



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF GRAGUATE STUDIES

DEPARTMENT OF CIVIL AND ENVIROMENTAL ENGINEERING

**CORRRLATION BETWEEN INDEX PROPERTIES AND SWELLING PRESSURE OF
EXPANSIVE SOILS FOUND AROUND KOYE AREA**

A Thesis submitted to:

The School of Graduate Studies, Addis Ababa institute of Technology,

In partial fulfillment of the requirements for the degree of

Master of Science in Civil Engineering under Geotechnical Engineering

By

Abdirshkur Kemal

Advisor

Henok Fikre (Dr-Ing)

November, 2015

Addis Ababa, Ethiopia



ADDIS ABABA UNIVERSITY

ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF GRAGUATE STUDIES

DEPARTMENT OF CIVIL AND ENVIROMENTAL ENGINEERING

**CORRRLATION BETWEEN INDEX PROPERTIES AND SWELLING PRESSURE OF
EXPANSIVE SOILS FOUND AROUND KOYE AREA**

By: - Abdirshkur Kemal

Approved by Board of Examiners

Dr.-Ing. Henok Fikre

Advisors

Signature

Date

Dr.-Ing. Samuel Tadesse

External Examiner

Signature

Date

Prof. Alemayehu Teferra

Internal Examiner

Signature

Date

Dr. Esayas G/Youhannes

Chairman

Signature

Date

ACKNOWLEDGEMENT

First of all, I would like to express my deepest gratitude to my advisor Dr.-Ing Henok Fikre for guiding and supervising my research work. He has been devoting his precious time and provides all the necessary materials and information to carry out the research.

Also I would like to extend my sincere thanks and appreciation especially to Prof. Alemayehu Teferra and Dr. Samuel Tadese for sharing their helpful opinion in improving this thesis test result during progressive report. Special thanks to all Addis Ababa institute of Technology Geotechnical laboratory assistance and Addis Ababa Housing Construction Project Office in provide important information in completing this thesis.

I am grateful to my beloved family and Geotechnical Engineering regular 2006 friends who have always support me emotionally and financially in my studies. Last but not least, a thousand thanks to my beloved friends, Ing. Belay Zeleke and Ing. Ashenafi Yilkal without your help; I wouldn't have the chance to complete my study.

TABLE OF CONTENT

<u>Content</u>	<u>Page</u>
ACKNOWLEDGEMENT	ii
TABLE OF CONTENT	iii
LIST OF SYMBOLS AND ABBREVIATIONS	vii
LIST OF TABLES	viii
LIST OF FIGURES	xii
ABSTRACT	xiii
1 INTRODUCTION	1
1.1 General	1
1.2 Topography Characteristics.....	3
1.3 Climatic Characteristics	3
1.4 Geological formation of the area.....	3
1.5 Background of Research	4
1.6 Research Objectives	4
1.6.1 General objective:	4
1.6.2 Specific objectives:	4
1.7 Scope of the Research	4
1.8 The Importance of the Research.....	4
2 LITERATURE REVIEW	5
2.1 Expansive Soil.....	5
2.2 Identification of Expansive Soils	6
2.2.1 Field Identification.....	6
2.2.2 Experimental Identification	6
2.2.2.1 Direct Measurement.....	6
2.2.2.2 Mineralogical Methods.....	7
2.2.2.2 Indirect Measurement.....	7
2.3 Classification of Expansive Soils.....	7
2.3.1 General classification systems	7

2.3.2	Classification specific to expansive soil	9
2.3.2.1	Classification based on indirect predictions of swell potential.....	10
2.4	Swelling pressure	11
2.4.1	Oedometer Tests	11
2.4.1.1	Constant Volume Method.....	11
2.4.1.2	Swell-Consolidation Method.....	11
2.4.1.3	Different Pressure Method.....	12
2.4.1.4	Double-Oedometer Method.....	12
2.4.2	Mechanics of Swell.....	13
2.4.3	Factors Influencing Swelling and Shrinking of a Soil	14
2.5	Index Properties.....	14
2.5.1	Grain Size Analysis Test.....	14
2.5.2	Moisture Content Test.....	15
2.5.3	Atterberg and Shrinkage Limit Test	15
2.5.3.1	Liquid Limit.....	16
2.5.3.2	Plastic Limit.....	16
2.5.3.3	Plasticity Index.....	16
2.5.3.4	Shrinkage Limit.....	16
2.5.4	Activity of clay	17
2.5.5	Specific Gravity Test	17
2.5.6	Free Swell	17
2.6	Review of Previous Researches	17
3	SAMPLING AND TESTING METHODOLOGY	20
3.1	Selection of Sampling Sites.....	20
3.2	Collection of Soil Samples.....	20
3.2.1	Collection of Disturbed Samples	21
3.2.2	Collection of Undisturbed Samples	21
3.3	Preparation of Disturbed Soil Samples	22

3.3.1	Preparation of soil for liquid limit, plastic limit and free swell	23
3.3.2	Preparation of soil for specific gravity.....	23
3.3.3	Preparation of the soil for particle size distribution test using wet sieves	23
3.3.4	Preparation of the soil for the particle size distribution using the hydrometer	23
3.4	Laboratory Testing	23
3.5	Analysis Method Used	24
4	RESULTS AND DISCUSSIONS	25
4.1	Koye's soil properties.....	25
4.1.1	Index properties	25
4.1.1.1	Results for the Atterberg Limit Test.....	26
4.1.1.2	Results for the Liquidity Index Test.....	26
4.1.1.3	Results for the Specific Gravity Test.....	27
4.1.1.4	Results for the Grain Size Analysis Test.....	28
4.1.1.5	Results for the Free Swell Test.....	29
4.1.2	Results for the Swelling Pressure	30
4.2	Koye's soil Classification.....	30
4.2.1	USCS and AASHTO Classification.....	31
4.2.2	Other Classifications.....	33
5	SWELLING PRESSURE PREDICTION	35
5.1	Introduction	35
5.2	Comparison with previously developed models	35
5.3	Formulation of New Empirical Equations	37
5.3.1	Scatter Plot and Best-Fit Curve.....	37
5.3.1.1	Swelling Pressure Vs Plasticity Index.....	37
5.3.1.2	Swelling Pressure Vs Natural Moisture Content.....	38
5.3.1.3	Swelling Pressure Vs Dry density.....	38
5.3.1.4	Swelling Pressure Vs Liquid Limit.....	39
5.3.1.5	Swelling Pressure Vs Plastic Limit.....	40

5.3.2	Multiple regression analysis	40
5.3.3	Graphical representation of measured and calculated values	44
6	CONCLUSION AND RECOMMENDATION	46
6.1	Conclusion.....	46
6.2	Recommendation.....	47
	REFERENCES	48
	Appendix A.....	50
	Representative Laboratory Test Results	50
	Appendix B.....	86
	SPSS 20 Regression Analysis Output.....	86
	Graphical representation of measured and calculated swelling pressure.....	102
	DECLARATION	105

LIST OF SYMBOLS AND ABBREVIATIONS

A= Activity

AASHTO= American Association of State Highway and Transportation Officials

USCS = Unified Soil Classification System

ASTM= American Society of Testing and Materials

FS= Free Swell

LL= Liquid Limit

LI = Liquidity Index

PL= Plastic Limit

ω = Natural Moisture Content

PI= Plasticity Index

G_s = Specific Gravity of Solids

CH= Inorganic clays of high plasticity

OH= Organic clays of high plasticity

CL = Inorganic clays of low to medium plasticity

MH = Inorganic silts of high plasticity

OL = Organic silts of low plasticity

ρ_{dry} = dry density

P_s = Swelling Pressure

Eqn. = Equation

SPSS = Statistical Package for Social Science

N = Number of sample

R= Correlation Coefficient

TP= Test Pit

LIST OF TABLES

	<u>Page</u>
Table 4.1: Description of test pits location	25
Table 4.2: Atterberg Limit Test Result of the Study Area.....	26
Table 4.3: Liquidity Index Test Result of the Study Area.....	27
Table 4.4: Specific Gravity of the Soil of the Study Area.....	28
Table 4.5: Grain Size Distribution of the Study Area.....	29
Table 4.6: Free swell of the Study Area	29
Table 4.7: Laboratory test results on undisturbed soil samples of the Study Area.....	30
Table 4.8: USCS Classification of the Study Area.....	31
Table 4.9: AASHTO Classification of the Study Area.....	32
Table 4.10: Activity test result of the Study Area	33
Table 4.11: Plasticity Index test result of the Study Area.....	34
Table 5.1: Comparasion of measured P_s with calculated using previously developed equation ..	36
Table 5.2: Input data for SPSS 20 computer program.....	41
Table 5.3: Input data for the control sample.....	41
Table 5.4: Newly developed possible empirical equations.....	42
Table 5.5: Calculated swelling pressure values using newly developed equations.....	43
Table 5.6: Calculated swelling pressure values using newly developed equations for control samples.....	43
Table 5.7: Checking accuracy of the newly developed formulas for Control Samples.....	43
Table A.1: Determination of moisture content for test pit TP_1	50
Table A.2: Determination of moisture content for test pit TP_2	50
Table A.3: Determination of moisture content for test pit TP_3	51
Table A.4: Determination of moisture content for test pit TP_6	51
Table A.5: Determination of moisture content for test pit TP_9	51
Table A.6: Determination of moisture content for test pit TP_11	52
Table A.7: Temperature Correction Factors for G_s	53
Table A.8: Determination of specific gravity for test pit TP_1	53
Table A.9: Determination of specific gravity for test pit TP_2	54
Table A.10: Determination of specific gravity for test pit TP_3	54
Table A.11: Determination of specific gravity for test pit TP_6	54
Table A.12: Determination of specific gravity for test pit TP_9	55
Table A.13: Determination of specific gravity for test pit TP_11	55
Table A.14: Liquid limit and plastic limit for test pit TP_1	56
Table A.15: Liquid limit and plastic limit for test pit TP_2	56
Table A.16: Liquid limit and plastic limit for test pit TP_3	57
Table A.17: Liquid limit and plastic limit for test pit TP_6 at 1.5m depth	58

Table A.18: Liquid limit and plastic limit for test pit TP_6 at 3m depth	58
Table A.19: Liquid limit and plastic limit for test pit TP_9 at 1.5m depth	59
Table A.20: Liquid limit and plastic limit for test pit TP_9 at 3m depth	60
Table A.21: Liquid limit and plastic limit for test pit TP_11 at 1.5m depth	60
Table A.22: Liquid limit and plastic limit for test pit TP_11 at 3m depth	61
Table A.23: Free Swell test result for test pit TP_1.....	62
Table A.24: Free Swell test result for test pit TP_2.....	62
Table A.25: Free Swell test result for test pit TP_3.....	62
Table A.26: Free Swell test result for test pit TP_6.....	63
Table A.27: Free Swell test result for test pit TP_9.....	63
Table A.28: Free Swell test result for test pit TP_11.....	63
Table A.29: Composite correction for Hydrometer readings for 151H, Hydrometer	65
Table A.30: Values of k for Use in Equation for Computing Diameter of Particle in Hydrometer Analysis.....	65
Table A.31: Sieve analysis for test pit TP_1.....	66
Table A.32: Hydrometer analysis for test pit TP_1	66
Table A.33: Sieve analysis for test pit TP_2.....	67
Table A.34: Hydrometer analysis for test pit TP_2	67
Table A.35: Sieve analysis for test pit TP_3.....	68
Table A.36: Hydrometer analysis for test pit TP_3	68
Table A.37: Sieve analysis for test pit TP_6 @ 1.5m depth.....	69
Table A.38: Hydrometer analysis for test pit TP_6 @ 1.5m depth	69
Table A.39: Sieve analysis for test pit TP_6 @ 3m depth.....	70
Table A.40: Hydrometer analysis for test pit TP_6 @ 3m depth	70
Table A.41: Sieve analysis for test pit TP_9 @ 1.5m depth.....	71
Table A.42: Hydrometer analysis for test pit TP_9 @ 1.5m depth	71
Table A.43: Sieve analysis for test pit TP_9 @ 3m depth.....	72
Table A.44: Hydrometer analysis for test pit TP_9 @ 3m depth	72
Table A.45: Sieve analysis for test pit TP_11 @ 1.5m depth.....	73
Table A.46: Hydrometer analysis for test pit TP_11 @ 1.5m depth	73
Table A.47: Sieve analysis for test pit TP_11 @ 3m depth.....	74
Table A.48: Hydrometer analysis for test pit TP_11 @ 3m depth	74
Table A.49: Bulk and dry density analysis for test pit TP_1,TP_2,TP_3,TP_6 , TP_9 and TP_11	75
Table A.50: Consolidation dial reading for test pit TP_1	76
Table A.51: Swelling pressure analysis for test pit TP_1	77
Table A.52: Consolidation dial reading for test pit TP_2.....	77
Table A.53: Swelling pressure analysis for test pit TP_2.....	78
Table A.54: Consolidation dial reading for test pit TP_3.....	78

Table A.55: Swelling pressure analysis for test pit TP_3.....	79
Table A.56: Consolidation dial reading for test pit TP_6 at depth of 1.5m.....	79
Table A.57: Swelling pressure analysis for test pit TP_6 at depth of 1.5m.....	80
Table A.58: Consolidation dial reading for test pit TP_6 at depth of 3m.....	80
Table A.59: Swelling pressure analysis for test pit TP_6 at depth of 3m.....	81
Table A.60: Consolidation dial reading for test pit TP_9 at depth of 1.5m.....	81
Table A.61: Swelling pressure analysis for test pit TP_9 at depth of 1.5m.....	82
Table A.62: Consolidation dial reading for test pit TP_9 at depth of 3m.....	82
Table A.63: Swelling pressure analysis for test pit TP_9 at depth of 3m.....	83
Table A.64: Consolidation dial reading for test pit TP_11 at depth of 1.5m.....	83
Table A.65: Swelling pressure analysis for test pit TP_11 at depth of 1.5m.....	84
Table A.66: Consolidation dial reading for test pit TP_11 at depth of 3m.....	84
Table A.67: Swelling pressure analysis for test pit TP_11 at depth of 3m.....	85
Table B.1 Regression analysis output for Equation 1.....	86
Table B.2 Regression analysis output for Equation 2.....	87
Table B.3 Regression analysis output for Equation 3.....	88
Table B.4 Regression analysis output for Equation 4.....	89
Table B.5 Regression analysis output for Equation 5.....	90
Table B.6 Regression analysis output for Equation 6.....	91
Table B.7 Regression analysis output for Equation 7.....	92
Table B.8 Regression analysis output for Equation 8.....	93
Table B.9 Regression analysis output for Equation 9.....	94
Table B.10 Regression analysis output for Equation 10.....	95
Table B.11 Regression analysis output for Equation 11.....	96
Table B.12 Regression analysis output for Equation 12.....	97
Table B.13 Regression analysis output for Equation 13.....	97
Table B.14 Regression analysis output for Equation 14.....	97
Table B.15 Regression analysis output for Equation 15.....	100

LIST OF FIGURES

	<u>Page</u>
Figure 1.1: Distribution of Expansive soils in Africa.....	1
Figure 1.2: Location of Koye on the map of Ethiopia.....	2
Figure 2.1:- Plasticity Chart.....	8
Figure 2.2:- Liquid limit Vs plasticity index chart for AASHTO soil classification method.....	9
Figure 2.3 Determination of swelling pressure by swelling consolidation method.....	12
Figure 3.1: visual investigation of crack.....	20
Figure 3.2: Location of Koye-Feche condominium in Addis Ababa city map.....	21
Figure 3.3: Location of test pits.....	22
Figure 4.1: Combined sieve-hydrometer analysis graph of the study area.....	28
Figure 4.2: Plasticity chart of the soil of the study area, according to Unified Soil Classification System (UCSC).....	31
Figure 4.3: Classification of the Soil of the Study Area According To AASHTO System.....	32
Figure 4.4: Activity chart of the Study Area.....	33
Figure 5.1: Swelling pressure Vs plasticity index of the study area.....	37
Figure 5.2: Swelling pressure Vs natural moisture content of the study area.....	38
Figure 5.3: Swelling Pressure Vs Dry Density of the Study Area.....	39
Figure 5.4: Swelling Pressure Vs Liquid Limit of the Study Area.....	39
Figure 5.5: Swelling Pressure Vs Plastic Limit of the Study Area.....	40
Figure 5.6: Comparisons of measured and calculated swelling pressure for equation 1 & 2.....	44
Figure 5.7: Comparisons of measured and calculated swelling pressure for equation 6 & 12.....	44
Figure A.1: Water content Vs log number of blows for test pit TP_1.....	56
Figure A.2: Water content Vs log number of blows for test pit TP_2.....	57
Figure A.3: Water content Vs log number of blows for test pit TP_3.....	57
Figure A.4: Water content Vs log number of blows for test pit TP_6 at 1.5m depth.....	58
Figure A.5: Water content Vs log number of blows for test pit TP_6 at 3m depth.....	59
Figure A.6: Water content Vs log number of blows for test pit TP_9 at 1.5m depth.....	59
Figure A.7: Water content Vs log number of blows for test pit TP_9 at 3m depth.....	60
Figure A.8: Water content Vs log number of blows for test pit TP_11 at 1.5m depth.....	61
Figure A.9: Water content Vs log number of blows for test pit TP_11 at 3m depth.....	61
Figure A.10: Determination of swelling pressure from e-logp curve for test pit TP_1.....	77
Figure A.11: Determination of swelling pressure from e-logp curve for test pit TP_2.....	78
Figure A.12: Determination of swelling pressure from e-logp curve for test pit TP_3.....	79
Figure A.13: Determination of swelling pressure from e-logp curve for test pit TP_6 at depth of 1.5m.....	80
Figure A.14: Determination of swelling pressure from e-logp curve for test pit TP_6 at depth of 3m.....	81

Figure A.15: Determination of swelling pressure from e-logp curve for test pit TP_9 at depth of 1.5m.....	82
Figure A.16: Determination of swelling pressure from e-logp curve for test pit TP_9 at depth of 3m.....	83
Figure A.17: Determination of swelling pressure from e-logp curve for test pit TP_11 at depth of 1.5m.....	84
Figure A.18: Determination of swelling pressure from e-logp curve for test pit TP_11 at depth of 3m	85
Figure B.1: Comparisons of measured and calculated swelling pressure for equation 3 & 4	102
Figure B.2: Comparisons of measured and calculated swelling pressure for equation 5 & 7	102
Figure B.3: Comparisons of measured and calculated swelling pressure for equation 8 & 9	103
Figure B.4: Comparisons of measured and calculated swelling pressure for equation 10 & 11	103
Figure B.5: Comparisons of measured and calculated swelling pressure for equation 13 & 14	104
Figure B.6: Comparisons of measured and calculated swelling pressure for equation 15	104

ABSTRACT

Among the clay soils in the world, expansive soils have a special mineralogical characteristic which leads to swelling when exposed to moisture change. This behavior is due to the presence of considerable amount of montmorillonite clay mineral.

As a result of swelling, pressure is exerted by the soil on the structures built on it and causes an increase in volume of the soil mass which also lifts the structure. Civil engineering structure constructed on such soils experience damage due to uneven movement caused by swelling and shrinkage process of the soil.

It is known that the magnitude of the swelling of expansive soils varies with environmental conditions. In this study, the correlation between index properties and swelling pressure (P_s) of expansive soil found around Koye area are examined. The data of samples were obtained from 19 samples out of 12 test pits in Koye area.

By taking those 19 disturbed and undisturbed samples from 12 test pits; both index properties and Swell-consolidation test were conducted according to ASTM standard. Then identification, classification and correlation between index properties and swelling pressure of the soil for the study area has been developed.

The test results showed that the Specific Gravity ranges from 2.67 to 2.84. The index property test showed that plasticity index ranges from 56.23 to 70.26%, liquid limit ranges from 90.37 to 113.31%, plastic limit ranges from 34.57 to 43.06%, and liquidity index range from -0.08 to 0.21. The clay content of the soil is from 56.59 to 72.48%. Free swell tests conducted on the collected samples showed a range from 95 to 217.5%. The undisturbed sample test results showed that the swelling pressure of the area ranges between 80 and 400 kPa, γ_{dry}/γ' ranges between 1.57 and 1.79 and moisture content range from 37.17 to 46.14%.

According to the Unified Soil Classification System, the soil is categorized as Fat clay with a potential of expansion. AASHTO Classification System also shows that the soil is Plastic Clay with high volume change capacity.

The new formulas are developed, by taking one or more of the five parameters (liquid limit, moisture content, plastic limit, dry density/effective, liquidity index and plastic index) in different combinations. The equations are developed by using SPSS 20 for windows software. Among the equations, equation 6 ($P_s = 965.22 + 38.53 * \gamma_{dry}/\gamma' - 26.99 * \omega + 8.68 * PL$) which describes the relation better than the others is proposed. Finally, conclusions and recommendations are made.

1 INTRODUCTION

1.1 General

Expansive soils are clay soils with high plasticity. These soils are known for their peculiar nature of expanding or shrinking when exposed to moisture change. In dry state, the soils exhibit a high bearing capacity which is gradually lost with increase in moisture content. If prevented from swelling following exposure to moisture, the soils exert high swelling pressure. The pressure build-up is usually responsible for cracking of buildings, distortion of pavement surfaces and damage to other structure [2].

Expansive soils are found in many arid and semiarid areas in worldwide such as Australia, Canada, China, India, and the United States [7]. In the Africa continent, expansive soils occur in many countries including South Africa, Ethiopia, Kenya, Mozambique, Ghana and Nigeria [2].

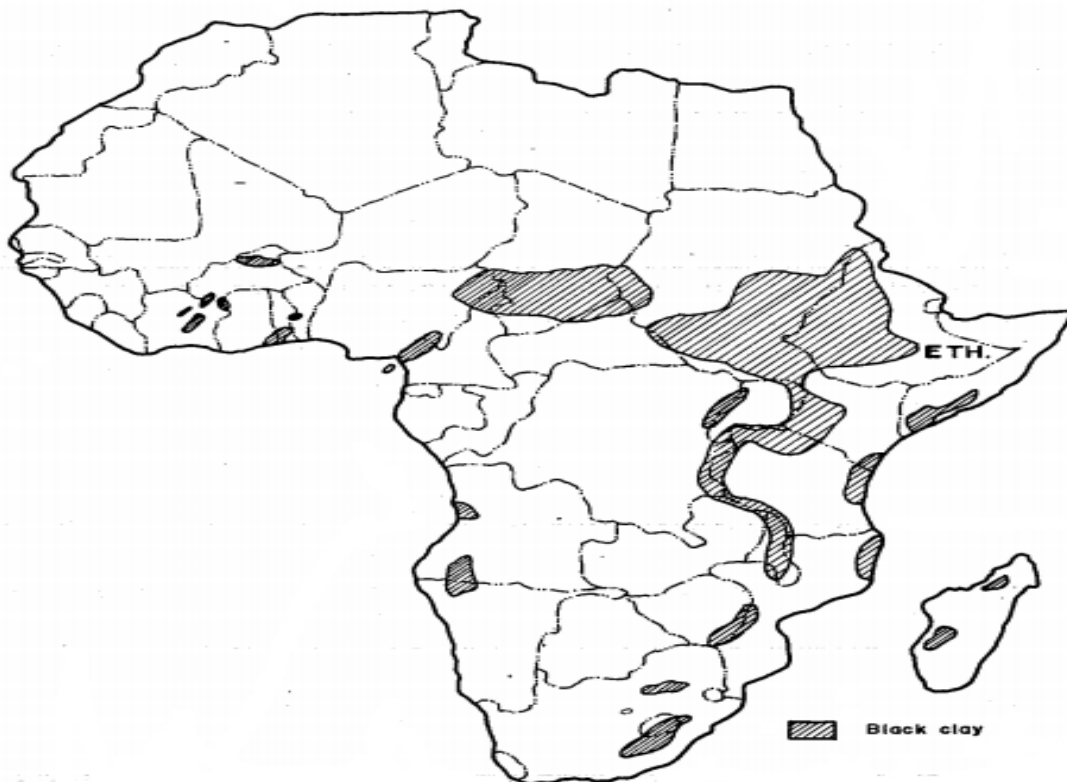


Figure 1.1: Distribution of Expansive soils in Africa [2]

Expansive soils are known to be widely spread in Ethiopia. Although the extent and range of distribution of this problematic soil has not been studied thoroughly: the southern, south-east and south –west part of the city Addis Ababa areas, where most of the recent construction are being

carried out and central part of Ethiopia following major truck roads like Addis-Ambo, Addis-Woliso, Addis-Debre Brhan, Addis-Gohatsion, Addis-modjo [5]. The main objective of this thesis is to develop the correlation between index properties and swelling pressure of expansive soils widely found around Koye areas.

Koye, which is located 27 kms from the center Addis Ababa (Paisa), is located around Akaki area about 7km of East of Tirunesh Beijing Hospital along the road under construction passing the Federal Prison (Kilinto branch), Addis Ababa Science and Technology university (AASTU) and the new Heineken Bear Brewery Factory. It is situated in the South eastern part of Addis Ababa, bounded from east and south by Oromiya region, from west by wereda 05, 08, and 01, and from north by Bole sub city and Oromiya region.

Today Koye has a development plan prepared by Addis Ababa city administration. In its master plan of Koye residential areas, government offices, roads, recreational areas and commercial areas are clearly indicated. In this area an extended construction of buildings and roads is going on. Among the construction are 10-90, 20-80 old, and 20-80 new and 40-60 condominium houses, Industry zone, Associations house and Addis-Adama express highway which extend from Tulu Dimtu to CMC exist. Addis Ababa housing project office constructed condominium houses in this area by sub dividing in to three projects namely Koye-Feche project 16, Koye-Feche project 17 and Koye-Feche project 18.



Figure 1.2: Location of Koye on the map of Ethiopia

1.2 Topography Characteristics

Koye is located at 8° 54' 0.00" N latitude and 38° 51' 0.00" E longitude and its altitude is averagely 2,271m (7,454ft) above sea level. However, most of the areas stretch over a predominantly flat land with imperceptible slope changes. There are also scattered and slightly depressed areas which form temporary swamps where rain water settles for short period of time.

1.3 Climatic Characteristics

The research area has maximum temperature of 28 °C and the minimum temperature of 4 °C. The weather is usually sunny and dry, but the Belg rains occur from February to April and the Meher rains occur from mid-June to mid-September. Generally the site is classified as wet climatic area [1].

1.4 Geological formation of the area

Addis Ababa is located in the western margin of the northern sector of the Cenozoic main Ethiopian Rift that extends for several kilometers from Chew Bahir in the south to the Afar. It's physiographic and lithostructural elements are related to rift forming tectonic-magmatic activity or geodynamic process continued to the present [10].

The geomorphology of Addis Ababa is generally characterized by valley plain surrounded by high standing volcanic mountains, namely Mt Entoto in the north, Mt Menagesha in the west, Mt Wechacha in the south west, Mt Furi in the south and Mt Yerer in the south east. The valley plain is not a monotonous flat surface and consists of undulating ridges and river valleys which can be marked as one travels from west to east across the city. The research area is located in southeast Addis Ababa close to Akaki River [10].

According to previous geological studies, the south eastern part of Addis Ababa is covered by volcanic rocks and superficial deposits consisting of the following three litho-stratigraphic units from top to bottom.

1. Alluvial and residual soils with varying proportion gravel, sand, silt and clay
2. Trachyte and associated pyroclastic (Yerer Volcanic)
3. Basalt and scoria fallout (Akaki Basic Volcanic)
4. Ignimbrites and variously welded tuffs (Addis Ababa Ignimbrites)

The top part of the sequence is due to fluvial deposition, alteration of the bedrock by combined processes of physical and chemical weathering. The other three units are related to Tertiary volcanic activity along structural fissures and volcanic centers at Furi and Yerer mountains. The units in some places show inter-fingering relationship and denote lateral variation in the disposition of lithological units, which is very common in the Addis Ababa area [10].

1.5 Background of Research

The odometer consolidation test is used to determine the swelling pressure of soil. It also provides some important compressibility indices such as compression index and the coefficient of volume compressibility to describe the consolidation of soil. However, odometer test is a complex, time consuming and expensive test as compared to other soil 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. The index properties tests are simple test as it needs only a short time to obtain the results.

Hence, the aim of this research is to establish the correlation between index properties and swelling pressure. The swelling pressure of soil can be identified based on the existing data to correlate these two types of parameters. By referring to the relation generated, the swelling pressure value can be predicted in response to the execution of the index properties test. Such correlation will bring a lot of conveniences to geotechnical engineers whenever they want to do quick and simple identification of the swelling pressure of soil.

1.6 Research Objectives

1.6.1 General objective:

- to investigate the relationship between the index properties and swelling Pressure of expansive soils found around Koye area.

1.6.2 Specific objectives:

- to study characteristics of expansive soils in the study area.
- to develop empirical equations which help in estimating the swelling pressure from index properties of soil for the study area.

1.7 Scope of the Research

This thesis has been intended to address the correlation between the index properties and swelling pressure of expansive soil found in the Koye area. The data used in the research was based on 17 undisturbed and disturbed samples from the site investigation.

1.8 The Importance of the Research

It is known that the magnitude of the swelling pressure of expansive soils varies with environmental conditions. Therefore, the empirical equations which could be developed can be easily used to calculate the swelling pressure of the study area. The results obtained from this research are necessary in preliminary foundation design of constructions in Koye.

2 LITERATURE REVIEW

2.1 Expansive Soil

Soil, a natural property of earth which is formed from small pieces of mineral particles and it may contain water, air and organic materials. It supports every construction which is designed by human such as buildings, retaining walls and embankments. There are many types of soil. The main soil groups are granular soil, fine-grained soil and organic soil.

The behaviour of soil is an important element which always concerned in civil engineering. The properties such as the plasticity, compressibility, or strength of soil always affect the design in construction. Geotechnical properties and behaviours of soil can be determined by several tests such as odometer test and Atterberg limits test.

Expansive soil, which is recognized by its considerable volume change upon exposure to moisture variation, has caused a number of problems in most structures constructed in Addis Ababa. Recent researches in assessing the failures caused on structures built on expansive soils showed that more than 60% of the structures are damaged due to causes associated with expansive soils [18]. The problems are either due to misunderstanding of the behaviour of the soil or lack of information on the engineering properties of the soil.

The six major natural hazards are earthquakes, landslides, expansive soils, hurricane, tornado and flood. A study points out that expansive soils tie with hurricane wind/storm surge for second place among America's most destructive natural hazards in terms of dollar losses to buildings. According to the study, it was projected that by the year 2000, losses due to expansive soil would exceed 4.5 billion dollars annually [7].

Expansive soils owe their expansive character mainly to the constituent clay mineral. The most important clay mineral, which is the cause for expansive nature is montmorillonite. Montmorillonite has an octahedral sheet sandwiched between two silica sheets. When this mineral is exposed to moisture, water is absorbed between interlayering lattice structures and exert an upward pressure. This upward pressure, known as swelling pressure, causes most of the damages associated with expansive soils.

Even though, expansive soils are found in different parts of the world, the engineering properties of the soil are not similar. The behaviour of expansive soils varies from place to place depending upon the type of parent material, climate and topography. Therefore, due to the fact that the engineering properties of expansive soil of Ethiopia are different from the same soil in other locality, researches on correlation between swelling pressure and index properties of expansive soils of Koye area has been done.

2.2 Identification of Expansive Soils

The key to all expansive soil classification system is the method of measuring swell potential, since soils are related by their measured swell potential. Swell potential may be measured directly in swell test or indirectly determined by correlation with other test results of swell test data. In almost every case swell potential is evaluated in laboratory in consolidation test device. This may yield swell potentials different from those for in-situ soils. Thus an accurate correlation between swell potential and other test results for a purpose of prediction of in-situ heave is difficult. These procedures, however, do provide good indicators of swell potential when the soil is subjected to the conditions used in the laboratory test.

2.2.1 Field Identification

Some of the important field identification methods that indicate the potential for expansiveness of soil are the following [7]:-

- A shiny surface is easily obtained when a partially dry piece of the soil is polished with a smooth object such as the top of a fingernail.
- The wet sample of the soil is sticky and it is relatively difficult to clean the soil from the hands.
- The appearance of cracking in nearby structure.
- They usually have a color of black and/ or grey.
- In the regions where there is seasonal moisture variation open closed fissures (a joint or similar discontinuity), slickenside (highly polished or glossy fissure surface) and shattering or micro-shattering, (presence of fissures forming granular fragments of clayey soils) may observed.

2.2.2 Experimental Identification

Generally, there are three different method of identifying expansive soil in the laboratory experiment [7]:-

2.2.2.1 Direct measurement

The most accurate and dependable method of determining the swelling potential and the swelling pressure of expansive clay is by direct measurement. As the name indicates, this type of test directly measures the pressure that a swelling soil exerts on any structure resting on it. It is a convenient and more reliable test because it directly tells the likely in-situ response of the soil for moisture variations.

The test can be done by the use of a conventional one-dimensional consolidometer which is available in most soil mechanics laboratories. The method quantitatively evaluates the volume change characteristics of Expansive soil.

2.2.2.2 Mineralogical Methods

The mineralogical composition of expansive soils has an important bearing on the swelling potential. There are a lot of factors contribute to the swelling potential of the clay like the negative electric charges on the surface of the clay mineral, the strength of the interlayer bonding, and the cation exchange capacity . Therefore, it is claimed by the clay mineralogists that the swelling potential of any clay can be evaluated by identifying of the constituent mineral through the following methods: X-ray Diffraction, Differential Thermal Analysis, Dye Adsorption, Chemical Analysis, and Electron Microscope Resolution. These different mineralogical identification methods are important in a research laboratory in exploring the basic properties of clays; however, they are impractical and uneconomical for practicing engineers.

2.2.2.3 Indirect Methods

This method is used to investigate the swelling potential of a soil by examining other parameters, which indirectly give information about the soil property. These 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) test.

2.3 Classification of Expansive Soils

The different classification systems are categorized into two:

- I. General classification systems:- which have evolved over many years and are based largely on correlation with actual performance
- II. Classification specific to expansive soils: - Theses systems are based on indirect and direct prediction of swell potential, as well as combinations, to arrive at a rating.

2.3.1 General classification systems

The most widely used general classification systems are [4]:-

I. Unified soil classification systems

The basis for USCS is liquid limit and plasticity index of a soil. The plasticity chart is a plot of PI and LL (in the ordinate and abscissa respectively) that describes the properties of clay and silt soils in terms of Atterberg limits. This chart consist of two lines namely A-line and U-line as shown below. The A-line is assumed to be a boundary between clay and silt soils. Which is

defined by an equation $PI = 0.73 \cdot (LL - 20)$. In these classification system a correlation is made between swell potential and unified soil classification as follows below [9] :-

Category	symbol	soil classification in unified system
Little or no expansion	1	GW, GP, GM, SW, SP, SM
Moderate expansion	2	GW, SC, ML, MH
High volume change	3	CL, OL, CH, OH
No rating		PT

The above classification system can be summarized as follow:

- All clay soil and organic soils exhibit high volume change.
- All clayey gravels and sands and all silts exhibit moderate volume changes.
- All sands and gravels exhibit little or no expansion.

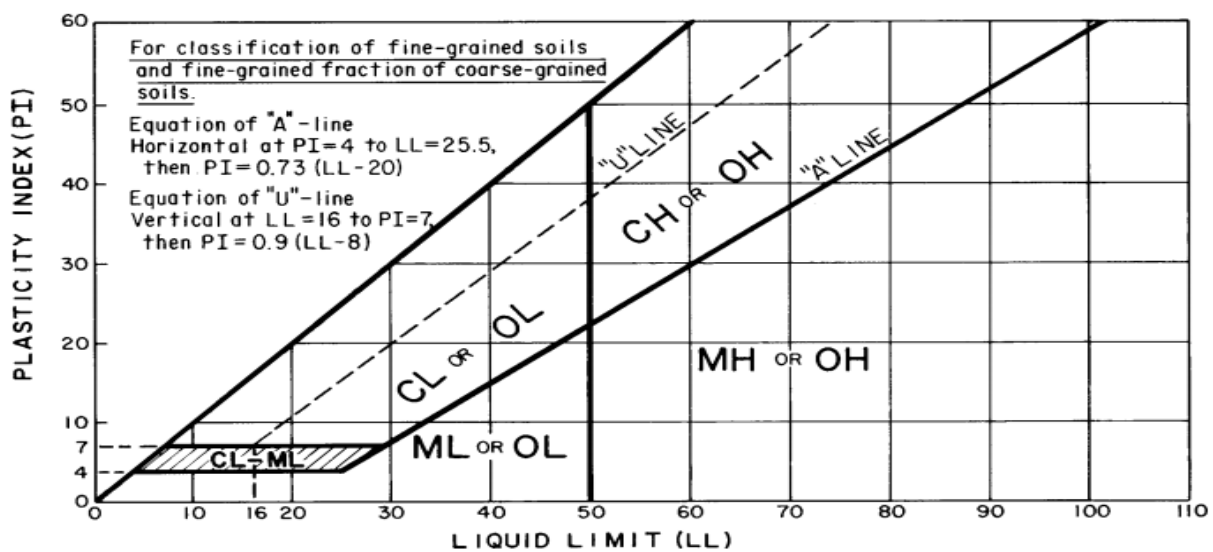


Figure 2.1:- Plasticity Chart

II. AASHTO classification

The AASHTO system uses similar techniques but the dividing line has an equation of the form $PI = LL - 30$. It generally classifies a soil broadly into granular material and silt-clay material.

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.

Group A-4:-The typical material of this group is a non-plastic or moderately plastic silty soil usually having 75 % or more passing a No. 200 sieve.

Group A-5:-The typical material of this group is similar to that described under Group A-4, except that it may be highly elastic as indicated by the high liquid limit.

Group A-6:-The typical material of this group is a plastic clay soil usually having 75 % or more passing a No. 200 sieve. Materials of this group usually have a high volume change between wet and dry states.

Group A-7:-The typical material of this group is similar to that described under Group A-6, except that it has the high liquid limits characteristic of Group A-5 and may be elastic as well as subject to high-volume change. Subgroup A-7-5 includes those materials with moderate plasticity indexes in relation to the liquid limit and which may be highly elastic as well as subject to considerable volume change. Subgroup A-7-6 includes those materials with high plasticity indexes in relation to liquid limit and which are subject to extremely high volume change [4].

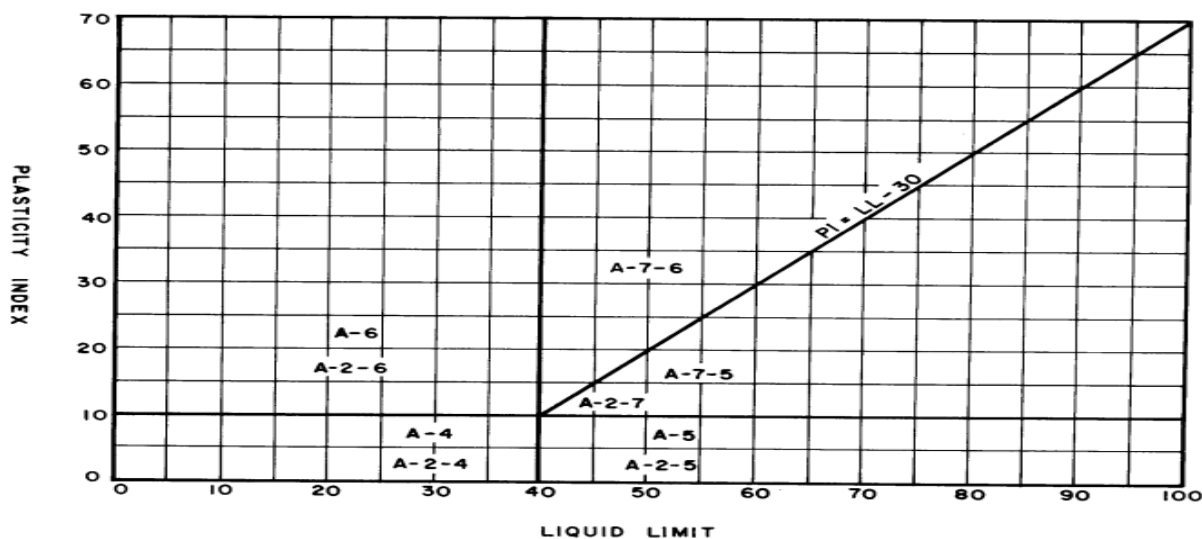


Figure 2.2:- Liquid limit Vs plasticity index chart for AASHTO soil classification method

2.3.2 Classification specific to expansive soil

The above classification system may give an initial alert that the soil may have expansive character and doesn't provide useful information. A parameter determined from the expansive soil identification tests have been combined in a number of different classification schemes to give qualitative rating on the expansiveness of the soil. But the direct use of such classification

systems as a basis for design may lead to an overly conservative construction in some places and inadequate construction in some areas. Hence, it is very important to emphasize that design decision has to be based on predicting testing and analysis, which provide reliable information [17].

2.3.2.1 Classification based on indirect predictions of swell potential

An indirect prediction of swell potential includes correlations based on index properties, swell, physical indicator and a combination of them. Some of such classification systems are:-

I. Skempton's method (Mckeen, 1976)

This method is developed, by combining Atterberg limits and clay content into a single parameter called Activity. Activity is defined as the ratio of the plastic index to percent of clay fraction finer than $2\mu\text{m}$. Skempton suggested three classes of clays according to their activity.

Activity	potential of expansion
$A_c < 0.75$	low (inactive)
$0.75 < A_c < 1.25$	medium (normal)
$A_c > 1.25$	high (active)

II. Seed, Woodward and Lundgreen

According to Seed, Woodward and Lundgreen [17], plasticity index is a parameter which can be used as a preliminary indicator of the swelling characteristics of a soil.

Seed, Woodward and Lundgreen suggested three classes of clays according to their plasticity index.

Plasticity index	Swell potential
0-10	low
10-35	medium
20-55	high
55 and above	very high

2.4 Swelling pressure

Swelling Pressure is the amount of pressure a soil exerts upon swelling or the pressure required recompressing the fully swollen sample back to its initial volume. 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. The available techniques for quantitative measurement swelling pressure of expansive soils can be categorized into three groups. Namely, oedometer tests, soil suction tests and empirical methodology [2].

2.4.1 Oedometer Tests

Among these techniques the oedometer tests are capable of simulating some of the factors which affect the swelling characteristics of expansive soils. It should be noted, however, that the oedometer tests have limitation. The oedometer tests consider moisture as well as volume change in one dimension only. In the in-situ, the above changes take place in three directions. For simplicity, however, the oedometer testing techniques have become popular and are extensively used. The different types of techniques under these methods are [2]:-

2.4.1.1 Constant Volume Method

The specimen in the constant volume method is allowed to absorb water without any increase in volume by increasing the applied pressure as the test proceeds until the sample reaches equilibrium. The more load is added to keep the volume of the sample constant while the sample absorbs water. The swelling pressure can be determined by plotting the applied pressure against change in volume. This method does not represent the in-situ condition where the applied load, after the structure is in service, does not change with time. When the swelling process occurs, a constant pressure acts rather than different pressure which increase with time to a counter act the swelling process. Information such as the amount of heave which could be expected under application of a certain load or load which could be applied to limit the heave within tolerable limit cannot be furnished by this method. The method needs uninterrupted monitoring for a long period.

2.4.1.2 Swell-Consolidation Method

In this method an undisturbed sample is allowed to absorb water under a load of 1psi (7kpa) and is put aside to fully expand and reach equilibrium. 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.

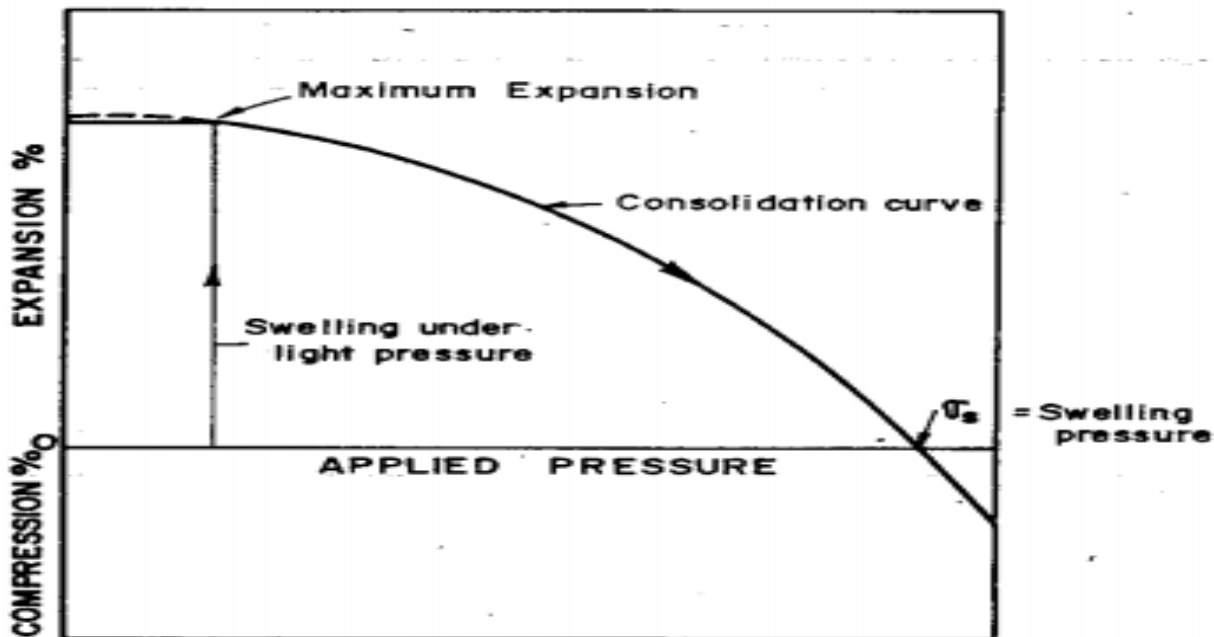


Figure 2.3 Determination of swelling pressure by swelling consolidation method

This method is quite popular and many investigators have used this method to establish a relationship between swell and applied pressure and to evaluate swelling pressure. The most serious drawback of this method is that it does not represent the normal sequence of load-submersion. In the field the soils is first subjected to the structural load and then swell later following exposure to moisture but not vice versa.

2.4.1.3 Different Pressure Method

In this method several identical samples (three or more) are loaded with different loads close to expected swelling pressure. The samples are set aside to consolidate in dry state. When equilibrium is reached, then they are subjected in water and the subsequent swell is recorded. The samples are again left until they reach equilibrium and the swelling practically ceases. The pressure corresponding to zero volume change is taken as the swelling pressure.

The different pressure method has the same sequence with regard to loading wetting events as in the field. That is, the loads are firstly applied to unsaturated soil and the soil under goes compression under these loads. Then, after a period of time, the soil comes in contact with the source of water and an upward movement starts.

2.4.1.4 Double-Odometer Method

This method was proposed by Jennings and Knight and has been used by many investigators to study the swell-pressure relationship of an expansive soil. This method is based on subjecting two identical samples to consolidation test. The first sample is consolidated at its natural moisture content while the second sample is first-allowed to absorb water and swell under light load followed by consolidation. For the two samples the applied pressures are plotted against vertical strain (or Void ratio) on the same diagram. The pressure corresponding to the intersection point of the two curves is taken as the swelling pressure.

This method usually gives a relatively high swelling pressure. This is due to the fact that 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.

2.4.2 Mechanics of Swell

Soil volume change is result from an imbalance in internal energy of the system (soil, water, air). Energy imbalances important in engineering result from moisture movement caused by loads, desiccation, and temperature changes. Response to a specific set of conditions is determined by the composition, structures, and geologic history of the soil. The largest component of volume change is that of the clay micelle which surrounds the individual clay particles in the soil. Water is forced out of the micelle by loads, desiccation, or temperature along energy gradient and reduction in volume results. When these influences are removed or reduced, the energy gradients are reversed, the available water is forced into the clay micelle and swell is produced [13].

The natural micro scale mechanisms, which contribute the major portion of volume changes in expansive soils, are [19]:-

- **Osmotic repulsion:** it is a pressure gradient developed in the double-layer water due to variations in the ionic concentration in the double layer.
- **Clay particle attraction:** as clay particles possess a net negative charge on their surfaces and edges which result in attractive forces for various cations and in particular for dipolar molecules such as water.
- **Cation hydration:** it is physical hydration of cations substituted into or attached to the clay particles.
- **Capillary imbibition:** it is a movement of water into a mass of clay particles resulting from surface tension effects of water and air mixtures in the pores of the clay mass.

2.4.3 Factors Influencing Swelling and Shrinking of a Soil

The factors influencing the shrink swell potential of a soil can be considered in three different groups [17].

- I. Soil characteristic that influence the basic nature of the internal force field. These includes:-
 - ✓ Clay mineralogy (Kaolinite, Montmorillonite and Elite)
 - ✓ Plasticity
 - ✓ Dry density
 - ✓ Soil suction
 - ✓ Soil water chemistry
 - ✓ Soil structures and fabrics
- II. The environment factor that influence the changes that may occur in the internal force system. These include.
 - ✓ Initial moisture condition
 - ✓ Moisture variation
 - ✓ Climate (Ground water ,Drainage and manmade water source, Vegetation ,Permeability, Temperature)
- III. State of stress, which include
 - ✓ Stress history
 - ✓ Surcharge load
 - ✓ Soil profile

2.5 Index Properties

Index property is a property, which helps in distinguishing the characteristics of a soil. Soil grain property and soil aggregate property are two main categories under this term. Soil grain property is based on the individual grains and depends on size, shape and mineralogical characteristics. Soil aggregate property, on the other hand is based on the property of the soil mass as a whole. Atterberg limit test, grain size analysis, specific gravity and free swell tests are among the tests which show the index property of a soil.

2.5.1 Grain Size Analysis Test

Since grain size analysis is one of the index property tests, the soil of the study area is examined for its grain size distribution. Grain size divides soil into two distinctive groups, namely cohesion less and cohesive soil. Soil particles, which are coarser than 0.075 mm, are generally termed as cohesionless and the finer ones like silt and clay are considered fine grained [16].

The property of cohesionless soil is greatly based on grain size distribution while the property of fine-grained soil is influenced by interparticle force. Hence, the behavior of a soil mass is dependent on the size of the particles it has. It is quite necessary then, to clearly know the proportion of different grains or particles a soil system contains. For coarse-grained soils this is done by sieve analysis. For fine-grained soils another method called hydrometer analysis is used for this purpose.

A sieve analysis test consists of shaking the soil through a stack of wire screens with openings of known size. The particle size is defined as the side dimension of a square hole in which the particle is retained.

The steady fall of soil particles through a liquid at rest is called sedimentation. The hydrometer method is based on Stokes equation that relates the velocity of free falling spherical particle through a liquid to the diameter of the particle, the specific gravity of the particle and the viscosity of the liquid. The hydrometer analysis assume that, the soil particles are spheres, the soil suspension is sufficiently low concentration to permit individual settling of grains without interference by others. That means small spheres in a liquid settle at different rate according to the size of sphere.

2.5.2 Moisture Content Test

Moisture content (w):- is defined as the ratio, expressed as a percentage, of the weight of water in a given soil mass to the weight of solid particles.

The change in water content in a soil's environment plays a major role in determining the degree of swelling and shrinking. A desiccated expansive soil has higher affinity for water and with the higher the affinity the more swell it exhibits. The same soil with higher initial moisture content will have a lesser affinity and exhibits less swelling. But upon drying the initially wet soil loses water more readily than the relatively dry soil and it exhibits higher shrinkage.

Generally, moisture content has an influence on the swelling potential of expansive soils. Natural moisture content of a soil is affected by climate, vegetation cover of the area and other artificial factors. Hence the same soil could have different moisture contents in different seasons of a year and in different times. Since such type of moisture content is likely to fluctuate any time it may not indicate the general property of the soil.

2.5.3 Atterberg and Shrinkage Limit Test

The Swedish soil scientist Albert Atterberg originally defined seven "limits of consistency" to classify fine-grained soils, but in current engineering practice only two of the limits, the liquid

and plastic limits, are commonly used [3]. (A third limit, called the shrinkage limit, is used occasionally.) The Atterberg limits are based on the moisture content of the soil.

2.5.3.1 Liquid Limit

The liquid limit is defined as the moisture content at which soil begins to behave as a liquid material and begins to flow on the application of a very small shearing force. When a soil becomes a viscous fluid, the soil will begin to flow under its own weight and very small amount of energy input. The liquid limit is primarily used by civil and geotechnical engineers as a physical property of a soil.

The liquid limit (LL) of a soil is the water content at the boundary between the liquid and plastic states. The water content at this boundary is arbitrarily defined as the water content at which, two halves of a soil pat placed in a brass cup, cut with standard groove, and dropped from a height of 1cm will undergo a groove closure of about 1.3 cm when the cup is dropped 25 times at the rate of 2 drops per sec. We can plot these results as blow count versus moisture content and interpolate the moisture content at 25 blows from this graph.

2.5.3.2 Plastic Limit

The plastic limit (PL) of a soil is the water content at the boundary between the plastic and semisolid state. The water content at this boundary is arbitrarily defined as the water content at which soil begins to crumble when rolled into threads of specified size 3.2mm.

2.5.3.3 Plasticity Index

Plasticity index (PI): the range of water content over which the soil behaves plastically. From the Atterberg limit values, it is possible to determine plasticity index using the formula:

Plasticity index, $PI = LL - PL$

From plasticity index, it is possible to determine the range of water content which exhibits plasticity and the presence of clay.

2.5.3.4 Shrinkage Limit

The shrinkage limit is the moisture content that defines where the soil volume will not reduce further if the moisture content is reduced.

2.5.4 Activity of clay

Activity which is defined as the ratio of the plastic index to percent of clay fraction finer than 0.002mm is one means of classifying expansive soils based on their index property. It is also used to estimate the swelling potential of given clay.

2.5.5 Specific Gravity Test

The specific gravity (**G**) of soil is defined as the ratio of mass in air of a given volume of soil particles to the weight in air of an equal volume of distilled water at standard temperature.

The specific gravity of a soil is used in calculating the phase relationships of soils water, and solids in a given volume of the soil. Also specific gravity of soils is an important quantity which is frequently used in calculation of percentage finer and diameter of the soil grains in hydrometer analysis.

2.5.6 Free Swell

The free swell of an expansive soil also termed as free swell index, is the increase in volume of a soil without any external constraint when subjected to submergence in water. Such soils have a possibility to damage the structure when the ground water table reaches the influence zone. It is therefore always essential to investigate the swelling or expansive nature of these soils which are likely to possess undesirable expansion characteristics.

The free swell test is one of the most commonly used simple tests for estimating soil swelling potential. This test is performed by pouring 10cc of dry soil, passing through sieve no 40 (0.425mm diameter), into a 100 cc graduated cylinder. The cylinder is then filled with distilled water and the swelled volume of the soil is measured after the material settles within 24 hours.

2.6 Review of Previous Researches

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

Several investigators attempted to develop correlations for prediction of swelling characteristics in terms of either compositional factors or environmental factors or combination of both. Many relationships have been established from which swelling pressure can be estimated based on index test and the physical state of the soil. Some of the researches are listed:-

Komornik and David, (1969) found out this empirical equation [9]: -

$$\text{Log } P_s = 0.132 + 0.0208 * LL + 0.0006688 * \gamma_d - 0.0269 * w \dots\dots\dots 2.1$$

Vijayvergiya and Ghazzaly (1973) found out those empirical equations [9]: -

$$\text{Log } P_s = \frac{1}{12} (0.4 * LL - w + 23.6) \dots\dots\dots 2.2$$

$$\text{Log } P_s = \frac{1}{19.5} (6.24 * \gamma_d + 0.65 * LL - 100) \dots\dots\dots 2.3$$

The engineering properties of expansive soil of Ethiopia are different from those in other locality; researches on relationship between index properties and swelling pressure of expansive soils of Ethiopia have been done. Some of the researches undertaken are listed below:-

Ashenafi Tamrat, (2013) studied about Index Properties and Swelling Pressure of Expansive soils found in Dukem using the regression analysis based on experimental results from 15 samples and found out this empirical equation [3]:-

$$P_s = 1.639 * \gamma_d + 32.676 * PL - 3110.94 \dots\dots\dots 2.4$$

Daniel Teklu, (2003) studied about Examining the Swelling Pressure of Addis Ababa Expansive Soils using multiple regression analysis based on experimental results from 17 samples and he recommended the following two empirical equations [9]:-

$$\text{Log } P_s = -5.00 - 0.0002064 * LL + 0.003477 * PI + 0.005827 * \gamma_d \dots\dots\dots 2.5$$

$$\text{Log } P_s = -9.384 + 0.02748 * W + 0.006307 * PI + 0.008359 * \gamma_d \dots\dots\dots 2.6$$

Dagmawe Negussie, (2007) studied about In-depth investigation of relationship between Index property and Swelling characteristic of Expansive soil in Bahir Dar using the regression analysis based on experimental results from 21 samples and found out this empirical equation [8]:-

$$\text{Log } P_s = 7.018 - 1.924 * \gamma_d - 0.042 * W - 0.008 * LL + 0.003 * CEC \dots\dots\dots 2.7$$

In the above equations

Where: P_s = Swelling pressure (kPa) for all eqn.

W , LL , PI , and PL = Moisture content, Liquid Limit, Plasticity Index, and Plastic Limit respectively (%)

γ_d = Dry density (Kg/m^3) for eqn. 2.4, 2.5, and 2.6

γ_d = Dry density (g/cm^3) for eqn. 2.1 and 2.7

γ_d = Dry density (KN/m³) for eqn. 2.3

CEC = Cation Exchange Capacity (meq/100gm) for eqn. 2.7

In these equations index properties that are believed to have significance for swelling are used as independent variables. Obviously the proposed equations might have served their purpose in areas where they have been specifically developed.

3 SAMPLING AND TESTING METHODOLOGY

In order to accomplish the objective of this thesis different field and laboratory works were conducted. In addition, a computer program (SPSS 20) was used to correlate swelling pressure with index properties. In this chapter detailed explanation could be presented about the sampling and test methodology used to conduct this thesis.

3.1 Selection of Sampling Sites

When selecting possible sampling sites, the major factor considered extremely important was that the site to be definitely located in the expansive soil region. To ensure samples covered a sufficient area of this formation, sites were identified by visual investigation and field identification of expansive soil (stated in chapter 2), if the soil show expansive nature, the samples were collected.



Figure 3.1: visual investigation of crack

3.2 Collection of Soil Samples

It was decided to collect approximately 19 samples from 12 test pits for testing to determine correlation between index properties and swelling pressure. The investigation involved collection of relevant geologic maps and associated reports and supplementary study materials from different sources. Regional geologic setting of the area is mainly referred from the country wide geologic map prepared by the Geological Survey of Ethiopia. Important attributes of the geomorphology, litho-structural elements and tectonic evolution is contained in other research papers dealing with the regional volcano-tectonic evolution of the Northwestern Plateau and western margin of the Main Ethiopian Rift Valley [10]. Subsurface explorations were performed boring test pits to a maximum depth of 3.0m.

3.2.1 Collection of Disturbed Samples

The disturbed soil was placed in tight plastic bag with a reference tag to describe the location of the sample and the depth taken. This was done to avoid the possibility of contaminating the sample being collected.

3.2.2 Collection of Undisturbed Samples

Undisturbed soil samples for this research were recovered by applying static force using hydraulic jack and pressing a Shelby tube. The sampling tube was then removed from the hole and the ends of the Shelby were immediately wax sealed and covered with plastic bags and labeled with necessary information for subsequent laboratory testing.

All samples that were collected, whether they comprised disturbed or undisturbed samples, were labeled appropriate and given a sample number prior to any preparation work on it.

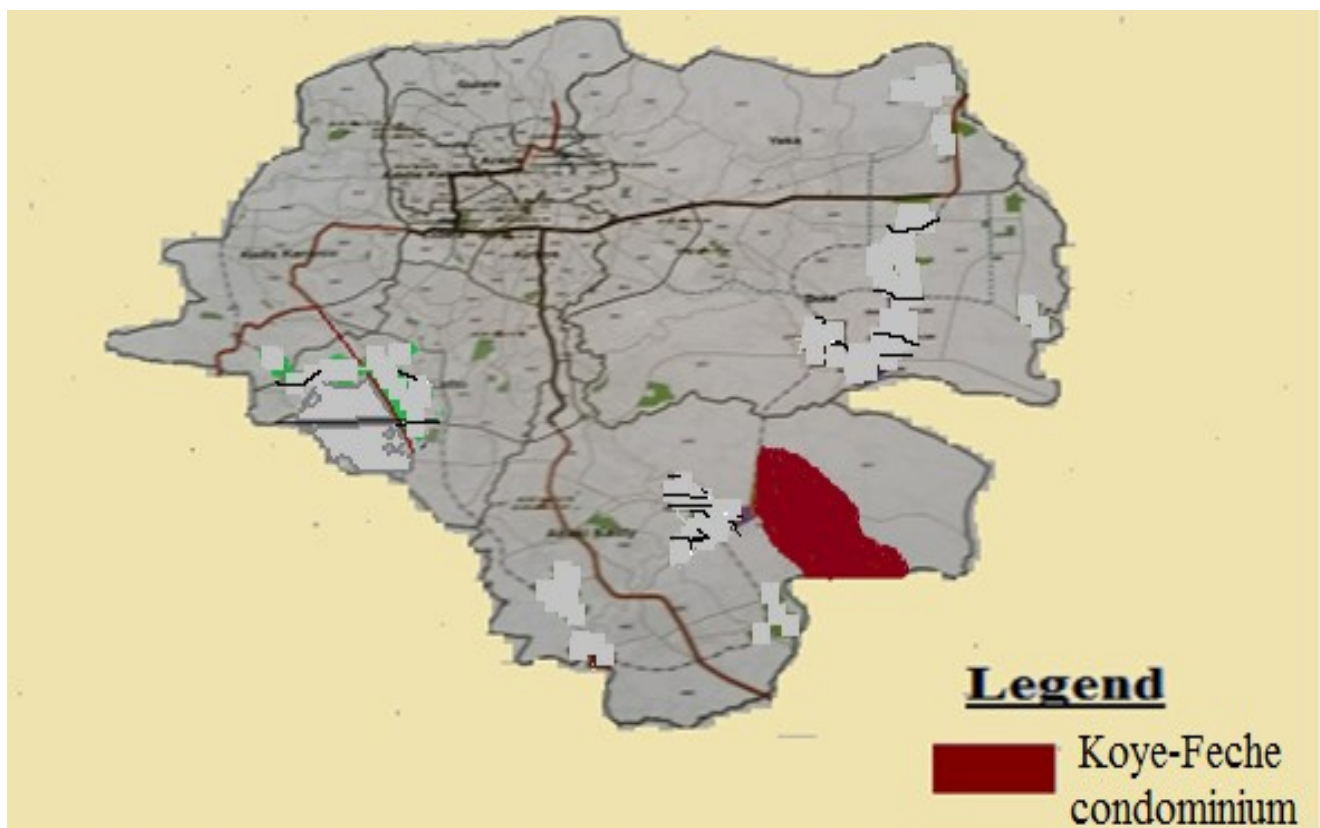


Figure 3.2: Location of Koye-Feche condominium in Addis Ababa city map

Source: Based on Maps from Addis Ababa city administration integrated land information center, Bureau of Land Development and Management, 2014

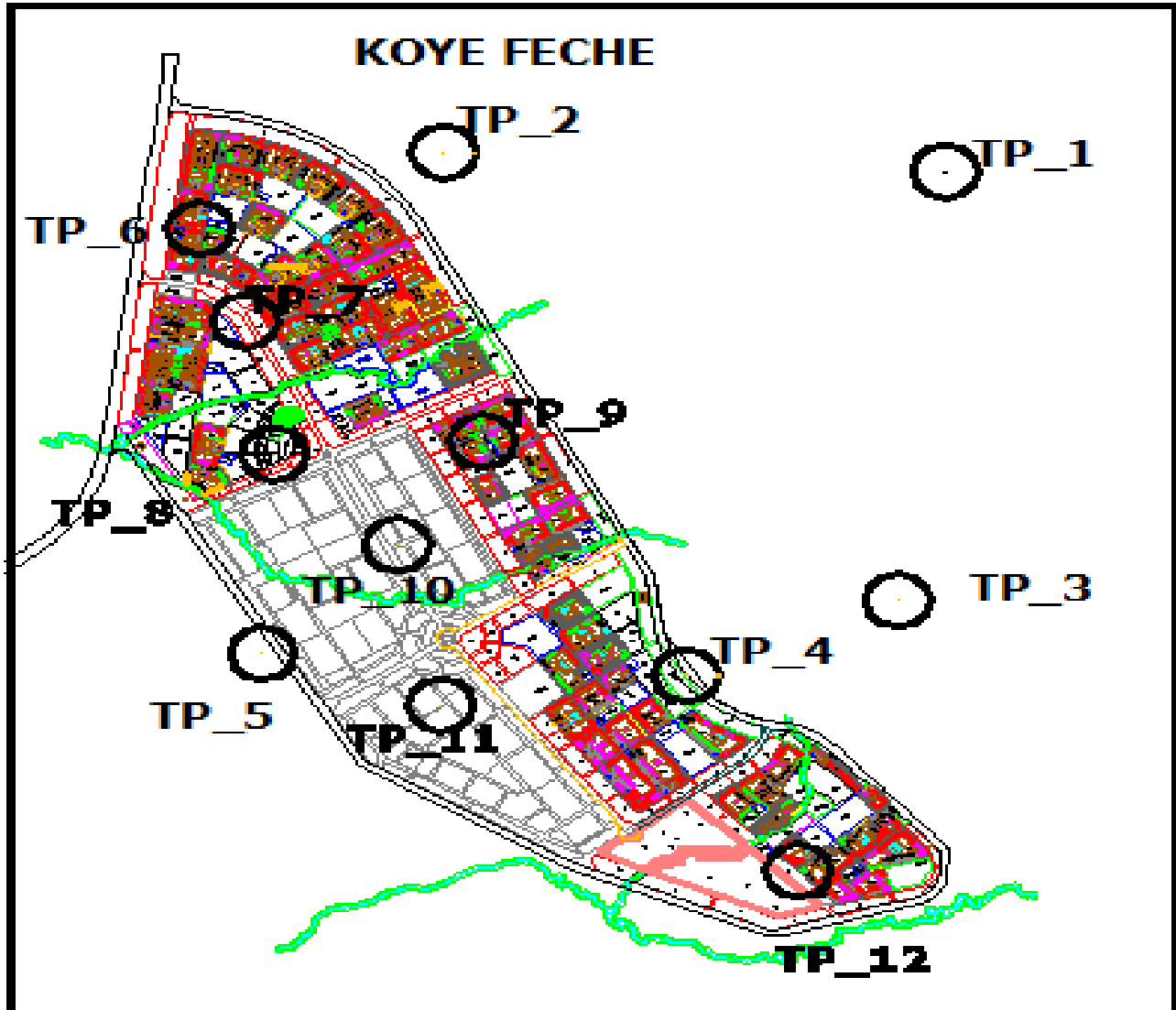


Figure 3.3: Location of test pits

3.3 Preparation of Disturbed Soil Samples

The disturbed samples recovered were used to determine results for the Atterberg limits, free swell, specific gravity and particle size distribution using both sieve and hydrometer methods.

The preliminary preparation of the soil sample was to take the dry sample and reduce all of the clods in the sample to pass through a 10mm screen. To achieve the required size, the clods were initially chopped up with a shovel and then made to crumble by hammer. During this process of chopping and crumbling extreme care was taken to ensure that individual particles were not crushed.

3.3.1 Preparation of soil for liquid limit, plastic limit and free swell

The method adopted for all of these tests was the dry preparation method using a mechanical device. The sample that has been rubbed down is then sieved through a 425 μ m sieve. After the entire sample has been sieved, the material which has passed through this sieve is then split to obtain a mass of at least 200 grams so all three tests can be performed.

3.3.2 Preparation of soil for specific gravity

The sample that has been rubbed down is then sieved through a 2mm sieve. After the entire sample has been sieved, the material which has passed through this sieve is oven dried and then weighs 25 gram of sample from oven dried for test.

3.3.3 Preparation of the soil for particle size distribution test using wet sieves

For fine-grained soils that may contain high fraction of clay soils, it was necessary to soak the soil prior to washing in order to keep the fine material from adhering to larger particles. The representative soak sample was measured before soaking and washing through the 75 μ m sieve. After washing, the material which has retained on 75 μ m sieve is oven dried and used for mechanical sieve.

3.3.4 Preparation of the soil for the particle size distribution using the hydrometer

The sample that has been rubbed down is then sieved through a 75 μ m sieve. After the entire sample had been sieved, 50gm of the material which has passed through 75 μ m sieve is used.

3.4 Laboratory Testing

For this thesis all testing was undertaken in a laboratory according to America Standard for Material Testing (ASTM) standard.

This laboratory is accredited for the following tests:-

- D-4220-95 Standard Practice for Preserving and Transporting of Soil samples
- D-2216 Determination of water content of a soil
- D-854 Determination of specific gravity of a soil
- D-421 Determination of sieve analysis of a soil
- D-422 Determination of hydrometer analysis of a soil

- D-4318 Determination of liquid limit and plastic limit of a soil
- D-2435 Determination of consolidation of a soil
- D-3282 AASHTO classification of a soil
- D-2487 USCS classification of a soil

3.5 Analysis Method Used

Generally in this analysis procedures the value of swelling pressure (P_s) was considered as the dependent variable whereas the liquid limit (LL), plastic limit (PL), plasticity index (PI), moisture content (ω), liquidity index (LI) and dry density/effective density (γ_{dry}/γ) values were the independent (Predictor) variables.

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

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

A Computer Program (SPSS 20) will be used to develop the empirical equations which correlate swelling pressure with index properties. SPSS is a statistical analysis and data management software package. It can take data from almost any type of file and use them to generate tabulated reports, charts, and plots of distributions and trends, descriptive statistics, and conduct complex statistical analyses.

The multiple regression equations take the form:

$$Y = b_1x_1 + b_2x_2 + \dots + c$$

The b 's are the regression coefficients, representing the amount the dependent variable changes when the independent changes 1 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.

To determine the strength of each correlation the R^2 value for the trend line was calculated. 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.

4 RESULTS AND DISCUSSIONS

4.1 Koye's soil properties

The location name, the test pits designation, colors of the soil and the depth where the samples were taken is shown in Table 4.1 and Figure 3.3.

Table 4.1: Description of test pits location

Location	Test pit ID	Color	Depth(m)	Northing	Easting	Elevation(m)
Tulu Mute	TP_1	Dark grey	3.0	483771	985819	2251.0
Ula	TP_2	Grey	3.0	481391	985930	2222.0
Gara Duba	TP_3	Reddish grey	3.0	483548	983311	2265.0
Near Koye Abo Church	TP_4	Yellowish grey	3.0	482543	982869	2250.0
Near Akaki-Kality Wereda 9	TP_5	Whitish grey	3.0	480535	982999	2204.0
Koye-Feche Project16 (pit 1)	TP_6	Black	1.5	480234	985486	2207.0
		Brownish grey	3.0	480234	985486	2205.5
Koye-Feche Project16 (pit 2)	TP_7	Black	1.5	480452	984938	2202.0
		Brownish grey	3.0	480452	984938	2200.5
Kersa	TP_8	Black	1.5	480590	984164	2196.0
		Brownish grey	3.0	480590	984164	2194.5
Koye-Feche Project17 (pit1)	TP_9	Black	1.5	481574	984241	2212.0
		Whitish grey	3.0	481574	984241	2210.5
Koye-Feche Project17 (pit2)	TP_10	Black	1.5	481172	983632	2207.0
		Whitish grey	3.0	481172	983632	2205.5
Koye-Feche Project18 (pit1)	TP_11	Black	1.5	481379	982695	2208.0
		Brownish grey	3.0	481379	982695	2206.5
Koye-Feche Project18 (pit2)	TP_12	Black	1.5	483070	981729	2248.0
		Dark grey	3.0	483070	981729	2246.5

4.1.1 Index properties

Index property is a property, which helps in distinguishing the characteristics of a soil. Soil grain property and soil aggregate property are two main categories under this term. Soil grain property is based on the individual grains and depends on size, shape and mineralogical characteristics. Soil aggregate property, on the other hand is based on the property of the soil mass as a whole.

Atterberg limit test, grain size analysis, specific gravity and free swell tests are among the tests which show the index property of a soil.

4.1.1.1 Results for the Atterberg Limit Test

The results of Atterberg limit test were given in Table 4.2. ASTM D-4318 is followed for the testing procedure. The detailed Atterberg limit test results are attached in Appendix A.

Table 4.2: Atterberg Limit Test Result of the Study Area

Test pit ID No	Depth(m)	Liquid Limit (%)	Plastic Limit (%)	PI (%)
TP_1	3.0	104.5	41.8	62.6
TP_2	3.0	100.9	38.0	62.9
TP_3	3.0	100.9	37.8	63.1
TP_4	3.0	90.4	34.6	56.2
TP_5	3.0	100.1	37.1	63.1
TP_6	1.5	97.3	37.0	60.3
	3.0	94.7	35.4	59.4
TP_7	1.5	108.0	40.8	67.2
	3.0	92.4	35.0	57.4
TP_8	1.5	100.1	37.2	62.9
	3.0	98.4	38.8	59.6
TP_9	1.5	99.8	38.6	61.2
	3.0	105.3	39.4	65.9
TP_10	1.5	111.8	42.7	69.1
	3.0	108.1	41.7	66.4
TP_11	1.5	110.9	42.5	68.4
	3.0	105.2	38.7	66.5
TP_12	1.5	109.8	41.8	68.0
	3.0	113.3	43.1	70.3

According to Seed, Woodward and Lund green, Plasticity Index (PI) is a parameter which can be used as a preliminary indicator of the swelling characteristics of a soil. Relating the Plasticity Index of the soil of the study area falls in the range of very high swelling potential.

4.1.1.2 Results for the Liquidity Index Test

Liquidity Index (LI): The Atterberg limits are found for remolded soil samples. These limits as such do not indicate the consistency of undisturbed soils. The index that is used to indicate the consistency of undisturbed soils is called as the liquidity index or water plasticity ratio. The liquidity index is expressed as: - $LI = \frac{\omega - PL}{PI}$

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

LI	Description of soil strength
LI < 0	Semisolid state – High strength but brittle, i.e. sudden fracture is expected
0 < LI < 1	Plastic state – Intermediate strength
LI > 1	Liquid state – Low strength

Table 4.3: Liquidity Index Test Result of the Study Area

Test pit ID No	Depth(m)	ω (%)	Plastic Limit (%)	PI (%)	LI	Remark
TP_1	3.0	44.55	41.8	62.6	0.04	Plastic state
TP_2	3.0	44.93	38.0	62.9	0.11	Plastic state
TP_3	3.0	45.02	37.8	63.1	0.11	Plastic state
TP_4	3.0	46.14	34.6	56.2	0.21	Plastic state
TP_5	3.0	38.90	37.1	63.1	0.03	Plastic state
TP_6	1.5	45.17	37.0	60.3	0.14	Plastic state
	3.0	42.63	35.4	59.4	0.12	Plastic state
TP_7	1.5	42.17	40.8	67.2	0.02	Plastic state
	3.0	43.65	35.0	57.4	0.15	Plastic state
TP_8	1.5	38.32	37.2	62.9	0.02	Plastic state
	3.0	39.34	38.8	59.6	0.01	Plastic state
TP_9	1.5	44.31	38.6	61.2	0.09	Plastic state
	3.0	45.33	39.4	65.9	0.09	Plastic state
TP_10	1.5	43.58	42.7	69.1	0.01	Plastic state
	3.0	43.16	41.7	66.4	0.02	Plastic state
TP_11	1.5	37.17	42.5	68.4	-0.08	Semisolid state
	3.0	37.83	38.7	66.5	-0.01	Semisolid state
TP_12	1.5	42.71	41.8	68.0	0.01	Plastic state
	3.0	45.32	43.1	70.3	0.03	Plastic state

4.1.1.3 Results for the Specific Gravity Test

Specific gravity of soil is the ratio of the unit weight of solids in the soil to the unit weight of water. The test results of specific gravity of study area were summarized in Table 4.4. The detailed Specific gravity test results are attached in Appendix A.

Table 4.4: Specific Gravity of the Soil of the Study Area

Test pit ID No	Depth(m)	G _s
TP_1	3.0	2.71
TP_2	3.0	2.68
TP_3	3.0	2.74
TP_4	3.0	2.82
TP_5	3.0	2.76
TP_6	1.5	2.67
	3.0	2.79
TP_7	1.5	2.74
	3.0	2.73
TP_8	1.5	2.71
	3.0	2.76
TP_9	1.5	2.67
	3.0	2.71
TP_10	1.5	2.74
	3.0	2.73
TP_11	1.5	2.68
	3.0	2.80
TP_12	1.5	2.84
	3.0	2.74

4.1.1.4 Results for the Grain Size Analysis Test

For coarse-grained soils sieve analysis and for fine-grained soils hydrometer analysis is used. In this study, Hydrometer and sieve analysis were performed on all the samples and a plot of percent finer against size of soil particle in millimeter on a semi-log scale was plotted. From this curve the proportion and type of soil grains was determined. The results were given in Figure 4.1 and Table 4.5. The detailed grain size analysis test results are attached in Appendix A.

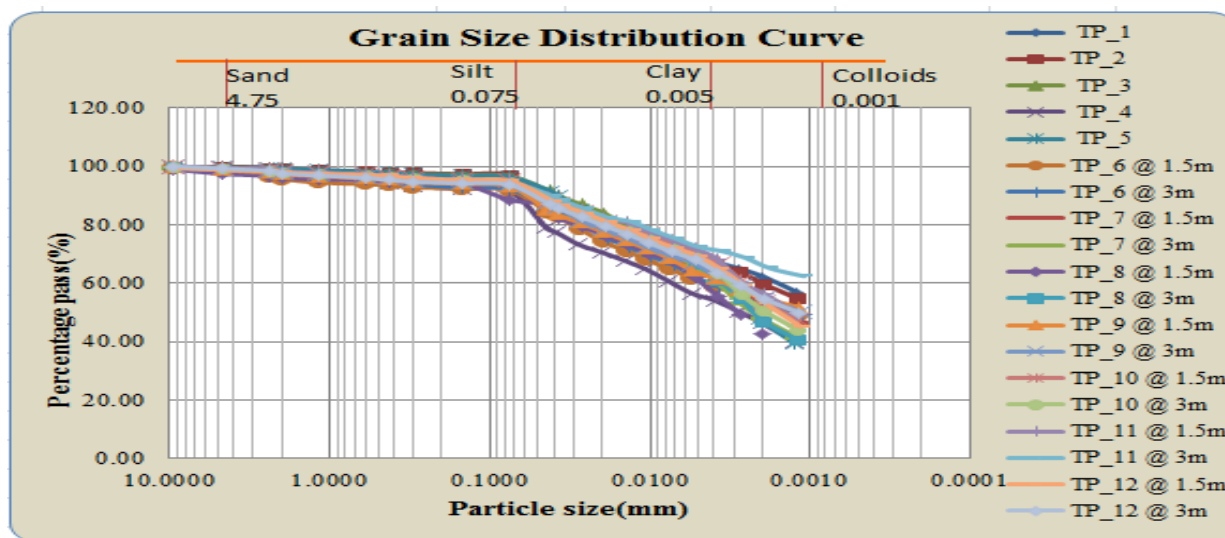


Figure 4.1: Combined sieve-hydrometer analysis graph of the study area

Table 4.5: Grain Size Distribution of the Study Area

Test pit ID No	Depth(m)	Gravel(%)	Sand (%)	Silt(%)	Clay (%)
TP_1	3.0	0.1	3.3	26.4	70.2
TP_2	3.0	0.1	2.8	27.6	69.4
TP_3	3.0	0.3	3.0	31.1	65.6
TP_4	3.0	0.6	7.8	35.0	56.6
TP_5	3.0	0.4	3.2	28.0	68.5
TP_6	1.5	1.6	6.6	30.2	61.7
	3.0	0.9	6.8	30.3	61.9
TP_7	1.5	0.6	4.9	28.5	66.0
	3.0	1.1	4.7	28.4	65.8
TP_8	1.5	1.0	4.8	26.5	67.7
	3.0	0.9	5.1	27.1	66.9
TP_9	1.5	1.3	5.5	28.8	64.4
	3.0	0.6	5.6	26.7	67.0
TP_10	1.5	0.5	4.4	24.4	70.6
	3.0	0.6	4.6	25.5	69.3
TP_11	1.5	0.5	4.6	23.2	71.8
	3.0	1.1	4.3	22.1	72.5
TP_12	1.5	1.2	3.8	25.8	69.3
	3.0	0.7	5.6	25.7	68.0

4.1.1.5 Results for the Free Swell Test

The free swell test is one of the most commonly used simple tests for estimating soil swelling potential. Results of the free swell tests of the study area were given in Table 4.6. The detailed free swell test results are attached in Appendix A.

Table 4.6: Free swell of the Study Area

Test pit ID No	Depth (m)	Free Swell (%)
TP_1	3.0	152.5
TP_2	3.0	132.5
TP_3	3.0	165.0
TP_4	3.0	95.0
TP_5	3.0	217.5
TP_6	1.5	175.0
	3.0	195.0
TP_7	1.5	192.5
	3.0	147.5
TP_8	1.5	202.5
	3.0	187.5
TP_9	1.5	122.5
	3.0	145.0
TP_10	1.5	215.0
	3.0	200.0
TP_11	1.5	217.5
	3.0	210.0
TP_12	1.5	180.0
	3.0	135.0

The soil of the study area can be classified as highly expansive as are greater than 100% except at near Abo church can be classified as marginal as are between 50-100%.

4.1.2 Results for the Swelling Pressure

Using the ASTM procedures, water content, dry density and swelling pressure tests were conducted on undisturbed soil samples. The results of the test were given in tabular form below Table 4.7. The detailed test results of undisturbed soil samples are attached in Appendix A.

From the undisturbed soil test value, one can observe that when the initial water content decrease the swelling pressure increases. In addition to this, the higher the dry density result in closer particle spacing, therefore causing greater particle interaction and higher swelling pressure.

Table 4.7: Laboratory test results on undisturbed soil samples of the Study Area

Test pit ID No	Depth(m)	$\rho_{\text{bulk}}(\text{g/cm}^3)$	$\rho_{\text{dry}}(\text{g/cm}^3)$	ω (%)	P_s (kPa)
TP_1	3.0	1.77	1.22	44.55	190
TP_2	3.0	1.63	1.12	44.93	150
TP_3	3.0	1.71	1.18	45.02	140
TP_4	3.0	1.62	1.11	46.14	80
TP_5	3.0	1.80	1.29	38.90	260
TP_6	1.5	1.74	1.20	45.17	150
	3.0	1.80	1.26	42.63	230
TP_7	1.5	1.83	1.29	42.17	250
	3.0	1.78	1.24	43.65	180
TP_8	1.5	1.76	1.28	38.32	250
	3.0	1.75	1.26	39.34	240
TP_9	1.5	1.72	1.19	44.31	140
	3.0	1.71	1.18	45.33	120
TP_10	1.5	1.77	1.23	43.58	200
	3.0	1.80	1.26	43.16	250
TP_11	1.5	1.81	1.32	37.17	400
	3.0	1.79	1.30	37.83	350
TP_12	1.5	1.81	1.27	42.71	250
	3.0	1.75	1.21	45.32	190

4.2 Koye's soil Classification

Soil classification is an important aspect of laboratory test, which tells the characteristic of the soil under interest. There are different methods of classification based on the identification tests performed on the soil.

Unified Soil Classification System (USCS) and the American Association of State Highway Transport Officials (AASHTO) method are among the widely used schemes of soil classification. There are also other classification methods specifically proposed for expansive soils.

4.2.1 USCS and AASHTO Classification

i) USCS Classification

According to USCS classification scheme the soil of the study area falls in CH or OH region but specific gravities were greater than two it categorized under CH (Fat clay), which shows that the soil is potentially expansive as shown in Figure 4.2 and Table 4.8.

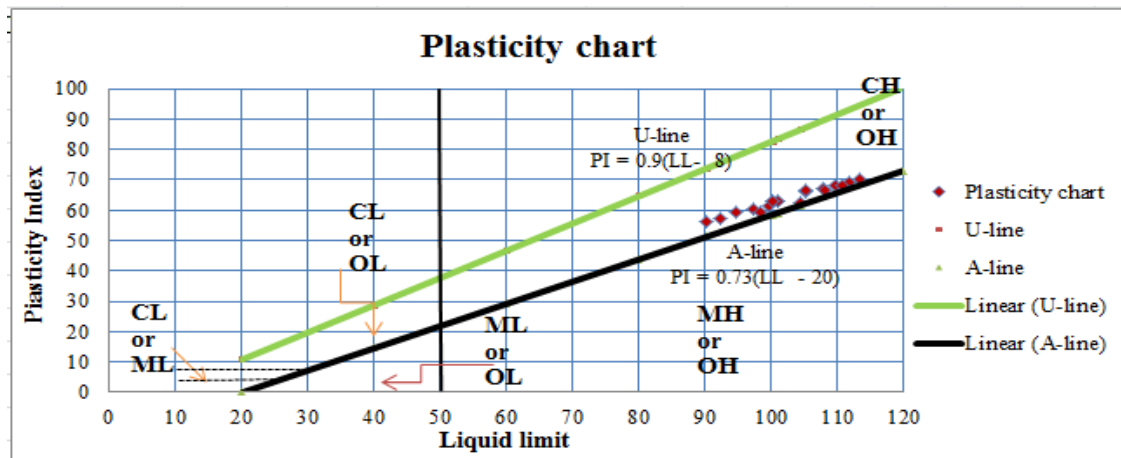


Figure 4.2: Plasticity chart of the soil of the study area, according to Unified Soil Classification System (USCS)

Table 4.8: USCS Classification of the Study Area

Test pit ID No	Depth(m)	Liquid Limit (%)	PI (%)	Percentage passing sieve No.200 (%)	USCS
TP_1	3.0	104.5	62.6	96.6	CH
TP_2	3.0	100.9	62.9	97.1	CH
TP_3	3.0	100.9	63.1	96.7	CH
TP_4	3.0	90.4	56.2	91.6	CH
TP_5	3.0	100.1	63.1	96.5	CH
TP_6	1.5	97.3	60.3	91.9	CH
	3.0	94.7	59.4	92.3	CH
TP_7	1.5	108.0	67.2	94.5	CH
	3.0	92.4	57.4	94.3	CH
TP_8	1.5	100.1	62.9	94.2	CH
	3.0	98.4	59.6	94.0	CH
TP_9	1.5	99.8	61.2	93.2	CH
	3.0	105.3	65.9	93.7	CH
TP_10	1.5	111.8	69.1	95.1	CH
	3.0	108.1	66.4	94.8	CH
TP_11	1.5	110.9	68.4	95.0	CH
	3.0	105.2	66.5	94.6	CH
TP_12	1.5	109.8	68.0	95.1	CH
	3.0	113.3	70.3	93.7	CH

II) AASHTO Classification

According to this 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 as shown in Figure 4.3 and Table 4.9. Subgroup A-7-5 includes those materials with moderate plasticity indexes in relation to the liquid limit and which may be highly elastic as well as considerable volume change between wet and dry states.

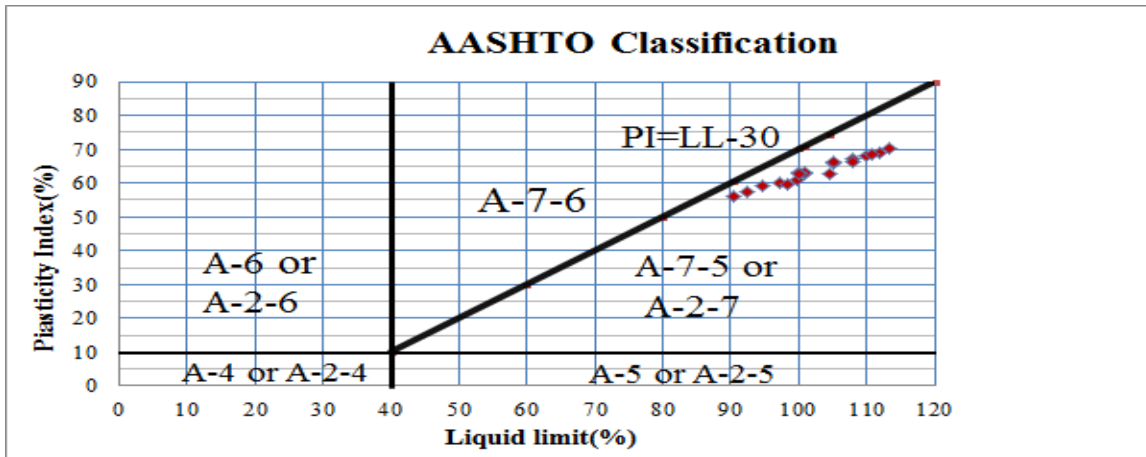


Figure 4.3: Classification of the Soil of the Study Area According To AASHTO System

Table 4.9: AASHTO Classification of the Study Area

Test pit ID No	Depth(m)	Liquid Limit (%)	Plastic Limit (%)	PI (%)	Percentage passing sieve No.200 (%)	AASHTO
TP_1	3.0	104.5	41.8	62.6	96.6	A-7-5
TP_2	3.0	100.9	38.0	62.9	97.1	A-7-5
TP_3	3.0	100.9	37.8	63.1	96.7	A-7-5
TP_4	3.0	90.4	34.6	56.2	91.6	A-7-5
TP_5	3.0	100.1	37.1	63.1	96.5	A-7-5
TP_6	1.5	97.3	37.0	60.3	91.9	A-7-5
	3.0	94.7	35.4	59.4	92.3	A-7-5
TP_7	1.5	108.0	40.8	67.2	94.5	A-7-5
	3.0	92.4	35.0	57.4	94.3	A-7-5
TP_8	1.5	100.1	37.2	62.9	94.2	A-7-5
	3.0	98.4	38.8	59.6	94.0	A-7-5
TP_9	1.5	99.8	38.6	61.2	93.2	A-7-5
	3.0	105.3	39.4	65.9	93.7	A-7-5
TP_10	1.5	111.8	42.7	69.1	95.1	A-7-5
	3.0	108.1	41.7	66.4	94.8	A-7-5
TP_11	1.5	110.9	42.5	68.4	95.0	A-7-5
	3.0	105.2	38.7	66.5	94.6	A-7-5
TP_12	1.5	109.8	41.8	68.0	95.1	A-7-5
	3.0	113.31	43.06	70.26	93.74	A-7-5

4.2.2 Other Classifications

I) Skempton’s method

Activity which is defined as the ratio of the plastic index to percent of clay fraction finer than 0.002mm is one means of classifying expansive soils based on their index property. According to Skempton, clays of the study area classified with respect to their activity in the range of active and normal clay. These values are shown below in Table 4.10 and Figure 4.4.

Table 4.10: Activity test result of the Study Area

Test pit ID No	Depth(m)	A
TP_1	3.0	1.01
TP_2	3.0	1.05
TP_3	3.0	1.13
TP_4	3.0	1.21
TP_5	3.0	1.32
TP_6	1.5	1.14
	3.0	1.12
TP_7	1.5	1.27
	3.0	1.20
TP_8	1.5	1.28
	3.0	1.26
TP_9	1.5	1.11
	3.0	1.20
TP_10	1.5	1.29
	3.0	1.31
TP_11	1.5	1.21
	3.0	1.02
TP_12	1.5	1.29
	3.0	1.29

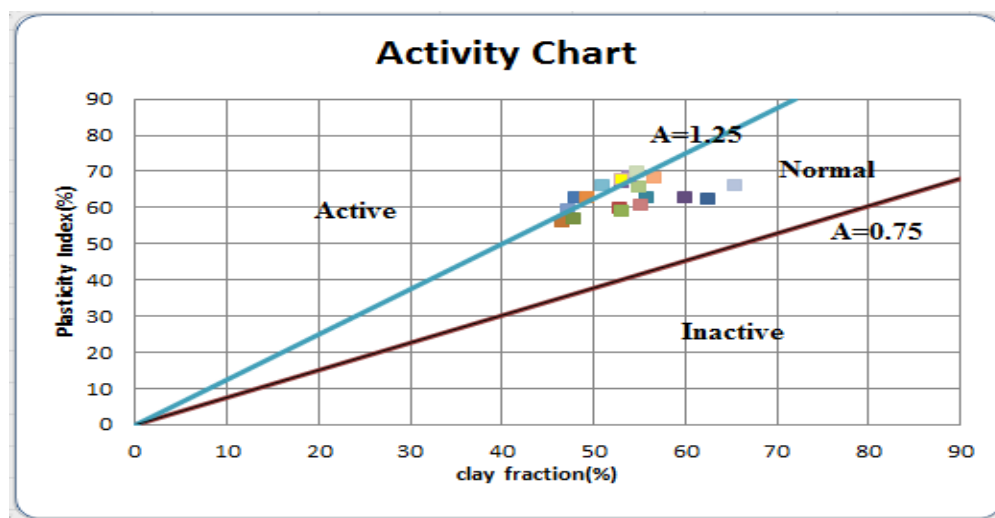


Figure 4.4: Activity chart of the Study Area

II) Seed, Woodward and Lundgreen

According to Seed, Woodward and Lundgreen [18], Plasticity Index is a parameter which can be used as a preliminary indicator of the swelling characteristics of a soil. Based on this classification all samples of the study area have plasticity index of 55 and above it categorized under very high swell potential as shown in Table 4.11.

Table 4.11: Plasticity Index test result of the Study Area

Test pit ID No	Depth(m)	PI (%)	Swelling potential
TP_1	3.0	62.63	Very high
TP_2	3.0	62.90	Very high
TP_3	3.0	63.11	Very high
TP_4	3.0	56.23	Very high
TP_5	3.0	63.07	Very high
TP_6	1.5	60.26	Very high
	3.0	59.38	Very high
TP_7	1.5	67.18	Very high
	3.0	57.41	Very high
TP_8	1.5	62.90	Very high
	3.0	59.59	Very high
TP_9	1.5	61.17	Very high
	3.0	65.90	Very high
TP_10	1.5	69.12	Very high
	3.0	66.41	Very high
TP_11	1.5	68.37	Very high
	3.0	66.48	Very high
TP_12	1.5	68.03	Very high
	3.0	70.26	Very high

5 SWELLING PRESSURE PREDICTION

5.1 Introduction

The evaluation of swell behavior of a soil using undisturbed samples is a difficult and expensive process. Therefore there is a need for simple routine tests to be performed on disturbed samples to achieve the same purpose. To facilitate this, empirical models had been put forwarded by different researchers to predict swell behavior of a soil.

The formation and development of soil structure has very erratic nature and the swell potential is dependent on the geology, environmental factors, soil characteristics and many other factors which vary from place to place. Therefore equations developed for soils in one place may not work at all if tested on soils of other place of the same region. Hence specific models have to be developed for specific areas in order to give fair evaluations.

These models comprise different soil parameters in different combinations. Index properties are the widely used parameters in these models because these properties have significance in indicating the swelling behavior of a soil. In general, previously developed empirical equations and equations to be developed in the future are not to be expected to determine swelling pressure precisely and accurately for all soils.

5.2 Comparison with previously developed models

As mentioned previously in chapter 2, there were different empirical equations developed to determine the swelling behavior of a soil. Some of the researchers studied neighboring the study areas were presented below.

Ashenafi Tamrat, (2013) [3]

$$P_s = 1.639 * \gamma_d + 32.676 * PL - 3110.94$$

Daniel Teklu, (2003) [9]

$$\text{Log } P_s = -5.00 - 0.0002064 * LL + 0.003477 * PI + 0.005827 * \gamma_d \dots\dots\dots (1)$$

$$\text{Log } P_s = -9.384 + 0.02748 * W + 0.006307 * PI + 0.008359 * \gamma_d \dots\dots\dots (2)$$

In the above equations

Where: P_s = Swelling pressure (kPa)

W, LL, PI, and PL = Moisture content, Liquid Limit, Plasticity Index, and Plastic Limit respectively (%)

$$\gamma_d = \text{Dry density (Kg/m}^3\text{)}$$

In these equations index properties that are believed to have significance for swelling are used as independent variables. At this point it is worthwhile to test these equations for the soil of the study area and to examine the outcome.

Table 5.1: Comparison of measured P_s with calculated using previously developed equation

Test pit ID No	Depth(m)	Measured P_s (kPa)	Calculated P_s (kPa) values using previously developed eqn.		
			Daniel Teklu		Ashenafi T.
			Eqn. 1	Eqn. 2	
TP_1	3.0	190	214	295	263
TP_2	3.0	150	55	43	-29
TP_3	3.0	140	119	130	58
TP_4	3.0	80	45	34	-159
TP_5	3.0	260	537	770	219
TP_6	1.5	150	145	173	59
	3.0	230	348	516	113
TP_8	1.5	250	429	537	197
	3.0	240	334	396	222
TP_9	1.5	140	133	145	100
	3.0	120	114	127	102
TP_10	1.5	200	251	357	305
	3.0	250	336	523	309
TP_11	1.5	400	826	1310	445
	3.0	350	615	886	286
TP_12	1.5	250	395	644	330
	3.0	190	180	249	275

As shown the result in above Table 5.1, the models are acceptable for soils based on which the models were developed and their use in general for all soils are not acceptable. The discrepancies noted might result mainly from variation of the nature of the soil, environmental, climatic condition and geologic formation of the region where the relation is developed to the study area. The purpose of this study could be to develop new empirical equations for swelling pressure by using the results of conventional odometer and index test results.

5.3 Formulation of New Empirical Equations

The relationship of two or more variables can be expressed in mathematical form by determining an equation connecting the two variables. Generally in this work, the value of swelling pressure (P_s) was considered as the dependent variable whereas liquid limit (LL), plasticity index (PI), plastic limit (PL), dry density/effective density (γ_{dry}/γ), liquidity index (LI) and moisture content (ω) are the independent (Predictor) variables.

5.3.1 Scatter Plot and Best-Fit Curve

The MS excel spread sheet is found to be the most powerful and manageable tool for scatter plot analysis and determination of correlation between two variables. However, when determination of the relationships among more than two variables are required (the dependent variable requires two or more independent variables) regression analysis is used and the SPSS software is found to be the most powerful and descriptive tool.

5.3.1.1 Swelling Pressure Vs Plasticity Index

The relationship between the swelling pressure and the plasticity index for all of the tested samples is shown in Figure 5.1. The best fitting trend line for this relationship is $P_s = 9.6414 \cdot PI - 404.63$. The strength of this equation in predicting an outcome from the plastic index is around 21.3 % or has $R^2 = 0.213$.

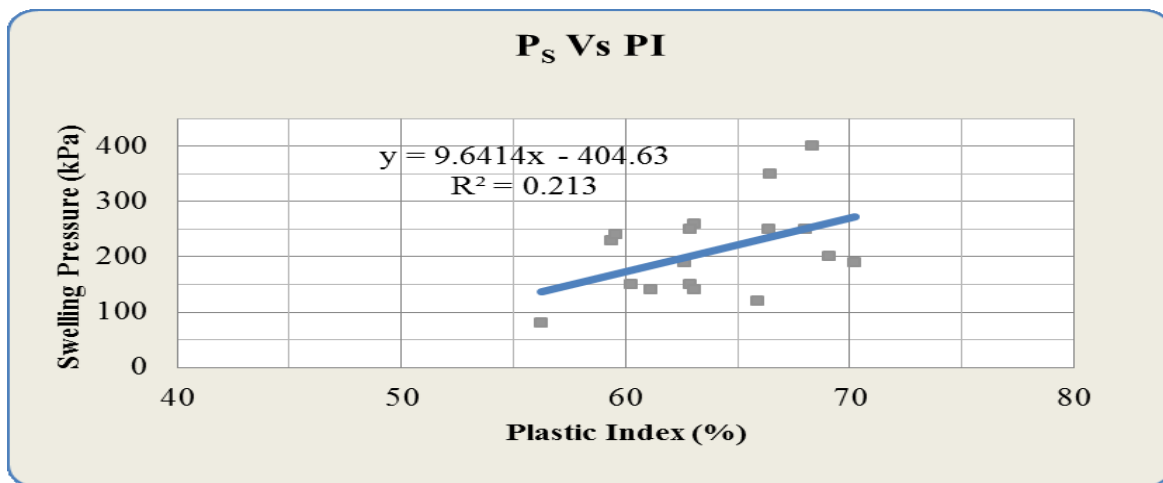


Figure 5.1: Swelling pressure Vs plasticity index of the study area

The swelling Pressure and the Plasticity index of the study area shows that the widely scattered points from the trend line this indicate that the relationship is weak. This shows that the determination of the Plasticity Index alone cannot satisfactorily indicate the swelling behavior of the soil of the study area.

5.3.1.2 Swelling Pressure Vs Natural Moisture Content

Natural moisture content is one of the factors, which influence the swelling characteristic of expansive soils. The best fitting trend line for this relationship is $P_s = -23.748*\omega + 1223.2$. The strength of this equation in predicting an outcome from the natural moisture content is around 78.0 % or has $R^2 = 0.78$.

A graph is plotted to see how it affects the swelling pressure of the study area. The results show a general trend of decreasing swelling pressure with increment of natural moisture content manifested in a polynomial relation as shown in Figure 5.2.

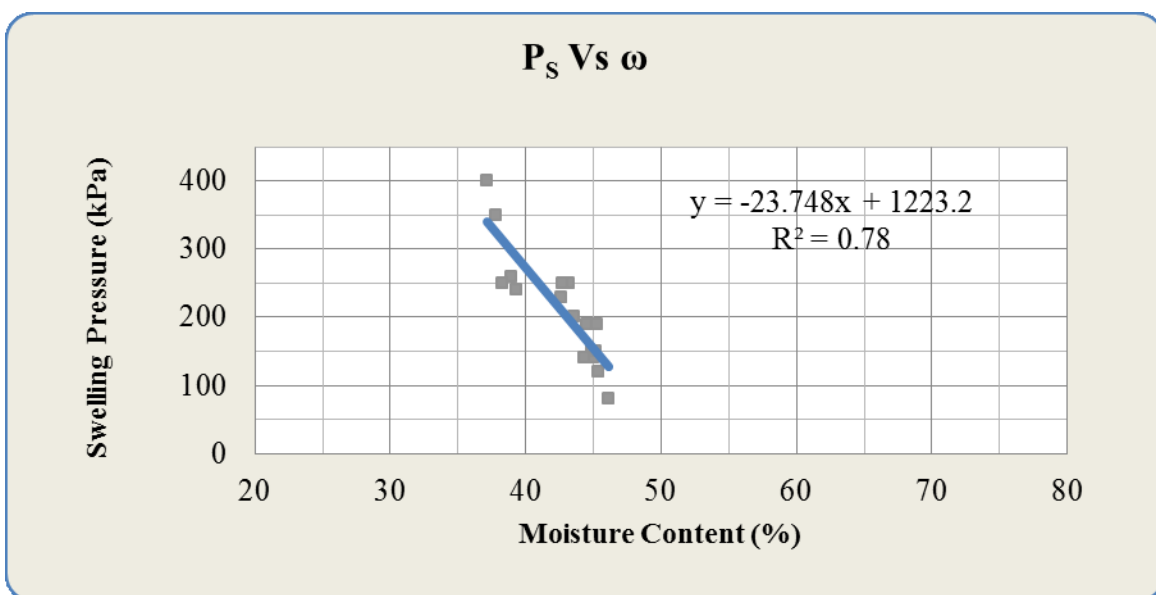


Figure 5.2: Swelling pressure Vs natural moisture content of the study area

5.3.1.3 Swelling Pressure Vs Dry Density

Dry density, which is a measure of the compactness of soil grains, is also another factor, which plays a role in swelling characteristic of expansive soils. A graph is plotted to see the relationship between the dry density and swelling pressure of the study area. The result shows that there is a tendency of increment of swelling pressure as the dry density increases as shown in Figure 5.3.

The best fitting trend line for this relationship is $P_s = 1250.5* \rho_{dry} - 1324.4$. The strength of this equation in predicting an outcome from the dry density is around 84.0 % or has an $R^2 = 0.84$ show that the relationship is strong.

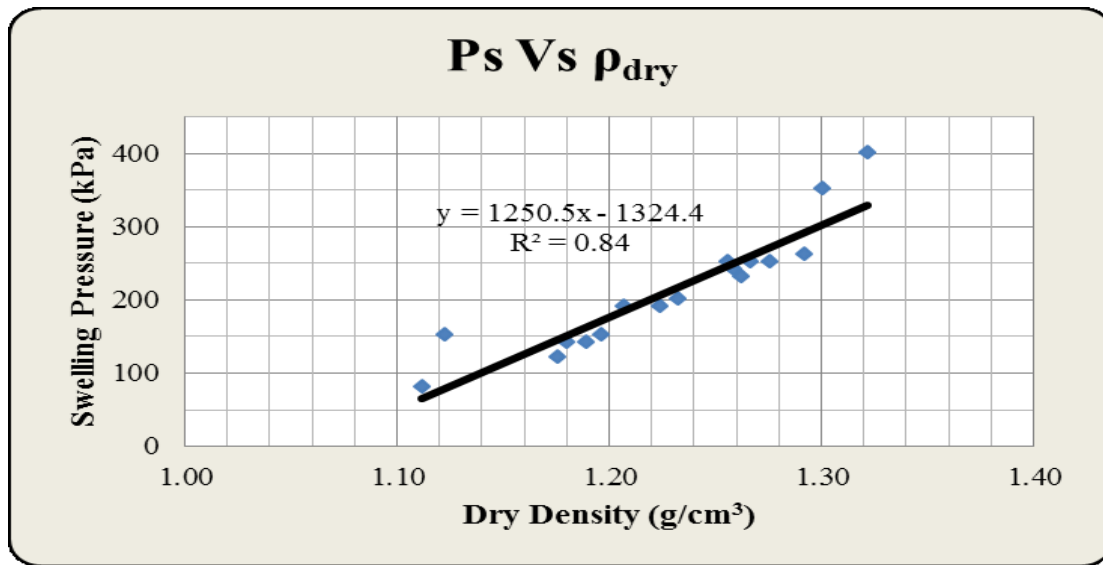


Figure 5.3: Swelling Pressure Vs Dry Density of the Study Area

5.3.1.4 Swelling Pressure Vs Liquid Limit

The best fitting trend line for relationship between swelling pressure and liquid limit is $P_s = 5.6746 * LL - 373.48$. As the strength of this correlation is only 19.5 % it is deemed not reliable enough to be used as a predictor for the estimation of the swelling pressure.

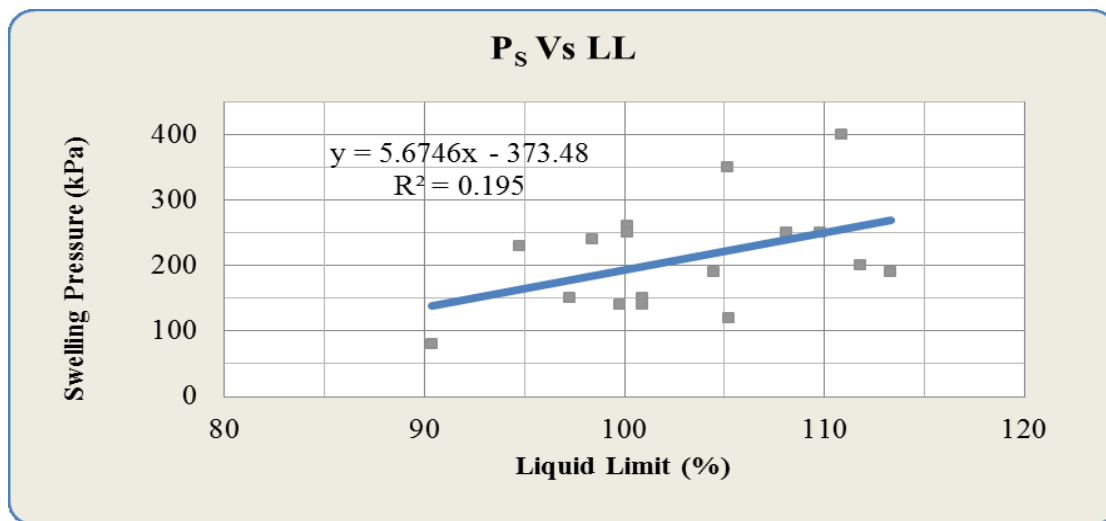


Figure 5.4: Swelling Pressure Vs Liquid Limit of the Study Area

The swelling Pressure and the Liquid Limit of the study area as shown in Figure 5.4 widely scattered points from the trend line. This shows that the determination of the Liquid Limit alone cannot satisfactorily indicate the swelling behavior of the soil of the study area.

5.3.1.5 Swelling Pressure Vs Plastic Limit

The best fitting trend line for relationship between swelling pressure and plastic limit is $P_s = 11.268 \cdot PL - 230.35$. As the strength of this correlation is only 13.20 % it is deemed not reliable enough to be used as a predictor for the estimation of the swelling pressure of the study area.

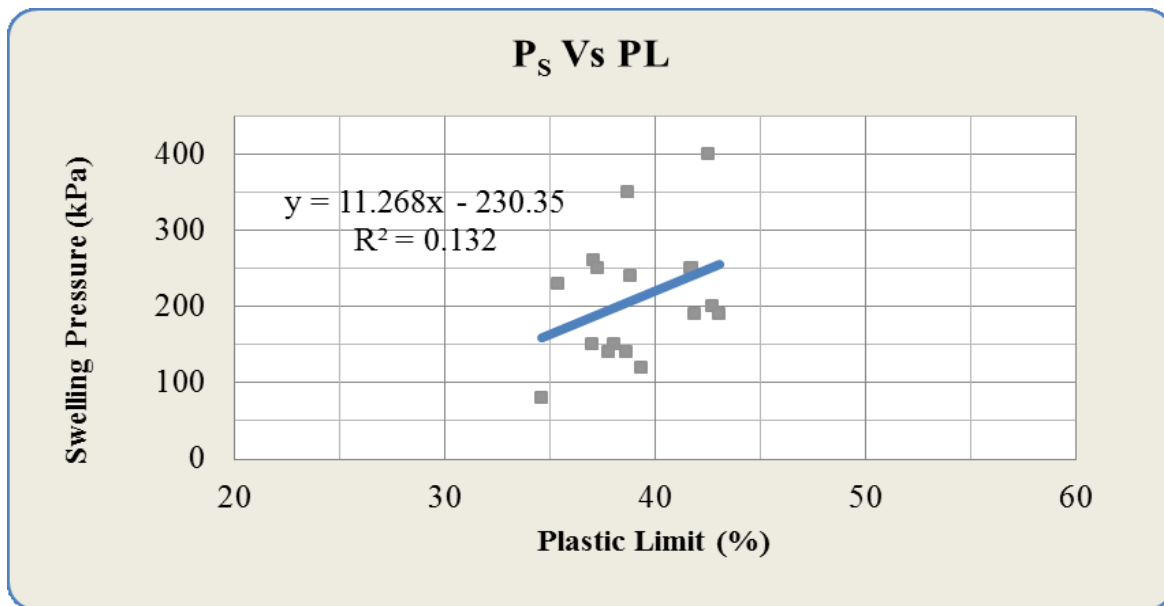


Figure 5.5: Swelling Pressure Vs Plastic Limit of the Study Area

5.3.2 Multiple regression analysis

A regression model that contains more than one predictor variable is called multiple regression models. The multiple regression equations take the form $y = b_1x_1 + b_2x_2 + \dots + c$. The b 's are the regression coefficients, representing the amount the dependent variable changes when the independent changes 1 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.

The regression coefficients are then calculated using SPSS 20 for windows software and tested for two samples, which are used as a control to test the relations. The input and outputs of the software are attached in Appendix B.

Out of these equations, equations with higher R^2 values were selected and using these equations the swelling pressure of the study area were calculated. Then a graph is plotted which shows the measured value against the predicted. The developed equations were also tested for two samples, which are used as a control to test the relations.

Table 5.2: Input data for SPSS 20 computer program

Test pit ID No	Depth(m)	Liquid Limit (LL), %	Plastic Limit (PL), %	Plasticity Index (PI), %	Dry Density/ Effective (ρ_{dry}/ρ')	Moisture Content (ω), %	Liquidity Index (LI)	Swelling Pressure (Ps), kPa
TP_1	3.0	104.47	41.84	62.63	1.59	44.55	0.04	190
TP_2	3.0	100.92	38.02	62.90	1.79	44.93	0.11	150
TP_3	3.0	100.91	37.80	63.11	1.66	45.02	0.11	140
TP_4	3.0	90.37	34.57	56.23	1.78	46.14	0.21	80
TP_5	3.0	100.14	37.07	63.07	1.63	38.90	0.03	260
TP_6	1.5	97.25	36.99	60.26	1.62	45.17	0.14	150
	3.0	94.73	35.36	59.38	1.58	42.63	0.12	230
TP_8	1.5	100.13	37.24	62.90	1.67	38.32	0.02	250
	3.0	98.42	38.83	59.59	1.67	39.34	0.01	240
TP_9	1.5	99.79	38.62	61.17	1.66	44.31	0.09	140
	3.0	105.26	39.36	65.90	1.66	45.33	0.09	120
TP_10	1.5	111.82	42.70	69.12	1.60	43.58	0.01	200
	3.0	108.10	41.68	66.41	1.57	43.16	0.02	250
TP_11	1.5	110.89	42.52	68.37	1.63	37.17	-0.08	400
	3.0	105.19	38.71	66.48	1.64	37.83	-0.01	350
TP_12	1.5	109.80	41.76	68.03	1.57	42.71	0.01	250
	3.0	113.31	43.06	70.26	1.60	45.32	0.03	190

Table 5.3: Input data for the control sample

Test pit ID No	Depth(m)	Liquid Limit (LL), %	Plastic Limit (PL), %	Plasticity Index (PI), %	Dry Density/ Effective (ρ_{dry}/ρ')	Moisture Content (ω), %	Liquidity Index (LI)	Swelling Pressure (Ps), kPa
TP_7	1.5	108.01	40.83	67.18	1.55	42.17	0.02	250
	3	92.37	34.96	57.41	1.59	43.65	0.15	180

The following possible empirical formulas are developed by taking one or more of important parameters (Liquid Limit, Plastic Limit, Plasticity Index, Moisture Content, liquidity index and Dry Density/effective density) in different combination as shown in Table 5.4.

Table 5.4: Newly developed possible empirical equations

Eqn.	Equations	N	R ²
Eqn.1	$P_s=988.21+39.94*(\gamma_{dry}/\gamma')-0.799*LL+10.44*PL-27.27*\omega$	17	0.930
Eqn.2	$P_s=908.09+33.43*(\gamma_{dry}/\gamma')-25.94*\omega+3.48*LL$	17	0.920
Eqn.3	$P_s=-422.67-51.98*(\gamma_{dry}/\gamma')-4.70*LL+18.68*PI$	17	0.329
Eqn.4	$P_s=-406.55-51.33*(\gamma_{dry}/\gamma')+14.17*LL-19.6*PL$	17	0.334
Eqn.5	$P_s=924.63+31.97*(\gamma_{dry}/\gamma')+5.17*PI-25.58*\omega$	17	0.906
Eqn.6	$P_s=965.22+38.533*(\gamma_{dry}/\gamma')-26.99*\omega+8.68*PL$	17	0.930
Eqn.7	$P_s=-417.16-51.88*(\gamma_{dry}/\gamma')-5.17*PL+14.19*PI$	17	0.330
Eqn.8	$P_s=-430.1-50.49*(\gamma_{dry}/\gamma')+11.19*PI$	17	0.323
Eqn.9	$P_s=-215.16-40.99*(\gamma_{dry}/\gamma')+12.403*PL$	17	0.207
Eqn.10	$P_s=-383.09-47.014*(\gamma_{dry}/\gamma')+6.432*LL$	17	0.291
Eqn.11	$P_s=1343.78+47.46*(\gamma_{dry}/\gamma')-28.20*\omega$	17	0.854
Eqn.12	$P_s=1015.62+41.29*(\gamma_{dry}/\gamma')-27.15*\omega+34.30*LL-24.74*PL-35.58*PI$	17	0.932
Eqn.13	$P_s=1018.58+39.70*(\gamma_{dry}/\gamma')-470.49*LI-19.69*\omega$	17	0.926
Eqn.14	$P_s=264.12+2.76*(\gamma_{dry}/\gamma')-1019.35*LI$	17	0.732
Eqn.15	$P_s=937.4+38.32*(\gamma_{dry}/\gamma')+422.16*LI-33.69*\omega+16.63*PL-0.33*PI$	17	0.931

Where: - P_s = Swelling pressure (kPa)

$$\frac{\gamma_{dry}}{\gamma'}, LI= \text{unitless}$$

ω , LL, PL and PI= Moisture content, Liquid Limit, Plastic Limit, Plasticity Index respectively (%)

To select the best equation, the swelling pressure were calculated for both input soil data and control samples soil data using newly developed equations. The results are shown in Table 5.5 and Table 5.6 below.

Table 5.5: Calculated swelling pressure values using newly developed equations

Test pit ID No	Depth(m)	Measured P _s (kPa)	Calculated Swelling Pressure(kPa)														
			Eqn. 1	Eqn. 2	Eqn. 3	Eqn. 4	Eqn. 5	Eqn. 6	Eqn. 7	Eqn. 8	Eqn. 9	Eqn. 10	Eqn. 11	Eqn. 12	Eqn. 13	Eqn. 14	Eqn. 15
TP_1	3.0	190	190.3	170.4	174.2	172.6	159.4	187.1	172.8	190.5	238.6	214.1	162.9	192.0	184.3	224.4	190.2
TP_2	3.0	150	150.8	154.9	185.6	187.0	157.6	151.3	186.1	183.4	183.0	181.8	161.7	153.0	153.4	157.0	149.6
TP_3	3.0	140	140.7	148.0	196.4	197.9	152.0	141.8	197.0	192.4	185.6	188.0	152.8	142.6	144.2	152.0	139.6
TP_4	3.0	80	89.9	86.6	111.0	105.6	91.9	88.5	109.7	109.3	140.7	114.5	127.1	80.7	84.2	59.4	93.9
TP_5	3.0	260	299.4	302.9	201.0	203.0	307.4	299.5	201.9	193.6	178.0	184.6	323.9	300.6	303.6	239.0	296.5
TP_6	1.5	150	129.8	130.3	162.1	163.6	132.4	129.5	162.5	162.2	177.1	166.1	146.9	133.1	129.9	130.3	129.8
	3.0	230	182.1	185.8	159.9	162.4	191.3	182.0	160.9	154.8	158.7	152.1	216.3	185.6	184.2	143.5	181.1
TP_8	1.5	250	318.7	319.4	195.6	197.5	322.7	318.3	196.5	189.6	178.3	182.5	342.3	319.9	322.3	251.1	315.5
	3.0	240	308.8	286.9	141.8	141.9	279.5	304.5	141.2	152.5	198.1	171.5	313.4	311.7	306.2	260.0	305.0
TP_9	1.5	140	169.8	162.8	165.3	165.8	160.4	168.4	165.2	170.6	195.8	180.7	173.1	172.5	168.4	173.9	169.0
	3.0	120	145.2	155.3	228.1	229.0	158.7	147.1	228.6	223.7	205.0	215.9	144.2	145.7	149.4	176.3	144.2
TP_10	1.5	200	220.3	221.5	260.4	259.4	218.2	221.2	259.9	262.6	248.8	260.9	190.8	218.8	218.2	255.6	222.6
	3.0	250	223.1	218.6	228.7	227.9	214.1	222.7	228.2	233.6	237.3	238.2	201.4	222.8	221.0	245.9	223.8
TP_11	1.5	400	394.9	385.2	249.5	248.6	379.0	393.5	249.0	253.0	245.6	253.7	372.7	393.0	388.1	348.4	398.3
	3.0	350	342.3	348.8	240.2	241.7	353.0	343.3	241.1	231.0	197.7	216.3	354.9	341.7	345.2	282.1	341.5
TP_12	1.5	250	234.5	235.9	251.3	250.8	233.8	235.2	251.1	252.1	238.6	249.4	213.7	233.4	233.5	254.3	235.9
	3.0	190	175.2	181.5	274.7	273.7	179.4	177.1	274.3	275.4	253.3	270.5	141.5	173.2	174.6	235.6	177.6

Table 5.6: Calculated swelling pressure values using newly developed equations for control samples

Test pit ID No	Depth(m)	Measured P _s (kPa)	Calculated Swelling Pressure(kPa)														
			Eqn. 1	Eqn. 2	Eqn. 3	Eqn. 4	Eqn. 5	Eqn. 6	Eqn. 7	Eqn. 8	Eqn. 9	Eqn. 10	Eqn. 11	Eqn. 12	Eqn. 13	Eqn. 14	Eqn. 15
TP_7	1.5	250	240.2	243.1	244.8	244.8	242.6	241.0	244.9	243.6	227.9	238.9	228.1	239.5	240.5	248.2	240.8
	3.0	180	152.6	151.6	133.8	136.2	155.5	151.7	134.6	132.3	153.5	136.5	188.2	157.2	151.1	114.4	153.6

Table 5.7: Checking accuracy of the newly developed formulas for Control Samples

Test pit ID No	Depth(m)	Measured P _s (kPa)	Difference from measured P _s (%)														
			Eqn. 1	Eqn. 2	Eqn. 3	Eqn. 4	Eqn. 5	Eqn. 6	Eqn. 7	Eqn. 8	Eqn. 9	Eqn. 10	Eqn. 11	Eqn. 12	Eqn. 13	Eqn. 14	Eqn. 15
TP_7	1.5	250	3.90	2.76	2.06	2.07	2.96	3.59	2.05	2.57	8.85	4.44	8.77	4.20	3.78	0.73	3.69
	3.0	180	15.20	15.77	25.69	24.33	13.61	15.75	25.24	26.50	14.72	24.16	4.55	12.65	16.04	36.47	14.69
		Average	9.55	9.26	13.88	13.20	8.28	9.67	13.65	14.54	11.78	14.30	6.66	8.43	9.91	18.60	9.19

5.3.3 Graphical representation of measured and calculated values

To investigate the approximation accuracy of newly developed formulas, the results of the best equations are compared with the actual measured value. A 45° line has been plotted to show the diagram of the regression equations from the test data (Fig 5.6, Fig 5.7). The comparison for others equations are presented in Appendix B.

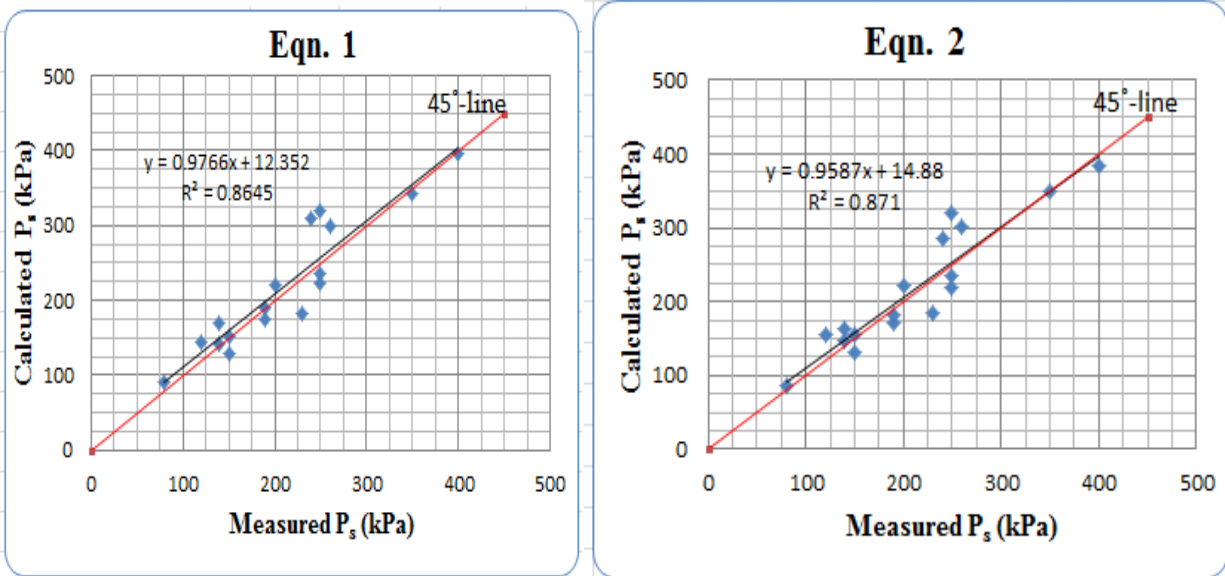


Figure 5.6: Comparisons of measured and calculated swelling pressure for equation 1 & 2

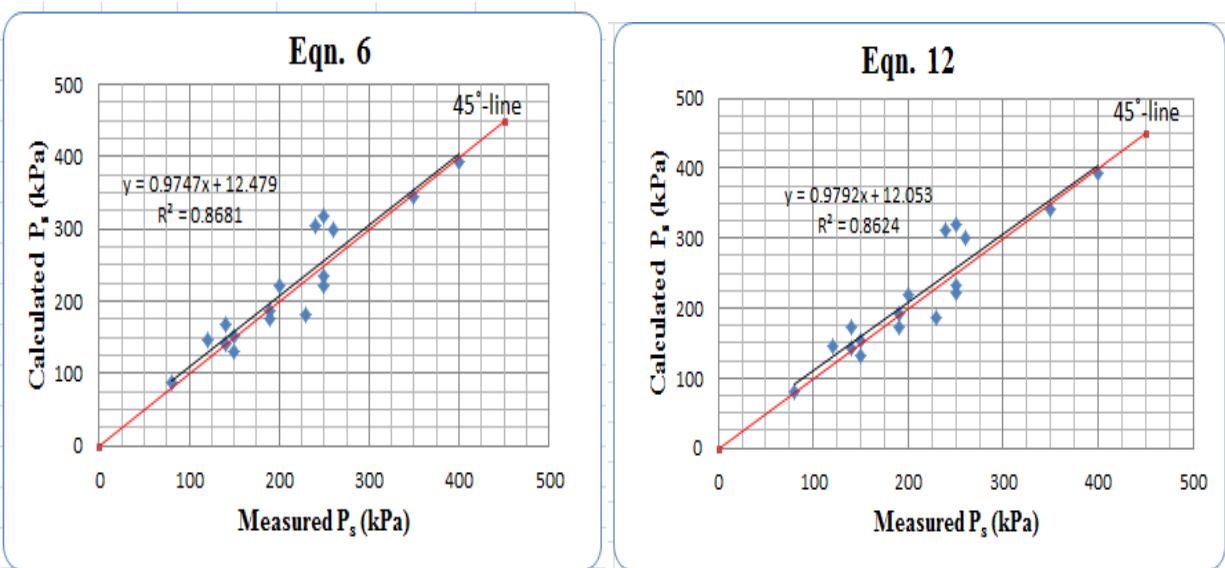


Figure 5.7: Comparisons of measured and calculated swelling pressure for equation 6 & 12

To select the best relation the following points are taken in to consideration

- The value of R^2 for the regression analysis should have relatively higher value and approaches to one.
- The slopes of the line for the measured verses calculate swelling pressure graph should have relatively higher value and approaches to one.
- The equation should give approximately the same swelling pressure value compared with the measured one for the control samples.
- Equations that have parameters which could be easily determined in soil mechanics laboratories.

The soil under investigation is found to be sensitive to dry density. So that, this important soil parameter normalizing by effective density and involved in all equations. The major difference between the equations is the number of independent variables or parameters involved in them. When one evaluates the equations based on the above considerations, all the equations have good regression analysis and the slope of the line of measured verses calculated swelling pressure graph are better approaches to one. And also most of the equations give approximately the same swelling pressure value compared with the measured one for the control samples with accuracy range of 6.66 % to 18.60 %.

As seen from the table and graphs equations 6, 1, 12 and 15 gave a better estimation of the measured swelling pressure. Among the three equations, equation 6 ($P_s = 965.22 + 38.53 * \frac{Y_{dry}}{Y} - 26.99 * \omega + 8.68 * PL$) describes the relation better than the others. This is because that, it has good regression analysis with coefficient of determination 0.930 and the slope of the line for the measured verses calculate swelling pressure graph better approaches to one. And also it has parameters which could be easily determined in soil mechanics laboratories and accuracy of calculated swelling pressure from actual swelling pressure for control sample is 9.67 % difference. Thus, one may use these suggested equations for the estimation of the swelling pressure of the study area alternatively.

6 Conclusion and Recommendation

6.1 Conclusion

1. Most of the study area up to 1.5m is covered by thick black clay soil. Based on different soil classification system the study area soil type is fat clay soil. This soil has very high swelling potential, so care should be taken to design light weight structure.
2. The regression analysis showed that there is a relationship between index properties and swelling characteristics of expansive soil of Koye area. Especially dry density in combination with other parameters is a powerful variable for prediction of swelling pressure of soils found around Koye area.
3. For different clay content, dry density and water content the swelling pressure of expansive soils found around Koye area range between 80kPa and 400kPa.
4. Evaluation of the previously developed equations with present study area showed that, specific prediction model is necessary for specific areas in order to get fair evaluations.
5. All newly developed formulas, in this study, predict the swelling pressure of the study area with various degrees of accuracy. But based on criteria stated in chapter 5, equation 6 ($P_s = 965.22 + 38.53 * \frac{\gamma_{dry}}{\gamma_r} - 26.99 * \omega + 8.68 * PL$) is recommended.
6. If anyone needs preliminary investigation to the nature of soil and its properties in this area, they can use this result. Also the equation of swelling pressure relating different soil properties will be applicable to this area in future, unless there is extensive change in geological formation of the strata.

6.2 Recommendation

- The equation developed may be further improved by increasing the number of samples and tests performed on a number of undisturbed samples during the driest season of the year.
- The prediction of swelling pressure by empirical relationships cannot be expected to yield accurate results. Therefore, for detail investigation swelling pressure should be determined from oedometer tests on a sample that have an expected initial condition that could yield maximum swelling pressure. For small projects and for preliminary design purpose of any size of building the equations developed can be used to predict the swelling pressure.

REFERENCES

1. Addis Ababa city administration integrated land information center, Bureau of Land Development and Management. Addis Ababa, Ethiopia: Sivanet Printing, 2014.
2. Alemayehu Tefera and Mesfin, L. Soil Mechanics. Addis Ababa : AAU Printing Press, 1999.
3. Ashenafi Tamrat, Study on Index Properties and Swelling Pressure of Expansive soils found in Dukem. Addis Ababa University: Unpublished M.Sc. Thesis, 2013.
4. ASTM, Special procedures for testing soil and rock for engineering purposes, 1996.
5. Ayenew Zewdie, Investigation into Shear Strength Characteristics of Expansive Soil of Ethiopia. Addis Ababa University: Unpublished M.Sc. Thesis, 2004.
6. Bowles, E. Engineering Properties of Soils and Their Measurement. 4. New York : McGraw-Hill Book Company, 1992.
7. Chen, F.H. Foundation on expansive soils. Amsterdam : Elsevier, 1988, 1975 and 1966.
8. Dagmawi Negussie, In-depth investigation of relationship between index properties of expansive soils in Bahirdar. Addis Ababa University : Unpublished M.Sc Thesis, 2007.
9. Daniel Tekle, Examining the Swelling Pressure of Addis Ababa Expansive Soil. Addis Ababa University: Unpublished M.Sc. Thesis, 2003.
10. Gondwana, Engineering Prv. Ltd. Co. Geotechnical investigation and laboratory testing and analysis of urban renewal/expansion area Koye-Feche condominium project. Addis Ababa: Unpublished.
11. John, N.C. Geotechnical Engineering Soil Mechanics. New york : John Wiley and Sons Inc., 1994.
12. Kibrom Gebrekrstos, Investigation into engineering properties of Mekelle soils with emphasis on expansive soils. Addis Ababa University: Unpublished M.Sc. Thesis, 2005.
13. Mckeen, R.G. Design and construction of airport pavements on expansive soils. Washington, D.C: U.S department of transportation federal aviation administration systems research and development services, 1976.
14. Mesfin Kassa, Relationship between Consolidation and Swelling Characteristics of Expansive Soils of Addis Ababa. Addis Ababa University: Unpublished M.Sc. Thesis, 2005.
15. Mitchell, J.K. Fundamentals of soil behavior. The Mc-graw hill companies, 1976.

16. Murthy, V.N.S. Soil Mechanics and Foundation Engineering. UBS Publishers Distributors Ltd, 2001.
17. Nelson, D.J and Debra, J.M. Expansive Soils Problems and Practice in Foundation and Pavement Engineering. New York: John Wiley and Sons, Inc., 1992.
18. Seed, H.B, Woodward, R.J. and Lundgren, R. Prediction of Swelling Potential for Compacted Clays. Proceedings ASCE, 1962.
19. Sisay, A. Assessment of damages of buildings constructed in expansive soil area of Addis Ababa. Addis Ababa University: Unpublished M.Sc. Thesis, 2004.
20. Snethen, R. A review of engineering experience with expansive soil in highway subgrades. U.S army engineering waterways experiment station, 1975.

Appendix A

Representative Laboratory Test Results

Representative moisture content test results

Formula used

$$\omega = \frac{(M_2 - M_3)}{(M_3 - M_1)} * 100\%$$

Table A.1: Determination of moisture content for test pit TP_1

Test Pit TP_1		
Depth, m	3	
Container no	B1	J3
Mass of container(M ₁),gm	15.70	15.40
Mass of container +wet soil(M ₂),gm	57.40	50.30
Mass of container +dry soil(M ₃),gm	44.60	39.50
Mass of Water (M ₂ -M ₃),gm	12.80	10.80
Mass of Dry Soil (M ₃ -M ₁),gm	28.90	24.10
Moisture content(ω),%	44.29	44.81
Average Moisture content(ω),%	44.55	

Table A.2: Determination of moisture content for test pit TP_2

Test Pit TP_2		
Depth, m	3	
Container no	J3	B1
Mass of container(M ₁),gm	15.30	15.60
Mass of container +wet soil(M ₂),gm	50.60	50.30
Mass of container +dry soil(M ₃),gm	39.70	39.50
Mass of Water (M ₂ -M ₃),gm	10.90	10.80
Mass of Dry Soil (M ₃ -M ₁),gm	24.40	23.90
Moisture content(ω),%	44.67	45.19
Average Moisture content(ω)	44.93	

Table A.3: Determination of moisture content for test pit TP_3

Test Pit TP_3		
Depth, m	3	
Container no	M1	B1
Mass of container(M_1),gm	15.70	15.80
Mass of container +wet soil(M_2),gm	42.20	48.30
Mass of container +dry soil(M_3),gm	33.90	38.30
Mass of Water (M_2-M_3),gm	8.30	10.00
Mass of Dry Soil (M_3-M_1),gm	18.20	22.50
Moisture content(ω),%	45.60	44.44
Average Moisture content(ω)	45.02	

Table A.4: Determination of moisture content for test pit TP_6

Test Pit TP_6				
Depth, m	1.5		3	
Container no	T9	C40	A58	A28
Mass of container(M_1),gm	15.5	14.30	15.5	15.60
Mass of container +wet soil(M_2),gm	37.4	32.90	47.4	50.60
Mass of container +dry soil(M_3),gm	30.6	27.10	37.9	40.10
Mass of Water (M_2-M_3),gm	6.80	5.80	9.50	10.50
Mass of Dry Soil (M_3-M_1),gm	15.10	12.80	22.40	24.50
Moisture content(ω),%	45.03	45.31	42.41	42.86
Average Moisture content(ω),%	45.17		42.63	

Table A.5: Determination of moisture content for test pit TP_9

Test Pit TP_9				
Depth, m	1.5		3	
Container no	4A	23A	M10	A27
Mass of container(M_1),gm	16.00	16.00	10.90	15.70
Mass of container +wet soil(M_2),gm	46.00	43.00	27.50	31.80
Mass of container +dry soil(M_3),gm	36.80	34.70	22.30	26.80
Mass of Water (M_2-M_3),gm	9.20	8.30	5.20	5.00
Mass of Dry Soil (M_3-M_1),gm	20.80	18.70	11.40	11.10
Moisture content(ω),%	44.23	44.39	45.61	45.05
Average Moisture content(ω),%	44.31		45.33	

Table A.6: Determination of moisture content for test pit TP_11

Test Pit TP_11				
Depth, m	1.5		3	
Container no	E7	C54	DYH	A2
Mass of container(M_1),gm	15.6	15.70	15.60	15.50
Mass of container +wet soil(M_2),gm	41.6	42.10	39.60	38.50
Mass of container +dry soil(M_3),gm	34.6	34.90	33.00	32.20
Mass of Water (M_2-M_3),gm	7.00	7.20	6.60	6.30
Mass of Dry Soil (M_3-M_1),gm	19.00	19.20	17.40	16.70
Moisture content(ω),%	36.84	37.50	37.93	37.72
Average Moisture content(ω),%	37.17		37.83	

Representative Specific gravity test results

Formula used

$$G_s = K * \left[\frac{M_s}{(M_s + M_2 - M_1)} \right]$$

Table A.7: Temperature Correction Factors for G_s

Temp., °c	Temp. Corre. factor, K
16	1.0007
17	1.0006
18	1.0004
19	1.0002
20	1.0000
21	0.9998
22	0.9996
23	0.9993
24	0.9991
25	0.9988
26	0.9986
27	0.9983
28	0.9980
29	0.9977
30	0.9974

Table A.8: Determination of specific gravity for test pit TP_1

Test Pit TP_1		
Depth, m	3	
Pycnometer no	1	2
Mass of dry soil(M_s),gm	25.00	25.00
Mass of pycnometer +water +soil(M_1),gm	160.40	161.10
Test temperature of sample, °c	27.40	27.10
Mass of pycnometer +water(M_2),gm	144.70	145.20
Specific gravity of soil at test temperature	2.69	2.75
Correction factor, K	0.9982	0.9983
Specific gravity of soil at 20°C	2.68	2.74
Average specific gravity of soil at 20°C	2.71	

Table A.9: Determination of specific gravity for test pit TP_2

Test Pit TP_2		
Depth, m	3	
Pycnometer no	1	2
Mass of dry soil(Ms),gm	25	25
Mass of pycnometer +water +soil(M1),gm	160.2	161
Test temperature of sample,°c	26.5	26.7
Mass of pycnometer +water(M2),gm	144.6	145.2
Specific gravity of soil at test temperature	2.66	2.72
Temp. Correction factor, K	0.9985	0.9984
Specific gravity of soil at 20°C	2.66	2.71
Average specific gravity of soil at 20°C	2.68	

Table A.10: Determination of specific gravity for test pit TP_3

Test Pit TP_3		
Depth, m	3	
Pycnometer no	1	2
Mass of dry soil(Ms),gm	25.00	25.00
Mass of pycnometer +water +soil(M1),gm	160.50	161.10
Test temperature of sample,°c	26.30	26.20
Mass of pycnometer +water(M2),gm	144.60	145.20
Specific gravity of soil at test temperature	2.75	2.75
Temp. Correction factor, K	0.99851	0.99854
Specific gravity of soil at 20°C	2.74	2.74
Average specific gravity of soil at 20°C	2.74	

Table A.11: Determination of specific gravity for test pit TP_6

Test Pit TP_6				
Depth, m	1.5		3	
Pycnometer no	1	2	1	2
Mass of dry soil(Ms),gm	25.00	25.00	25.00	25.00
Mass of pycnometer +water +soil(M1),gm	160.30	161.00	160.80	161.30
Test temperature of sample,°c	23.70	23.60	24.70	24.90
Mass of pycnometer +water(M2),gm	144.70	145.30	144.70	145.30
Specific gravity of soil at test temperature	2.66	2.69	2.81	2.78
Correction factor, K	0.9992	0.9992	0.9989	0.9988
Specific gravity of soil at 20°C	2.66	2.69	2.81	2.77
Average specific gravity of soil at 20°C	2.67		2.79	

Table A.12: Determination of specific gravity for test pit TP_9

Test Pit TP_9				
Depth, m	1.5		3	
Pycnometer no	1	2	1	2
Mass of dry soil(Ms),gm	25.00	25.00	25.00	25.00
Mass of pycnometer +water +soil(M1),gm	160.40	160.80	160.40	161.00
Test temperature of sample,°c	27.40	28.50	27.90	28.80
Mass of pycnometer +water(M2),gm	144.70	145.20	144.50	145.30
Specific gravity of soil at test temperature	2.69	2.66	2.75	2.69
Correction factor, K	0.9982	0.9979	0.9980	0.9978
Specific gravity of soil at 20°C	2.68	2.65	2.74	2.68
Average specific gravity of soil at 20°C	2.67		2.71	

Table A.13: Determination of specific gravity for test pit TP_11

Test Pit TP_11				
Depth, m	1.5		3	
Pycnometer no	1	2	1	2
Mass of dry soil(Ms),gm	25.00	25.00	25.00	25.00
Mass of pycnometer +water +soil(M1),gm	160.50	160.90	160.50	161.30
Test temperature of sample,°c	26.80	27.60	27.00	29.10
Mass of pycnometer +water(M2),gm	144.80	145.20	144.50	145.10
Specific gravity of soil at test temperature	2.69	2.69	2.78	2.84
Correction factor, K	0.9984	0.9981	0.9983	0.9977
Specific gravity of soil at 20°C	2.68	2.68	2.77	2.83
Average specific gravity of soil at 20°C	2.68		2.80	

Representative Liquid Limit and Plastic Limit test results

Table A.14: Liquid limit and plastic limit for test pit TP_1

Test Pit TP_1 @ 3m depth	Liquid Limit				Plastic Limit	
Trail No	1	2	3	4	1	2
Container No	A14	C52	CB	D210	TA3	D25
Mass of container, gm	11.5	15.8	30.8	13.9	15.9	15.9
Mass of cont. +wet soil, gm	32.7	32.9	50.4	34.4	19.6	20
Mass of cont. +dry soil, gm	22.1	24.2	40.3	23.7	18.5	18.8
Mass of water, gm	10.6	8.8	10.1	10.7	1.1	1.2
Mass of dry soil, gm	10.6	8.4	9.5	9.8	2.6	2.9
Water content(ω), %	100.0	105.0	106.3	109.2	42.31	41.38
No of blows	34.0	27.0	23.0	14.0	.....
Result, %	104.47				41.84	

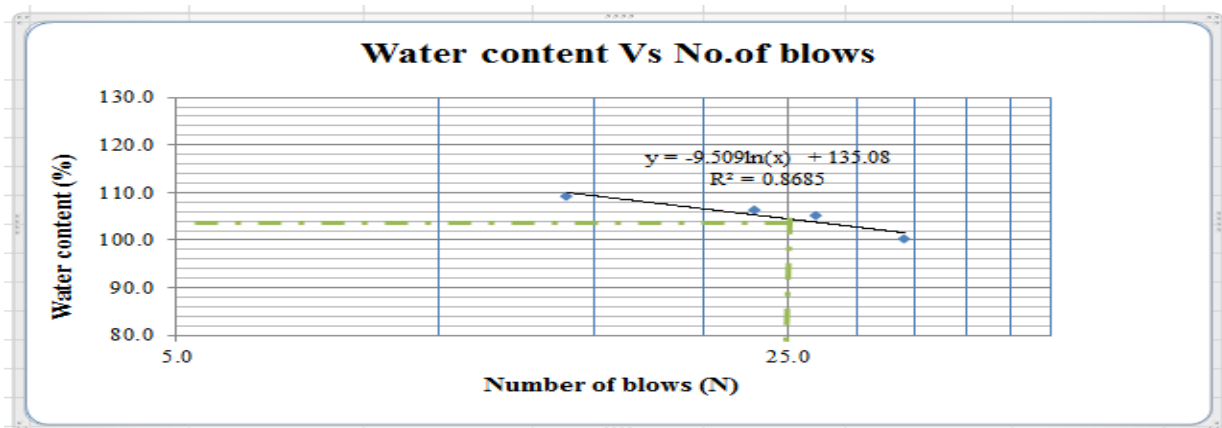


Figure A.1: Water content Vs log number of blows for test pit TP_1

Table A.15: Liquid limit and plastic limit for test pit TP_2

Test Pit TP_2 @ 3m depth	Liquid Limit				Plastic Limit	
Trail No	1.0	2.0	3.0	4.0	1	2
Container No	E5	B4	C3	Z4	TA3	D25
Mass of container, gm	15.6	15.7	15.7	14.1	15.9	15.9
Mass of cont. +wet soil, gm	39.9	41.7	32.4	40.9	20.9	20.7
Mass of cont. +dry soil, gm	28.1	28.6	23.9	27.1	19.5	19.4
Mass of water, gm	11.8	13.0	8.5	13.8	1.4	1.3
Mass of dry soil, gm	12.5	12.9	8.2	13.0	3.6	3.5
Water content(ω), %	94.4	100.5	103.4	106.2	38.89	37.14
No of blows	35.0	27.0	23.0	17.0	.....
Result, %	100.92				38.02	

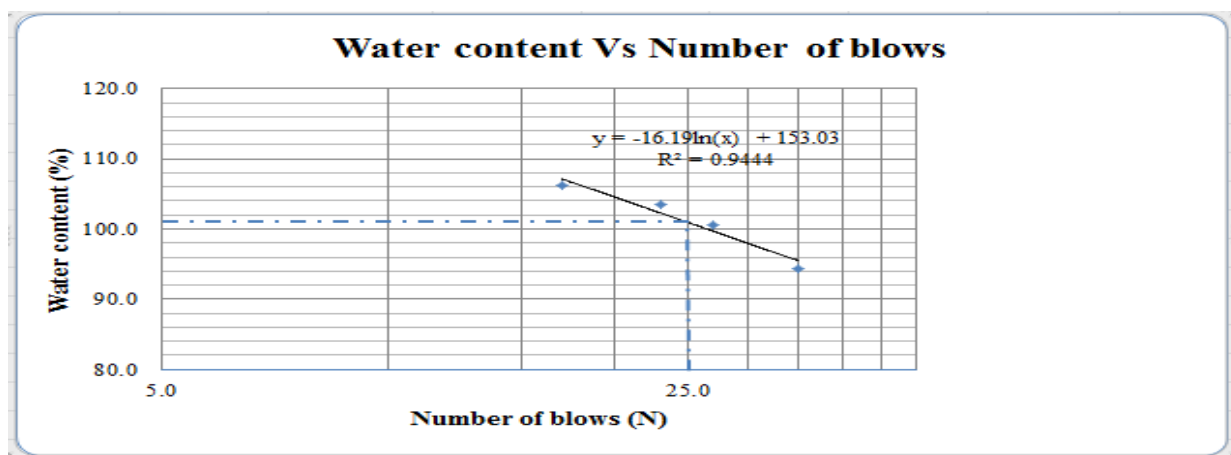


Figure A.2: Water content Vs log number of blows for test pit TP_2

Table A.16: Liquid limit and plastic limit for test pit TP_3

Test Pit TP_3 @ 3m depth	Liquid Limit				Plastic Limit	
	1.0	2.0	3.0	4.0	1	2
Trail No	1.0	2.0	3.0	4.0	1	2
Container No	A100	B25	A101	H21	D25	TA3
Mass of container, gm	15.6	15.6	11.6	15.7	15.8	15.8
Mass of cont. +wet soil, gm	32.7	37.3	34.3	37.3	22.1	21.9
Mass of cont. +dry soil, gm	24.3	26.4	22.8	26.2	20.4	20.2
Mass of water, gm	8.4	10.9	11.5	11.1	1.7	1.7
Mass of dry soil, gm	8.7	10.8	11.2	10.5	4.6	4.4
Water content(ω), %	96.6	100.9	102.7	105.7	36.96	38.64
No of blows	34.0	27.0	23.0	15.0	.....	.....
Result, %	100.91				37.80	

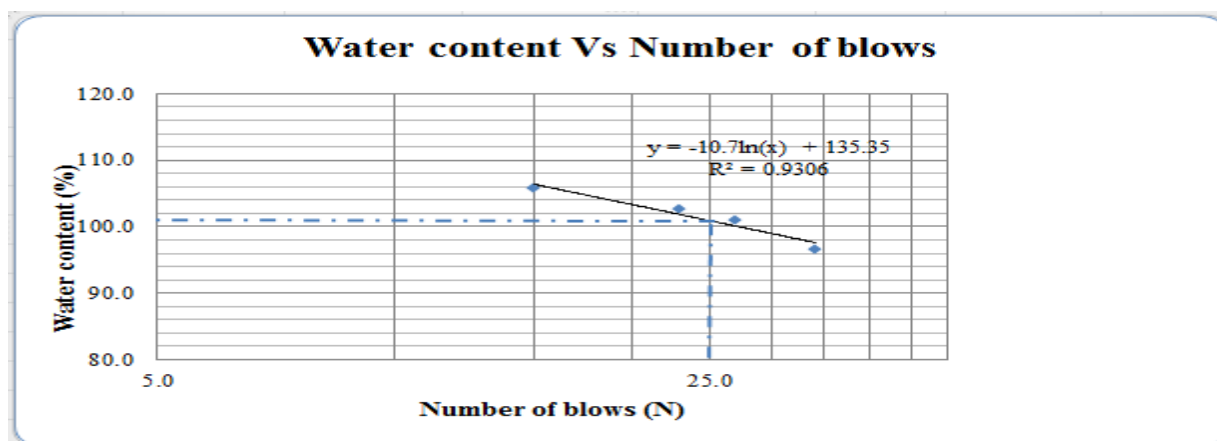


Figure A.3: Water content Vs log number of blows for test pit TP_3

Table A.17: Liquid limit and plastic limit for test pit TP_6 at 1.5m depth

Test Pit TP_6 @ 1.5m depth	Liquid Limit				Plastic Limit	
	1.0	2.0	3.0	4.0	1	2
Trail No	1.0	2.0	3.0	4.0	1	2
Container No	A3	T2	A30	A24	DA	C44
Mass of container, gm	15.9	15.5	15.5	15.7	15.7	15.8
Mass of cont. +wet soil, gm	32.7	33.4	32.0	33.7	22.4	22.8
Mass of cont. +dry soil, gm	24.7	24.6	23.8	24.6	20.6	20.9
Mass of water, gm	8.0	8.8	8.2	9.1	1.8	1.9
Mass of dry soil, gm	8.8	9.1	8.3	8.9	4.9	5.1
Water content(ω), %	90.9	96.7	98.8	102.2	36.73	37.25
No of blows	38.0	27.0	23.0	17.0	.....
Result, %	97.25				36.99	

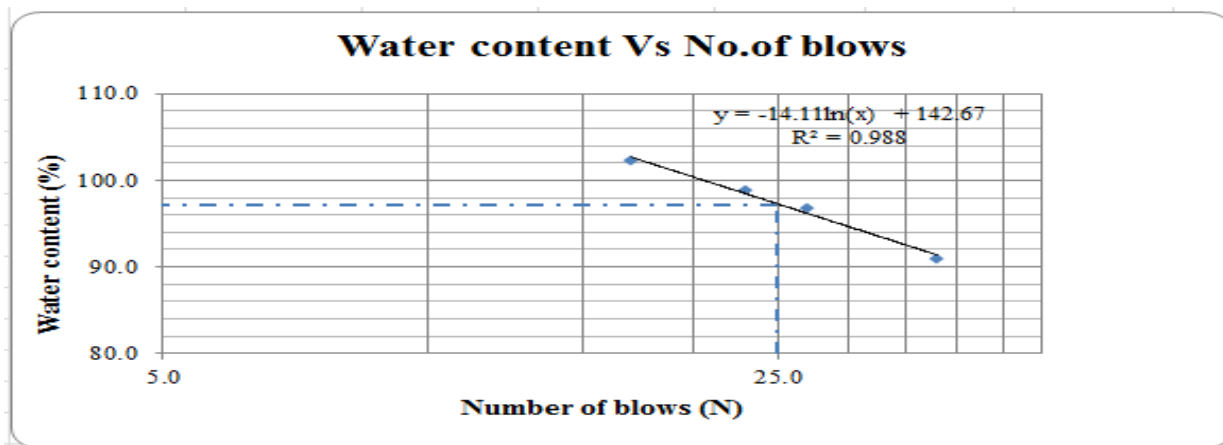


Figure A.4: Water content Vs log number of blows for test pit TP_6 at 1.5m depth

Table A.18: Liquid limit and plastic limit for test pit TP_6 at 3m depth

Test Pit TP_6 @ 3m depth	Liquid Limit				Plastic Limit	
	1	2	3	4	1	2
Trail No	1	2	3	4	1	2
Container No	D34	DA	A24	B1	D34	AL4
Mass of container, gm	15.6	15.8	15.4	15.8	15.5	15.5
Mass of cont. +wet soil, gm	32.9	36.2	33.2	34.2	22	22.4
Mass of cont. +dry soil, gm	24.6	26.3	24.5	25.0	20.3	20.6
Mass of water, gm	8.3	9.9	8.7	9.2	1.7	1.8
Mass of dry soil, gm	9.0	10.5	9.1	9.2	4.8	5.1
Water content(ω), %	92.2	94.3	95.6	100.0	35.42	35.29
No of blows	34.0	27.0	23.0	12.0	.....
Result, %	94.73				35.36	

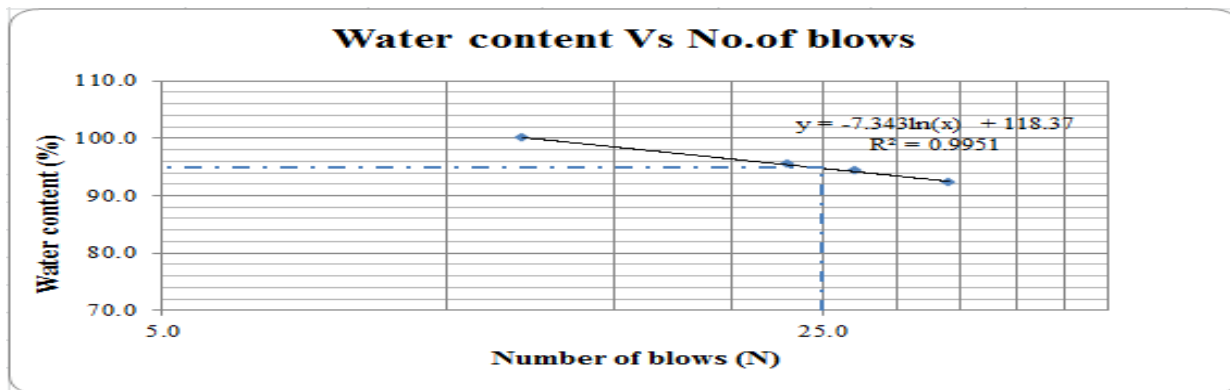


Figure A.5: Water content Vs log number of blows for test pit TP_6 at 3m depth

Table A.19: Liquid limit and plastic limit for test pit TP_9 at 1.5m depth

Test Pit TP_9 @ 1.5m depth	Liquid Limit				Plastic Limit	
Trail No	1	2	3	4	1	2
Container No	F3	N4	B4	T9	A3	MT
Mass of container, gm	15.5	15.4	15.8	15.8	15.8	15.6
Mass of cont. +wet soil, gm	33.3	32.1	31.7	33.0	22.6	21
Mass of cont. +dry soil, gm	24.6	23.8	23.7	24.2	20.7	19.5
Mass of water, gm	8.7	8.3	8.0	8.8	1.9	1.5
Mass of dry soil, gm	9.1	8.4	7.9	8.4	4.9	3.9
Water content(ω), %	95.6	98.8	101.3	104.8	38.78	38.46
No of blows	38.0	27.0	21.0	16.0	.....
Result, %	99.79				38.62	

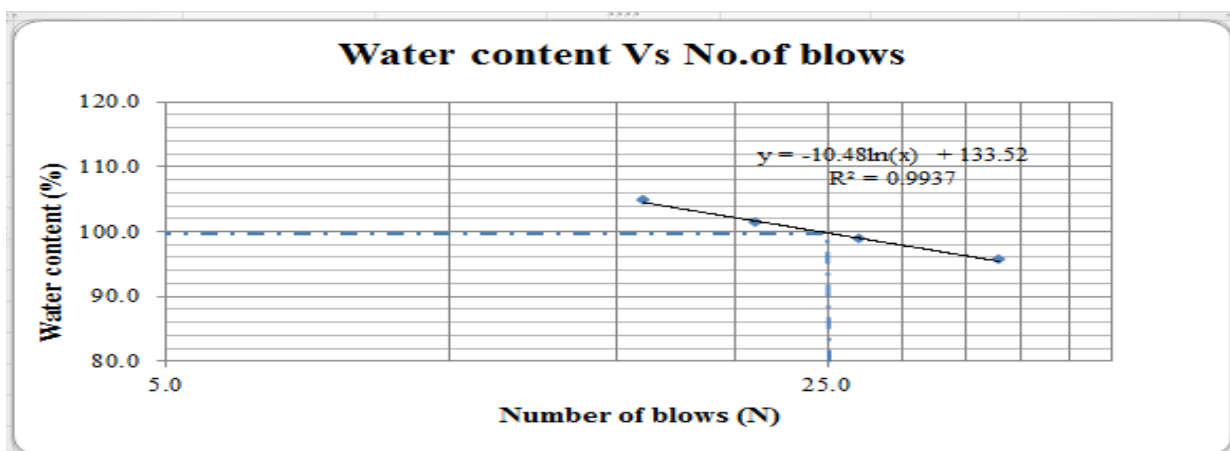


Figure A.6: Water content Vs log number of blows for test pit TP_9 at 1.5m depth

Table A.20: Liquid limit and plastic limit for test pit TP_9 at 3m depth

Test Pit TP_9 @ 3m depth	Liquid Limit				Plastic Limit	
	1	2	3	4	1	2
Trail No	1	2	3	4	1	2
Container No	IL6	SM	TA3	M10	D34	G11
Mass of container, gm	15.6	15.7	15.9	15.8	15.6	15.7
Mass of cont. +wet soil, gm	33.1	32.5	32.6	35.7	22.3	22.1
Mass of cont. +dry soil, gm	24.3	23.9	24.0	25.3	20.4	20.3
Mass of water, gm	8.8	8.6	8.6	10.4	1.9	1.8
Mass of dry soil, gm	8.7	8.2	8.1	9.5	4.8	4.6
Water content(ω), %	101.1	104.9	106.2	109.5	39.58	39.13
No of blows	35.0	27.0	23.0	17.0	.....
Result, %	105.26				39.36	

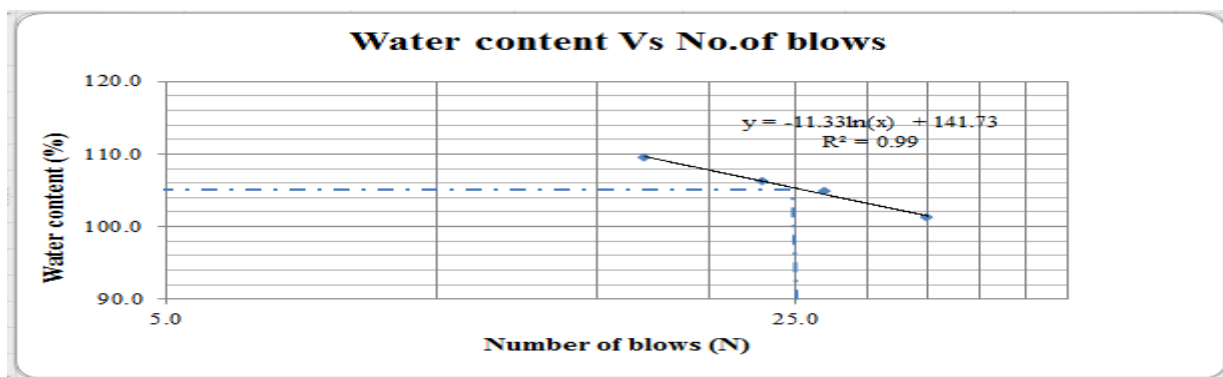


Figure A.7: Water content Vs log number of blows for test pit TP_9 at 3m depth

Table A.21: Liquid limit and plastic limit for test pit TP_11 at 1.5m depth

Test Pit TP_11 @ 1.5m depth	Liquid Limit				Plastic Limit	
	1	2	3	4	1	2
Trail No	1	2	3	4	1	2
Container No	P33	M10	B1	MT	E10	PR
Mass of container, gm	15.7	15.8	15.8	15.6	15.9	15.3
Mass of cont. +wet soil, gm	34.0	32.0	32.9	33.9	22	21.6
Mass of cont. +dry soil, gm	24.7	23.5	23.8	24.0	20.2	19.7
Mass of water, gm	9.3	8.5	9.1	9.9	1.8	1.9
Mass of dry soil, gm	9.0	7.7	8.0	8.4	4.3	4.4
Water content(ω), %	103.3	110.4	113.8	117.9	41.86	43.18
No of blows	34.0	27.0	23.0	17.0	.....
Result, %	110.89				42.52	

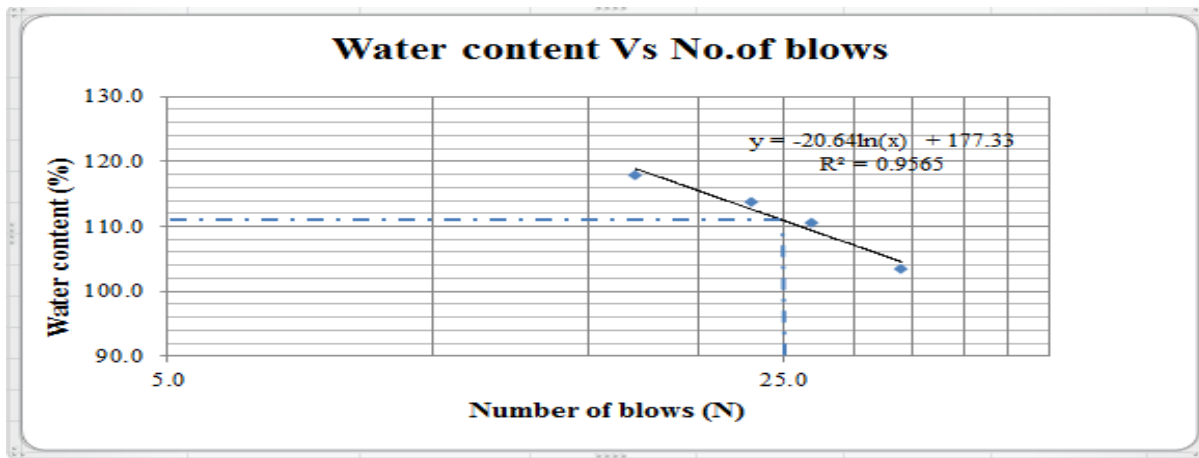


Figure A.8: Water content Vs log number of blows for test pit TP_11 at 1.5m depth

Table A.22: Liquid limit and plastic limit for test pit TP_11 at 3m depth

Test Pit TP_11 @ 3m depth	Liquid Limit				Plastic Limit	
Trail No	1	2	3	4	1	2
Container No	M41	DC2	H20	C44	G3	GH
Mass of container, gm	15.4	15.5	15.6	15.7	15.7	15.8
Mass of cont. +wet soil, gm	33.5	33.8	32.9	33.9	22.5	21.9
Mass of cont. +dry soil, gm	24.4	24.4	24.0	24.4	20.6	20.2
Mass of water, gm	9.1	9.4	8.9	9.5	1.9	1.7
Mass of dry soil, gm	9.0	8.9	8.4	8.7	4.9	4.4
Water content(ω), %	101.1	105.6	106.0	109.2	38.78	38.64
No of blows	35.0	27.0	23.0	16.0	.....
Result, %	105.19				38.71	

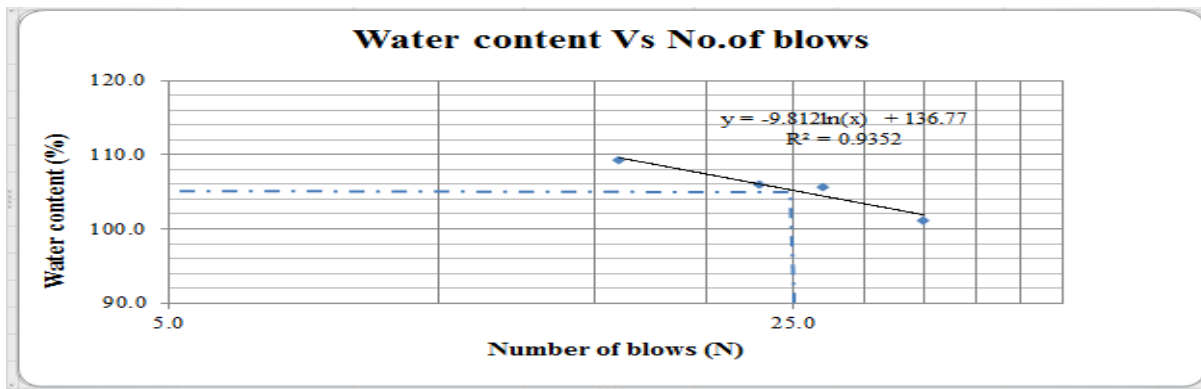


Figure A.9: Water content Vs log number of blows for test pit TP_11 at 3m depth

Representative Free Swell test results

Formula used

$$FS = \left[\frac{(V_f - V_i)}{V_i} \right] * 100\%$$

Table A.23: Free Swell test result for test pit TP_1

Test Pit TP_1		
Depth, m	3	
Sample No.	1	2
Initial volume, ml	10	10
Final volume, ml	24	26.5
Free Swell, %	140	165
Average FS, %	152.5	

Table A.24: Free Swell test result for test pit TP_2

Test Pit TP_2		
Depth, m	3	
Sample No.	1	2
Initial volume, ml	10	10
Final volume, ml	21	25.5
Free Swell, %	110	155
Average FS, %	132.5	

Table A.25: Free Swell test result for test pit TP_3

Test Pit TP_3		
Depth, m	3	
Sample No.	1	2
Initial volume, ml	10	10
Final volume, ml	27	26
Free Swell, %	170	160
Average FS, %	165	

Table A.26: Free Swell test result for test pit TP_6

Test Pit TP_6				
Depth, m	1.5		3	
Sample No.	1	2	1	2
Initial volume,ml	10	10	10	10
Final volume,ml	27	28	30	29
Free Swell,%	170	180	200	190
Average FS,%	175		195	

Table A.27: Free Swell test result for test pit TP_9

Test Pit TP_9				
Depth, m	1.5		3	
Sample No.	1	2	1	2
Initial volume,ml	10	10	10	10
Final volume,ml	22.5	22	24	25
Free Swell,%	125	120	140	150
Average FS,%	122.5		145	

Table A.28: Free Swell test result for test pit TP_11

Test Pit TP_11				
Depth, m	1.5		3	
Sample No.	1	2	1	2
Initial volume,ml	10	10	10	10
Final volume,ml	31.5	32	31.5	30.5
Free Swell,%	215	220	215	205
Average FS,%	217.5		210	

Representative Grain Size Analysis test results

Formula used

For Sieve Analysis

Mass of retained = Mass of sieve +retained - Mass of sieve

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

Cumulative percentage retained = Summation of Percentage retained at each sieve

Percentage finer = 100 - Cumulative percentage retained

For Hydrometer Analysis

Corrected Hydrometer reading (R_C) = Actual Hydrometer reading (R_A) - Composition correction

Effective depth (L), cm = $-264.52 * R_A + 280.82$

Grain size (D), mm = $K * \sqrt{\frac{L}{T}}$ Where T= Elapse time, min

K= Constant from table A.29

Percentage finer(P) = $\left\{ \left[\frac{G_s}{G_s - G_1} \right] * \frac{V}{M_s} \right\} * (R_c - G_1) * 100\%$

Where G_s =specific gravity of soil used

G_1 = specific gravity of water=1

V= volume of suspension=1000ml

M_s = Dry mass of soil =50gm

Combined Percentage finer(Pa) = $P * \frac{W_1}{W}$

Where W_1 = weight soil finer than No 200 sieve

W = Total soil mass used in combined analysis

Table A.29: Composite correction for Hydrometer readings for 151H, Hydrometer

Test temp.,c	16	18	20	22	24	26	28
Composite correction	0.0035	0.0031	0.0027	0.0023	0.0019	0.0015	0.0013

Table A.30: 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	0.01225	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

Table A.31: Sieve analysis for test pit TP_1

							W	1200
Test Pit TP_1 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of seive+ retained, gm	Mass of retained, gm	Percen. retained, %	Comm. Pecen. retained, %	Percen. finer, %	
1/2"	12.500	459.2	459.2	0.0	0.00	0.00	100.00	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1264.3	1.4	0.12	0.12	99.88	
No.8	2.360	990.1	994.2	4.1	0.34	0.46	99.54	
No.10	2.000	956.0	960.2	4.2	0.35	0.81	99.19	
No.16	1.180	894.6	900.1	5.5	0.46	1.27	98.73	
No.30	0.600	831.0	837.1	6.1	0.51	1.78	98.23	
No.40	0.425	786.1	790.2	4.1	0.34	2.12	97.88	
No.50	0.300	750.1	755.5	5.4	0.45	2.57	97.43	
No.100	0.150	778.5	784.0	5.5	0.46	3.03	96.98	
No.200	0.075	764.0	768.4	4.4	0.37	3.39	96.61	
Pan	....	735.0	735.2	0.2	.....	.....	....

Table A.32: Hydrometer analysis for test pit TP_1

								G _s	2.71
Test Pit TP_1 @ 3m depth									
Elapse time(T), min	Actual Hydromet er reading	Comp.cor rection	Corrected Hydrometer reading	Effective depth, cm	Test temp.	Coefficient (K)	Grain size(D), mm	Percentag finer(P), %	Combined Percentag finer, %
0.75	1.0320	0.00308	1.02892	7.835	18.1	0.01376	0.04448	91.61	88.50
1	1.0315	0.00308	1.02842	7.968	18.1	0.01376	0.03885	90.02	86.97
2	1.0305	0.00308	1.02742	8.232	18.1	0.01376	0.02792	86.86	83.91
4	1.0295	0.00308	1.02642	8.497	18.1	0.01337	0.01949	83.69	80.85
8	1.0285	0.00312	1.02538	8.761	17.9	0.01380	0.01444	80.39	77.67
15	1.0275	0.00314	1.02436	9.026	17.8	0.01382	0.01072	77.16	74.55
30	1.0270	0.00312	1.02388	9.158	17.9	0.01380	0.00762	75.64	73.08
60	1.0260	0.00306	1.02294	9.422	18.2	0.01375	0.00545	72.67	70.20
120	1.0250	0.00300	1.02200	9.687	18.5	0.01370	0.00389	69.69	67.32
240	1.0240	0.00276	1.02124	9.952	19.7	0.01349	0.00275	67.28	65.00
480	1.0230	0.00266	1.02034	10.216	20.2	0.01341	0.00196	64.43	62.24
1440	1.0220	0.00340	1.01860	10.481	16.5	0.01405	0.0012	58.92	56.92

Table A.33: Sieve analysis for test pit TP_2

							W	1200
Test Pit TP_2 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of +retained, gm	Mass of retained, gm	Percentage retained, %	Comm. percentage retained, %	Percen. finer, %	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1264.3	1.4	0.12	0.12	99.88	
No.8	2.360	990.1	993.4	3.3	0.27	0.39	99.61	
No.10	2.000	956.0	960.7	4.7	0.39	0.78	99.22	
No.16	1.180	894.6	898.8	4.2	0.35	1.13	98.87	
No.30	0.600	831.0	838.1	7.1	0.59	1.72	98.28	
No.40	0.425	786.1	789.4	3.3	0.27	2.00	98.00	
No.50	0.300	750.1	752.5	2.4	0.20	2.20	97.80	
No.100	0.150	778.3	782.5	4.2	0.35	2.55	97.45	
No.200	0.075	764.0	768.6	4.6	0.38	2.93	97.07	
Pan	....	735.2	735.3	0.1	.....	.....	.....

Table A.34: Hydrometer analysis for test pit TP_2

								G _s	2.68
Test Pit TP_2 @ 3m depth									
Elapse time(T), min	Actual Hydro. Reading	Compo. correction	Corrected Hydro. Reading	Effective depth, cm	Test temp.	Coefficient (K)	Grain size(D), mm	Percentage finer(P), %	Combined Percentage finer, %
0.75	1.03200	0.00310	1.02890	7.835	18.0	0.0138	0.0446	92.12	89.42
1	1.03150	0.00310	1.02840	7.968	18.0	0.0138	0.03895	90.52	87.87
2	1.03000	0.00312	1.02688	8.364	17.9	0.0138	0.02826	85.68	83.17
4	1.02900	0.00312	1.02588	8.629	17.9	0.0138	0.0203	82.49	80.07
8	1.02800	0.00310	1.02490	8.893	18.0	0.0138	0.01455	79.37	77.04
15	1.02700	0.00306	1.02394	9.158	18.2	0.0138	0.01075	76.31	74.07
30	1.02650	0.00312	1.02338	9.290	17.9	0.0138	0.00769	74.52	72.34
60	1.02550	0.00306	1.02244	9.555	18.2	0.0138	0.00549	71.53	69.43
120	1.02450	0.00292	1.02158	9.819	18.9	0.0136	0.0039	68.79	66.77
240	1.02350	0.00280	1.02070	10.084	19.5	0.0135	0.00277	65.98	64.05
480	1.02200	0.00264	1.01936	10.481	20.3	0.0134	0.00197	61.71	59.90
1440	1.02100	0.00328	1.01772	10.745	17.1	0.0140	0.00121	56.48	54.83

Table A.35: Sieve analysis for test pit TP_3

							W	1200
Test Pit TP_3 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of seive+ retained, gm	Mass of retained, gm	Percentag retained, %	Comm. percentage retained, %	Percentag finer, %	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1267.1	4.2	0.35	0.35	99.65	
No.8	2.360	990.1	993.3	3.2	0.27	0.62	99.38	
No.10	2.000	956.0	960.3	4.3	0.36	0.97	99.03	
No.16	1.180	894.6	899.9	5.3	0.44	1.42	98.58	
No.30	0.600	831.0	836.8	5.8	0.48	1.90	98.10	
No.40	0.425	786.1	790.1	4.0	0.33	2.23	97.77	
No.50	0.300	750.1	754.2	4.1	0.34	2.57	97.43	
No.100	0.150	778.5	780.9	2.4	0.20	2.77	97.23	
No.200	0.075	764.0	770.6	6.6	0.55	3.32	96.68	
Pan	.....	735.0	735.4	0.4	.....	.....	.....

Table A.36: Hydrometer analysis for test pit TP_3

								G _s	2.74
Test Pit TP_3 @ 3m depth									
Elapse time(T), min	Actual Hydromet reading	Compos. correction	Corrected Hydromet reading	Effective depth, cm	Test temp., c	Coefficien (K)	Grain size(D), mm	Percentag finer(P), %	Combined Percentag finer, %
0.75	1.03300	0.00288	1.03012	7.571	19.1	0.013403	0.0426	94.80	91.65
1	1.03250	0.00294	1.02956	7.703	18.8	0.013454	0.0373	93.03	89.94
2	1.03150	0.00292	1.02858	7.968	18.9	0.013437	0.0268	89.95	86.96
4	1.03050	0.00292	1.02758	8.232	18.9	0.013437	0.0193	86.80	83.92
8	1.02900	0.00296	1.02604	8.629	18.7	0.013471	0.0140	81.96	79.23
15	1.02750	0.00294	1.02456	9.026	18.8	0.013454	0.0104	77.30	74.73
30	1.02600	0.00294	1.02306	9.422	18.8	0.013454	0.0075	72.58	70.16
60	1.02450	0.00294	1.02156	9.819	18.8	0.013454	0.0054	67.86	65.60
120	1.02350	0.00288	1.02062	10.084	19.1	0.013403	0.0039	64.90	62.74
240	1.02200	0.00288	1.01912	10.481	19.1	0.013403	0.0028	60.18	58.18
480	1.02100	0.0027	1.01830	10.745	20.0	0.01325	0.0020	57.60	55.68
1440	1.02000	0.00338	1.01662	11.010	16.6	0.013832	0.0012	52.31	50.57

Table A.37: Sieve analysis for test pit TP_6 @ 1.5m depth

							W	1200
Test Pit TP_6 @ 1.5m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of seive +retained, gm	Mass of retained, gm	Percentag retained, %	Commul. percentage retained, %	Percentag finer,%	
1/2"	12.500	459.2	459.2	0.0	0.00	0.00	100.00	
3.8"	9.500	1164.5	1170.6	6.1	0.51	0.51	99.49	
No.4	4.750	1262.9	1275.4	12.5	1.04	1.55	98.45	
No.8	2.360	990.1	1010.7	20.6	1.72	3.27	96.73	
No.10	2.000	956.0	968.1	12.1	1.01	4.28	95.73	
No.16	1.180	894.6	908.9	14.3	1.19	5.47	94.53	
No.30	0.600	831.0	838.0	7.0	0.58	6.05	93.95	
No.40	0.425	786.1	790.8	4.7	0.39	6.44	93.56	
No.50	0.300	750.1	758.3	8.2	0.68	7.12	92.88	
No.100	0.150	778.5	783.8	5.3	0.44	7.57	92.43	
No.200	0.075	764.0	770.6	6.6	0.55	8.12	91.88	
Pan	.....	735.0	735.5	0.5	.....	.....	.....

Table A.38: Hydrometer analysis for test pit TP_6 @ 1.5m depth

							G _s	2.67	
Test Pit TP_6 @ 1.5m depth									
Elapse time(T), min	Actual Hydromet reading	Composit. correction	Corrected Hydromet er reading	Effectve depth, cm	Test temp.,c	Coefficien (K)	Grain size(D), mm	Percentag finer(P),%	Combined Percentag finer,%
0.75	1.0305	0.00182	1.02868	8.23214	24.4	0.01295	0.0429	91.67	84.23
1	1.0300	0.00182	1.02818	8.36440	24.4	0.01295	0.0375	90.08	82.76
2	1.0285	0.00178	1.02672	8.76118	24.6	0.01292	0.027	85.41	78.48
4	1.0270	0.00176	1.02524	9.15796	24.7	0.01291	0.0195	80.68	74.13
8	1.0260	0.00178	1.02422	9.42248	24.6	0.01292	0.014	77.42	71.13
15	1.0250	0.00182	1.02318	9.68700	24.4	0.01295	0.0104	74.09	68.08
30	1.0240	0.00192	1.02208	9.95152	23.9	0.01303	0.0075	70.58	64.85
60	1.0230	0.00200	1.02100	10.21604	23.5	0.01309	0.0054	67.12	61.68
120	1.0220	0.00198	1.02002	10.48056	23.6	0.01307	0.0039	63.99	58.80
240	1.0210	0.00186	1.01914	10.74508	24.2	0.01298	0.0027	61.18	56.21
480	1.0195	0.00154	1.01796	11.14186	25.8	0.01275	0.0019	57.41	52.75
1440	1.0185	0.00188	1.01662	11.40638	24.1	0.01300	0.0012	53.12	48.81

Table A.39: Sieve analysis for test pit TP_6 @ 3m depth

							W	1200
Test Pit TP_6 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of +retained, gm	Mass of retained, gm	Percentage retained, %	Commul. percentage retained, %	Percentage finer, %	
1/2"	12.500	459.2	459.2	0.0	0.00	0.00	100.00	
3.8"	9.500	1164.5	1168.2	3.7	0.31	0.31	99.69	
No.4	4.750	1262.9	1270.5	7.6	0.63	0.94	99.06	
No.8	2.360	990.1	1001.8	11.7	0.97	1.92	98.08	
No.10	2.000	956.0	966.8	10.8	0.90	2.82	97.18	
No.16	1.180	894.6	905.0	10.4	0.87	3.68	96.32	
No.30	0.600	831.0	840.6	9.6	0.80	4.48	95.52	
No.40	0.425	786.1	795.3	9.2	0.77	5.25	94.75	
No.50	0.300	750.1	761.1	11.0	0.92	6.17	93.83	
No.100	0.150	778.5	790.8	12.3	1.03	7.19	92.81	
No.200	0.075	764.0	770.6	6.6	0.55	7.74	92.26	
Pan	.....	735.0	735.6	0.6	.....	.....	.....

Table A.40: Hydrometer analysis for test pit TP_6 @ 3m depth

							G _s	2.79	
Test Pit TP_6 @ 3m depth									
Elapse time(T), min	Actual Hydromet er reading	Compos. correction	Corrected Hydromet er reading	Effective depth, cm	Test temp., c	Coefficient (K)	Grain size(D), mm	Percentage finer(P), %	Combined Percentage finer, %
0.75	1.0315	0.00188	1.02962	7.968	24.1	0.01245	0.0406	92.33	85.18
1	1.0310	0.00188	1.02912	8.100	24.1	0.01245	0.0354	90.77	83.75
2	1.0295	0.00170	1.02780	8.497	25.0	0.01232	0.0254	86.66	79.95
4	1.0280	0.00176	1.02624	8.893	24.7	0.01236	0.0184	81.80	75.46
8	1.0270	0.00184	1.02516	9.158	24.3	0.01242	0.0133	78.43	72.36
15	1.0260	0.00190	1.02410	9.422	24.0	0.01246	0.0099	75.12	69.31
30	1.0250	0.00192	1.02308	9.687	23.9	0.01247	0.0071	71.94	66.38
60	1.0235	0.00196	1.02154	10.084	23.7	0.01250	0.0051	67.14	61.95
120	1.0225	0.00206	1.02044	10.348	23.2	0.01257	0.0037	63.72	58.78
240	1.0215	0.00194	1.01956	10.613	23.8	0.01249	0.0026	60.97	56.25
480	1.0200	0.00158	1.01842	11.010	25.6	0.01224	0.0019	57.42	52.97
1440	1.0190	0.00188	1.01712	11.274	24.1	0.01245	0.0011	53.37	49.23

Table A.41: Sieve analysis for test pit TP_9 @ 1.5m depth

							W	1200
Test Pit TP_9 @ 1.5m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of +retained, gm	Mass of retained, gm	Percentage retained, %	Commul. percentage retained, %	Percentage finer, %	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1278.0	15.1	1.26	1.26	98.74	
No.8	2.360	990.1	1000.4	10.3	0.86	2.12	97.88	
No.10	2.000	956.0	963.4	7.4	0.62	2.73	97.27	
No.16	1.180	894.6	900.9	6.3	0.52	3.26	96.74	
No.30	0.600	831.0	840.7	9.7	0.81	4.07	95.93	
No.40	0.425	786.1	792.2	6.1	0.51	4.57	95.43	
No.50	0.300	750.1	758.3	8.2	0.68	5.26	94.74	
No.100	0.150	778.5	786.8	8.3	0.69	5.95	94.05	
No.200	0.075	764.0	774.3	10.3	0.86	6.81	93.19	
Pan	.....	735.0	735.2	0.2	.....	.....	.....

Table A.42: Hydrometer analysis for test pit TP_9 @ 1.5m depth

								G _s	2.67
Test Pit TP_9 @ 1.5m depth									
Elapse time(T), min	Actual Hydromet er reading	Compos. correction	Corrected Hydromet er reading	Effective depth, cm	Test temp., c	Coefficient (K)	Grain size(D), mm	Percentage finer(P), %	Combined Percentage finer, %
0.75	1.0310	0.00242	1.02858	8.100	21.4	0.01342	0.0441	91.42	85.19
1	1.0305	0.00242	1.02808	8.232	21.4	0.01342	0.0385	89.82	83.70
2	1.0295	0.00240	1.02710	8.497	21.5	0.01340	0.0276	86.68	80.78
4	1.0285	0.00240	1.02610	8.761	21.5	0.01340	0.0198	83.48	77.80
8	1.0275	0.00244	1.02506	9.026	21.3	0.01343	0.0143	80.16	74.70
15	1.0265	0.00238	1.02412	9.290	21.6	0.01338	0.0105	77.15	71.90
30	1.0255	0.00246	1.02304	9.555	21.2	0.01345	0.0076	73.70	68.68
60	1.0240	0.00240	1.02160	9.952	21.5	0.01340	0.0055	69.09	64.39
120	1.0230	0.00236	1.02064	10.216	21.7	0.01337	0.0039	66.02	61.52
240	1.0215	0.00206	1.01944	10.613	23.2	0.01314	0.0028	62.18	57.95
480	1.0205	0.00206	1.01844	10.877	23.2	0.01314	0.002	58.98	54.97
1440	1.0195	0.00214	1.01736	11.142	22.8	0.01320	0.0012	55.53	51.75

Table A.43: Sieve analysis for test pit TP_9 @ 3m depth

							W	1200
Test Pit TP_9 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of seive +retained, gm	Mass of retained, gm	Percentage retained,%	Commul. pecentage retained, %	Percentag e finer,%	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1270.7	7.8	0.65	0.65	99.35	
No.8	2.360	990.1	1000.5	10.4	0.87	1.52	98.48	
No.10	2.000	956.0	960.7	4.7	0.39	1.91	98.09	
No.16	1.180	894.6	901.0	6.4	0.53	2.44	97.56	
No.30	0.600	831.0	841.1	10.1	0.84	3.28	96.72	
No.40	0.425	786.1	792.2	6.1	0.51	3.79	96.21	
No.50	0.300	750.1	760.8	10.7	0.89	4.68	95.32	
No.100	0.150	778.5	788.1	9.6	0.80	5.48	94.52	
No.200	0.075	764.0	773.4	9.4	0.78	6.27	93.73	
Pan	.....	735.0	735.1	0.1	.....	.....	.....

Table A.44: Hydrometer analysis for test pit TP_9 @ 3m depth

									G _s	2.71
Test Pit TP_9 @ 3m depth										
Elapse time(T), min	Actual Hydromet er reading	Compos. correction	Corrected Hydromet er reading	Effective depth,cm	Test temp.,c	Coefficient (K)	Grain size(D), mm	Percentage finer(P),%	Combined Percentage finer,%	
0.75	1.0320	0.00248	1.02952	7.835	21.1	0.01326	0.0429	93.53	87.67	
1	1.0315	0.00248	1.02902	7.968	21.1	0.01326	0.0374	91.94	86.18	
2	1.0300	0.00252	1.02748	8.364	20.9	0.01330	0.0272	87.06	81.61	
4	1.0290	0.00254	1.02646	8.629	20.8	0.01331	0.0196	83.83	78.58	
8	1.0280	0.00254	1.02546	8.893	20.8	0.01331	0.014	80.66	75.61	
15	1.0270	0.00258	1.02442	9.158	20.6	0.01334	0.0104	77.37	72.52	
30	1.0260	0.00256	1.02344	9.422	20.7	0.01333	0.0075	74.26	69.61	
60	1.0250	0.00244	1.02256	9.687	21.3	0.01323	0.0053	71.48	67.00	
120	1.0235	0.00244	1.02106	10.084	21.3	0.01323	0.0038	66.72	62.54	
240	1.0220	0.00214	1.01986	10.481	22.8	0.01300	0.0027	62.92	58.98	
480	1.0205	0.00206	1.01844	10.877	23.2	0.01294	0.0019	58.42	54.76	
1440	1.0190	0.00214	1.01686	11.274	22.8	0.01300	0.0012	53.42	50.07	

Table A.45: Sieve analysis for test pit TP_11 @ 1.5m depth

							W	1200
Test Pit TP_11 @ 1.5m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of +retained, gm	Mass of retained, gm	Percentage retained, %	Commul. percentage retained, %	Percentage finer, %	
1/2"	12.500	459.2	459.2	0.0	0.00	0.00	100.00	
3.8"	9.500	1164.5	1164.5	0.0	0.00	0.00	100.00	
No.4	4.750	1262.9	1268.4	5.5	0.46	0.46	99.54	
No.8	2.360	990.1	996.1	6.0	0.50	0.96	99.04	
No.10	2.000	956.0	963.7	7.7	0.64	1.60	98.40	
No.16	1.180	894.6	900.5	5.9	0.49	2.09	97.91	
No.30	0.600	831.0	837.9	6.9	0.57	2.67	97.33	
No.40	0.425	786.1	792.3	6.2	0.52	3.18	96.82	
No.50	0.300	750.1	758.1	8.0	0.67	3.85	96.15	
No.100	0.150	778.5	786.2	7.7	0.64	4.49	95.51	
No.200	0.075	764.0	770.4	6.4	0.53	5.03	94.98	
Pan		735.0	735.1	0.1				

Table A.46: Hydrometer analysis for test pit TP_11 @ 1.5m depth

							G _s	2.68	
Test Pit TP_11 @ 1.5m depth									
Elapse time(T), min	Actual Hydromet er reading	Compos. correction	Corrected Hydromet er reading	Effective depth, cm	Test temp., c	Coefficient (K)	Grain size(D), mm	Percentage finer(P), %	Combined Percentage finer, %
0.75	1.0320	0.00248	1.02952	7.835	21.1	0.01326	0.0429	94.11	89.38
1	1.0315	0.00248	1.02902	7.968	21.1	0.01326	0.0374	92.52	87.87
2	1.0305	0.00232	1.02818	8.232	21.9	0.01314	0.0267	89.84	85.32
4	1.0295	0.00234	1.02716	8.497	21.8	0.01315	0.0192	86.59	82.24
8	1.0290	0.00234	1.02666	8.629	21.8	0.01315	0.0137	84.99	80.72
15	1.0280	0.00230	1.02570	8.893	22.0	0.01312	0.0101	81.93	77.82
30	1.0270	0.00232	1.02468	9.158	21.9	0.01314	0.0073	78.68	74.73
60	1.0260	0.00230	1.02370	9.422	22.0	0.01312	0.0052	75.56	71.76
120	1.0250	0.00248	1.02252	9.687	21.1	0.01326	0.0038	71.79	68.19
240	1.0240	0.00210	1.02190	9.952	23.0	0.01297	0.0026	69.82	66.31
480	1.0230	0.00188	1.02112	10.216	24.1	0.01281	0.0019	67.33	63.95
1440	1.0220	0.00274	1.01926	10.481	19.8	0.01347	0.0011	61.40	58.32

Table A.47: Sieve analysis for test pit TP_11 @ 3m depth

							W	1200
Test Pit TP_11 @ 3m depth								
Sieve No	Sieve opening, mm	Mass of sieve, gm	Mass of +retained, gm	Mass of retained, gm	Percentage retained, %	Commul. pecentage retained, %	Percentage finer, %	
1/2"	12.500	459.2	459.2	0.0	0.00	0.00	100.00	
3.8"	9.500	1164.5	1170.7	6.2	0.52	0.52	99.48	
No.4	4.750	1262.9	1269.7	6.8	0.57	1.08	98.92	
No.8	2.360	990.1	996.8	6.7	0.56	1.64	98.36	
No.10	2.000	956.0	961.7	5.7	0.48	2.12	97.88	
No.16	1.180	894.6	899.7	5.1	0.43	2.54	97.46	
No.30	0.600	831.0	839.4	8.4	0.70	3.24	96.76	
No.40	0.425	786.1	795.2	9.1	0.76	4.00	96.00	
No.50	0.300	750.1	756.3	6.2	0.52	4.52	95.48	
No.100	0.150	778.5	782.7	4.2	0.35	4.87	95.13	
No.200	0.075	764.0	770.2	6.2	0.52	5.38	94.62	
Pan		735.0	735.1	0.1				

Table A.48: Hydrometer analysis for test pit TP_11 @ 3m depth

							G _s	2.80	
Test Pit TP_11 @ 3m depth									
Elapse time(T), min	Actual Hydromet er reading	Compos. correction	Corrected Hydromet er reading	Effective depth, cm	Test temp., c	Coefficient (K)	Grain size(D), mm	Percentage finer(P), %	Combined Percentage finer, %
0.75	1.0330	0.00242	1.03058	7.571	21.4	0.01285	0.0408	95.07	89.95
1	1.0325	0.00242	1.03008	7.703	21.4	0.01285	0.0357	93.51	88.48
2	1.0315	0.00242	1.02908	7.968	21.4	0.01285	0.0256	90.41	85.54
4	1.0305	0.00242	1.02808	8.232	21.4	0.01285	0.0184	87.30	82.60
8	1.0300	0.00242	1.02758	8.364	21.4	0.01285	0.0131	85.74	81.13
15	1.0290	0.00240	1.02660	8.629	21.5	0.01284	0.0097	82.70	78.24
30	1.0280	0.00236	1.02564	8.893	21.7	0.01281	0.007	79.71	75.42
60	1.0270	0.00236	1.02464	9.158	21.7	0.01281	0.005	76.60	72.48
120	1.0265	0.00236	1.02414	9.290	21.7	0.01281	0.0036	75.05	71.01
240	1.0255	0.00214	1.02336	9.555	22.8	0.01264	0.0025	72.62	68.71
480	1.0245	0.00184	1.02266	9.819	24.3	0.01242	0.0018	70.45	66.65
1440	1.0240	0.00278	1.02122	9.952	19.6	0.01313	0.0011	65.97	62.42

Representative Bulk and Dry Density test results

Formula used

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

Volume of the ring = $(\Pi * D^2 / 4) * H = 39.27 \text{ cm}^3$

Where: - D= Diameter of ring=50mm

H= Height of ring=20mm

Bulk density = Mass of soil / Volume of the ring

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

Table A.49: Bulk and dry density analysis for test pit TP_1, TP_2, TP_3, TP_6 , TP_9 and TP_11

Test pit	TP_1	TP_2	TP_3	TP_6 @1.5m	TP_6 @3m	TP_9 @1.5m	TP_9 @3m	TP_11 @1.5m	TP_11 @3m
Mass of ring, gm	37.60	68.70	37.60	37.60	37.60	37.60	37.60	37.60	37.60
Mass of ring+soil, gm	107.10	132.60	104.80	105.80	108.30	105.00	104.70	108.80	108.00
Mass of soil, gm	69.50	63.90	67.20	68.20	70.70	67.40	67.10	71.20	70.40
Volume of the ring, cm^3	39.27	39.27	39.27	39.27	39.27	39.27	39.27	39.27	39.27
Initial Water content, %	44.55	44.93	45.02	45.17	42.63	44.31	45.33	39.27	36.76
Final Water content, %	42.47	37.27	38.38	47.19	43.94	54.55	49.01	41.24	43.10
Bulk density, gm/cm^3	1.770	1.627	1.711	1.737	1.800	1.716	1.709	1.813	1.793
Dry density, gm/cm^3	1.224	1.123	1.180	1.196	1.262	1.189	1.176	1.302	1.311

Representative Swelling Pressure test results

Formula used

$$A = \Pi * D^2 / 4 = 19.635 \text{cm}^2$$

Where: - D= Diameter of ring = 5cm

A= Area of the ring

Seating load = 7kpa

$$e_o = \frac{H_i - H_s}{H_s}$$

Where: - e_o = Initial void ratio

H_i = Height of sample = 20mm

H_s = Height of solid = $\frac{M_s}{A * G_s * \rho_w}$

M_s = Mass of dry specimen after test

ρ_w = Density of water = 1gm/cm^3

G_s = Specific gravity of specimen

$$H_f = H_i - \Sigma \Delta H$$

$$H_v = H_f - H_s$$

$$\Delta e = \frac{\Delta H}{H_s}$$

Where: - ΔH = Final dial reading – Initial dial reading at each loading

H_f = Height of specimen after test

H_v = Height of void

Table A.50: Consolidation dial reading for test pit TP_1

Initial dial reading=1.6mm						
TP_1						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	0.834	1.076	1.346	1.712	2.284	3.036
0.1	0.906	1.150	1.454	1.878	2.450	3.144
0.25	0.924	1.162	1.476	1.896	2.462	3.172
0.5	0.942	1.168	1.482	1.912	2.484	3.184
1	0.958	1.174	1.488	1.916	2.498	3.194
2	0.972	1.178	1.496	1.950	2.502	3.212
4	0.984	1.190	1.512	1.962	2.524	3.236
8	0.994	1.208	1.532	1.992	2.562	3.272
15	1.008	1.228	1.556	2.022	2.602	3.316
30	1.022	1.248	1.578	2.064	2.658	3.388
60	1.034	1.270	1.608	2.112	2.732	3.488
120	1.048	1.290	1.640	2.162	2.822	3.614
240	1.058	1.312	1.674	2.218	2.930	3.780
480	1.066	1.326	1.696	2.252	2.986	3.900
1440	1.076	1.346	1.712	2.284	3.036	3.996

Table A.51: Swelling pressure analysis for test pit TP_1

Pressure, kpa	ΔH (mm)	Cummula. ΔH (mm)	$H_f = H_i - \Sigma \Delta H$, mm	$H_v = H_f - H_s$	$e_f = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-0.766	-0.766	20.766	11.66	1.281	-0.084	1.281
50	0.242	-0.524	20.524	11.419	1.254	-0.058	1.254
100	0.270	-0.254	20.254	11.149	1.224	-0.028	1.224
200	0.366	0.112	19.888	10.783	1.184	0.012	1.184
400	0.572	0.684	19.316	10.211	1.121	0.075	1.121
800	0.752	1.436	18.564	9.459	1.039	0.158	1.039
1600	0.960	2.396	17.604	8.499	0.933	0.263	0.933

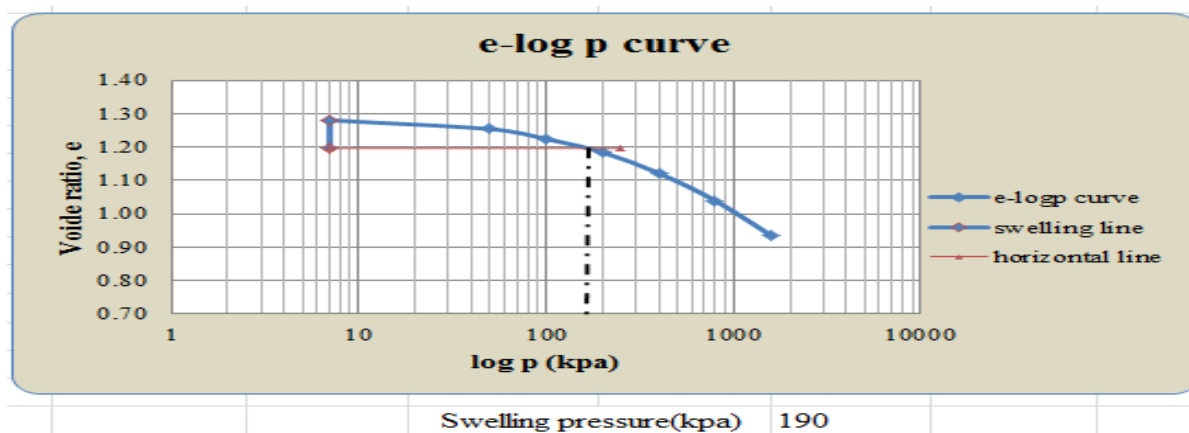


Figure A.10: Determination of swelling pressure from e-log p curve for test pit TP_1

Table A.52: Consolidation dial reading for test pit TP_2

Setting load dial reading=2mm						
TP_2						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
Time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	1.254	1.458	1.822	2.426	3.116	3.930
0.1	1.344	1.544	2.044	2.670	3.334	4.050
0.25	1.352	1.566	2.086	2.714	3.356	4.074
0.5	1.356	1.594	2.122	2.732	3.378	4.090
1	1.360	1.632	2.144	2.756	3.404	4.102
2	1.366	1.656	2.172	2.782	3.428	4.122
4	1.374	1.682	2.196	2.808	3.454	4.144
8	1.378	1.702	2.218	2.836	3.488	4.174
15	1.384	1.730	2.246	2.864	3.526	4.216
30	1.394	1.750	2.280	2.898	3.576	4.270
60	1.402	1.768	2.316	2.948	3.640	4.350
120	1.422	1.782	2.356	2.996	3.716	4.470
240	1.436	1.796	2.390	3.056	3.836	4.590
480	1.450	1.810	2.414	3.084	3.880	4.698
1440	1.458	1.822	2.426	3.116	3.930	4.798

Table A.53: Swelling pressure analysis for test pit TP_2

Pressure, kpa	ΔH (mm)	Cummula. ΔH (mm)	$H_f = H_i - \Sigma \Delta H_s$, mm	$H_v = H_f - H_s$	$e_f = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-0.746	-0.746	20.746	10.61	1.047592	-0.07363	1.05
50	0.204	-0.542	20.542	10.410	1.027458	-0.05349	1.03
100	0.364	-0.178	20.178	10.046	0.991531	-0.01757	0.99
200	0.604	0.426	19.574	9.442	0.931918	0.042045	0.93
400	0.69	1.116	18.884	8.752	0.863816	0.110147	0.86
800	0.814	1.930	18.070	7.938	0.783476	0.190487	0.78
1600	0.868	2.798	17.202	7.070	0.697806	0.276157	0.70

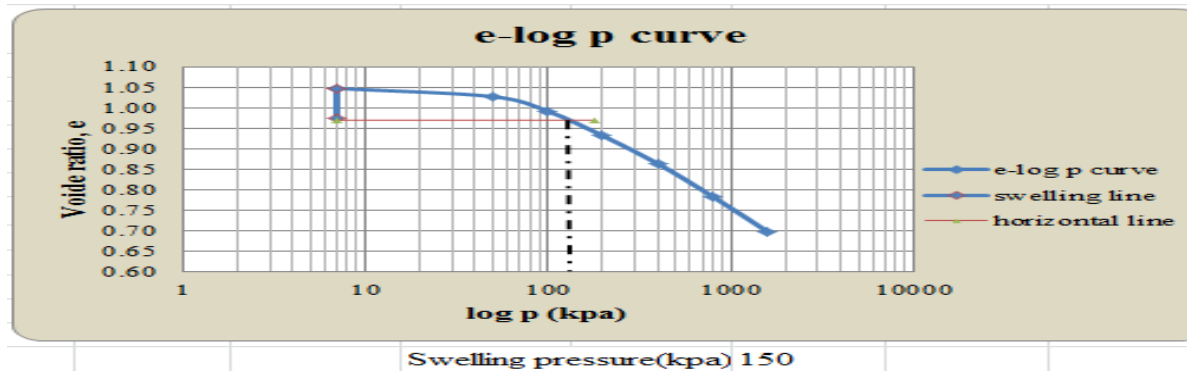


Figure A.11: Determination of swelling pressure from e-log p curve for test pit TP_2

Table A.54: Consolidation dial reading for test pit TP_3

Initial dial reading=4.4						
TP_3						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
Time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	4.030	4.146	4.308	4.630	5.112	5.820
0.1	4.044	4.164	4.382	4.708	5.184	5.852
0.25	4.050	4.182	4.398	4.732	5.226	5.874
0.5	4.058	4.190	4.404	4.750	5.236	5.896
1	4.070	4.198	4.416	4.762	5.248	5.910
2	4.076	4.204	4.430	4.780	5.262	5.922
4	4.082	4.212	4.440	4.798	5.278	5.944
8	4.086	4.220	4.456	4.830	5.310	5.996
15	4.094	4.228	4.470	4.856	5.340	6.020
30	4.106	4.236	4.490	4.890	5.412	6.096
60	4.114	4.248	4.516	4.930	5.466	6.170
120	4.122	4.264	4.552	4.984	5.590	6.266
240	4.132	4.280	4.584	5.040	5.690	6.330
480	4.138	4.294	4.610	5.084	5.758	6.378
1440	4.146	4.308	4.630	5.112	5.820	6.414

Table A.55: Swelling pressure analysis for test pit TP_3

Pressure, kpa	$\Delta H(\text{mm})$	Cummula. $\Delta H(\text{mm})$	$H_f = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_f - H_s$	$e_r = H_v/H_s$	$\Delta e = \Delta H/H_s$	$e = e_o - \Delta e$
7	-0.37	-0.37	20.37	11.18	1.2165	-0.04026	1.22
50	0.116	-0.254	20.254	11.06	1.203906	-0.02764	1.20
100	0.162	-0.092	20.092	10.90	1.186278	-0.01001	1.19
200	0.322	0.230	19.770	10.58	1.15124	0.025027	1.15
400	0.482	0.712	19.288	10.10	1.098792	0.077475	1.10
800	0.708	1.420	18.580	9.39	1.021752	0.154515	1.02
1600	0.594	2.014	17.986	8.80	0.957117	0.21915	0.96

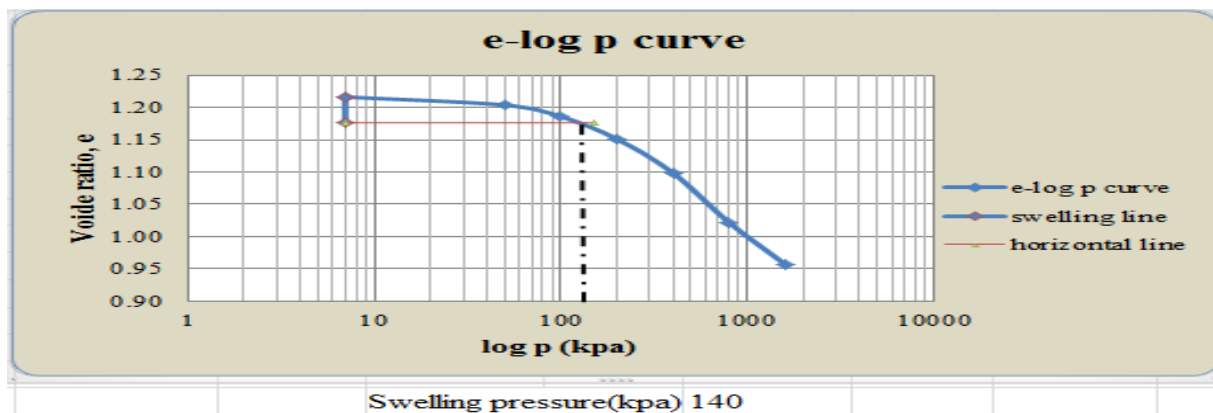


Figure A.12: Determination of swelling pressure from e-log p curve for test pit TP_3

Table A.56: Consolidation dial reading for test pit TP_6 at depth of 1.5m

Initial dial reading=6.8						
TP_6 @ 1.5m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
Time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	5.958	6.118	6.610	7.024	7.670	8.322
0.1	5.964	6.270	6.680	7.130	7.704	8.430
0.25	5.980	6.318	6.730	7.174	7.742	8.442
0.5	6.004	6.338	6.744	7.196	7.782	8.452
1	6.022	6.356	6.754	7.216	7.798	8.468
2	6.038	6.378	6.770	7.236	7.830	8.492
4	6.046	6.400	6.786	7.258	7.858	8.526
8	6.054	6.428	6.804	7.294	7.894	8.602
15	6.060	6.446	6.828	7.316	7.934	8.682
30	6.072	6.472	6.848	7.350	8.020	8.736
60	6.078	6.498	6.872	7.412	8.074	8.842
120	6.090	6.532	6.908	7.476	8.150	8.978
240	6.102	6.570	6.958	7.564	8.230	9.136
480	6.112	6.596	6.990	7.622	8.282	9.264
1440	6.118	6.610	7.024	7.670	8.322	9.314

Table A.57: Swelling pressure analysis for test pit TP_6 at depth of 1.5m

Pressure, kpa	$\Delta H(\text{mm})$	Cummula. $\Delta H(\text{mm})$	$H_r = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_r - H_s$	$e_r = H_v/H_s$	$\Delta e = \Delta H/H_s$	$e = e_o - \Delta e$
7	-0.842	-0.842	20.842	11.67	1.273026	-0.09183	1.27
50	0.160	-0.682	20.682	11.513	1.255577	-0.07438	1.26
100	0.492	-0.190	20.190	11.021	1.201919	-0.02072	1.20
200	0.414	0.224	19.776	10.607	1.156768	0.024429	1.16
400	0.646	0.870	19.130	9.961	1.086316	0.094882	1.09
800	0.652	1.522	18.478	9.309	1.015209	0.165989	1.02
1600	0.992	2.514	17.486	8.317	0.907021	0.274177	0.91

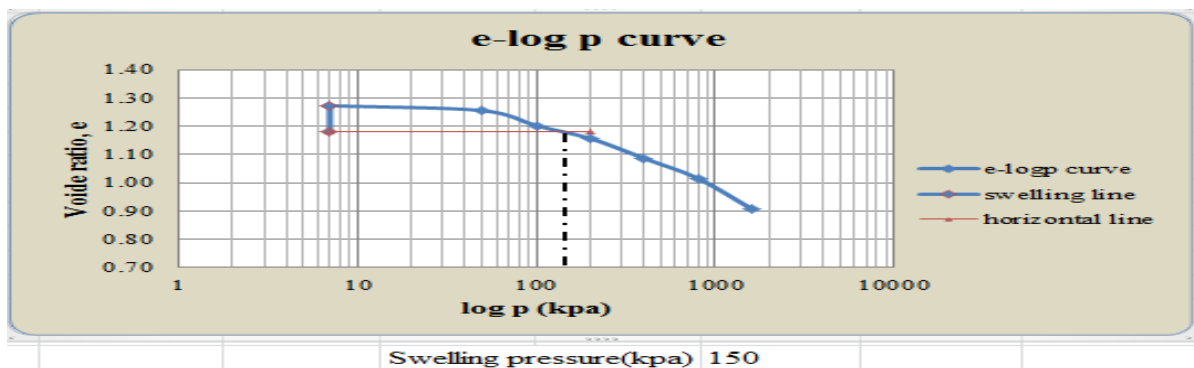


Figure A.13: Determination of swelling pressure from e-log p curve for test pit TP_6 at depth of 1.5m

Table A.58: Consolidation dial reading for test pit TP_6 at depth of 3m

TP_6 @ 3m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	1.224	1.496	1.754	2.118	2.692	3.438
0.1	1.306	1.55	1.854	2.278	2.85	3.544
0.25	1.324	1.562	1.876	2.296	2.862	3.572
0.5	1.342	1.568	1.882	2.312	2.884	3.584
1	1.358	1.574	1.888	2.316	2.898	3.594
2	1.372	1.578	1.896	2.35	2.902	3.612
4	1.384	1.59	1.912	2.362	2.924	3.636
8	1.394	1.608	1.932	2.392	2.962	3.672
15	1.408	1.628	1.956	2.422	3.002	3.716
30	1.422	1.648	1.978	2.464	3.058	3.788
60	1.438	1.67	2.008	2.512	3.132	3.888
120	1.454	1.69	2.04	2.562	3.222	4.014
240	1.47	1.712	2.074	2.618	3.33	4.184
480	1.484	1.726	2.096	2.652	3.386	4.304
1440	1.496	1.752	2.118	2.692	3.438	4.39

Table A.59: Swelling pressure analysis for test pit TP_6 at depth of 3m

Pressure, kpa	$\Delta H(\text{mm})$	Cummul. $\Delta H(\text{mm})$	$H_r = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_r - H_s$	$e_r = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-0.976	-0.976	20.976	12.09	1.360	-0.110	1.360
50	0.272	-0.704	20.704	11.815	1.329	-0.079	1.329
100	0.256	-0.448	20.448	11.559	1.300	-0.050	1.300
200	0.364	-0.084	20.084	11.195	1.259	-0.009	1.259
400	0.574	0.490	19.510	10.621	1.195	0.055	1.195
800	0.746	1.236	18.764	9.875	1.111	0.139	1.111
1600	0.952	2.188	17.812	8.923	1.004	0.246	1.004

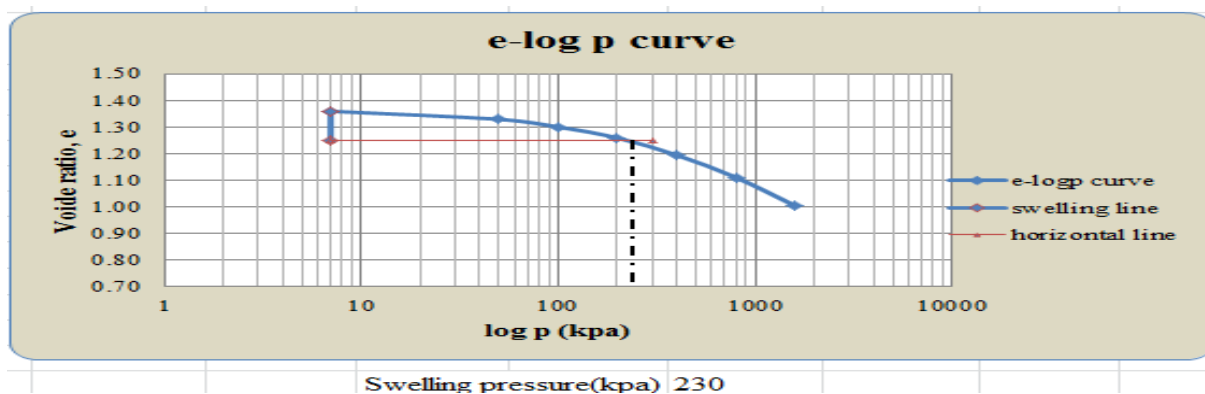


Figure A.14: Determination of swelling pressure from e-log p curve for test pit TP_6 at depth of 3m

Table A.60: Consolidation dial reading for test pit TP_9 at depth of 1.5m

Initial dial reading=7.4						
TP_9 @ 1.5m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	6.448	6.964	7.258	7.834	8.368	9.022
0.1	6.570	7.020	7.390	7.936	8.404	9.110
0.25	6.600	7.060	7.456	7.950	8.450	9.122
0.5	6.620	7.074	7.482	7.960	8.470	9.134
1	6.636	7.086	7.500	7.984	8.490	9.148
2	6.650	7.100	7.522	8.004	8.502	9.172
4	6.668	7.116	7.542	8.028	8.524	9.206
8	6.688	7.132	7.570	8.056	8.562	9.288
15	6.698	7.148	7.590	8.072	8.602	9.356
30	6.724	7.170	7.624	8.104	8.680	9.416
60	6.768	7.190	7.668	8.160	8.732	9.502
120	6.810	7.210	7.710	8.208	8.802	9.638
240	6.894	7.232	7.762	8.270	8.886	9.824
480	6.930	7.248	7.796	8.320	8.962	9.924
1440	6.964	7.258	7.834	8.368	9.022	9.994

Table A.61: Swelling pressure analysis for test pit TP_9 at depth of 1.5m

Pressure, kpa	ΔH (mm)	Cummulat. ΔH (mm)	$H_r = H_i - \Sigma \Delta H_s$, mm	$H_v = H_r - H_s$	$e_r = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-0.952	-0.952	20.952	12.555	1.495	-0.113	1.495
50	0.516	-0.436	20.436	12.039	1.434	-0.052	1.434
100	0.294	-0.142	20.142	11.745	1.399	-0.017	1.399
200	0.576	0.434	19.566	11.169	1.330	0.052	1.330
400	0.534	0.968	19.032	10.635	1.266	0.115	1.266
800	0.654	1.622	18.378	9.981	1.189	0.193	1.189
1600	0.972	2.594	17.406	9.009	1.073	0.309	1.073

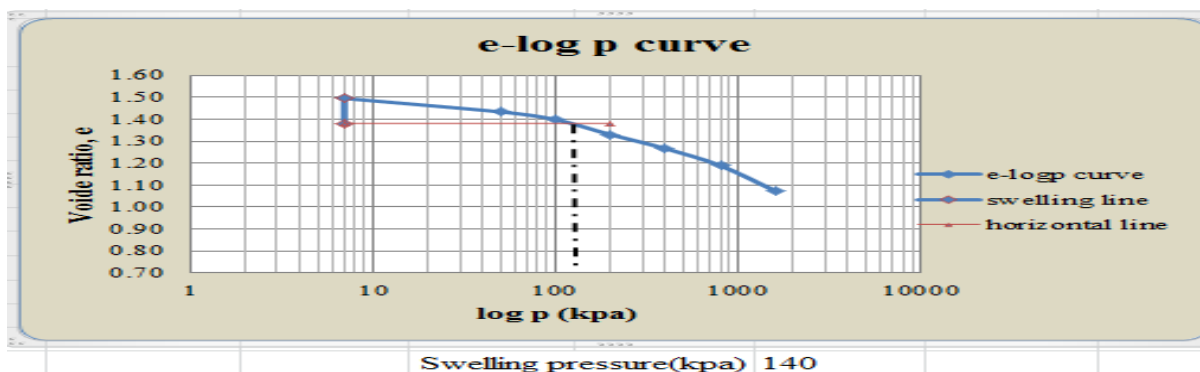


Figure A.15: Determination of swelling pressure from e-log p curve for test pit TP_9 at depth of 1.5m

Table A.62: Consolidation dial reading for test pit TP_9 at depth of 3m

Initial dial reading=6.6						
TP_9 @ 3m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	5.9820	6.2780	6.5440	6.992	7.652	8.574
0.1	6.102	6.354	6.702	7.234	7.934	8.744
0.25	6.124	6.362	6.73	7.254	7.97	8.792
0.5	6.132	6.376	6.742	7.286	7.992	8.814
1	6.144	6.386	6.754	7.306	8.02	8.824
2	6.152	6.392	6.772	7.336	8.05	8.836
4	6.164	6.406	6.792	7.362	8.086	8.858
8	6.176	6.422	6.816	7.398	8.134	8.892
15	6.188	6.43	6.838	7.43	8.176	8.982
30	6.216	6.438	6.864	7.47	8.228	9.056
60	6.236	6.454	6.878	7.512	8.294	9.15
120	6.254	6.492	6.904	7.558	8.38	9.272
240	6.266	6.518	6.95	7.6002	8.454	9.398
480	6.272	6.534	6.976	7.63	8.51	9.476
1440	6.278	6.544	6.992	7.652	8.574	9.556

Table A.63: Swelling pressure analysis for test pit TP_9 at depth of 3m

Pressure, kpa	$\Delta H(\text{mm})$	Cummula. $\Delta H(\text{mm})$	$H_r = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_r - H_s$	$e_r = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-0.618	-0.618	20.618	12.111	1.424	-0.073	1.424
50	0.296	-0.322	20.322	11.815	1.389	-0.038	1.389
100	0.266	-0.056	20.056	11.549	1.358	-0.007	1.358
200	0.448	0.392	19.608	11.101	1.305	0.046	1.305
400	0.660	1.052	18.948	10.441	1.227	0.124	1.227
800	0.922	1.974	18.026	9.519	1.119	0.232	1.119
1600	0.982	2.956	17.044	8.537	1.004	0.347	1.004

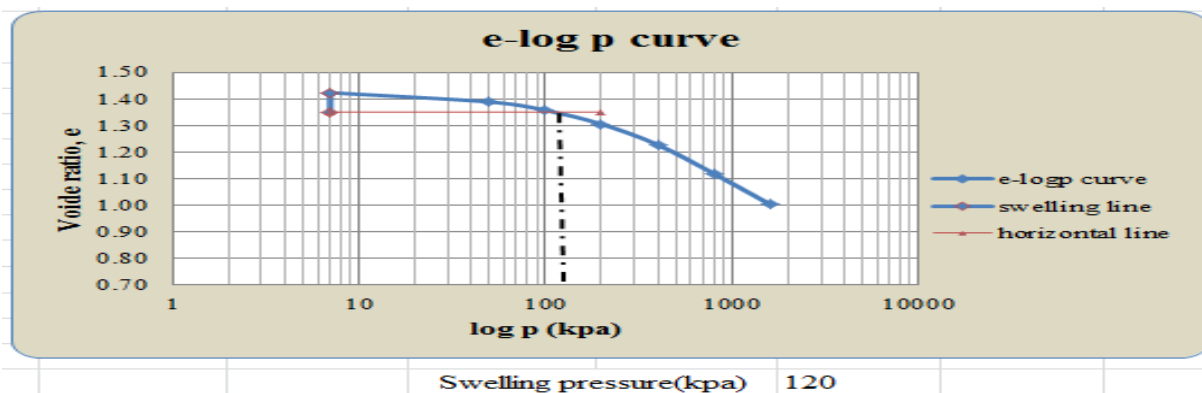


Figure A.16: Determination of swelling pressure from e-log p curve for test pit TP_9 at depth of 3m

Table A.64: Consolidation dial reading for test pit TP_11 at depth of 1.5m

Initial dial reading=6.4						
TP_11 @ 1.5m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
Time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	4.824	5.050	5.292	5.696	6.446	7.036
0.1	4.890	5.094	5.390	5.900	6.510	7.204
0.25	4.914	5.104	5.410	5.932	6.538	7.252
0.5	4.926	5.112	5.422	5.946	6.556	7.274
1	4.934	5.120	5.436	5.962	6.570	7.284
2	4.942	5.128	5.452	5.976	6.588	7.296
4	4.952	5.138	5.470	5.994	6.610	7.318
8	4.964	5.152	5.490	6.016	6.638	7.364
15	4.976	5.166	5.512	6.044	6.684	7.446
30	4.990	5.184	5.544	6.086	6.716	7.516
60	5.010	5.210	5.574	6.150	6.764	7.630
120	5.024	5.234	5.602	6.202	6.842	7.732
240	5.034	5.256	5.644	6.282	6.904	7.878
480	5.040	5.274	5.672	6.372	6.970	7.976
1440	5.050	5.292	5.696	6.446	7.036	8.036

Table A.65: Swelling pressure analysis for test pit TP_11 at depth of 1.5m

Pressure, kpa	$\Delta H(\text{mm})$	Cummula. $\Delta H(\text{mm})$	$H_r = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_r - H_s$	$e_r = H_v/H_s$	$\Delta e = \Delta H/H_s$	$e = e_o - \Delta e$
7	-1.576	-1.576	21.576	10.85	1.012076	-0.14697	1.01
50	0.226	-1.350	21.350	10.627	0.991	-0.12589	0.99
100	0.242	-1.108	21.108	10.385	0.968433	-0.10333	0.97
200	0.404	-0.704	20.704	9.981	0.930757	-0.06565	0.93
400	0.750	0.046	19.954	9.231	0.860816	0.00429	0.86
800	0.590	0.636	19.364	8.641	0.805795	0.05931	0.81
1600	1.000	1.636	18.364	7.641	0.71254	0.152566	0.71

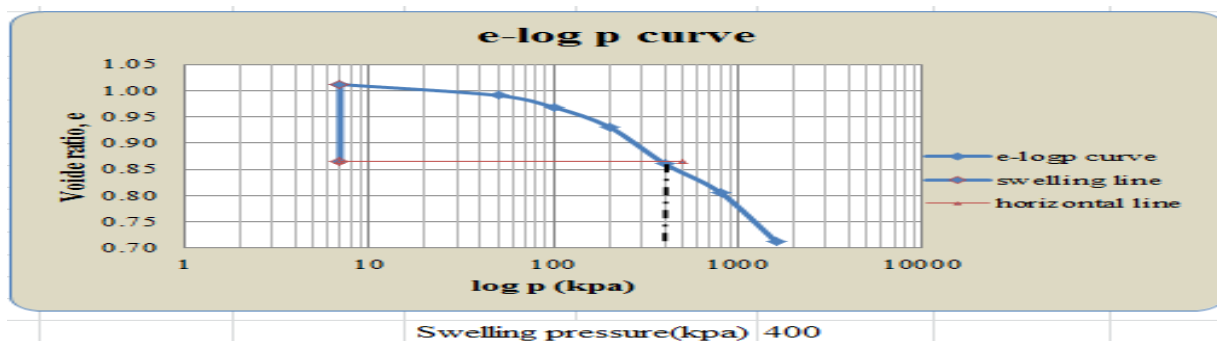


Figure A.17: Determination of swelling pressure from e-log p curve for test pit TP_11 at depth of 1.5m

Table A.66: Consolidation dial reading for test pit TP_11 at depth of 3m

Initial dial reading=5.0						
TP_11 @ 3m						
	50kpa	100kpa	200kpa	400kpa	800kpa	1600kpa
time(min)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)	Dial reading(mm)
0	3.516	3.802	4.086	4.578	5.150	5.850
0.1	3.590	3.850	4.230	4.690	5.270	5.950
0.25	3.606	3.864	4.246	4.702	5.284	5.972
0.5	3.616	3.876	4.272	4.726	5.296	5.984
1	3.626	3.884	4.294	4.744	5.310	5.994
2	3.642	3.894	4.322	4.764	5.330	6.012
4	3.658	3.906	4.344	4.790	5.354	6.036
8	3.676	3.922	4.376	4.822	5.384	6.072
15	3.694	3.944	4.404	4.858	5.422	6.116
30	3.712	3.964	4.444	4.892	5.472	6.188
60	3.732	3.994	4.484	4.924	5.542	6.288
120	3.756	4.036	4.512	4.982	5.636	6.374
240	3.776	4.056	4.536	5.050	5.734	6.450
480	3.792	4.070	4.554	5.106	5.790	6.526
1440	3.802	4.086	4.578	5.150	5.850	6.596

Table A.67: Swelling pressure analysis for test pit TP_11 at depth of 3m

Pressure, kpa	$\Delta H(\text{mm})$	Cummula. $\Delta H(\text{mm})$	$H_f = H_i - \Sigma \Delta H, \text{mm}$	$H_v = H_f - H_s$	$e_f = H_v / H_s$	$\Delta e = \Delta H / H_s$	$e = e_o - \Delta e$
7	-1.484	-1.484	21.484	11.875	1.236	-0.154	1.236
50	0.286	-1.198	21.198	11.589	1.206	-0.125	1.206
100	0.284	-0.914	20.914	11.305	1.176	-0.095	1.176
200	0.492	-0.422	20.422	10.813	1.125	-0.044	1.125
400	0.572	0.150	19.850	10.241	1.066	0.016	1.066
800	0.700	0.850	19.150	9.541	0.993	0.088	0.993
1600	0.746	1.596	18.404	8.795	0.915	0.166	0.915

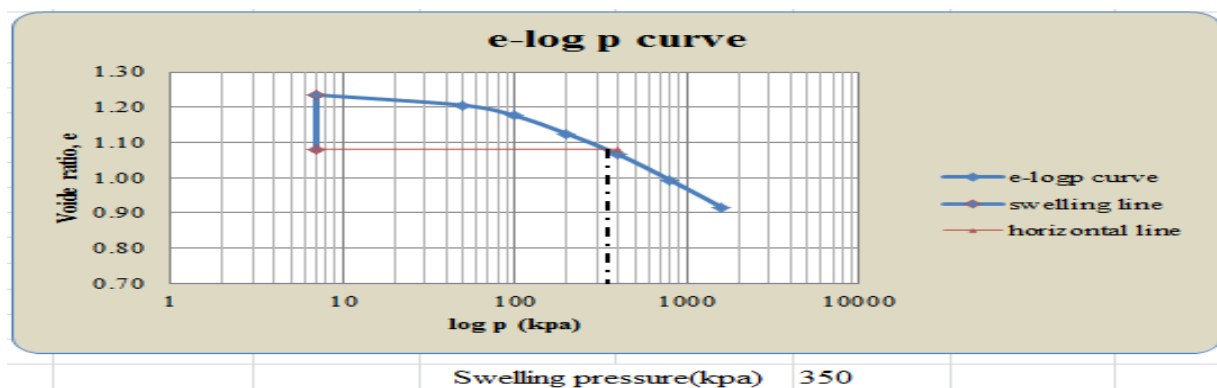


Figure A.18: Determination of swelling pressure from e-log p curve for test pit TP_11 at depth of 3m

Appendix B

SPSS 20 Regression Analysis Output

Table B.1 Regression analysis output for Equation 1

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Moisture Content(ω), Plastic Limit(PL), γ_{dry}/γ' Liquid Limit(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	0.964	0.930	0.907	24.972

a. Predictors: (Constant), Moisture content(ω), Plastic Limit(PL), γ_{dry}/γ' , Liquid Limit(LL)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	99692.995	4	24923.249	39.965	.000 ^b
	Residual	7483.476	12	623.623		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Moisture Content(ω), Plastic Limit(PL), γ_{dry}/γ' , Liquid Limit(LL)

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	988.207	171.206		5.772	0.000
γ_{dry}/γ'	39.938	14.721	0.269	2.713	0.019
1 Liquid Limit(LL)	-.799	3.378	-0.062	-.237	0.817
Plastic Limit(PL)	10.444	7.843	0.337	1.332	0.208
Moisture Content(ω)	-27.271	2.694	-1.014	-10.124	0.000

a. Dependent Variable: Swelling pressure (P_s)

Table B.2 Regression analysis output for Equation 2

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Liquid limit(LL), Moisture content(ω), γ_{dry}/γ' ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.959 ^a	0.920	0.901	25.704

a. Predictors: (Constant), Liquid Limit(LL), Moisture Content(ω), γ_{dry}/γ'

ANOVA^a

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	98587.088	3	32862.363	49.737	0.000 ^b
Residual	8589.382	13	660.722		
Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Liquid Limit(LL), Moisture content(ω), γ_{dry}/γ'

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
1	(Constant)	908.089	164.986		5.504	0.000
	γ_{dry}/γ'	33.427	14.293	0.225	2.339	0.036
	Liquid limit(LL)	3.481	1.069	0.271	3.258	0.006
	Moisture content(ω)	-25.914	2.566	-0.963	-10.097	0.000

a. Dependent Variable: Swelling pressure(P_s)

Table B.3 Regression analysis output for Equation 3

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plasticity Index(PI), γ_{dry}/γ' , Liquid Limit(LL) ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.574 ^a	0.329	0.174	74.370

a. Predictors: (Constant), Plasticity Index(PI), γ_{dry}/γ' , Liquid Limit(LL)

ANOVA^a

Model	Sum of Squares	df	Mean Square	F	Sig.	
1	Regression	35273.797	3	11757.932	2.126	0.146 ^b
	Residual	71902.673	13	5530.975		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plasticity Index(PI), γ_{dry}/γ' , Liquid Limit (LL)

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-422.665	305.155		-1.385	0.189
	γ_{dry}/γ_r	-51.979	34.820	-0.350	-1.493	0.159
	Liquid Limit(LL)	-4.696	13.342	-0.365	-0.352	0.730
	Plasticity Index(PI)	18.684	21.836	0.894	0.856	0.408

a. Dependent Variable: Swelling pressure(P_s)

Table B.4 Regression analysis output for Equation 4

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plastic Limit(PL), γ_{dry}/γ_r , Liquid Limit(LL) ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.578 ^a	0.334	0.180	74.114

a. Predictors: (Constant), Plastic Limit(PL), γ_{dry}/γ_r , Liquid Limit(LL)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	35768.478	3	11922.826	2.171	0.141 ^b
	Residual	71407.993	13	5492.923		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plastic Limit(PL), γ_{dry}/γ_r , Liquid Limit(LL)

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	
	B	Std. Error	Beta			
1	(Constant)	-406.547	301.695		-1.348	0.201
	γ_{dry}/γ_r	-51.328	34.542	-0.346	-1.486	0.161
	Liquid Limit(LL)	14.174	9.013	1.102	1.573	0.140
	Plastic Limit(PL)	-19.596	21.546	-0.632	-0.910	0.380

a. Dependent Variable: Swelling pressure (P_s)

Table B.5 Regression analysis output for Equation 5

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Moisture content(ω), Plasticity Index(PI), γ_{dry}/γ_r ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.952 ^a	0.906	0.884	27.890

a. Predictors: (Constant), Moisture content(ω), Plasticity Index(PI), γ_{dry}/γ_r

ANOVA^a

Model	Sum of Squares	df	Mean Square	F	Sig.	
1	Regression	97063.924	3	32354.641	41.593	0.000 ^b
	Residual	10112.546	13	777.888		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Moisture content(ω), Plasticity Index(PI), γ_{dry}/γ_r

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	924.634	189.434		4.881	0.000
1 γ_{dry}/γ'	31.969	15.896	0.215	2.011	0.066
Moisture content(ω)	-25.580	2.854	-0.951	-8.962	0.000
Plasticity Index (PI)	5.167	1.945	0.247	2.657	0.020

a. Dependent Variable: Swelling pressure (P_s)

Table B.6 Regression analysis output for Equation 6

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plastic Limit(PL), Moisture Content(ω), γ_{dry}/γ' ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.964 ^a	0.930	0.914	24.048

a. Predictors: (Constant), Plastic Limit(PL), Moisture Content(ω), γ_{dry}/γ'

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	99658.087	3	33219.362	57.439	0.000 ^b
	Residual	7518.383	13	578.337		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plastic Limit (PL), Moisture Content(ω), γ_{dry}/γ'

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	965.215	135.737		7.111	0.000
1 γ_{dry}/γ'	38.533	12.972	0.260	2.970	0.011
Moisture Content(ω)	-26.992	2.332	-1.004	-11.574	0.000
Plastic Limit(PL)	8.678	2.321	0.280	3.739	0.002

a. Dependent Variable: Swelling pressure(P_s)

Table B.7 Regression analysis output for Equation 7

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plasticity Index(PI), γ_{dry}/γ' , Plastic limit(PL) ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.575 ^a	0.330	0.176	74.300

a. Predictors: (Constant), Plasticity Index(PI), γ_{dry}/γ' , Plastic limit(PL)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	35410.042	3	11803.347	2.138	0.145 ^b
	Residual	71766.429	13	5520.495		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plasticity Index(PI), γ_{dry}/γ' , Plastic limit(PL)

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-417.162	305.978		-1.363	0.196
	γ_{dry}/γ_r	-51.875	34.716	-0.349	-1.494	0.159
	Plastic limit(PL)	-5.165	13.389	-0.166	-0.386	0.706
	Plasticity Index(PI)	14.189	9.167	0.679	1.548	0.146

a. Dependent Variable: Swelling pressure (P_s)

Table B.8 Regression analysis output for Equation 8

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plasticity Index(PI), γ_{dry}/γ_r ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.568 ^a	0.323	0.226	72.005

a. Predictors: (Constant), PI, γ_{dry}/γ_r

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	34588.563	2	17294.282	3.336	0.065 ^b
	Residual	72587.907	14	5184.851		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plasticity Index(PI), γ_{dry}/γ_r

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-430.099	294.744		-1.459	0.167
	γ_{dry}/γ'	-50.491	33.463	-0.340	-1.509	0.154
	Plasticity Index(PI)	11.191	4.712	0.535	2.375	0.032

a. Dependent Variable: Swelling pressure(P_s)

Table B.9 Regression analysis output for Equation 9

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plastic limit(PL), γ_{dry}/γ' ^b	.	Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.455 ^a	0.207	0.094	77.916

a. Predictors: (Constant), Plastic limit(PL), γ_{dry}/γ'

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	22183.560	2	11091.780	1.827	0.197 ^b
	Residual	84992.911	14	6070.922		
	Total	107176.471	16			

a. Dependent Variable: P_s

b. Predictors: (Constant), Plastic limit(PL), γ_{dry}/γ'

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-215.162	290.222		-.741	0.471
	γ_{dry}/γ'	-40.985	35.650	-.276	-1.150	0.270
	Plastic limit(PL)	12.403	7.448	.400	1.665	0.118

a. Dependent Variable: Swelling pressure(P_s)

Table B.10 Regression analysis output for Equation 10

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Liquid limit(LL), γ_{dry}/γ' ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.540 ^a	0.291	0.190	73.655

a. Predictors: (Constant), Liquid limit(LL), γ_{dry}/γ'

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	31224.565	2	15612.283	2.878	0.090 ^b
	Residual	75951.905	14	5425.136		
	Total	107176.471	16			

a. Dependent Variable: P_s

b. Predictors: (Constant), Liquid Limit(LL), γ_{dry}/γ'

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-383.087	298.730		-1.282	0.221
	γ_{dry}/γ'	-47.014	34.003	-0.317	-1.383	0.188
	Liquid Limit(LL)	6.432	2.945	0.500	2.184	0.046

a. Dependent Variable: Swelling pressure (P_s)

Table B.11 Regression analysis output for Equation 11

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Moisture Content(ω), γ_{dry}/γ' ^b	.	Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.924 ^a	0.854	0.834	33.383

a. Predictors: (Constant), Moisture Content(ω), γ_{dry}/γ'

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	91574.099	2	45787.050	41.085	0.000 ^b
	Residual	15602.371	14	1114.455		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure (P_s)

b. Predictors: (Constant), Moisture Content (ω), γ_{dry}/γ'

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1343.779	125.489		10.708	0.000
	γ_{dry}/γ'	47.461	17.699	0.320	2.682	0.018
	Moisture Content(ω)	-28.201	3.206	-1.049	-8.796	0.000

a. Dependent Variable: Swelling pressure(P_s)

Table B.12 Regression analysis output for Equation 12

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Plasticity Index(PI), Moisture Content(ω), Plastic limit(PL), γ_{dry}/γ' , Liquid limit(LL) ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.965 ^a	0.932	0.900	25.832

a. Predictors: (Constant), Plasticity Index (PI), Moisture Content (ω), Plastic limit (PL), γ_{dry}/γ' , Liquid limit(LL)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	99835.806	5	19967.161	29.921	0.000 ^b
	Residual	7340.664	11	667.333		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Plasticity Index(PI), Moisture Content(ω), Plastic limit(PL), γ_{dry}/γ_r ,
Liquid limit(LL)

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1015.619	186.754		5.438	0.000
	γ_{dry}/γ_r	41.285	15.504	.278	2.663	0.022
	Moisture Content(ω)	-27.154	2.798	-1.010	-9.705	0.000
	Liquid limit(LL)	34.301	75.956	2.667	0.452	0.660
	Plastic limit(PL)	-24.736	76.478	-0.797	-0.323	0.752
	Plasticity Index(PI)	-35.575	76.902	-1.701	-0.463	0.653

a. Dependent Variable: Swelling pressure(P_s)

Table B.13 Regression analysis output for Equation 13

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Liquidity Index(LI), γ_{dry}/γ_r , Moisture Content(ω) ^b		Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.963 ^a	0.926	0.909	24.625

a. Predictors: (Constant), Liquidity Index(LI), γ_{dry}/γ_r , Moisture Content(ω)

ANOVA^a

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	99293.314	3	33097.771	54.581	0.000 ^b
	Residual	7883.156	13	606.397		
	Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), Liquidity Index(LI), γ_{dry}/γ' , Moisture Content(ω)

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1018.575	129.910		7.841	0.000
	γ_{dry}/γ'	39.701	13.236	0.267	2.999	0.010
	Moisture Content(ω)	-19.687	3.360	-0.732	-5.860	0.000
	Liquidity Index(LI)	-470.492	131.869	-0.397	-3.568	0.003

a. Dependent Variable: Swelling pressure(P_s)

Table B.14 Regression analysis output for Equation 14

Variables Entered/Removed^a

Model	Variables Entered	Variables Removed	Method
1	Liquidity Index(LI), γ_{dry}/γ' ^b	.	Enter

a. Dependent Variable: Swelling pressure(P_s)

b. All requested variables entered.

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.856 ^a	0.732	0.694	45.281

a. Predictors: (Constant), Liquidity Index(LI), γ_{dry}/γ'

ANOVA ^a

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	78470.834	2	39235.417	19.135	0.000 ^b
Residual	28705.637	14	2050.403		
Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), LI, γ_{dry}/γ'

Coefficients ^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	264.124	31.863		8.289	0.000
	γ_{dry}/γ'	2.758	21.400	0.019	0.129	0.899
	LI	-1019.348	170.691	-0.861	-5.972	0.000

a. Dependent Variable: Swelling pressure(P_s)

Table B.15 Regression analysis output for Equation 15

Variables Entered/Removed ^a

Model	Variables Entered	Variables Removed	Method
1	Plastic Limit(PL), moisture Content(ω), γ_{dry}/γ' , Plasticity Index(PI), Liquidity Index(LI) ^b	.	Enter

a. Dependent Variable: Swelling pressure(P_s)

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	0.965 ^a	0.931	0.900	25.930

a. Predictors: (Constant), γ_{dry}/γ_r , Liquidity Index(LI), Plasticity Index(PI), Moisture

Content(ω), Plastic Limit(PL)

ANOVA^a

Model	Sum of Squares	df	Mean Square	F	Sig.
1 Regression	99780.232	5	19956.046	29.679	.000 ^b
Residual	7396.238	11	672.385		
Total	107176.471	16			

a. Dependent Variable: Swelling pressure(P_s)

b. Predictors: (Constant), γ_{dry}/γ_r , Liquidity Index(LI), Plasticity Index(PI), Moisture

Content(ω), Plastic Limit(PL)

Coefficients^a

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	937.404	236.869		3.957	0.002
γ_{dry}/γ_r	38.321	16.177	0.258	2.369	0.037
1 Liquidity Index(LI)	422.162	1219.932	0.356	0.346	0.736
Plasticity Index(PI)	-0.334	3.890	-0.016	-0.086	0.933
Moisture Content(ω)	-33.693	18.703	-1.253	-1.801	0.099
Plastic Limit(PL)	16.625	20.521	0.536	0.810	0.435

a. Dependent Variable: Swelling pressure(P_s)

Graphical representation of measured and calculated swelling pressure

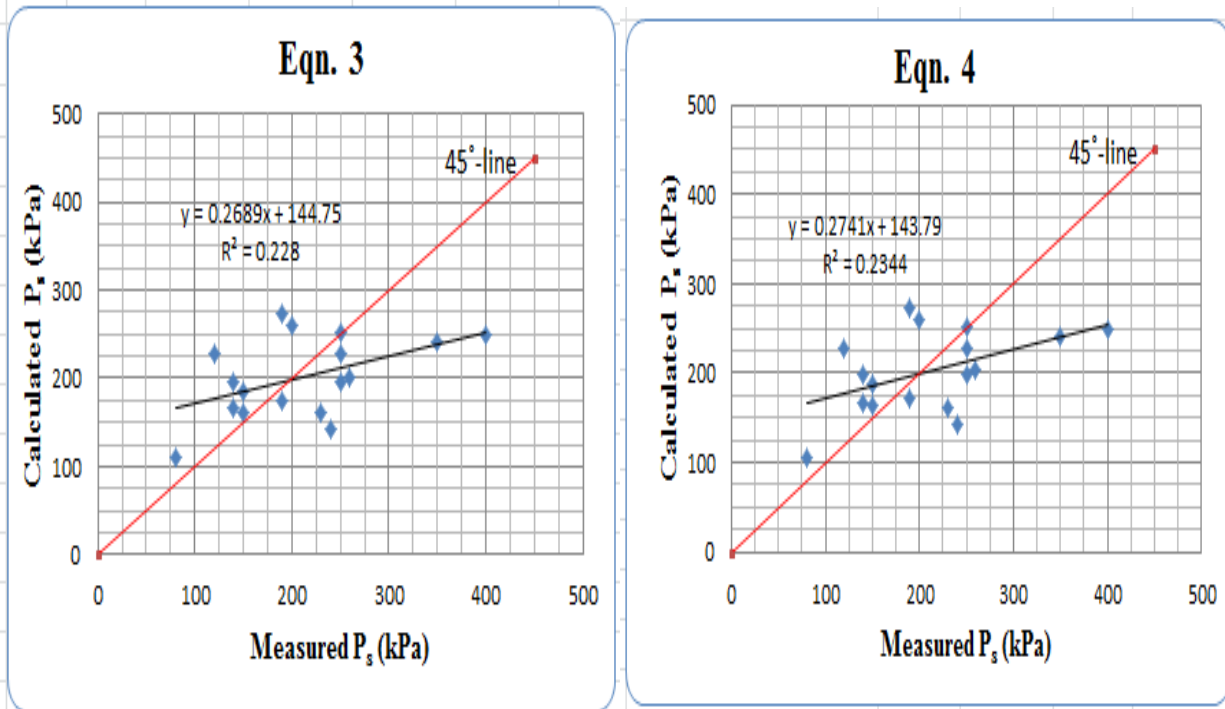


Figure B.1: Comparisons of measured and calculated swelling pressure for equation 3 & 4

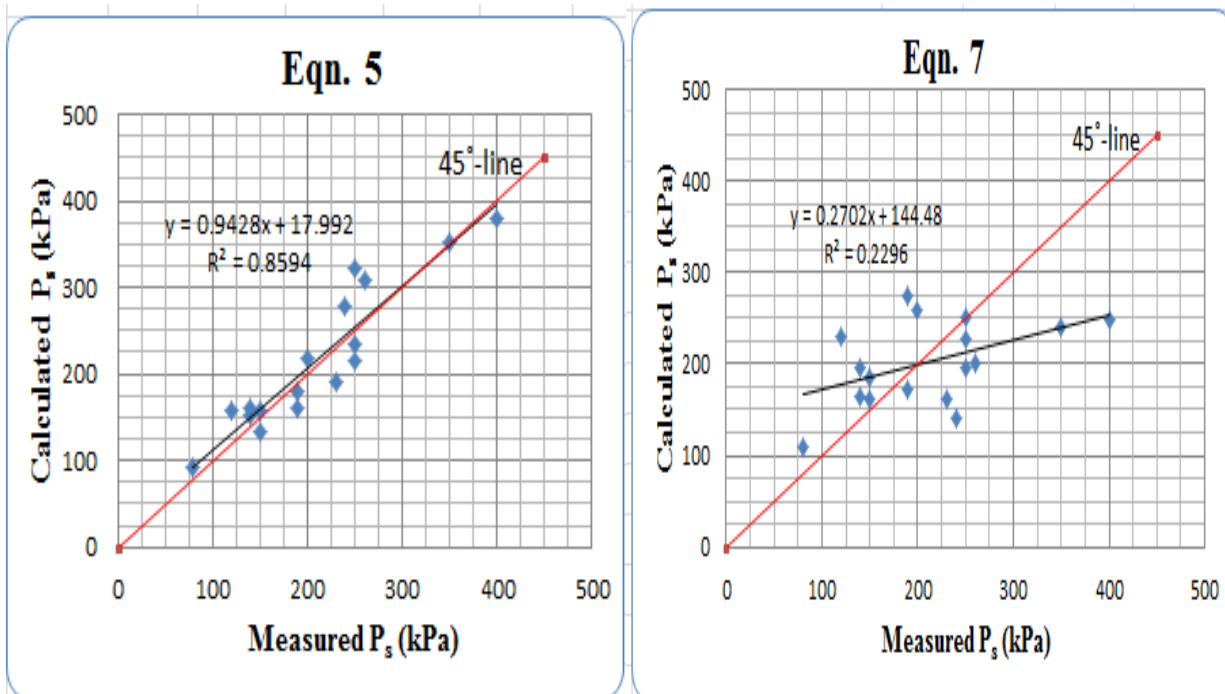


Figure B.2: Comparisons of measured and calculated swelling pressure for equation 5 & 7

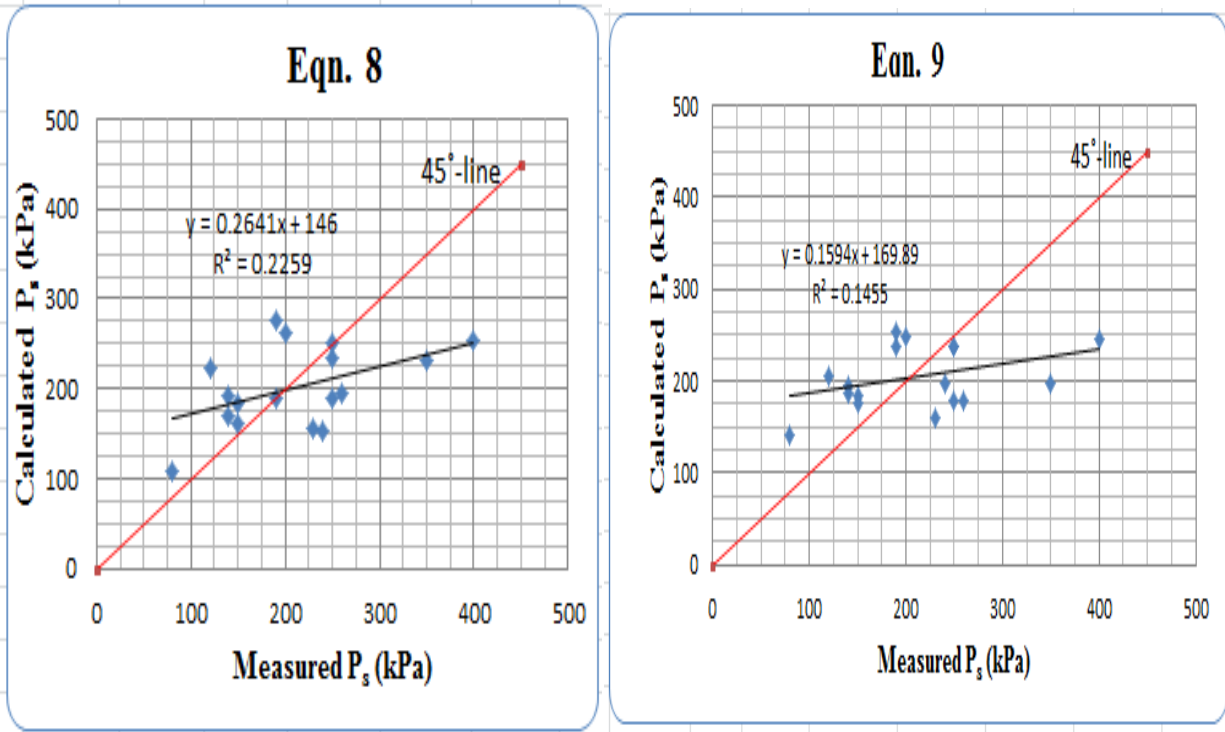


Figure B.3: Comparisons of measured and calculated swelling pressure for equation 8 & 9

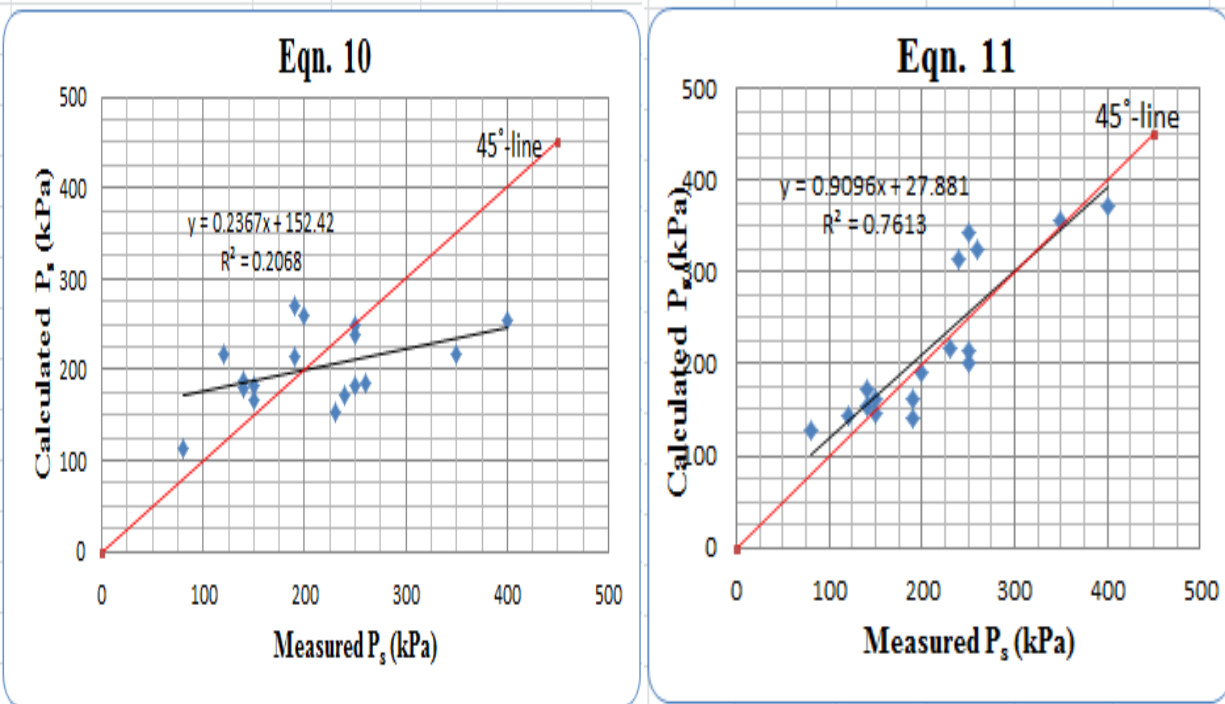


Figure B.4: Comparisons of measured and calculated swelling pressure for equation 10 & 11

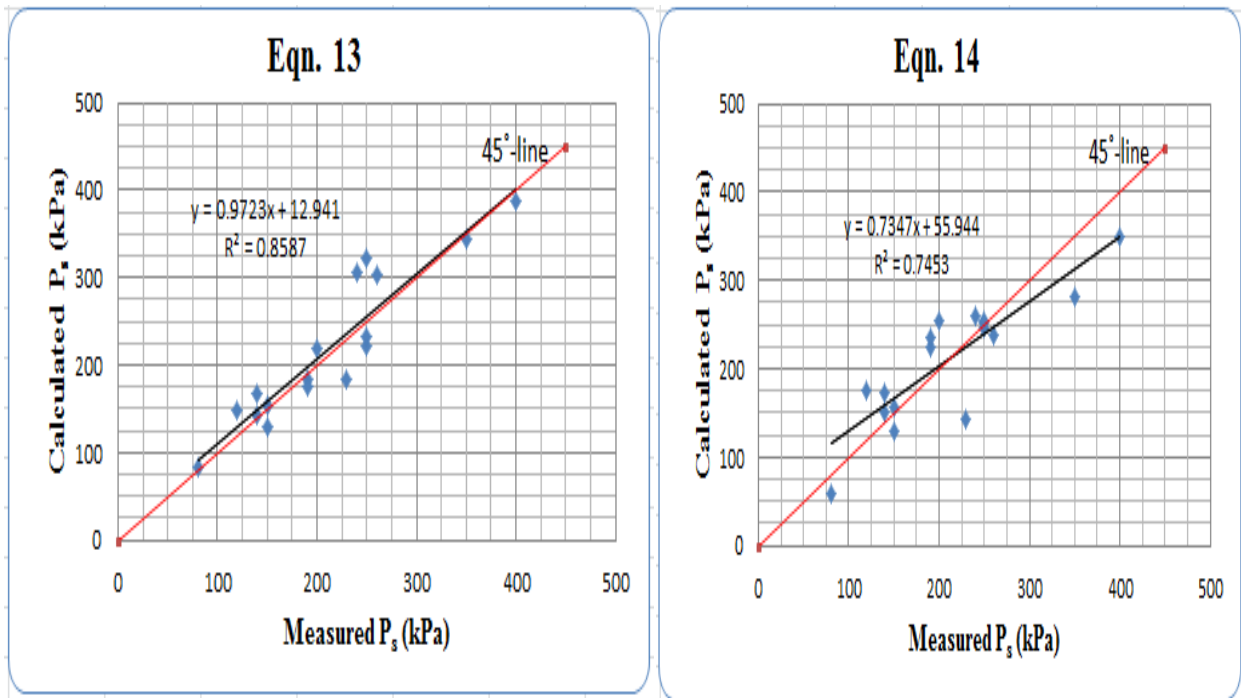


Figure B.5: Comparisons of measured and calculated swelling pressure for equation 13 & 14

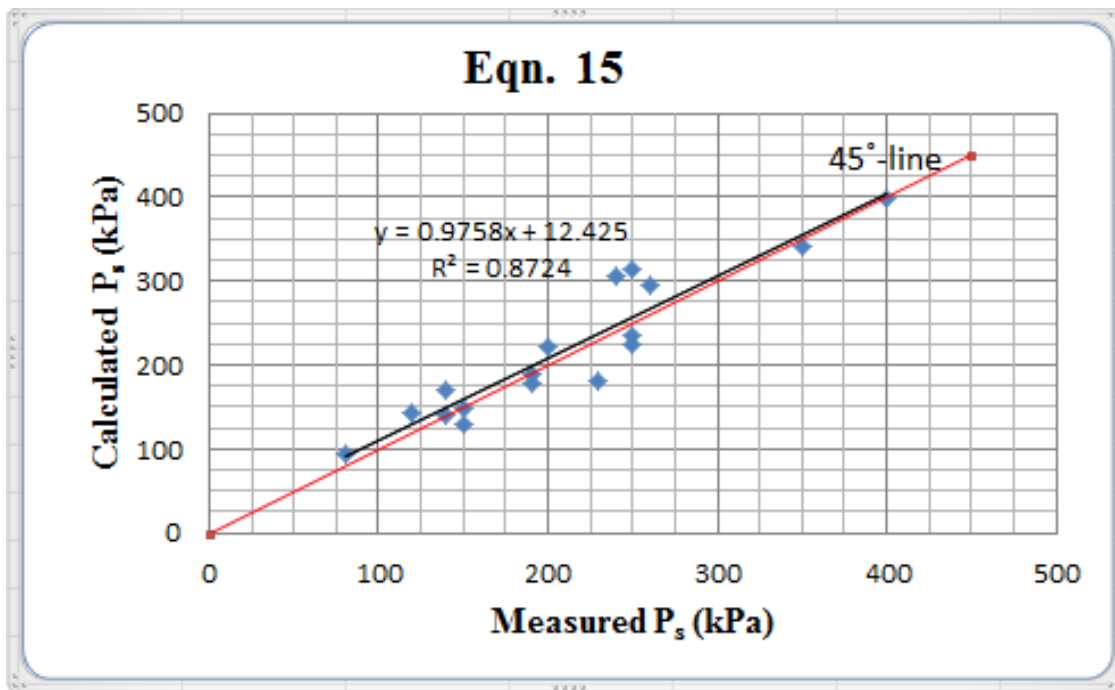


Figure B.6: Comparisons of measured and calculated swelling pressure for equation 15

DECLARATION

I, the undersigned, declare that this thesis is my original work performed under the supervision of my research advisor Dr.-Ing. Henok Fikre and has not been presented as a thesis for a degree in any other university. All sources of the materials used for this thesis have been duly acknowledged.

Name: - Abdirshkur Kemal

Signature:-

Place: - Addis Ababa institute of Technology (AAiT), Addis Ababa

Date: - November, 2015