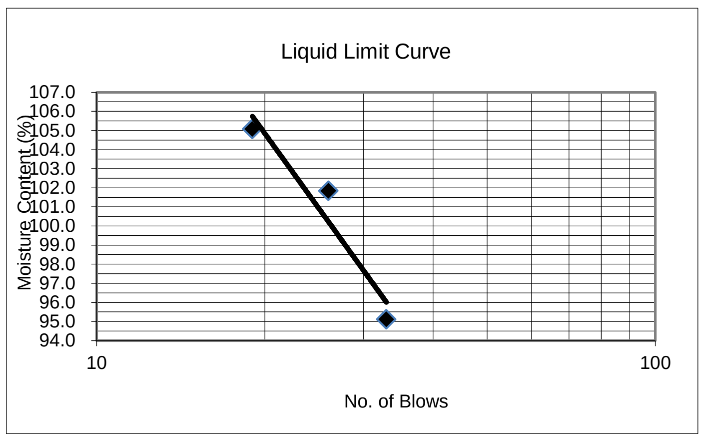
$$w = \frac{W_w}{W_s} \ x100$$

$M_w$ = Weight of water

Ms = Weight of dry soil.

*TP1 @3.0m,*

| Number of blows | 33 | 26 | 19 | 1 | 2 |
|---|---|---|---|---|---|
| Container ID | D1 | A | B2 | F | L1 |
| Wt. of Container +Wet soil (gm) | 28.90 | 31.60 | 28.90 | 13.90 | 13.60 |
| Wt. of Container +Dry soil (gm) | 19.20 | 20.40 | 18.50 | 12.50 | 12.20 |
| Wt. of water (gm) | 9.70 | 11.20 | 10.40 | 1.40 | 1.40 |
| Wt. of Container weight (gm) | 9.00 | 9.40 | 8.6 | 8.7 | 8.3 |
| Wt. of Dry soil (gm) | 10.20 | 11.00 | 9.90 | 3.80 | 3.90 |
| Moisture content % | 95.1 | 101.8 | 105.1 | 36.8 | 35.9 |
| | 100.7 | | Average % | 36.4 | |




| Soil classification | | | |
|---|---|---|---|
| | Wt of sample | % Retain | % Pass |
| Total | 257.0 | | |
| | | | 100 |
| 2.00 | 3.4 | 1.3 | 98.7 |
| 0.425 | 11.5 | 4.5 | 94.2 |
| 0.075 | 18.6 | 7.2 | 87.0 |

Summary L.L.: 102

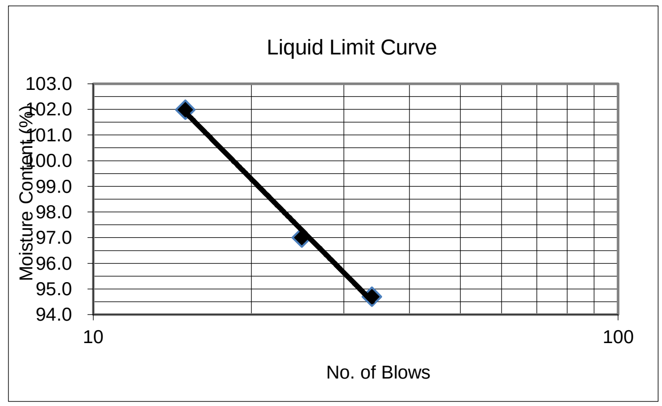
P.L : 36

P.I.: 66

Soil classification : A-7-5

TP 2 @ 1.5m

| | | | | | |
|---|---|---|---|---|---|
| Number of blows | 34 | 25 | 15 | 1 | 2 |
| Container ID | H1 | BA | G1 | 4 | W |
| Wt. of Container +Wet soil (gm) | 31.20 | 28.40 | 28.20 | 15.50 | 13.90 |
| Wt. of Container +Dry soil (gm) | 20.50 | 18.70 | 17.90 | 13.60 | 12.10 |
| Wt. of water (gm) | 10.70 | 9.70 | 10.30 | 1.90 | 1.80 |
| Wt. of Container weight (gm) | 9.20 | 8.70 | 7.8 | 8.3 | 6.8 |
| Wt. of Dry soil (gm) | 11.30 | 10.00 | 10.10 | 5.30 | 5.30 |
| Moisture content % | 94.7 | 97.0 | 102.0 | 35.8 | 34.0 |
| | 97.9 | | Average % | 34.9 | |




| Soil classification | | | |
|---|---|---|---|
| | Wt of sample | % Retain | % Pass |
| Total | 211.5 | | |
| | | | 100 |
| 2.00 | 0.8 | 0.4 | 99.6 |
| 0.425 | 3.6 | 1.7 | 97.9 |
| 0.075 | 11.1 | 5.2 | 92.7 |

Summary L.L.: 97

P.L : 35

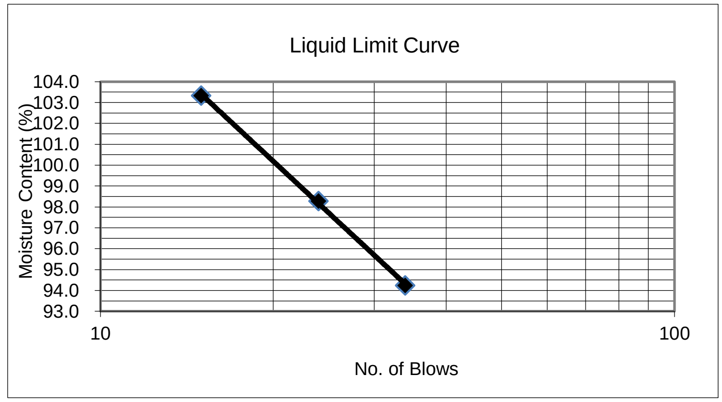
P.I.: 62

Soil classification : A-7-5

TP 6 @ 1.5m

| | | | | | |
|---|---|---|---|---|---|
| Number of blows | 34 | 24 | 15 | | |
| Wt. of Container +Wet soil (gm) | 43.20 | 37.50 | 41.70 | 26.70 | 29.80 |
| Wt. of Container +Dry soil (gm) | 33.40 | 26.10 | 32.40 | 25.80 | 28.30 |
| Wt. of water (gm) | 9.80 | 11.40 | 9.30 | 0.90 | 1.50 |
| Wt. of Container weight (gm) | 23.00 | 14.50 | 23.4 | 23 | 23.5 |
| Wt. of Dry soil (gm) | 10.40 | 11.60 | 9.00 | 2.80 | 4.80 |
| Moisture content % | 94.2 | 98.3 | 103.3 | 32.1 | 31.3 |
| | 98.6 | | Average % | 31.7 | |

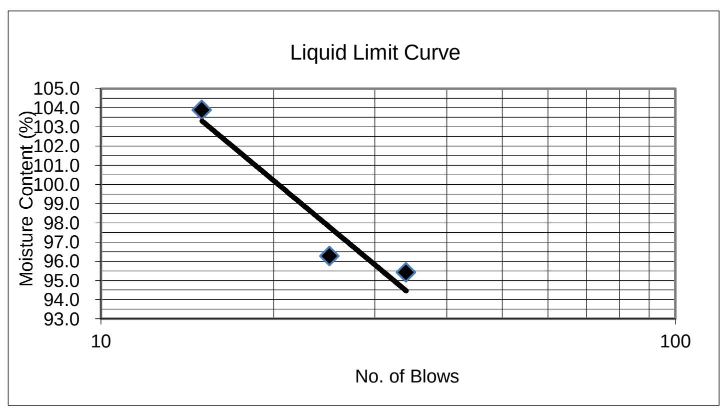
| Soil classification | | | |
|---|---|---|---|
| | Wt of sample | % Retain | % Pass |
| Total | 244.6 | | |
| | | | 100 |
| 2.00 | 1.9 | 0.8 | 99.2 |
| 0.425 | 2.6 | 1.1 | 98.2 |
| 0.075 | 18.4 | 7.5 | 90.6 |




Summary L.L.: 97
P.L : 32
P.I.: 65
Soil classification : A-7-5

TP 8 @ 1.5m

| Number of blows | 34 | 25 | 15 | | |
|---|---|---|---|---|---|
| Wt. of Container +Wet soil (gm) | 39.50 | 44.20 | 36.10 | 23.00 | 19.60 |
| Wt. of Container +Dry soil (gm) | 29.10 | 33.90 | 25.40 | 21.60 | 18.20 |
| Wt. of water (gm) | 10.40 | 10.30 | 10.70 | 1.40 | 1.40 |
| Wt. of Container weight (gm) | 18.20 | 23.20 | 15.1 | 17.4 | 14.0 |
| Wt. of Dry soil (gm) | 10.90 | 10.70 | 10.30 | 4.20 | 4.20 |
| Moisture content % | 95.4 | 96.3 | 103.9 | 33.3 | 33.3 |
| | 98.5 | | Average % | 33.3 | |

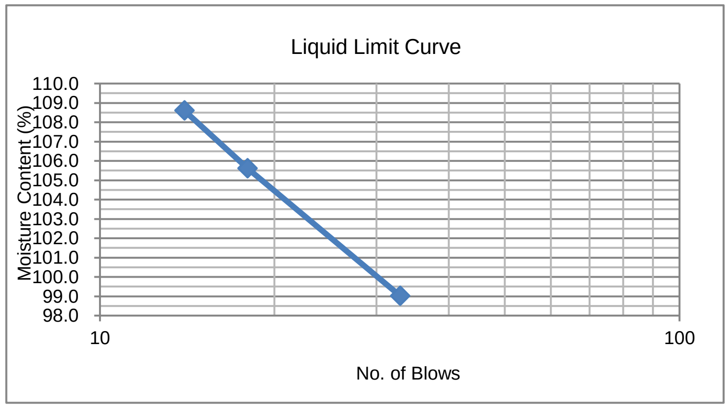



| Soil classification | | | |
|---|---|---|---|
| | Wt of sample | % Retain | % Pass |
| Total | 249.6 | | |
| | | | 100 |
| 2.00 | 1.1 | 0.4 | 99.6 |
| 0.425 | 3.6 | 1.4 | 98.1 |
| 0.075 | 10.2 | 4.1 | 94.0 |

Summary L.L.: 96
P.L : 33
P.I.: 63
Soil classification : A-7-5

TP 9 @ 3.0m

| | | | | | |
|---|---|---|---|---|---|
| Number of blows | 33 | 18 | 14 | | |
| Wt. of Container +Wet soil (gm) | 43.60 | 47.50 | 48.20 | 36.50 | 33.50 |
| Wt. of Container +Dry soil (gm) | 33.60 | 36.20 | 38.10 | 35.30 | 31.60 |
| Wt. of water (gm) | 10.00 | 11.30 | 10.10 | 1.20 | 1.90 |
| Wt. of Container weight (gm) | 23.50 | 25.50 | 28.8 | 32.2 | 26.4 |
| Wt. of Dry soil (gm) | 10.10 | 10.70 | 9.30 | 3.10 | 5.20 |
| Moisture content % | 99.0 | 105.6 | 108.6 | 38.7 | 36.5 |
| | 104.4 | | Average % | 37.6 | |




| Soil classification | | | |
|---|---|---|---|
| | Wt of sample | % Retain | % Pass |
| Total | 261.5 | | |
| | | | 100 |
| 2.00 | 1.2 | 0.5 | 99.5 |
| 0.425 | 4.1 | 1.6 | 98.0 |
| 0.075 | 8.6 | 3.3 | 94.7 |

Summary L.L.: 105

P.L : 38

P.I.: 67

Soil classification : A-7-5

Representative Linear Shrinkage Test Result

$$Ls=(1-\frac{Ld}{L})*100$$

| LINEAR SHRINKAGE | | |
|---|---|---|
| TP=1 | | |
| depth =1.5m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 121 | 121.5 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 13.57143 | 13.21429 |
| Average | 13.39285714 | |
| TP=2 | | |
| depth =3.0m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 111 | 111.8 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 20.71429 | 20.14286 |
| Average | 20.42857143 | |
| TP=6 | | |
| depth =3.0m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 117 | 116.8 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 16.42857 | 16.57143 |
| Average | 16.5 | |
| TP=8 | | |
| depth =1.5m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 112 | 113 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 20 | 19.28571 |
| Average | 19.64285714 | |
| TP=9 | | |
| depth =3.0m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 109 | 108.5 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 22.14286 | 22.5 |
| Average | 22.32142857 | |
| TP=11 | | |
| depth =3.0m | | |

| | | |
|---|---|---|
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 115.1 | 115 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 17.78571 | 17.85714 |
| Average | 17.82142857 | |
| TP=12 | | |
| depth =1.5m | | |
| Test No | 1 | 2 |
| Mould length(L)mm | 140 | 140 |
| Oven dried length(Ld)mm | 123.8 | 123.4 |
| Linear shrinkage Ls=(1-Ld/L)*100 | 11.57143 | 11.85714 |
| Average | 11.71428571 | |

Representative Specific Gravity Test Results

$$G_s = \frac{Ms}{M_2 + M_s - M_1}$$

| | |
|---|---|
| Project : | Thesis |
| Sample of : | TP-1 |
| Depth : | 1.5m |

| | 1 | 2 |
|---|---|---|
| 1. Bottle Number | 1 | 2 |
| 2. Weight of Bottle | 44.8 | 46.7 |
| 3. Weight of Sample | 20.1 | 23.9 |
| 4. Weight of Bottle + Sample | 65.2 | 70.8 |
| 5. Weight of Bottle with full of Water | 99.80 | 99.80 |
| 6. Weight of Bottle + Sample + Water | 112.50 | 114.70 |
| 7. Test temperature | 28.00 | 28.00 |
| 8. Volume of Sample (3+5-6) | 7.40 | 9.00 |
| 9. Specific Gravity (3/7) | 2.716 | 2.656 |
| 10. correction factor K | 0.998 | 0.998 |

| | | |
|---|---|---|
| | | |
| 11. Specific gravity of soil @ 20 DC | 2.711 | 2.650 |
| Average Specific Gravity ((A+B)/2) | 2.681 | |

| | |
|---|---|
| Project : | Thesis |
| Sample of : | TP-4 |
| Depth : | 1.5m |

| | 1 | 2 |
|---|---|---|
| 1. Bottle Number | M | B |
| 2. Weight of Bottle | 45.4 | 41.3 |
| 3. Weight of Sample | 21 | 20.9 |
| 4. Weight of Bottle + Sample | 66.4 | 62.2 |
| 5. Weight of Bottle with full of Water | 144.70 | 144.50 |
| 6. Weight of Bottle + Sample + Water | 158.00 | 157.70 |
| 7. Test temperature | 29.00 | 29.10 |
| 8. Volume of Sample (3+5-6) | 7.70 | 7.70 |
| 9. Specific Gravity (3/7) | 2.727 | 2.714 |
| 10. correction factor K | 0.998 | 0.998 |
| 11. Specific gravity of soil @ 20 DC | 2.721 | 2.708 |
| Average Specific Gravity ((A+B)/2) | 2.715 | |

| | |
|---|---|
| Project : | Thesis |
| Sample of : | TP-8 |
| Depth : | 3.0m |

| | 1 | 2 |
|---|---|---|
| 1. Bottle Number | L | H |
| 2. Weight of Bottle | 44.1 | 44 |
| 3. Weight of Sample | 21.6 | 20 |
| 4. Weight of Bottle + Sample | 65.7 | 64 |
| 5. Weight of Bottle with full of Water | 99.10 | 99.10 |
| 6. Weight of Bottle + Sample + Water | 112.70 | 111.70 |
| 7. Test temperature | 28.50 | 111.70 |
| 8. Volume of Sample (3+5-6) | 8.00 | 7.40 |
| 9. Specific Gravity (3/7) | 2.700 | 2.703 |
| 10. correction factor K | 0.998 | 0.998 |
| 11. Specific gravity of soil @ 20 DC | 2.694 | 2.697 |
| Average Specific Gravity ((A+B)/2) | 2.696 | |

| | |
|---|---|
| Project : | Thesis |
| Sample of : | TP-11 |
| Depth : | 1.5m |

| | 1 | 2 |
|---|---|---|
| 1. Bottle Number | 1 | 2 |
| 2. Weight of Bottle | 44 | 44.1 |
| 3. Weight of Sample | 22.1 | 20.6 |
| 4. Weight of Bottle + Sample | 66.1 | 64.7 |
| 5. Weight of Bottle with full of Water | 99.80 | 99.80 |
| 6. Weight of Bottle + Sample + Water | 113.30 | 112.40 |
| 7. Test temperature | 28.00 | 28.50 |
| 8. Volume of Sample (3+5-6) | 8.60 | 8.00 |
| 9. Specific Gravity (3/7) | 2.570 | 2.575 |
| 10. correction factor K | 0.998 | 0.998 |
| 11. Specific gravity of soil @ 20 DC | 2.565 | 2.570 |
| Average Specific Gravity ((A+B)/2) | 2.567 | |

| | |
|---|---|
| Project : | Thesis |
| Sample of : | TP-11 |
| Depth : | 3.0m |

| | 1 | 2 |
|---|---|---|
| 1. Bottle Number | 1 | 2 |
| 2. Weight of Bottle | 44 | 44.1 |
| 3. Weight of Sample | 20 | 20.6 |
| 4. Weight of Bottle + Sample | 66.1 | 64.7 |
| 5. Weight of Bottle with full of Water | 99.80 | 99.80 |
| 6. Weight of Bottle + Sample + Water | 112.40 | 112.80 |
| 7. Test temperature | 29.00 | 28.50 |
| 8. Volume of Sample (3+5-6) | 7.40 | 7.60 |
| 9. Specific Gravity (3/7) | 2.703 | 2.711 |
| 10. correction factor K | 0.998 | 0.998 |
| 11. Specific gravity of soil @ 20 DC | 2.696 | 2.705 |
| Average Specific Gravity ((A+B)/2) | 2.701 | |

## Representative Sieve and Hydrometer Analysis

### Wet Sieve Analysis

Weight of retained = Weight ass of sieve +retained – Weight of sieve

Percentage retained = (Weight of retained / Total Weight used in sieve analysis) *100%

Cumulative percentage retained = Summation of Percentage retained at each sieve

Percentage finer = 100 - Cumulative percentage retained

### Hydrometer Analysis

For the soil fraction with size finer than 0.075mm (sieve No. 200) or from hydrometer analysis

$P = (G_s / (Gs - G_w) \times (V/Ws) \times (R_c - G_1) * 100\ \%$

$D = K\sqrt{(L/T)}$, Where

Ws = total weight of dry soil which is represented by the soil used in

hydrometer analysis

V = volume of sedimentation tank = 1000 $cm^3$

P = percent finer

D = diameter of particles in mm

$G_s$ = specific gravity of soil

$G_w$ = specific gravity of water = 1

K = coefficient which depend on temperature and can be obtained from Table3 of ASTM D422-63

L = effective depth in cm = 280.82-264.52R or from Table2 of ASTM D422-63

T = elapsed time from beginning of sedimentation to the taking of reading

$R_A$ = actual hydrometer reading

$R_c$ = corrected hydrometer reading = R- (composite correction)

Composite correction is due to the three effects: temperature, reading from upper meniscus and effect of the dispersing agent (sodium hexametphosphate) on density of distilled water.

Values of composite correction (experimental and obtained from the laboratory)

| Temperature in $^{0}$ C | 16 | 18 | 20 | 22 | 24 | 26 | 28 |
|---|---|---|---|---|---|---|---|
| Composite correction | 0.0035 | 0.0031 | 0.0027 | 0.0023 | 0.0019 | 0.0015 | 0.0013 |

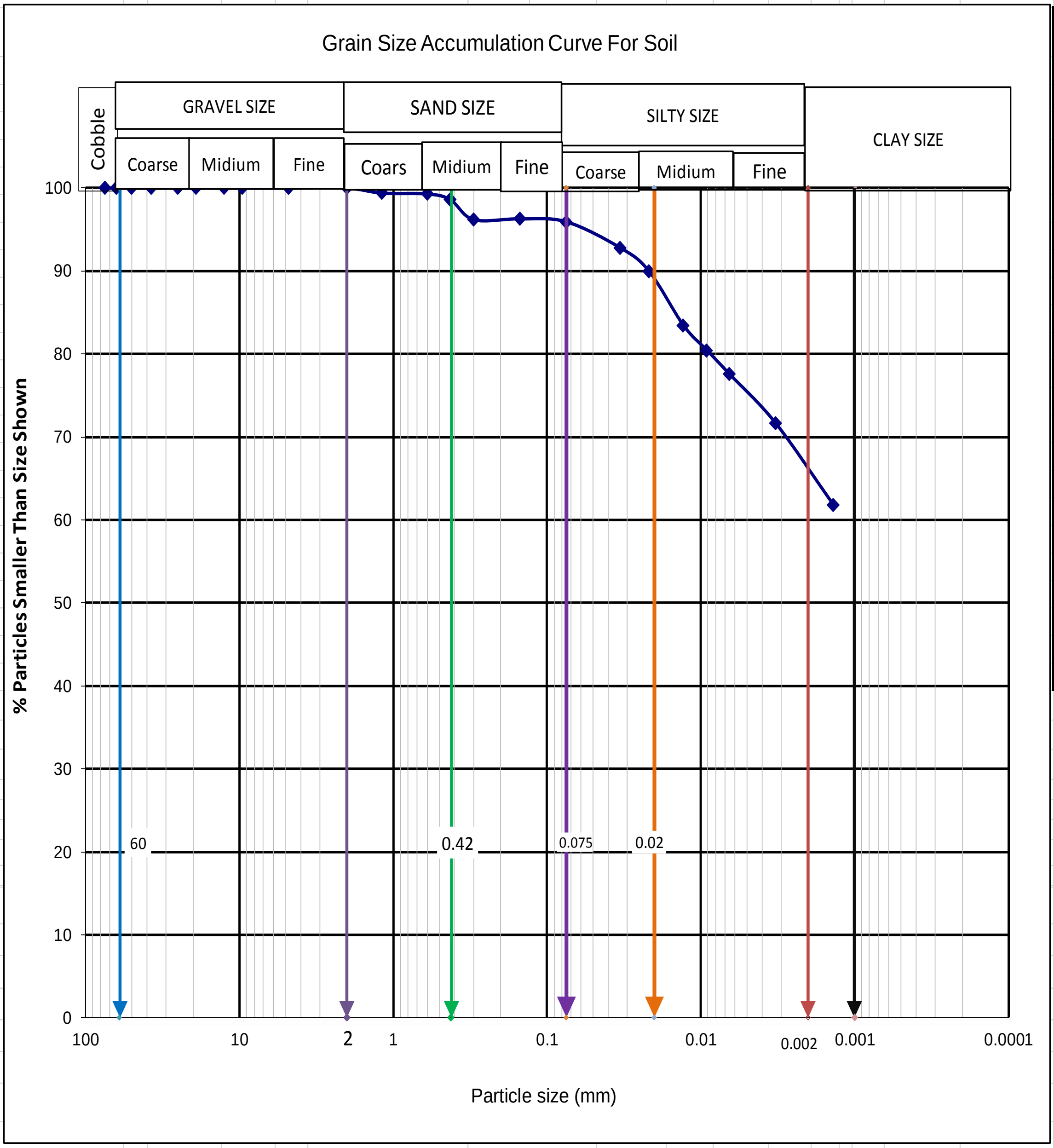
Values of k for Use in Equation for Computing Diameter of Particle in Hydrometer Analysis

| Temp.,c | Specific Gravity of Soil Particles | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | 2.45 | 2.5 | 2.55 | 2.6 | 2.65 | 2.7 | 2.75 | 2.8 | 2.85 |
| 16 | 0.0151 | 0.01505 | 0.01481 | 0.01457 | 0.01435 | 0.01414 | 0.01394 | 0.01374 | 0.01356 |
| 17 | 0.01511 | 0.01486 | 0.01462 | 0.01439 | 0.01417 | 0.01396 | 0.01376 | 0.01356 | 0.01338 |
| 18 | 0.01492 | 0.01467 | 0.01443 | 0.01421 | 0.01399 | 0.01378 | 0.01359 | 0.01339 | 0.01321 |
| 19 | 0.01474 | 0.01449 | 0.01425 | 0.01403 | 0.01382 | 0.01361 | 0.01342 | 0.01323 | 0.01305 |
| 20 | 0.01456 | 0.01431 | 0.01408 | 0.01386 | 0.01365 | 0.01344 | 0.01325 | 0.01307 | 0.01289 |
| 21 | 0.01438 | 0.01414 | 0.01391 | 0.01369 | 0.01348 | 0.01328 | 0.01309 | 0.01291 | 0.01273 |
| 22 | 0.01421 | 0.01397 | 0.01374 | 0.01353 | 0.01332 | 0.01312 | 0.01294 | 0.01276 | 0.01258 |
| 23 | 0.01404 | 0.01381 | 0.01358 | 0.01337 | 0.01317 | 0.01297 | 0.01279 | 0.01261 | 0.01243 |
| 24 | 0.01388 | 0.01365 | 0.01342 | 0.01321 | 0.01301 | 0.01282 | 0.01264 | 0.01246 | 0.01229 |
| 25 | 0.01372 | 0.01349 | 0.01327 | 0.01306 | 0.01286 | 0.01267 | 0.01249 | 0.01232 | 0.01215 |
| 26 | 0.01357 | 0.01334 | 0.01312 | 0.01291 | 0.01272 | 0.01253 | 0.01235 | 0.01218 | 0.01201 |
| 27 | 0.01342 | 0.01319 | 0.01297 | 0.01277 | 0.01258 | 0.01239 | 0.01221 | 0.01204 | 0.01188 |
| 28 | 0.01327 | 0.01304 | 0.01283 | 0.01264 | 0.01244 | 0.01255 | 0.01208 | 0.01191 | 0.01175 |
| 29 | 0.01312 | 0.0129 | 0.01269 | 0.01269 | 0.0123 | 0.01212 | 0.01195 | 0.01178 | 0.01162 |
| 30 | 0.01298 | 0.01276 | 0.01256 | 0.01236 | 0.01217 | 0.01199 | 0.01182 | 0.01165 | 0.01149 |

| Particle Size Analysis of Soil AASHTO T 88 | | |
|---|---|---|
| Project : | Thesis | |
| Station/Location | TP 2 @3.0m | |
| Sample of : | Soil | |
| Grain size analysis test result | | |
| Soil sample in gram | | 500 |

| SIEVESIZE IN {MM} | Weight Retained in | % Retained | % Passing |
|---|---|---|---|
| 1.180 | 1.20 | 0.24 | 99.76 |
| 0.600 | 4.80 | 0.96 | 99.04 |
| 0.425 | 9.10 | 1.82 | 98.18 |
| 0.300 | 11.20 | 2.24 | 97.76 |
| 0.150 | 17.10 | 3.42 | 96.58 |
| 0.075 | 21.40 | 4.28 | 95.72 |

| Test pit 2 @ 3.0m | | | | | | | Specific Gravity 2.712 | | |
|---|---|---|---|---|---|---|---|---|---|
| HYDROMETER ANALYSIS | | | | | | | | | |
| Dry and Clock Time | Hydro meter Readin g | Composit e correction | Correcte d Hydrome ter Reading (R) | Test Tem perat ure oc | Coefficie nt (K) from table | Effecti ve Depth (cm) L | Particle Sizes (mm) | Percentage finer (P) % | Combined Percent finer % |
| 0.5 | 1.0330 | 0.00276 | 1.0302 | 19.7 | 0.00135 | 7.6 | 0.00526 | 95.8071028 | 88.57366654 |
| 1 | 1.0320 | 0.0027 | 1.0293 | 20 | 0.01344 | 7.8 | 0.0375 | 92.82897196 | 85.82038458 |
| 2 | 1.0310 | 0.0026 | 1.0284 | 20.5 | 0.01366 | 8.1 | 0.0275 | 89.97757009 | 83.18426355 |
| 4 | 1.0300 | 0.0026 | 1.0274 | 20.5 | 0.01366 | 8.4 | 0.0198 | 86.80934579 | 80.25524019 |
| 8 | 1.0290 | 0.00266 | 1.0263 | 20.2 | 0.01341 | 8.6 | 0.0139 | 83.45102804 | 77.15047542 |
| 15 | 1.0280 | 0.0026 | 1.0254 | 20.5 | 0.01366 | 8.9 | 0.0105 | 80.4728972 | 74.39719346 |
| 30 | 1.0270 | 0.0025 | 1.0245 | 21 | 0.01328 | 9.2 | 0.0074 | 77.62149533 | 71.76107243 |
| 60 | 1.0260 | 0.0025 | 1.0235 | 21 | 0.01328 | 9.4 | 0.0053 | 74.45327103 | 68.83204907 |
| 120 | 1.0250 | 0.00238 | 1.0226 | 21.2 | 0.01325 | 9.7 | 0.0038 | 71.66523364 | 66.2545085 |
| 240 | 1.0240 | 0.00245 | 1.0216 | 21.5 | 0.01320 | 10.0 | 0.0027 | 68.27523364 | 63.1204535 |
| 480 | 1.0230 | 0.0025 | 1.0205 | 21 | 0.01328 | 10.2 | 0.0019 | 64.94859813 | 60.04497897 |
| 1440 | 1.0220 | 0.0025 | 1.0195 | 21 | 0.01328 | 10.2 | 0.0011 | 61.78037383 | 57.11595561 |

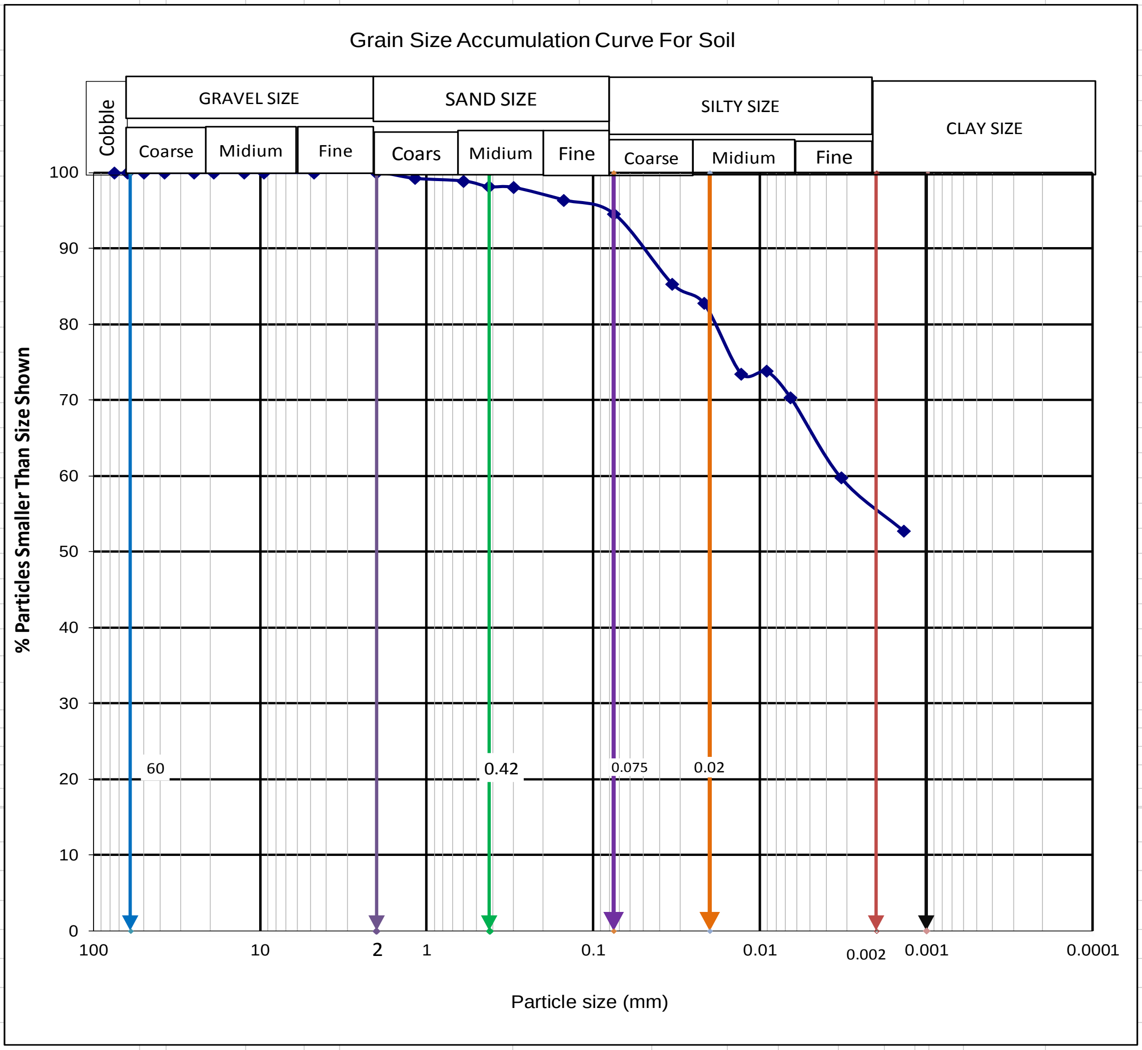



| SIEVESIZE IN (mm) | % Passing |
|---|---|
| 75 | 100 |
| 63 | 100 |
| 50 | 100 |
| 37.5 | 100 |
| 25 | 100 |
| 19 | 100 |
| 12.5 | 100 |
| 9.5 | 100 |
| 4.75 | 100 |
| 2.00 | 100 |
| 1.18 | 99.40 |
| 0.600 | 99.30 |
| 0.425 | 98.60 |
| 0.300 | 96.20 |
| 0.150 | 96.30 |
| 0.075 | 95.95 |
| 0.033 | 92.83 |
| 0.022 | 89.98 |
| 0.013 | 83.45 |
| 0.009 | 80.47 |
| 0.007 | 77.62 |
| 0.003 | 71.67 |
| 0.001 | 61.78 |

| Particle Size Analysis of Soil AASHTO T 88 | | | |
|---|---|---|---|
| Project : | Thesis | | |
| Station/Location | TP 7@3.0 | | |
| Sample of : | Soil | | |
| Grain size analysis test result | | | |
| Soil sample in gram | | | 500 |
| SIEVESIZE IN {MM} | Weight Retained in | % Retained | % Passing |
| 1.180 | 3.10 | 0.62 | 99.38 |

| | | | |
|---|---|---|---|
| 0.600 | 5.50 | 1.10 | 98.90 |
| 0.425 | 13.70 | 2.74 | 97.26 |
| 0.300 | 18.10 | 3.62 | 96.38 |
| 0.150 | 23.40 | 4.68 | 95.32 |
| 0.075 | 27.30 | 5.46 | 94.54 |

| Test pit 7 @ 3.0m | | | | | | | | Specific Gravity | 2.674 |
|---|---|---|---|---|---|---|---|---|---|
| HYDROMETER ANALYSIS | | | | | | | | | |
| Dry and Clock Time | Hydro meter Reading | Composite correction | Corrected Hydro meter Reading (R) | Test Temperature oc | Coefficient (K) from table | Effective Depth (cm) L | Particle Sizes (mm) | Percentage finer (P) % | Combined Percent finer % |
| 0.5 | 1.0300 | 0.0023 | 1.0277 | 22 | 0.01332 | 8.4 | 0.05460 | 88.49438471 | 83.67144074 |
| 1 | 1.0290 | 0.0023 | 1.0267 | 22 | 0.01320 | 8.6 | 0.0387 | 85.29964158 | 80.65081111 |
| 2 | 1.0280 | 0.0021 | 1.0259 | 23 | 0.01317 | 8.9 | 0.0278 | 82.74384707 | 78.23430741 |
| 4 | 1.0270 | 0.0021 | 1.0249 | 23 | 0.01317 | 9.2 | 0.0200 | 79.54910394 | 75.21367778 |
| 8 | 1.0250 | 0.002 | 1.0230 | 23.5 | 0.01309 | 9.7 | 0.0144 | 73.479092 | 69.47448148 |
| 15 | 1.0250 | 0.0019 | 1.0231 | 24 | 0.01301 | 9.7 | 0.0105 | 73.79856631 | 69.77654444 |
| 30 | 1.0240 | 0.002 | 1.0220 | 23.5 | 0.01309 | 10.0 | 0.0076 | 70.28434886 | 66.45385185 |
| 60 | 1.0230 | 0.00245 | 1.0206 | 21.5 | 0.01340 | 10.2 | 0.0055 | 65.65197133 | 62.07393889 |
| 120 | 1.0210 | 0.0023 | 1.0187 | 22 | 0.01332 | 10.7 | 0.0040 | 59.74169654 | 56.48577407 |
| 240 | 1.0200 | 0.0023 | 1.0177 | 22 | 0.01332 | 11.0 | 0.0029 | 56.54695341 | 53.46514444 |
| 480 | 1.0200 | 0.0027 | 1.0173 | 20 | 0.01365 | 11.0 | 0.0021 | 55.26905615 | 52.25689259 |
| 1440 | 1.0190 | 0.0025 | 1.0165 | 21 | 0.01348 | 11.3 | 0.0012 | 52.71326165 | 49.84038889 |

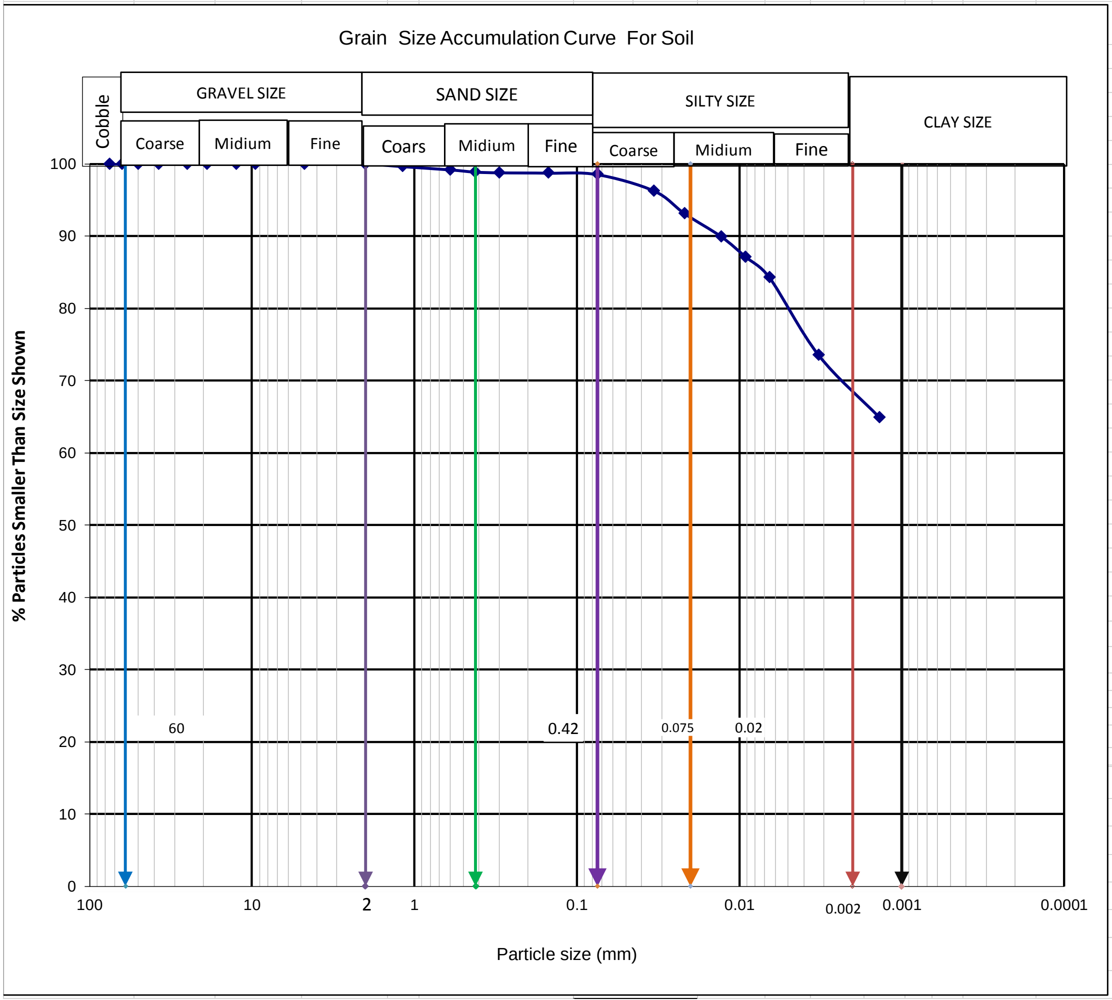



| SIEVESIZE IN (mm) | % Passing |
|---|---|
| 75 | 100 |
| 63 | 100 |
| 50 | 100 |
| 37.5 | 100 |
| 25 | 100 |
| 19 | 100 |
| 12.5 | 100 |
| 9.5 | 100 |
| 4.75 | 100 |
| 2.00 | 100 |
| 1.18 | 99.25 |
| 0.600 | 98.90 |
| 0.425 | 98.15 |
| 0.300 | 98.05 |
| 0.150 | 96.40 |
| 0.075 | 94.55 |
| 0.033 | 85.30 |
| 0.022 | 82.74 |
| 0.013 | 73.48 |
| 0.009 | 73.80 |
| 0.007 | 70.28 |
| 0.003 | 59.74 |
| 0.001 | 52.71 |

| Particle Size Analysis of Soil AASHTO T 88 | | | |
|---|---|---|---|
| Project : | Thesis | | |
| Station/Location | TP-9@ 3.0 | | |
| Sample of : | Soil | | |
| Grain size analysis test result | | | |
| Soil sample in gram | | | 500 |
| SIEVESIZE IN {MM} | Weight Retained in | % Retained | % Passing |
| 1.180 | 1.60 | 0.32 | 99.68 |
| 0.600 | 3.10 | 0.62 | 99.38 |
| 0.425 | 5.20 | 1.04 | 98.96 |
| 0.300 | 6.40 | 1.28 | 98.72 |
| 0.150 | 7.10 | 1.42 | 98.58 |
| 0.075 | 7.20 | 1.44 | 98.56 |

| | | |
|---|---|---|
| Test pit 9 @ 3.0m | Specific Gravity | 2.729 |

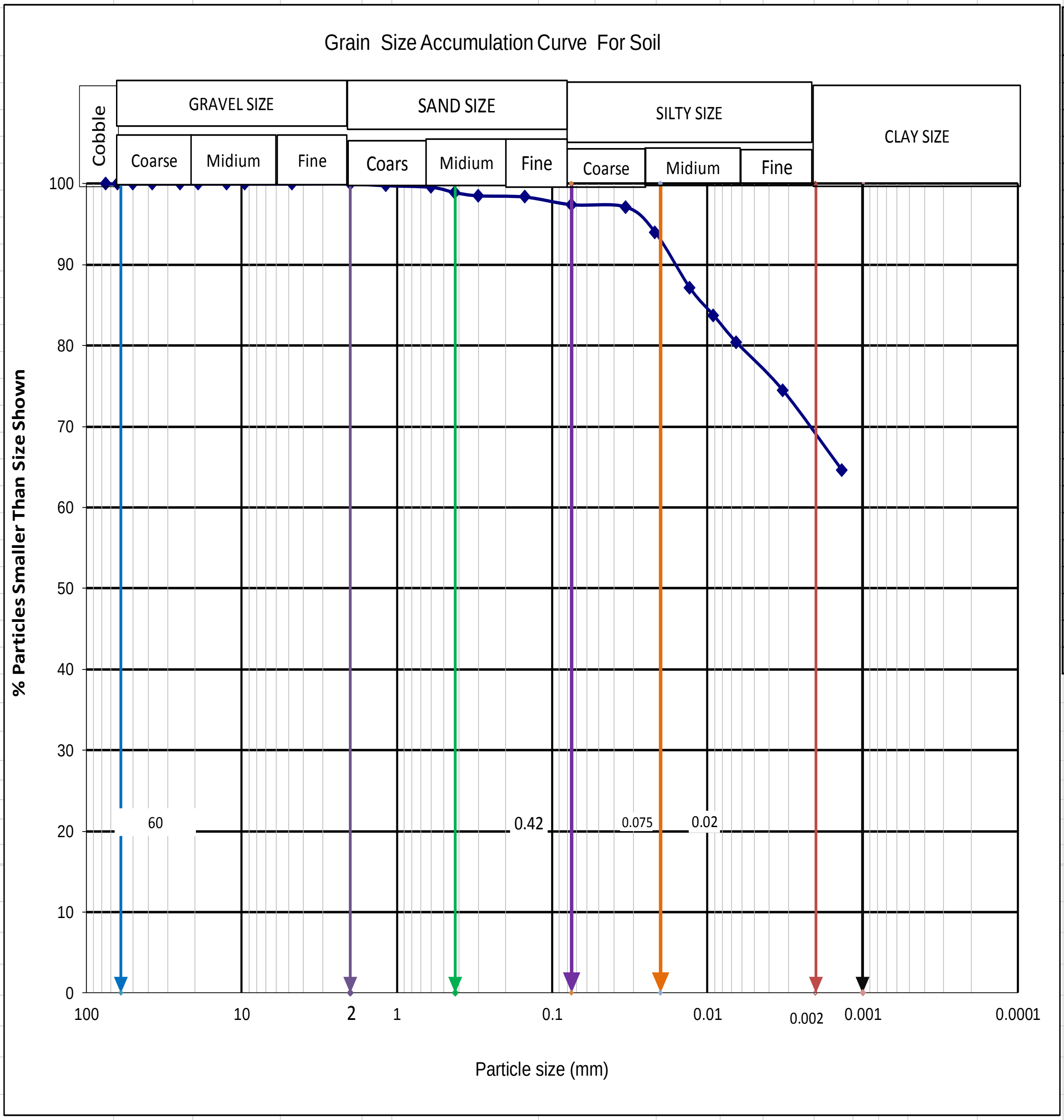
| HYDROMETER ANALYSIS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dry and Clock Time | Hydrometer Reading | Composite correction | Corrected Hydrometer Reading (R) | Test Temperature oc | Coefficient (K) from table | Effective Depth (cm) L | Particle Sizes (mm) | Percentage finer (P) % | Combined Percent finer % |
| 0.5 | 1.0340 | 0.0025 | 1.0315 | 21 | 0.01328 | 7.3 | 0.05074 | 99.43724696 | 95.80778745 |
| 1 | 1.0330 | 0.0025 | 1.0305 | 21 | 0.01328 | 7.6 | 0.0366 | 96.28050896 | 92.76627039 |
| 2 | 1.0320 | 0.0025 | 1.0295 | 21 | 0.01325 | 7.8 | 0.0262 | 93.12377097 | 89.72475333 |
| 4 | 1.0310 | 0.00238 | 1.0286 | 21.2 | 0.01323 | 8.1 | 0.0188 | 90.34584153 | 87.04821831 |
| 8 | 1.0310 | 0.0025 | 1.0285 | 21 | 0.01328 | 8.1 | 0.0134 | 89.96703297 | 86.68323626 |
| 15 | 1.0300 | 0.0024 | 1.0276 | 21.3 | 0.01320 | 8.4 | 0.0099 | 87.12596877 | 83.94587091 |
| 30 | 1.0290 | 0.0023 | 1.0267 | 22 | 0.01328 | 8.6 | 0.0071 | 84.28490457 | 81.20850555 |
| 60 | 1.0270 | 0.00238 | 1.0246 | 21.2 | 0.01325 | 9.2 | 0.0052 | 77.71888953 | 74.88215006 |
| 120 | 1.0260 | 0.0027 | 1.0233 | 20 | 0.01328 | 9.4 | 0.0037 | 73.55199537 | 70.86734754 |
| 240 | 1.0250 | 0.0023 | 1.0227 | 22 | 0.01312 | 9.7 | 0.0026 | 71.65795257 | 69.0424373 |
| 480 | 1.0240 | 0.0027 | 1.0213 | 20 | 0.01344 | 10.0 | 0.0019 | 67.23851938 | 64.78431342 |
| 1440 | 1.0230 | 0.00245 | 1.0206 | 21.5 | 0.01328 | 10.2 | 0.0011 | 64.87096588 | 62.50317562 |




| SIEVESIZE IN (mm) | % Passing |
|---|---|
| 75 | 100 |
| 63 | 100 |
| 50 | 100 |
| 37.5 | 100 |
| 25 | 100 |
| 19 | 100 |
| 12.5 | 100 |
| 9.5 | 100 |
| 4.75 | 100 |
| 2.00 | 100 |
| 1.18 | 99.65 |
| 0.600 | 99.20 |
| 0.425 | 98.90 |
| 0.300 | 98.80 |
| 0.150 | 98.75 |
| 0.075 | 98.55 |
| 0.033 | 96.28 |
| 0.022 | 93.12 |
| 0.013 | 89.97 |
| 0.009 | 87.13 |
| 0.007 | 84.28 |
| 0.003 | 73.55 |
| 0.001 | 64.87 |

| Particle Size Analysis of Soil AASHTO T 88 | | | |
|---|---|---|---|
| Project : | Thesis | | |
| Station/Location | TP-12@3.0 | | |
| Sample of : | Soil | | |
| Grain size analysis test result | | | |
| Soil sample in gram | | | 500 |
| SIEVESIZE IN {MM} | Weight Retained in | % Retained | % Passing |
| 1.180 | 1.40 | 0.28 | 99.72 |
| 0.600 | 3.80 | 0.76 | 99.24 |
| 0.425 | 9.50 | 1.90 | 98.10 |
| 0.300 | 11.30 | 2.26 | 97.74 |
| 0.150 | 12.20 | 2.44 | 97.56 |
| 0.075 | 12.80 | 2.56 | 97.44 |
| Test pit 12 @ 3.0m | | Specific Gravity | 2.732 |

| HYDROMETER ANALYSIS | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Dry and Clock Time | Hydrometer Reading | Composite correction | Corrected Hydrometer Reading (R) | Test Temperature oc | Coefficient (K) from table | Effective Depth (cm) L | Particle Sizes (mm) | Percentage finer (P) % | Combined Percent finer % |
| 0.5 | 1.0340 | 0.0021 | 1.0319 | 23 | 0.01297 | 7.3 | 0.04956 | 100.6360277 | 98.06980901 |
| 1 | 1.0330 | 0.0022 | 1.0308 | 22.5 | 0.01305 | 7.6 | 0.0360 | 97.16581986 | 94.68809145 |
| 2 | 1.0320 | 0.0022 | 1.0298 | 22.5 | 0.01305 | 7.8 | 0.0258 | 94.01108545 | 91.61380277 |
| 4 | 1.0310 | 0.0025 | 1.0285 | 21 | 0.01328 | 8.1 | 0.0189 | 89.90993072 | 87.61722748 |
| 8 | 1.0300 | 0.00238 | 1.0276 | 21.2 | 0.01324 | 8.4 | 0.0136 | 87.13376443 | 84.91185344 |
| 15 | 1.0290 | 0.00245 | 1.0266 | 21.5 | 0.01320 | 8.6 | 0.0100 | 83.75819861 | 81.62236455 |
| 30 | 1.0280 | 0.0025 | 1.0255 | 21 | 0.01328 | 8.9 | 0.0072 | 80.44572748 | 78.39436143 |
| 60 | 1.0270 | 0.0025 | 1.0245 | 21 | 0.01328 | 9.2 | 0.0052 | 77.29099307 | 75.32007275 |
| 120 | 1.0260 | 0.0024 | 1.0236 | 21.3 | 0.01323 | 9.4 | 0.0037 | 74.4517321 | 72.55321293 |
| 240 | 1.0250 | 0.0023 | 1.0227 | 22 | 0.01312 | 9.7 | 0.0026 | 71.61247113 | 69.78635312 |
| 480 | 1.0240 | 0.0027 | 1.0213 | 20 | 0.01344 | 10.0 | 0.0019 | 67.19584296 | 65.48234896 |
| 1440 | 1.0230 | 0.0025 | 1.0205 | 21 | 0.01328 | 10.2 | 0.0011 | 64.67205543 | 63.02291801 |




| SIEVESIZE IN (mm) | % Passing |
|---|---|
| 75 | 100 |
| 63 | 100 |
| 50 | 100 |
| 37.5 | 100 |
| 25 | 100 |
| 19 | 100 |
| 12.5 | 100 |
| 9.5 | 100 |
| 4.75 | 100 |
| 2.00 | 100 |
| 1.18 | 99.80 |
| 0.600 | 99.60 |
| 0.425 | 98.95 |
| 0.300 | 98.55 |
| 0.150 | 98.40 |
| 0.075 | 97.45 |
| 0.033 | 97.17 |
| 0.022 | 94.01 |
| 0.013 | 87.13 |
| 0.009 | 83.76 |
| 0.007 | 80.45 |
| 0.003 | 74.45 |
| 0.001 | 64.67 |

Representative Free Swell Test Results

$$Freeswell(\%)=\frac{Finalvolume-Initialvolume}{InitialVolume}x100$$

| Method of Test IS:2720 (Part 40) 1977 | | | |
|---|---|---|---|
| Location/station | TP-1 | Location/station | TP-1 |
| Depth (m) | 1.5m | Depth (m) | 3.0m |
| Original Volume of dry Sample (Vi)ml | | Original Volume of dry Sample (Vi)ml | |
| 10 | | 10 | |
| Final Volume (Vf)ml | | Final Volume (Vf)ml | |
| 21.8 | | 32 | |
| Free Swell (%)= (Vf-Vi)*100/Vi | 118 | Free Swell (%)= (Vf-Vi)*100/Vi | 220 |

| | | | |
|---|---|---|---|
| Location/station | TP-2 | Location/station | TP-2 |
| Depth (m) | 1.5m | Depth (m) | 3.0m |
| Original Volume of dry Sample (Vi)ml | | Original Volume of dry Sample (Vi)ml | |
| 10 | | 10 | |
| Final Volume (Vf)ml | | Final Volume (Vf)ml | |
| 30 | | 32.5 | |
| Free Swell (%)= (Vf-Vi)*100/Vi | 200 | Free Swell (%)= (Vf-Vi)*100/Vi | 225 |
| Location/station | TP-3 | Location/station | TP-3 |
| Depth (m) | 1.5m | Depth (m) | 3m |
| Original Volume of dry Sample (Vi)ml | | Original Volume of dry Sample (Vi)ml | |
| 10 | | 10 | |
| Final Volume (Vf)ml | | Final Volume (Vf)ml | |
| 32.5 | | 30 | |
| Free Swell (%)= (Vf-Vi)*100/Vi | 225 | Free Swell (%)= (Vf-Vi)*100/Vi | 200 |

| | |
|---|---|
| Location/station TP-7<br>Depth (m) 1.5m<br>Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>33.5<br>Free Swell (%)= (Vf-Vi)*100/Vi 235 | Location/station TP-7<br>Depth (m) 3.0m<br>Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>31<br>Free Swell (%)= (Vf-Vi)*100/Vi 210 |
| Location/station TP-8 | Location/station TP-8 |
| Depth (m) 1.5m | Depth (m) 3m |
| Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>29.5<br>Free Swell (%)= (Vf-Vi)*100/Vi 195 | Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>31<br>Free Swell (%)= (Vf-Vi)*100/Vi 210 |

| | |
|---|---|
| Location/station TP-9<br>Depth (m) 1.5m<br>Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>30.5<br>Free Swell (%)= (Vf-Vi)*100/Vi 205 | Location/station TP-9<br>Depth (m) 3m<br>Original Volume of dry Sample (Vi)ml<br>10<br>Final Volume (Vf)ml<br>34<br>Free Swell (%)= (Vf-Vi)*100/Vi 240 |

## Representative Swelling Pressure Test Results

Bulk and Dry density

Mass of soil= (Mass of ring + soil) – Mass of ring

Volume of the ring = $(\Pi * D^2/4) * H = 79.42cm^3$

Where: - D= Diameter of ring=50mm

H= Height of ring=20mm

Bulk density = Weight of soil / Volume of the ring

Dry density = Bulk density / (1+ water content in decimal)

$A = \Pi * D^2/4 = 31.77cm^2$

Where: - D= Diameter of ring

A= Area of the ring

Seating load = 7kpa

$e_o = \frac{Hi-Hs}{Hs}$ where, $e_o$- Initial void ratio

Hi- Height of sample

Hs- Height of solid, $Hs = \frac{Ms}{A * Gs * \rho w}$

Ms - Mass of dry specimen after test

ρw - Density of water = $1gm/cm^3$ &

Gs -Specific gravity of specimen

$H_f = Hi - S\Delta H$

$Hv = H_f - Hs$

$\Delta e = \frac{\Delta H}{Hs}$, where ΔH = Final dial reading – Initial dial reading at each loading

Hf = Height of specimen after test & Hv = Height of void

1D consolidation Using Free Swell Method

| |
|---|
| 1D Consolidation Test ASTM-D-2435 & D-4546<br>Project: Thesis<br>Location Test Pit 1<br>Depth, m 3.0m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 7.00 | 7.900 | 7.810 | 7.600 | 7.410 | 7.200 | 6.820 | 6.140 |
| 0.15 | - | 7.990 | 7.800 | 7.600 | 7.400 | 7.180 | 6.740 | 5.870 |
| 0.30 | - | 7.980 | 7.800 | 7.590 | 7.390 | 7.150 | 6.700 | 5.850 |
| 1 | - | 7.970 | 7.790 | 7.580 | 7.370 | 7.130 | 6.640 | 5.840 |
| 2 | - | 7.950 | 7.780 | 7.570 | 7.630 | 7.100 | 6.620 | 5.820 |
| 4 | - | 7.940 | 7.760 | 7.550 | 7.350 | 7.090 | 6.570 | 5.780 |
| 8 | - | 7.930 | 7.750 | 7.530 | 7.330 | 7.080 | 6.530 | 5.750 |
| 15 | - | 7.920 | 7.730 | 7.510 | 7.320 | 7.040 | 6.480 | 5.700 |
| 30 | - | 7.900 | 7.740 | 7.500 | 7.310 | 7.000 | 6.420 | 5.640 |
| 60 | - | 7.880 | 7.710 | 7.490 | 7.300 | 6.950 | 6.380 | 5.590 |
| 120 | - | 7.860 | 7.680 | 7.470 | 7.290 | 6.920 | 6.330 | 5.510 |
| 240 | - | 7.850 | 7.660 | 7.450 | 7.260 | 6.880 | 6.280 | 5.470 |
| 480 | - | 7.830 | 7.620 | 7.430 | 7.240 | 6.850 | 6.210 | 5.420 |
| 1440 | 7.90 | 7.810 | 7.600 | 7.410 | 7.200 | 6.820 | 6.140 | 5.360 |

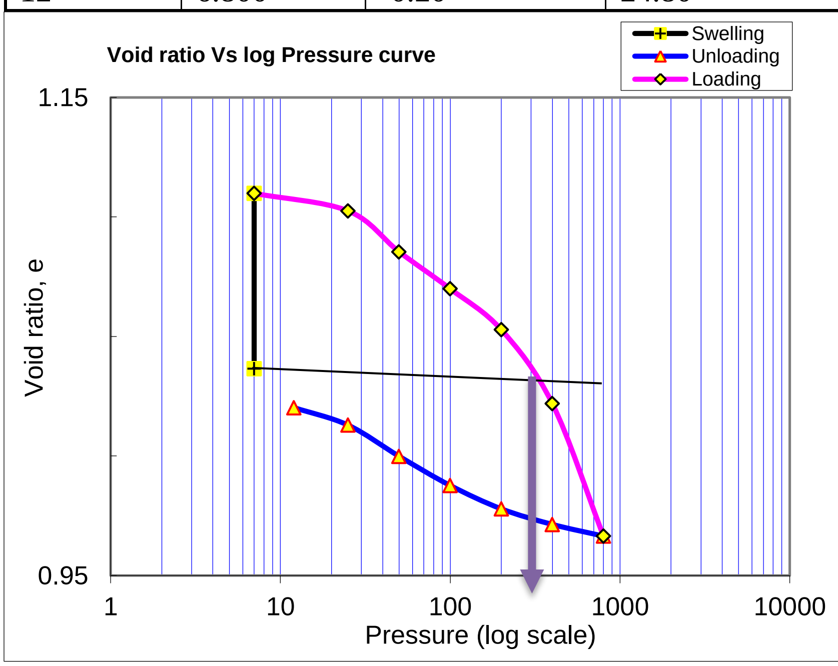
Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 6.140 | 6.200 | 6.280 | 6.400 | 6.550 | 6.710 | 6.800 |

| | |
|---|---|
| [A] In the beginning of the test | |
| Sample type : | Un disturbed |
| Ring Area,$cm^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load, kPa | 7 |
| Initial Void Ratio, $e_o$: | 1.11 |
| Initial moisture content,% | 39.65 |
| Specific Gravity: | 2.7 |
| Wet density,g/cm3 | 1.78 |
| [B] In the end of the test | |

| | |
|---|---|
| Final Moisture Content,% | 34.19 |
| Dry specimen wt ($m_s$), gm: | 105.3 |
| Dry density,g/cm3 | 1.37 |
| Height of Solids($H_s$), mm | 12.28 |
| Final Void Ratio, $e_f$: | 1.02 |

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 7.000 | 0.00 | 25.00 | 12.72 | 1.04 |
| 7 | 7.900 | 0.90 | 25.90 | 13.62 | 1.11 |
| 25 | 7.810 | 0.81 | 25.81 | 13.53 | 1.10 |
| 50 | 7.600 | 0.60 | 25.60 | 13.32 | 1.09 |
| 100 | 7.410 | 0.41 | 25.41 | 13.13 | 1.07 |
| 200 | 7.200 | 0.20 | 25.20 | 12.92 | 1.05 |
| 400 | 6.820 | -0.18 | 24.82 | 12.54 | 1.02 |
| 800 | 6.140 | -0.86 | 24.14 | 11.86 | 0.97 |
| Unloading | | | | | |
| 800 | 6.140 | -0.86 | 24.14 | 11.86 | 0.97 |
| 400 | 6.200 | -0.80 | 24.20 | 11.92 | 0.97 |
| 200 | 6.280 | -0.72 | 24.28 | 12.00 | 0.98 |
| 100 | 6.400 | -0.60 | 24.40 | 12.12 | 0.99 |
| 50 | 6.550 | -0.45 | 24.55 | 12.27 | 1.00 |
| 25 | 6.710 | -0.29 | 24.71 | 12.43 | 1.01 |
| 12 | 6.800 | -0.20 | 24.80 | 12.52 | 1.02 |



| 1D Consolidation Test ASTM-D-2435 & D-4546 | |
|---|---|
| Project: | Thesis |
| Location | Test Pit 4 |
| Depth, m | 1.5m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 5.50 | 6.600 | 6.610 | 6.330 | 6.050 | 5.700 | 5.280 | 4.620 |
| 0.15 | - | 6.850 | 6.600 | 6.320 | 6.040 | 5.680 | 5.250 | 4.570 |
| 0.30 | - | 6.840 | 6.580 | 6.300 | 6.030 | 5.670 | 5.210 | 4.510 |
| 1 | - | 6.830 | 6.570 | 6.280 | 6.010 | 5.650 | 5.160 | 4.460 |
| 2 | - | 6.810 | 6.550 | 6.260 | 5.990 | 5.610 | 5.110 | 4.400 |
| 4 | - | 6.790 | 6.530 | 6.230 | 5.970 | 5.570 | 5.070 | 4.330 |
| 8 | - | 6.770 | 6.500 | 6.210 | 5.940 | 5.540 | 5.020 | 4.250 |
| 15 | - | 6.740 | 6.480 | 6.190 | 5.910 | 5.510 | 4.970 | 4.180 |
| 30 | - | 6.710 | 6.450 | 6.170 | 5.870 | 5.500 | 4.930 | 4.110 |
| 60 | - | 6.690 | 6.420 | 6.160 | 5.840 | 5.450 | 4.880 | 4.070 |
| 120 | - | 6.670 | 6.400 | 6.130 | 5.800 | 5.410 | 4.820 | 4.010 |
| 240 | - | 6.650 | 6.380 | 6.090 | 5.760 | 5.360 | 4.760 | 3.940 |
| 480 | - | 6.630 | 6.360 | 6.060 | 5.740 | 5.340 | 4.700 | 3.860 |
| 1440 | 6.60 | 6.610 | 6.330 | 6.050 | 5.700 | 5.280 | 4.620 | 3.750 |

Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

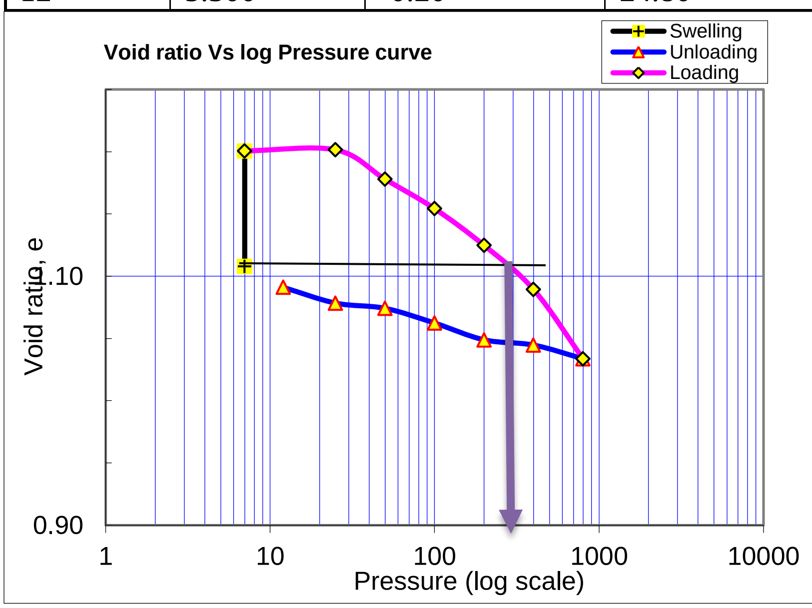
| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 4.620 | 4.750 | 4.800 | 4.960 | 5.100 | 5.150 | 5.300 |

| [A] In the beginning of the test | |
|---|---|
| Sample type : | Un disturbed |
| Ring Area,$cm^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load, kPa | 7 |
| Initial Void Ratio, $e_o$: | 1.20 |
| Initial moisture content,% | 39.76 |
| Specific Gravity: | 2.715 |
| Wet density,g/cm3 | 1.68 |
| [B] In the end of the test | |
| Final Moisture Content,% | 30.60 |

| | |
|---|---|
| Dry specimen wt ($m_s$), gm: | 102.3 |
| Dry density,g/cm3 | 1.33 |
| Height of Solids($H_s$), mm | 11.86 |
| Final Void Ratio, $e_f$: | 1.09 |

[C]Calculation table:

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 5.500 | 0.00 | 25.00 | 13.14 | 1.11 |
| 7 | 6.600 | 1.10 | 26.10 | 14.24 | 1.20 |
| 25 | 6.610 | 1.11 | 26.11 | 14.25 | 1.20 |
| 50 | 6.330 | 0.83 | 25.83 | 13.97 | 1.18 |
| 100 | 6.050 | 0.55 | 25.55 | 13.69 | 1.15 |
| 200 | 5.700 | 0.20 | 25.20 | 13.34 | 1.12 |
| 400 | 5.280 | -0.22 | 24.78 | 12.92 | 1.09 |
| 800 | 4.620 | -0.88 | 24.12 | 12.26 | 1.03 |
| Unloading | | | | | |
| 800 | 4.620 | -0.88 | 24.12 | 12.26 | 1.03 |
| 400 | 4.750 | -0.75 | 24.25 | 12.39 | 1.04 |
| 200 | 4.800 | -0.70 | 24.30 | 12.44 | 1.05 |
| 100 | 4.960 | -0.54 | 24.46 | 12.60 | 1.06 |
| 50 | 5.100 | -0.40 | 24.60 | 12.74 | 1.07 |
| 25 | 5.150 | -0.35 | 24.65 | 12.79 | 1.08 |
| 12 | 5.300 | -0.20 | 24.80 | 12.94 | 1.09 |



| 1D Consolidation Test ASTM-D-2435 & D-4546 | |
|---|---|
| Project: | Thesis |
| Location | Test Pit 6 |
| Depth, m | 3.0m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 8.10 | 9.300 | 9.220 | 8.740 | 8.360 | 7.920 | 7.470 | 6.540 |
| 0.15 | - | 9.510 | 9.100 | 8.730 | 8.340 | 7.900 | 7.450 | 6.510 |
| 0.30 | - | 9.490 | 9.000 | 8.710 | 8.310 | 7.870 | 7.410 | 6.470 |
| 1 | - | 9.470 | 8.980 | 8.680 | 8.290 | 7.850 | 7.380 | 6.410 |
| 2 | - | 9.430 | 8.970 | 8.650 | 8.260 | 7.810 | 7.340 | 6.350 |
| 4 | - | 9.410 | 8.950 | 8.630 | 8.220 | 7.760 | 7.290 | 6.290 |
| 8 | - | 9.390 | 8.930 | 8.610 | 8.190 | 7.710 | 7.250 | 6.230 |
| 15 | - | 9.370 | 8.900 | 8.570 | 8.150 | 7.650 | 7.200 | 6.170 |
| 30 | - | 9.340 | 8.870 | 8.510 | 8.110 | 7.600 | 7.140 | 6.120 |
| 60 | - | 9.320 | 8.840 | 8.480 | 8.080 | 7.570 | 7.080 | 6.060 |
| 120 | - | 9.290 | 8.820 | 8.460 | 8.030 | 7.540 | 7.030 | 6.010 |
| 240 | - | 9.260 | 8.770 | 8.420 | 8.000 | 7.520 | 6.670 | 5.940 |
| 480 | - | 9.240 | 8.760 | 8.390 | 7.960 | 7.500 | 6.630 | 5.830 |
| 1440 | 9.30 | 9.220 | 8.740 | 8.360 | 7.920 | 7.470 | 6.540 | 5.720 |

Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

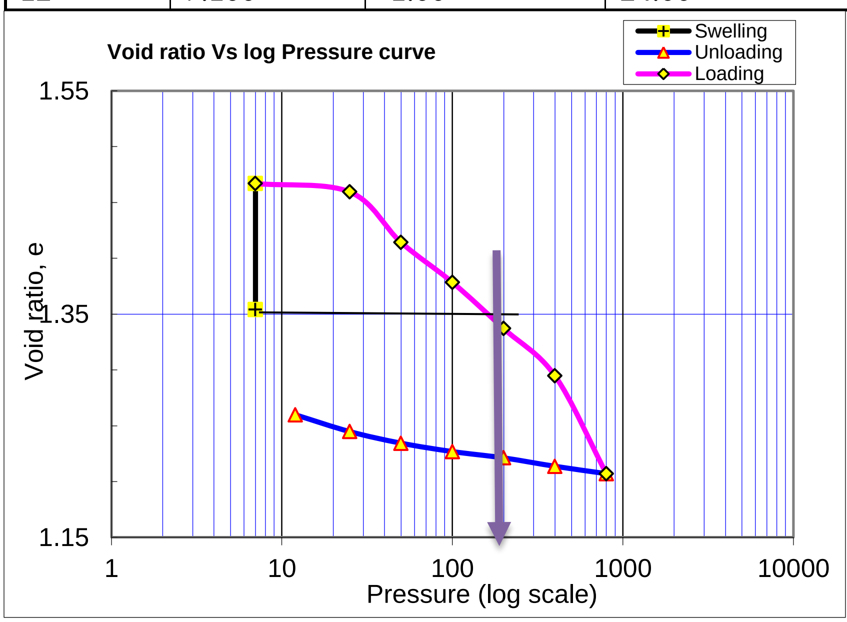
| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 6.540 | 6.610 | 6.690 | 6.750 | 6.830 | 6.940 | 7.100 |

| [A] In the beginning of the test | |
|---|---|
| Sample type : | Un disturbed |
| Ring Area,$cm^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load, kPa | 7 |
| Initial Void Ratio, $e_o$: | 1.47 |
| Initial moisture content,% | 41.10 |
| Specific Gravity: | 2.7 |
| Wet density,g/cm3 | 1.65 |
| [B] In the end of the test | |
| Final Moisture Content,% | 43.91 |
| Dry specimen wt ($m_s$), gm: | 91.1 |

| | |
|---|---|
| Dry density,g/cm3 | 1.22 |
| Height of Solids($H_s$), mm | 10.62 |
| Final Void Ratio, $e_f$: | 1.26 |

[C]Calculation table:

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 8.100 | 0.00 | 25.00 | 14.38 | 1.35 |
| 7 | 9.300 | 1.20 | 26.20 | 15.58 | 1.47 |
| 25 | 9.220 | 1.12 | 26.12 | 15.50 | 1.46 |
| 50 | 8.740 | 0.64 | 25.64 | 15.02 | 1.41 |
| 100 | 8.360 | 0.26 | 25.26 | 14.64 | 1.38 |
| 200 | 7.920 | -0.18 | 24.82 | 14.20 | 1.34 |
| 400 | 7.470 | -0.63 | 24.37 | 13.75 | 1.29 |
| 800 | 6.540 | -1.56 | 23.44 | 12.82 | 1.21 |
| Unloading | | | | | |
| 800 | 6.540 | -1.56 | 23.44 | 12.82 | 1.21 |
| 400 | 6.610 | -1.49 | 23.51 | 12.89 | 1.21 |
| 200 | 6.690 | -1.41 | 23.59 | 12.97 | 1.22 |
| 100 | 6.750 | -1.35 | 23.65 | 13.03 | 1.23 |
| 50 | 6.830 | -1.27 | 23.73 | 13.11 | 1.23 |
| 25 | 6.940 | -1.16 | 23.84 | 13.22 | 1.24 |
| 12 | 7.100 | -1.00 | 24.00 | 13.38 | 1.26 |



| 1D Consolidation Test ASTM-D-2435 & D-4546 | |
|---|---|
| Project: | Thesis |
| Location | Test Pit 7 |
| Depth, m | 1.5m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 3.85 | 5.100 | 5.050 | 4.770 | 4.510 | 4.200 | 3.750 | 3.200 |
| 0.15 | - | 5.350 | 5.040 | 4.760 | 4.500 | 4.180 | 3.730 | 3.160 |
| 0.30 | - | 5.340 | 5.030 | 4.750 | 4.480 | 4.170 | 3.700 | 3.120 |
| 1 | - | 5.330 | 5.010 | 4.740 | 4.460 | 4.160 | 3.680 | 3.070 |
| 2 | - | 5.300 | 4.980 | 4.720 | 4.430 | 4.150 | 3.650 | 3.040 |
| 4 | - | 5.280 | 4.960 | 4.700 | 4.420 | 4.130 | 3.610 | 3.000 |
| 8 | - | 5.250 | 4.930 | 4.670 | 4.400 | 4.110 | 3.570 | 2.940 |
| 15 | - | 5.230 | 4.910 | 4.650 | 4.370 | 4.080 | 3.520 | 2.870 |
| 30 | - | 5.200 | 4.880 | 4.630 | 4.350 | 4.040 | 3.480 | 2.810 |
| 60 | - | 5.170 | 4.860 | 4.600 | 4.320 | 4.010 | 3.410 | 2.750 |
| 120 | - | 5.140 | 4.820 | 4.580 | 4.290 | 3.960 | 3.350 | 2.670 |
| 240 | - | 5.110 | 4.800 | 4.540 | 4.260 | 3.910 | 3.300 | 2.600 |
| 480 | - | 5.080 | 4.790 | 4.530 | 4.220 | 3.840 | 3.240 | 2.520 |
| 1440 | 5.10 | 5.050 | 4.770 | 4.510 | 4.200 | 3.750 | 3.200 | 2.430 |

Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

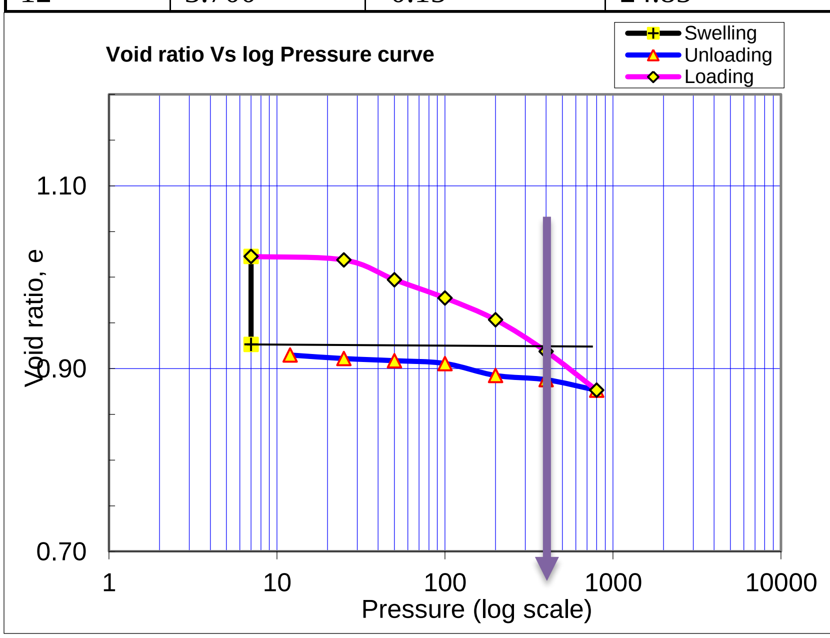
| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 3.200 | 3.350 | 3.410 | 3.580 | 3.620 | 3.650 | 3.700 |

| | |
|---|---|
| [A] In the beginning of the test | |
| Sample type : | Un disturbed |
| Ring Area,cm$^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load, kPa | 7 |
| Initial Void Ratio, $e_o$: | 1.02 |
| Initial moisture content,% | 38.82 |
| Specific Gravity: | 2.651 |
| Wet density,g/cm3 | 1.81 |
| [B] In the end of the test | |
| Final Moisture Content,% | 31.47 |

| | |
|---|---|
| Dry specimen wt ($m_s$), gm: | 109.3 |
| Dry density,g/cm3 | 1.41 |
| Height of Solids($H_s$), mm | 12.98 |
| Final Void Ratio, $e_f$: | 0.91 |

[C]Calculation table:

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 3.850 | 0.00 | 25.00 | 12.02 | 0.93 |
| 7 | 5.100 | 1.25 | 26.25 | 13.27 | 1.02 |
| 25 | 5.050 | 1.20 | 26.20 | 13.22 | 1.02 |
| 50 | 4.770 | 0.92 | 25.92 | 12.94 | 1.00 |
| 100 | 4.510 | 0.66 | 25.66 | 12.68 | 0.98 |
| 200 | 4.200 | 0.35 | 25.35 | 12.37 | 0.95 |
| 400 | 3.750 | -0.10 | 24.90 | 11.92 | 0.92 |
| 800 | 3.200 | -0.65 | 24.35 | 11.37 | 0.88 |
| Unloading | | | | | |
| 800 | 3.200 | -0.65 | 24.35 | 11.37 | 0.88 |
| 400 | 3.350 | -0.50 | 24.50 | 11.52 | 0.89 |
| 200 | 3.410 | -0.44 | 24.56 | 11.58 | 0.89 |
| 100 | 3.580 | -0.27 | 24.73 | 11.75 | 0.91 |
| 50 | 3.620 | -0.23 | 24.77 | 11.79 | 0.91 |
| 25 | 3.650 | -0.20 | 24.80 | 11.82 | 0.91 |
| 12 | 3.700 | -0.15 | 24.85 | 11.87 | 0.91 |



| 1D Consolidation Test ASTM-D-2435 & D-4546 | |
|---|---|
| Project: | Thesis |
| Location | Test Pit 9 |
| Depth, m | 1.5m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 5.41 | 6.880 | 6.710 | 6.430 | 6.160 | 5.570 | 4.980 | 4.260 |
| 0.15 | - | 7.010 | 6.700 | 6.410 | 6.150 | 5.540 | 4.960 | 4.220 |
| 0.30 | - | 6.980 | 6.680 | 6.400 | 6.130 | 5.510 | 4.910 | 4.200 |
| 1 | - | 6.970 | 6.670 | 6.380 | 6.110 | 5.480 | 4.860 | 4.150 |
| 2 | - | 6.950 | 6.650 | 6.360 | 6.070 | 5.460 | 4.820 | 4.080 |
| 4 | - | 6.920 | 6.650 | 6.330 | 6.020 | 5.420 | 4.770 | 4.020 |
| 8 | - | 6.900 | 6.620 | 6.310 | 5.970 | 5.360 | 4.730 | 3.950 |
| 15 | - | 6.870 | 6.600 | 6.280 | 5.930 | 5.310 | 4.660 | 3.820 |
| 30 | - | 6.850 | 6.570 | 6.250 | 5.880 | 5.260 | 4.600 | 3.740 |
| 60 | - | 6.830 | 6.530 | 6.270 | 5.820 | 5.210 | 4.530 | 3.680 |
| 120 | - | 6.800 | 6.490 | 6.240 | 5.760 | 5.170 | 4.440 | 3.610 |
| 240 | - | 6.780 | 6.480 | 6.200 | 5.700 | 5.110 | 4.380 | 3.520 |
| 480 | - | 6.750 | 6.450 | 6.180 | 5.630 | 5.040 | 4.310 | 3.470 |
| 1440 | 6.88 | 6.710 | 6.430 | 6.160 | 5.570 | 4.980 | 4.260 | 3.330 |

Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

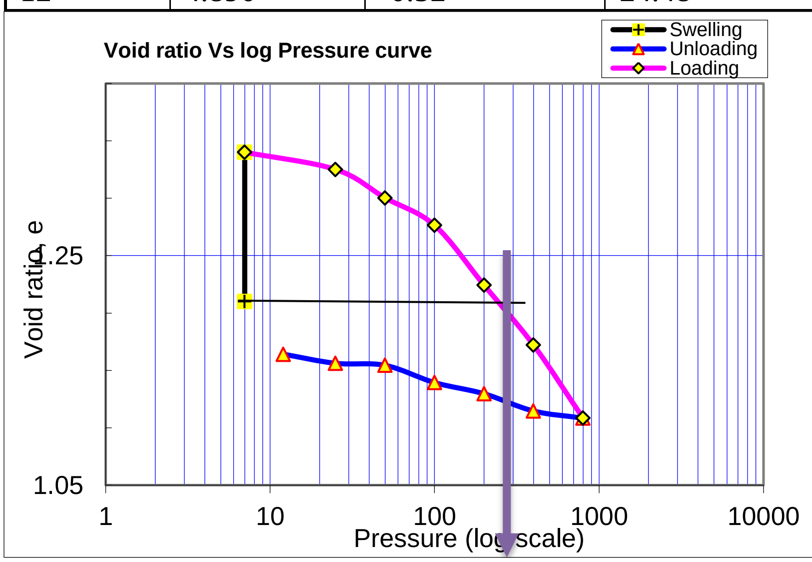
| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 4.260 | 4.330 | 4.500 | 4.610 | 4.780 | 4.800 | 4.890 |

| [A] In the beginning of the test | |
|---|---|
| Sample type : | Un disturbed |
| Ring Area,$cm^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load,(KPa) | 7 |
| Initial Void Ratio, $e_o$: | 1.34 |
| Initial moisture content,% | 39.35 |
| Specific Gravity: | 2.702 |
| Wet density,g/cm3 | 1.72 |
| [B] In the end of the test | |
| Final Moisture Content,% | 40.89 |

| | |
|---|---|
| Dry specimen wt ($m_s$), gm: | 97.1 |
| Dry density,g/cm3 | 1.28 |
| Height of Solids($H_s$), mm | 11.31 |
| Final Void Ratio, $e_f$: | 1.16 |

[C]Calculation table:

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 5.410 | 0.00 | 25.00 | 13.69 | 1.21 |
| 7 | 6.880 | 1.47 | 26.47 | 15.16 | 1.34 |
| 25 | 6.710 | 1.30 | 26.30 | 14.99 | 1.33 |
| 50 | 6.430 | 1.02 | 26.02 | 14.71 | 1.30 |
| 100 | 6.160 | 0.75 | 25.75 | 14.44 | 1.28 |
| 200 | 5.570 | 0.16 | 25.16 | 13.85 | 1.22 |
| 400 | 4.980 | -0.43 | 24.57 | 13.26 | 1.17 |
| 800 | 4.260 | -1.15 | 23.85 | 12.54 | 1.11 |
| Unloading | | | | | |
| 800 | 4.260 | -1.15 | 23.85 | 12.54 | 1.11 |
| 400 | 4.330 | -1.08 | 23.92 | 12.61 | 1.11 |
| 200 | 4.500 | -0.91 | 24.09 | 12.78 | 1.13 |
| 100 | 4.610 | -0.80 | 24.20 | 12.89 | 1.14 |
| 50 | 4.780 | -0.63 | 24.37 | 13.06 | 1.15 |
| 25 | 4.800 | -0.61 | 24.39 | 13.08 | 1.16 |
| 12 | 4.890 | -0.52 | 24.48 | 13.17 | 1.16 |



| |
|---|
| 1D Consolidation Test ASTM-D-2435 & D-4546 |
| Project: Thesis |
| Location Test Pit 11 |
| Depth, m 1.5m |

| | Dial Guage Reading, mm | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Time(min.) | 7 [kPa] | 12 [kPa] | 25 [kPa] | 50 [kPa] | 100 [kPa] | 200 [kPa] | 400 [kPa] | 800 [kPa] |
| 0 | 3.90 | 4.510 | 4.350 | 4.020 | 3.740 | 3.220 | 2.610 | 1.870 |
| 0.15 | - | 4.680 | 4.340 | 4.010 | 3.720 | 3.200 | 2.580 | 1.850 |
| 0.30 | - | 4.660 | 4.320 | 4.000 | 3.700 | 3.170 | 2.520 | 1.830 |
| 1 | - | 4.640 | 4.310 | 3.980 | 3.670 | 3.140 | 2.470 | 1.800 |
| 2 | - | 4.610 | 4.280 | 3.960 | 3.650 | 3.100 | 2.410 | 1.730 |
| 4 | - | 4.580 | 4.260 | 3.950 | 3.610 | 3.060 | 2.360 | 1.690 |
| 8 | - | 4.540 | 4.240 | 3.930 | 3.570 | 3.020 | 2.310 | 1.600 |
| 15 | - | 4.510 | 4.210 | 3.910 | 3.510 | 2.950 | 2.250 | 1.540 |
| 30 | - | 4.480 | 4.190 | 3.880 | 3.460 | 2.900 | 2.190 | 1.490 |
| 60 | - | 4.460 | 4.160 | 3.850 | 3.400 | 2.840 | 2.130 | 1.420 |
| 120 | - | 4.430 | 4.120 | 3.820 | 3.340 | 2.780 | 2.080 | 1.360 |
| 240 | - | 4.400 | 4.070 | 3.790 | 3.300 | 2.720 | 2.020 | 1.300 |
| 480 | - | 4.380 | 4.050 | 3.760 | 3.260 | 2.680 | 1.950 | 1.230 |
| 1440 | 4.51 | 4.350 | 4.020 | 3.740 | 3.220 | 2.610 | 1.870 | 1.150 |

Cumulative Dial Guage Reading At The End Of Each Consecutive Unloading

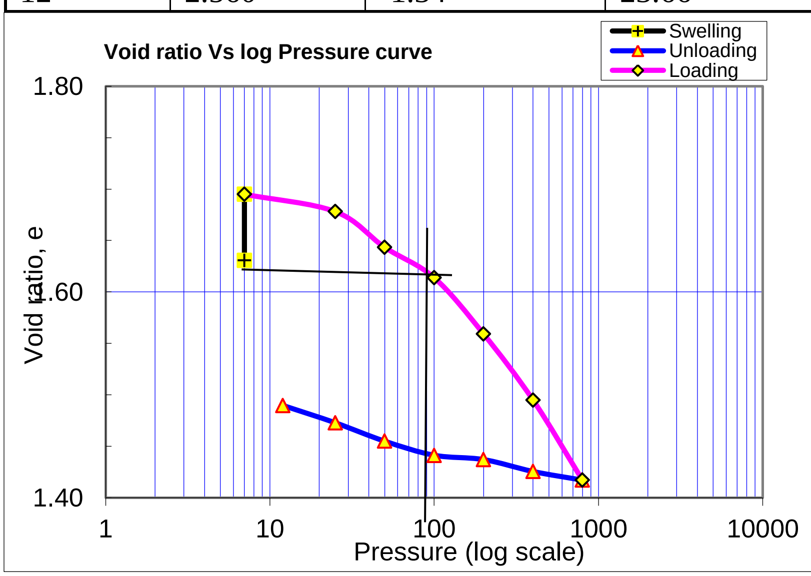
| Dial Guage Reading, mm | | | | | | |
|---|---|---|---|---|---|---|
| 800 [kPa] | 400 [kPa] | 200 [kPa] | 100 [kPa] | 50 [kPa] | 25 [kPa] | 12 [kPa] |
| 1.870 | 1.950 | 2.060 | 2.100 | 2.230 | 2.400 | 2.560 |

| | |
|---|---|
| [A] In the beginning of the test | |
| Sample type : | Un disturbed |
| Ring Area,$cm^2$: | 31.77 |
| Height of sample, mm: | 25 |
| Seating Load, kPa | 7 |
| Initial Void Ratio, $e_o$: | 1.69 |
| Initial moisture content,% | 44.21 |
| Specific Gravity: | 2.567 |
| Wet density,g/cm3 | 1.34 |
| [B] In the end of the test | |
| Final Moisture Content,% | 37.81 |

| Dry specimen wt ($m_s$), gm: | 77.5 |
|---|---|
| Dry density,g/cm3 | 1.06 |
| Height of Solids($H_s$), mm | 9.50 |
| Final Void Ratio, $e_f$: | 1.49 |

[C]Calculation table:

| Applied pressure P (kPa) | Final Dial Reading (mm) | Change In Specimen Height (mm) | Final Specimen Height (mm) | Void Height,$H_v$ (mm) | Void Ratio, E |
|---|---|---|---|---|---|
| Loading | | | | | |
| 7 | 3.900 | 0.00 | 25.00 | 15.50 | 1.63 |
| 7 | 4.510 | 0.61 | 25.61 | 16.11 | 1.69 |
| 25 | 4.350 | 0.45 | 25.45 | 15.95 | 1.68 |
| 50 | 4.020 | 0.12 | 25.12 | 15.62 | 1.64 |
| 100 | 3.740 | -0.16 | 24.84 | 15.34 | 1.61 |
| 200 | 3.220 | -0.68 | 24.32 | 14.82 | 1.56 |
| 400 | 2.610 | -1.29 | 23.71 | 14.21 | 1.50 |
| 800 | 1.870 | -2.03 | 22.97 | 13.47 | 1.42 |
| Unloading | | | | | |
| 800 | 1.870 | -2.03 | 22.97 | 13.47 | 1.42 |
| 400 | 1.950 | -1.95 | 23.05 | 13.55 | 1.43 |
| 200 | 2.060 | -1.84 | 23.16 | 13.66 | 1.44 |
| 100 | 2.100 | -1.80 | 23.20 | 13.70 | 1.44 |
| 50 | 2.230 | -1.67 | 23.33 | 13.83 | 1.46 |
| 25 | 2.400 | -1.50 | 23.50 | 14.00 | 1.47 |
| 12 | 2.560 | -1.34 | 23.66 | 14.16 | 1.49 |



# APPENDIX B

## MULTIPLE LINEAR REGRESSION

SPSS 20 Linear Regression Outputs

Multiple Linear Regression Analysis for **Eqn-1**

**Variables Entered/Removed[a]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | DD, PL, PI, Ls, W, LI, LL[b] | . | Enter |

a. Dependent Variable: Ps

b. All requested variables entered.

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .982[a] | .965 | .942 | 21.0132 |

a. Predictors: (Constant), DD, PL, PI, Ls, W, LI, LL

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 132585.010 | 7 | 18940.716 | 42.896 | .000[b] |
| | Residual | 4857.095 | 11 | 441.554 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps

b. Predictors: (Constant), DD, PL, PI, Ls, W, LI, LL

**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 590.437 | 412.662 | | 1.431 | .180 |
| | LL | 4.812 | 23.377 | .276 | .206 | .841 |
| | PL | 44.375 | 26.580 | 1.400 | 1.669 | .123 |
| | PI | -.206 | 23.006 | -.008 | -.009 | .993 |
| | LI | 3046.765 | 1347.783 | 2.232 | 2.261 | .045 |
| | Ls | 1.264 | 3.412 | .039 | .370 | .718 |
| | W | -76.878 | 24.510 | -1.555 | -3.137 | .009 |
| | DD | 358.950 | 117.905 | .444 | 3.044 | .011 |

a. Dependent Variable: Ps

Multiple Linear Regression Analysis for **Eqn-2**

**Variables Entered/Removed**[a]

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | W, PL, PI, Ls, LI, LL[b] | . | Enter |

a. Dependent Variable: Ps

b. All requested variables entered.

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .967[a] | .935 | .902 | 27.3093 |

a. Predictors: (Constant), W, PL, PI, Ls, LI, LL

**ANOVA**[a]

| Model | | Sum of Squares | Df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 128492.501 | 6 | 21415.417 | 28.715 | .000[b] |
| | Residual | 8949.604 | 12 | 745.800 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps

b. Predictors: (Constant), W, PL, PI, Ls, LI, LL

**Coefficients**[a]

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 1460.706 | 386.790 | | 3.776 | .003 |
| | LL | 6.266 | 30.375 | .360 | .206 | .840 |
| | PL | 52.446 | 34.372 | 1.654 | 1.526 | .153 |
| | PI | .760 | 29.897 | .030 | .025 | .980 |
| | LI | 3576.057 | 1736.983 | 2.620 | 2.059 | .062 |
| | Ls | 2.966 | 4.375 | .091 | .678 | .511 |
| | W | -101.189 | 30.116 | -2.047 | -3.360 | .006 |

a. Dependent Variable: Ps

Multiple Linear Regression Analysis for **Eqn-10**

**Variables Entered/Removed[a]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | DD, PL, PI, Ls, LI, LL[b] | . | Enter |

a. Dependent Variable: Ps
b. All requested variables entered.

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .966[a] | .933 | .900 | 27.6905 |

a. Predictors: (Constant), DD, PL, PI, Ls, LI, LL

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 128240.964 | 6 | 21373.494 | 27.875 | .000[b] |
| | Residual | 9201.141 | 12 | 766.762 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps
b. Predictors: (Constant), DD, PL, PI, Ls, LI, LL

**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 409.668 | 538.463 | | .761 | .461 |
| | LL | -17.712 | 29.316 | -1.016 | -.604 | .557 |
| | PL | .307 | 29.733 | .010 | .010 | .992 |
| | PI | 15.783 | 29.563 | .628 | .534 | .603 |
| | LI | -1007.852 | 502.602 | -.738 | -2.005 | .068 |
| | Ls | 2.871 | 4.445 | .088 | .646 | .531 |
| | DD | 479.434 | 146.894 | .593 | 3.264 | .007 |

a. Dependent Variable: Ps

Multiple Linear Regression Analysis for **Eqn-11**

**Variables Entered/Removed[a]**

| Model | Variables Entered | Variables Removed | Method |
|---|---|---|---|
| 1 | W, PI, DD[b] | . | Enter |

a. Dependent Variable: Ps
b. All requested variables entered.

**Model Summary**

| Model | R | R Square | Adjusted R Square | Std. Error of the Estimate |
|---|---|---|---|---|
| 1 | .973[a] | .947 | .936 | 22.1099 |

a. Predictors: (Constant), W, PI, DD

**ANOVA[a]**

| Model | | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|---|
| 1 | Regression | 130109.392 | 3 | 43369.797 | 88.718 | .000[b] |
| | Residual | 7332.714 | 15 | 488.848 | | |
| | Total | 137442.105 | 18 | | | |

a. Dependent Variable: Ps
b. Predictors: (Constant), W, PI, DD

**Coefficients[a]**

| Model | | Unstandardized Coefficients | | Standardized Coefficients | t | Sig. |
|---|---|---|---|---|---|---|
| | | B | Std. Error | Beta | | |
| 1 | (Constant) | 762.301 | 420.825 | | 1.811 | .090 |
| | PI | -.466 | 1.988 | -.019 | -.234 | .818 |
| | DD | 409.074 | 116.988 | .506 | 3.497 | .003 |
| | W | -24.907 | 6.853 | -.504 | -3.634 | .002 |

a. Dependent Variable: Ps