



ADDIS ABABA INSTITUTE OF TECHNOLOGY (AAiT)

SCHOOL OF GRADUATE STUDIES

DEPARTMENT OF CIVIL ENGINEERING

**STUDY ON INDEX PROPERTIES AND SWELLING PRESSURE OF EXPANSIVE
SOILS FOUND IN DUKEM**

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In partial fulfillment of the requirements for the degree of

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BY

Ashenafi Tamrat

Advisor

Hadush Seged (Dr.)

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By: Ashenafi Tamrat

Approved by Board of Examiners

Dr. Hadush Seged

Advisor

Signature

Dr. Samuel Tadesse

External Examiner

Signature

Prof. Alemayehu Teferra

Internal Examiner

Signature

Dr. Bikila Teklu

Chairman

Signature

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Symbols and Abbreviations

IACMAG	International Association for Computer Methods and Advances in Geomechanics
AASHTO	American association of state highway and transport official
U.S.B.R	United states bureau of public roads classification
ASTM	American Society for Testing and Materials
CEC	Cation Exchange Capacity
PVC	Potential Volume Change
G _s	Specific gravity of solids
S _p	Swelling pressure
BS	British Standard
W _{n/w}	Moisture content
PI	Plasticity index
SL	Shrinkage limit
γ _d	Dry density
LL	Liquid limit
PL	Plastic limit
F _s	Free swell
Eqn	Equation
Ac	Activity
T.P	Test pit

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Abstract

Expansive soil and bedrock underlie more than one third of world's land surface. It is recorded in other countries that each year, damage to buildings, roads, pipelines, and other structures by Expansive soils is much higher than damage that are caused by floods, hurricanes, tornadoes, and earthquakes combined. Such damages occur when the pressure exerted by the soil is greater than the foundation pressure. Consequently assessing the swelling pressure is an important step in designing structures on Expansive soil.

In this thesis Expansive soil mainly found in Dukem town has been assessed. To do this different literature is reviewed and Index properties and swelling pressure tests on 24 disturbed and 18 undisturbed samples were conducted. Based on the index property test results and different classification systems, the study area soil types are identified. Moreover, the validity to our condition of empirical expressions that relate the swelling pressure to the index and physical properties, developed by several researchers is checked and new equations are developed.

The new formulas are developed, by taking one or more of the soil property parameters (Liquid limit, plastic limit, shrinkage limit, moisture content, dry density and plastic index) in different combinations. To develop the equations, 15 test results are used as an input data for SPSS 15 windows software. The equations are then tested for three control samples. The best equation is proposed, and conclusions and recommendations are made. Lastly, future works are suggested.

Chapter 1

Introduction

1.1 General

Expansive soil and bedrock underlie more than one third of world's land surface. Each year, damage to buildings, roads, pipelines, and other structures by Expansive soils is much higher than damage that are caused by floods, hurricanes, tornadoes, and earthquakes combined. The losses include severe structural damage, cracked driveways, sidewalks and basement floors, heaving of roads and highway structures, collapse of buildings, and disruption of pipelines and sewer lines [9].

In the African continent, Expansive soils occur in many countries including South Africa, Ethiopia, Kenya, Mozambique, Ghana, and Nigeria as shown in fig 1.1 below [1].

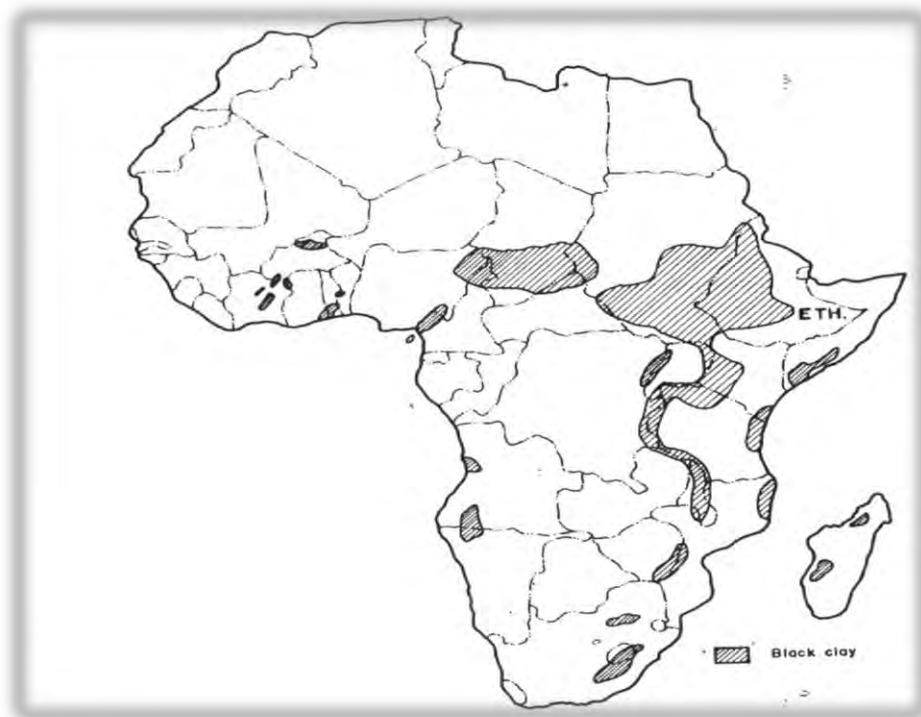


Fig 1.1 Distribution of Expansive soils in Africa [1].

Expansive soil is 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 of Addis Ababa areas,, where most of the recent construction are being carried out and central part of Ethiopia following the major trunk roads like Addis-Ambo, Addis-Woliso, Addis-Debre Birhan, Addis-Gohatsion, Addis-Modjo. Also areas like Bahir Dar, Mekele, and Gambela etc. are partly covered by Expansive soil [4].The main objective of this thesis is to study the index properties and Swelling Pressure of Expansive soils widely found in Dukem town.

Dukem, one of the fast growing areas of the country is located 37 km from the capital city of Ethiopia, Addis Ababa. The town is planned to be one of the largest industry areas in Ethiopia. In the town, different huge factories- East Africa Bottling, Elsewedy cable factory, marble factory etc. have been constructed and many more are planned.

According to the master plan of the town, many constructions will be carried out in the town. East industry zone is one of the big projects to be constructed by Chines firms. In this industry zone eighty (80) different types of factories will be included. In addition to this, other two industry areas are prepared for Ethiopia and foreign investors. Each industry area will contain around thirty (30) factories. Moreover, the Addis-Adama new railway and express highway will pass through the town.

The soil profile of the town can be divided into Expansive and non-Expansive soils. The Expansive soil covers wider area of the town. Expansive soil is clay soils which may be black or gray in colors. It has a potential to heave and shrink with the variation of moisture content. Heaving occurs due to the development of swelling pressure in the soil. This causes most of damages associated with Expansive soil [6].

Therefore, in order to design light weight structures on Expansive soil, determination of swelling pressure in addition to index properties and shear strength parameters of the soil is necessary. Many investigations have been conducted on the properties of Expansive soils found in different towns [2, 8, 7 and 11]. But a little work has been done in Dukem town.

1.2 Objectives

The objective of this study is:-

- To study the index properties and swelling characteristics of expansive soil found in Dukem town.
- To develop some correlations between index properties and swelling pressure of expansive soils found in Dukem town.

1.3 Methodology

In order to attain the objective of this thesis, different journals, books and most related researches accomplished on expansive soils have been reviewed. Then different field and laboratory works (particularly index properties tests and consolidation for swelling pressure determination) are conducted. In addition, a computer program (SPSS 15) is used to correlate swelling pressure with index properties. The detail explanation will be presented in chapter three.

1.4 Reviews of previous works

Some researchers have been conducted on the area of Expansive soils in the previous years. Particularly, M.Sc thesis conducted on: - In depth investigation of relationship between Index property and swelling characteristic of Expansive soil in Bahir-dar [7] and Examining the swelling pressure of Addis Ababa Expansive soil [8] have close similarity with this thesis. But, the main difference between the previous conducted and this research is the study area and some study parameters are added here.

1.5 Organization of the Thesis

This thesis is organized into 6 Chapters. Chapter 1 presents the general description and major Engineering problems associated with Expansive soils. The origin, formation, mineralogy and the different classification soils are presented in Chapter 2. Material and methods used to conduct the thesis are discussed in Chapter 3. Chapter 4 presents the Laboratory test results and discussions on the results obtained from the tests. Examining swelling pressure prediction models and development of new models are given in Chapter 5. Finally, Chapter 6 presents Conclusions and recommendations.

Chapter 2

Literature Review

2.1 Expansive Soil in General

Expansive soil is a term generally applied to any soil or rock material that has a potential for shrinking or swelling under changing moisture conditions [13]. Subsequent swelling and shrinkage of this soil due to change in moisture cause damages to different structures, particularly light weight buildings and pavements.

2.2 Origin of Expansive soil

The origin of Expansive soil is related to a combination of conditions and processes that results in the formation of clay minerals having a particular chemical and mineralogical make up, which, when in contact with water expands. Variations in the conditions and processes may also form other clay minerals, most of which are non-Expansive. The conditions or processes that determine the clay mineralogy include composition of the parent material and degree of physical and chemical weathering to which the materials are subjected [6].

2.2.1 Parent Material

The parent materials that can be associated with Expansive soils are classified into two groups [6]. The first group comprises the basic igneous rocks and the second group comprises the sedimentary rocks that contain montmorillonite as a constituents. The basic igneous rocks are comparatively low in silica and rich in metallic base such as the pyroxenes, amphiboles, biotite and olivine fall within this category. Such rocks include the gabbros, basalts and volcanic glass. Shale and clay stones are one of sedimentary rocks that contain montmorillonite as a constituent. Limestone and marls rich in magnesium can also weather to clay. These constituents of the shales and clay stones contain varying amount of volcanic ash and glass, which are subsequently weathered to montmorillonite.

2.2.2 Weathering, Climate and Topography

The weathering process by which clay is formed includes physical, biological and chemical process. The most important weathering process responsible for the formation of montmorillonite is the chemical weathering, which include hydrolysis, hydration, oxidation, carbonation and solution, of parent rock mineral which generally consists of ferromagnesium mineral, calcic feldspars, volcanic glass, volcanic rocks and volcanic ash. The formation is aided in alkaline environment, presence of magnesium ion and lack of leaching. Such condition is favorable in semi-arid regions with relatively low rain fall or seasonal moderate rainfall particularly where evaporation exceeds precipitation. Under these conditions enough water is available for the alteration process but the accumulated cations will not be removed by rainwater [8].

Topography has a major influence on drainage characteristics that in turn is known to have major effect on soil mineralogy. Its control over soil properties is particularly strong in tropical environments reflecting the importance of lateral movements of water and soil material. Gentle slope, usually less than 3° , results in slow movements or stagnation of water, to maintain high concentration of Ca^{+} for the synthesis of motmorillonite [4].

Climate is the principal factor governing the rate and type of soil formation. The two important components of climate are the amount and distribution of precipitation, and temperature. The amount and distribution of precipitation affects the availability of moisture and the relative humidity of the soil atmosphere; it influences the concentration or chemical activity of solutions in the system. Warm climate with alternating dry and wet seasons is favorable for the formation of montmorillonite [4].

Expansive soils are in abundance where desiccation phenomenon is common i.e., where the annual evaporation exceeds the precipitation.

2.3 Clay mineralogy

The three most common types of clay minerals are Montmorillonite, Illite, and Kaolinite.

2.3.1 Montmorillonite

Montmorillonite is the most common of all the clay minerals and is well known for its swelling properties. Its basic structure consists of an alumina sheet sandwiched between two silica sheets and is symbolically represented as shown in Fig 2.1a.

The basic montmorillonite units are stacked one on top of the other (as shown in fig 2.1b), but the bond between the individual units is relatively weak and water is easily able to penetrate between the sheets and cause their separation and hence swelling. Therefore, montmorillonite has very high degree of expansiveness [1].

2.3.2 Illite

Illite has a basic structure similar to that of montmorillonite (fig 2.1a). However, the basic illite units are bonded together by potassium ions which are non-exchangeable (fig 2.1b). Because of this, the illite units are reasonably stable and so that mineral swells much less than montmorillonite. Hence, illite has moderate degree of expansiveness [1].

2.3.3 Kaolinite

Kaolinite has a structural unit made up of alumina sheets joined to silica sheet and is symbolized as indicated in Fig 2.1a. Kaolinite consists of many such layers stacked one on top of the other as shown in Fig 2.1b.

The bond that exists between layers is tight and hence it is difficult to separate the layers. As a result kaolinite is relatively stable and water is unable to penetrate between the layers. Consequently kaolinite has low degree of expansiveness [1].

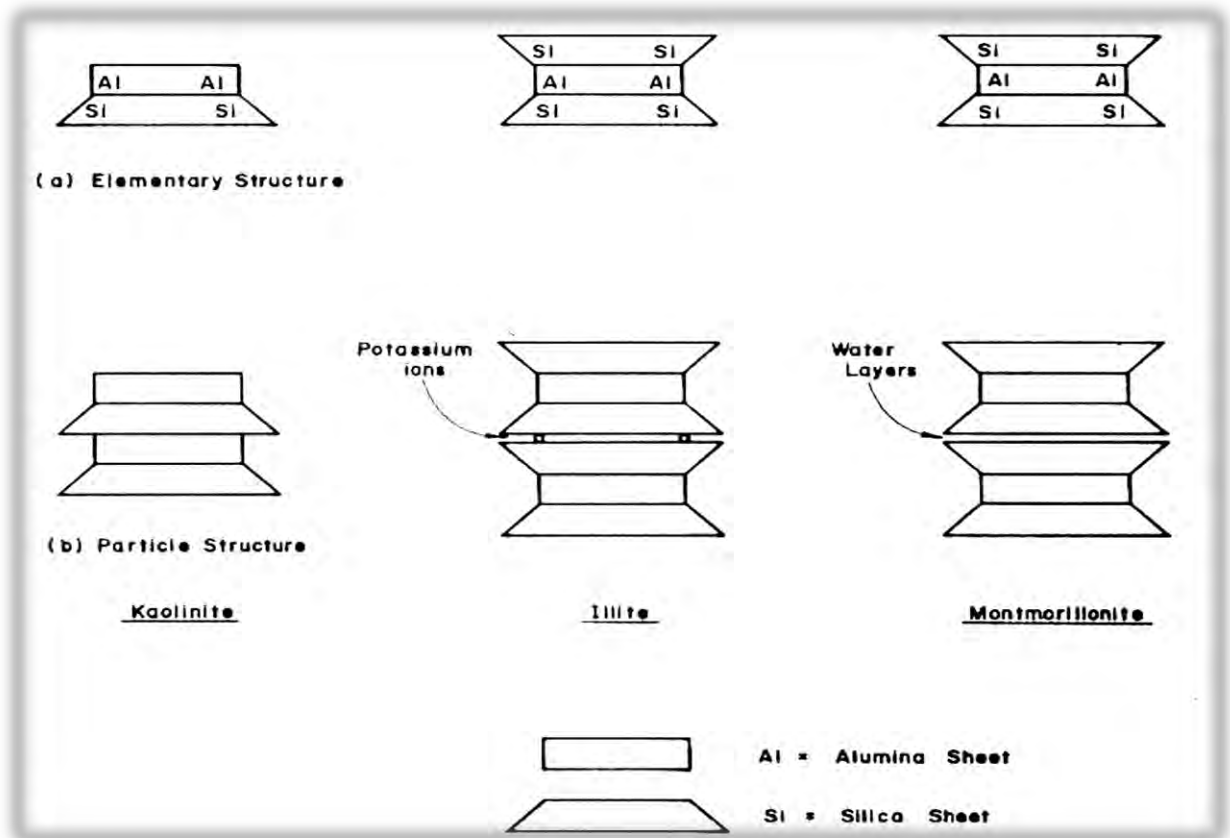


Fig. 2.1 Symbolic representation of clay minerals structure [1].

2.4 Identification and Classification of Expansive Soils

The key to all Expansive soil classification systems is the method of measuring swell potential, since soils are rated 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 the laboratory in a 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.

2.4.1 Field Identification

Some of the important field identification method that indicates the potential for expansiveness of a soil is the following [6 and 8]:-

- 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 structures.
- They usually have a color of black and/or gray
- In the regions where there is seasonal moisture variation open or 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.

2.4.2 Experimental Identification

Generally, there are three different method of identifying Expansive soil in the laboratory and field experiment.

2.4.2.1 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.

2.4.2.1.1 Mineralogical identification

Type of clay mineral is a fundamental factor, which determines the expansive behavior of a soil. Mineralogical test is used to identify this mineral.

This method is used for identifying the mineralogy of clay particles such as characteristic crystal dimensions, characteristic reaction to heat treatment, size and shape of clay particles and charge deficiency and surface activity of clay particle. These properties are a fundamental factor controlling Expansive soil behavior [6].

The various techniques under this method are X-ray diffraction, Differential thermal analysis, Dye absorption, Electron microscope Base Exchange capacity, Infrared spectroscopy and Radio frequency electrical dispersion. But these methods are not suitable for routine tests because, they are time consuming, require expensive test equipment and, the results are interpreted by specially trained technicians.

2.4.2.2 Indirect methods

Indirect methods are used to investigate the swelling potential of a soil by examining other parameters, which indirectly yield excellent indices of expansive properties. Such tests are easy and can be performed in average soil mechanics laboratory. The commonly used test here is the index property tests (consist of Grain size analysis, liquid limit, plastic limit, shrinkage limit, free swell and vertical swell). Also Cation Exchange Capacity (CEC) and Potential Volume Change (PVC) test can be used.

2.4.3 Classification methods of Expansive Soils

The different classification systems are categorized into two:-

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

2.4.3.1 General classification system

The most widely used general classification systems are:-

i. AASHTO Classification

As shown in the Fig 2.2 soils that lie on A6, A7 and borderline soils A-4, A-6, and A-7 may be considered as potentially expansive. [15]

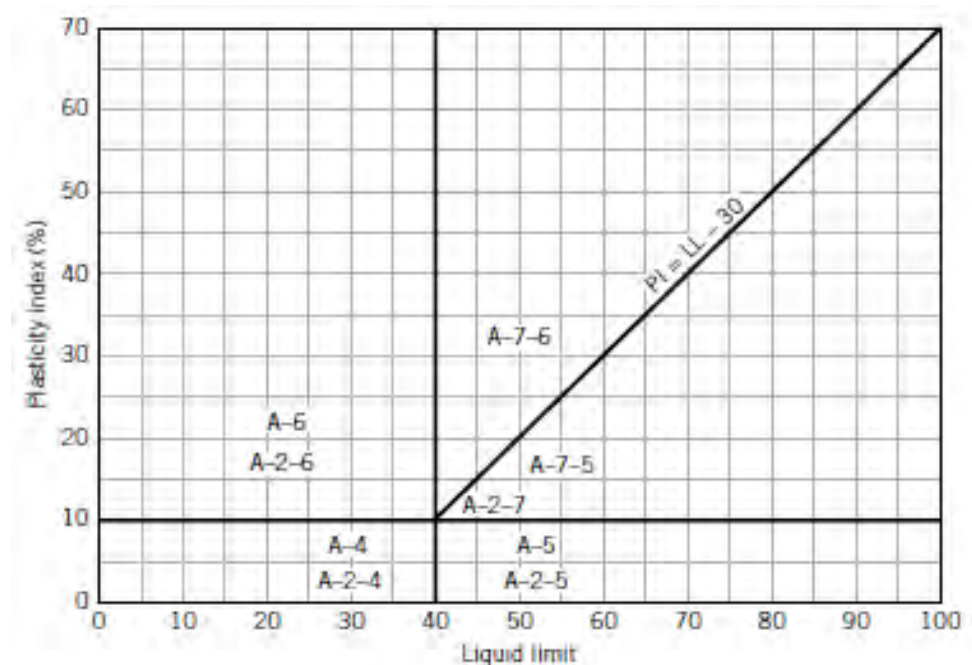


Fig. 2.2 Liquid limit against plasticity index chart for AASHTO soil classification method [15]

ii. Unified Soil Classification Systems

In this classification system a correlation is made between swell potential and unified soil classification as shown in Table 2.1. [8]

Table 2.1 unified soil classification. [8]

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 sands and gravels, grouped in symbol number 1, exhibit little or no expansion.
- ❖ All clayey gravels and sands and all silts, grouped in symbol number 2, exhibit moderate volume changes.
- ❖ All clay soil and organic soils, grouped in symbol number 3, exhibit high volume change.

In the above classification soils rated as CH or OH may be considered as potentially Expansive.

2.4.3.2 Classification Specific to Expansive Soil

The above classification system may give an initial alert that the soil may have expansive character but does not 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 [13].

Hence, it is very important to emphasize that design decision has to be based on predicting testing and analysis, which provide reliable information.

i. 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:-

- Alemayehu and Mesfin [1999]

One may use to check as the accuracy of laboratory test results for Expansive soils found in Ethiopia.

Table 2.2 Indicative properties of Ethiopian Expansive soils.[1]

Clay content smaller than 2 μ m	50-80%
Liquid limit	80-120%
Plasticity limit	55-90%
Shrinkage limit	10-16%
Free swell	90-123%

- Skempton's method (McKeen, 1976)

Skempton classifies clays according to their activities. Following his classification, three degree of colloidal activity (Activity, $A_c = PI /$ percentage by weight finer than 2 μ m) have been established as indicated in table 2.3.

Table 2.3 degree of colloidal activity (Skempton's method)

Degree of activity	Activity
Inactive clay	<0.75
Normal clay	0.75-1.25
Active clay	>1.25

Following this classification:-

- ❖ montmorillonitic clay (expansive clay) is defined as active

- ❖ Illitic clay as normal and
- ❖ Kaolinitic clay as inactive.

➤ U.S.B.R Classification Method

This method was developed by Holtz and Gibbs [12] to establish degree of expansion based on simultaneous consideration of shrinkage limit (sl), plasticity index (PI), percent smaller than 0.001mm (1 μ m), free swell (Fs) and percent swell under a pressure of 1psi. The relationship between degree of swell and indicative clay properties as established by Holtz and Gibbs are presented in table 2.4.

Table 2.4 U.S.B.R Classification method

Degree of expansion or swell	Swell in oedometer under a pressure of 1psi.(%)	SL,%	PI,%	Percent smaller than 1 μ m	FS, %
Very high	>30	<10	>32	>27	>100
High	20—30	6--12	23--45	18--37	>100
Medium	10—20	8--18	12--34	12--27	50--100
Low	<10	>13	<20	<17	<50

➤ Altmeyer (Mckeen, 1976)

He has suggested rating for degree of expansion based on volumetric shrinkage limit (SL) and linear shrinkage (LS) as shown in Table 2.5.

Table 2.5 Altmeyer classification of expansive soil

Volumetric SL, %	Liner LS, %	Degree of expansion
<10	>8	Critical
10—12	5—8	Marginal
>12	<5	non critical

➤ Seed, Woodward and Lundgreen [18]

According to Seed, Woodward and Lundgreen, Plasticity Index is a parameter which can be used as a preliminary indicator of the swelling characteristics of a soil (table 2.6).

Table 2.6 seed, Woodward and Lundgreen classification of expansive soil.

Swell Potential	Plasticity Index
Low	0-15
Medium	10_35
High	20-55
Very High	35 and above

➤ Chen Method [6]

In this method, a correlation is made between swell data and percent less than No. 200 sieve, liquid limit, and standard penetration resistance. The classification is as given in table 2.7 [6].

Table 2.7 Chen method of classification of Expansive soil

< No 200 sieve, %	LL, %	Standard penetration blows	Probable Expansion, %	degree of expansion
<30	<30	<10	<1	Low
30—60	30—40	10—20	1—5	Medium
60—95	60	20—30	3—10	high
>95	>60	>30	>10	very high

The classification system developed based on single property alone such as: based on activity (Skempton, 1953), based on shrinkage limit and linear shrinkage (Altmeyer, 1956), based on index property (Kantey and Brink, 1952), etc. are difficult to use alone as a classification system because they may lead to wrong conclusion. But, Chen method of classification of expansive soil, classification based on bureau of reclamation method, U.S.B.R Classification method, etc.

are a better indirect classification system developed by combining index property, swell and physical indicator.

2.5 Mechanics of Swelling

Swelling in expansive soils will take place if there is change in the environment. Environmental change can consist of pressure release due to excavation, desiccation caused by temperature increase, and volume increase because of the introduction of moisture. By far the most important element for swelling is the effect of water on expansive soils. With the introduction of water volumetric expansion takes place. If pressure is applied to prevent expansion, the pressure required to maintain the initial volume is the swelling pressure [6].

2.5.1 Moisture Transfer

The pattern of moisture migration depends on the geological formation, climatic condition, topographic features, soil types and ground water level. The most common method of moisture transfer is by gravity. The moisture migration can occur in all direction. Moisture migration can be caused by different reasons. Fractures and fissures, shrinkage cracks, capillary force, vapor transfer, thermal gradients, etc are some of the sources that cause moisture migration and swelling on expansive soils [6].

2.5.2 Moisture Equilibrium

In natural ground, the moisture content of the partially saturated soil is in general equilibrium with the applied stress, the forces due to evaporation and transpiration at ground surface and the capillary forces. When building or pavement covers the area, the evaporation and transpiration forces are eliminated and a new set of equilibrium must be established. The new equilibrium requires the flow of moisture compatible with the new condition. The force causing the moisture change or flow is termed soil suction [6].

2.5.3 Depth of Moisture Fluctuation

In covered area there is no gain or loss of moisture to the atmosphere. The moisture content of the soil decreases with depth as shown in curve 1 of Fig 2.3. In uncovered natural conditions evaporation and transpiration causes loss of moisture content in the soil near the ground surface. Hence the moisture content will increase with depth. However the influence of evaporation decreases with depth and at some depth, H_d , the moisture content equilibrium remains the same as the covered condition [6].

The value of H_d depends on the climatic condition, type of soil, and the location of the water table. This depth represents the total thickness of the material, which has a potential to expand because of change of moisture content. The maximum depth of H_d is equal to the depth of the water table, and the minimum depth is equal to the depth of the seasonal moisture contents fluctuation (H_s). During wet months with heavier precipitation and higher humidity, the moisture content of near surface soil increases and the moisture profile represented by curve 2 alters its shape to curve 3. As shown in Fig 2.3. [6]

The watering of lawns, planting of trees and shrubs, discharge of roof chains, formation of drainage channels and swales, and the possibility of utility line leakage will all increase the value of H_s . [6]

When areas are covered by structures such as buildings, pavements, sidewalks or aprons evaporation is blocked or partially retarded. The moisture content beneath the covered area decreases due to gravitational migration, capillary action, and vapor and liquid thermal transfer and, in course of several years, the depth of seasonal moisture content fluctuation H_s can approach to the depth of desiccation H_d [6].

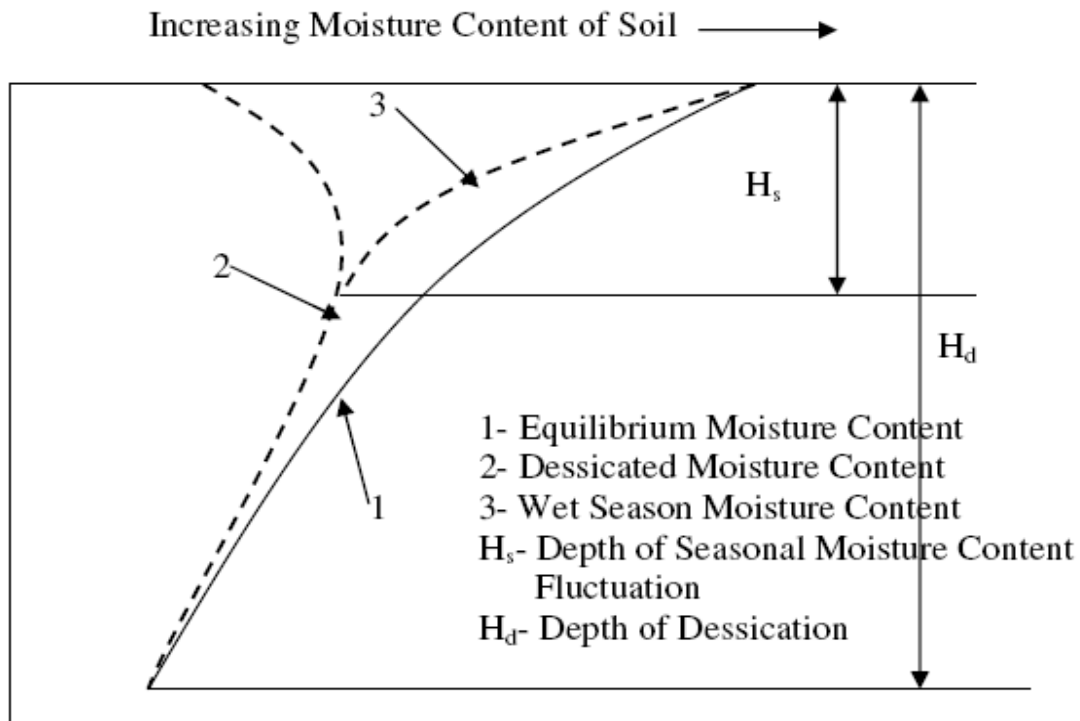


Fig 2.3 Moisture content variation with depth below ground surface [Chen, 1966]

2.5.4 Volume change in micro-scale mechanisms

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. This means water molecules only attached with clay fraction. Also the process will not change the chemical property of the clay.

- ❖ Capillary imbibitions: 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

2.6 Factors induce swelling and shrinking of a soil

Shrink and Swell in expansive soil can be induced by different factors. Generally, these factors are categorized into three groups namely:-

- ❖ The soil characteristics,
- ❖ The environmental factors and
- ❖ The state of stress.

2.6.1 The Soil Characteristics

The soil characteristics influence the basic nature of the internal force field between particles. The following properties are categorized in this group.

i. Clay mineralogy

A clay mineral has two fundamental units which forms its structure. These fundamental units are a tetrahedral unit, which Silicon atom is in the center and four Oxygen ions arranged tetrahedrally, and octahedral unit, which has an Aluminum atom in the center and six Oxygen or hydroxyl ions arranged octahedrally around the Aluminum. The combination of these units in different arrangement leads to the formation of different clay minerals. Some of the major minerals include Kaolinite, Montmorilonite and Illite.

The existence of Montmorilonite minerals is more responsible for the swelling of the soil. This is because the bond between the fundamental units which forms the structure is weaker than the other mineral and it is easily affected by water [7 and 17].

ii. Dry density

Density in general shows the spacing of particles in a system. As dry density increases there is a closer spacing between particles and swelling potential increases [7 and 13].

iii. Plasticity

Soils exhibiting plastic behavior over wide range of moisture content and that have high liquid limits have greater potential for swelling and shrinking. Plasticity is an indicator of swell potential [7 and 13].

iv. Soil Structure and Fabric

The term fabric refers to the arrangement of particles, particle groups and pore spaces in a soil. Structure has a broader meaning of the combined effect of fabric, composition and inter-particle force. The unique relationship between water content of a soil and matric suction is influenced by soil fabric which in turn affects the swelling potential of the soil [7 and 6].

v. Soil Suction

Soil suction is a measure of a soil's affinity for water and it is a parameter, which indicates the intensity with which it will attract water. Higher soil suction shows higher affinity for water and vice versa. Since expansion of a soil is predicted on the assumption that the volume change is equal to the volume of water taken up by the soil, higher soil suction could be used as an indication of swelling potential [7 and 6].

vi. Soil Water Chemistry

Soil water has different type of dissolved minerals, which can react with the clay. Clay particles are platelets like in shape and they have negative charges on their surface and positive charges on their edge. The negative charges on the surface of these particles are balanced by the cations from the soil water. These cations are sodium, calcium, magnesium and potassium, which dissolve in the soil water and are adsorbed on the clay surface as exchangeable cations to balance the negative electrical surface charge.

If the soil water chemistry is changed either by changing the amount of water or the chemical composition, the inter particle force field which is dependent on the negative surface charge and electro- chemistry of the soil water will change. This change disturbs the equilibrium and the

system tries to adjust itself to the new condition which is manifested as shrinkage or swelling [7 and 17].

2.6.2 Environmental Factors

Environmental factors influence the changes that may occur in the internal force system. These factors are mostly associated with moisture. Some of the factors are:

- ❖ Initial moisture condition,
- ❖ Climate
- ❖ Ground water
- ❖ Drainage and manmade water sources
- ❖ Vegetation

2.6.3 Stress Condition

Over consolidation, magnitude of surcharge load, thickness and location of potentially expansive layers influence shrink-swell phenomenon occurring in the system. These include the following Stress history, Loading and Soil profile.

2.7 Effect of Initial Dry Density

The dry density is an important factor in determining the magnitude of volume change. The swell or the swelling pressure of an expansive soil increases with increasing dry density for constant moisture content. The reason is that higher densities result in closer particles spacing, therefore causing greater particle interaction.

As swelling pressure is the built in property of expansive soil and will not be affected by placement condition or environmental condition, only initial dry density and the amount and the type of clay mineral affect the swelling pressure [6].

Chapter 3

Material and Methods

In order to accomplish the objective of this thesis different field and laboratory works were conducted. In addition, a Computer Program (SPSS 15) was used to correlate swelling pressure with index properties. In this Chapter detail explanation will be presented about the material and method used to conduct this thesis.

3.1 Field work

After reviewing the literature and before conducting laboratory test, the following activities are undertaken.

3.1.1 Site observation

This section includes the observation of the color of the distribution of the different type of soils, the condition of the existing structures, type of vegetation and depth of crack on the ground surface. The observation result shows that:

- ❖ Approximately 80% of the town is covered by black clay soil.
- ❖ 15% of the area covered by mountains which are mainly consist of cinder and gravel.
- ❖ The remaining 5% is covered by red clay soil.
- ❖ Around 50% of the existing structures constructed on black clay soil show appearance of cracking.
- ❖ As shown in Table 3.1 below, during dry season 0.01-1.08 m open fissures have been observed.
- ❖ Around 60% of the area is used for cash crop production. The remaining part of the town used for residential and industry area.

Table 3.1 Depth of crack, color of the soil and depth of each layer

From original ground level up to 3.0m			crack depth(m) (average)
Area name	colors of the soil layers	Depth of each layers (m)	
Dukem Primary School (1)	Black	0-1.00	0-0.1
	Brown	1.00-1.55	
Stadium (2)	Black	0-1.05	0.5-0.85
	Brown	1.05-3.00	
Al-Mehdi Industry (3)	black mix with white ash	0-0.20	0-0.55
	Black	0.20-0.83	
	Brown	0.83-1.10	
	dark brown	1.10-1.45	
	black mix with red cinder	1.45-1.95	
Eastern Industrial Zone (4)	Black	0-1.25	0.60-1.00
	dark brown	1.25-2.90	
Technical School (5)	Black	0-1.12	0.33-0.43
	Brown	1.12-2.95	
Atlabachew real state (6)	Black	0-1.20	0.35-0.50
	Brown	1.20-3.00	
kotch (east Africa tiger brand) (7)	Black	0-1.00	0.5-0.85
	Brown	1.00-3.00	
Asse Marble factory (8)	Black	0-2.00	0.5-1.08
	Gray	2.00-3.00	
Right side of medhanialem church (9)	Black	0-0.42	0-0.15
	Yellowish	0.42-2.20	

From original ground level up to 3.0m			crack depth(m) (average)
Area name	colors of the soil layers	Depth of each layers (m)	
	dark yellow	2.20-3.00	
Elsewedy cable factory (10)	Black	0-1.00	0-0.30
	dark brown	1.00-2.20	
Dalota (in front of high tension tower) (11)	black mix with boulder	0-1.20	0-0.30
Dalota around dukem border (12)	black	0-0.30	0.25-0.55
	dark brown	0.30-3.00	
Mendelo (13)	Black	0-0.40	0-0.10

3.1.2 Soil Profile below 3m Depth

The general soil profile of the town has been observed from river side and test pits dug for toilet purposes. This investigation shows that the depth of expansive soil generally seems less than 3m. All the results are shown in Table 3.2 below.

Table 3.2 soil profile of Dukem town below 3m

Below 3.0m		
Area name	colors of the soil layers below 3.0m	Depth interval of each layer below ground level (m)
Dukem Primary School (1)	Light red	1.55-5.50
	Red	below 6.00
Stadium (2)	Light red	3.00-5.00
	Red	below 5.00
Al-Mehdi Industry (3)	Red mix with sand	below 1.95

Below 3.0m		
Area name	colors of the soil layers below 3.0m	Depth interval of each layer below ground level (m)
Eastern Industrial Zone (4)	Red	below 2.90
Technical School (5)	Red	below 2.95
Atlabachew real state (6)	Red	3.00-5.50
kotch (east Africa bottling (7)	Red	3.00-5.00
Asse Marbel factory (8)	Gray	3.00-5.25
	Red	below 5.25
Right side of medhanialem church (9)	Dark yellow	below 3.00
Elsewedy cable factory (10)	Base rock	below 2.200
Dalota infront of high tension (11)	Select material then base rock	below 1.20
Dalota around dukem boarder (12)	Red	below 3.00
Mandelo (13)	Cinder material	below 0.40

3.1.3 Selection of the Area for Sample Collection

In order to select areas for sample collection the following factors are taken into considerations.

- ❖ Uniform distribution of the test pits to represent the whole part of the study area.
- ❖ The upper part of the soil should be covered by black clay soil.
- ❖ In some areas, bedrock or cinder materials are overlain by thin black expansive soil. In this case the sample was not collect.
- ❖ Using field identification of expansive soil (stated in chapter 2), if the soil show expansive nature, the samples was collected.

3.1.4 Collecting Disturbed and Undisturbed Soil Sample.

Based on the area sample selection criteria, stated in sub-topic 3.1.3, from 13 test pits, 24 disturbed and based on index property testes, 18 undisturbed samples were collected from different depths. The samples are taken at a depth below 1.0m and above 3.0m at. The locations of test pits are shown in Fig 3.1.

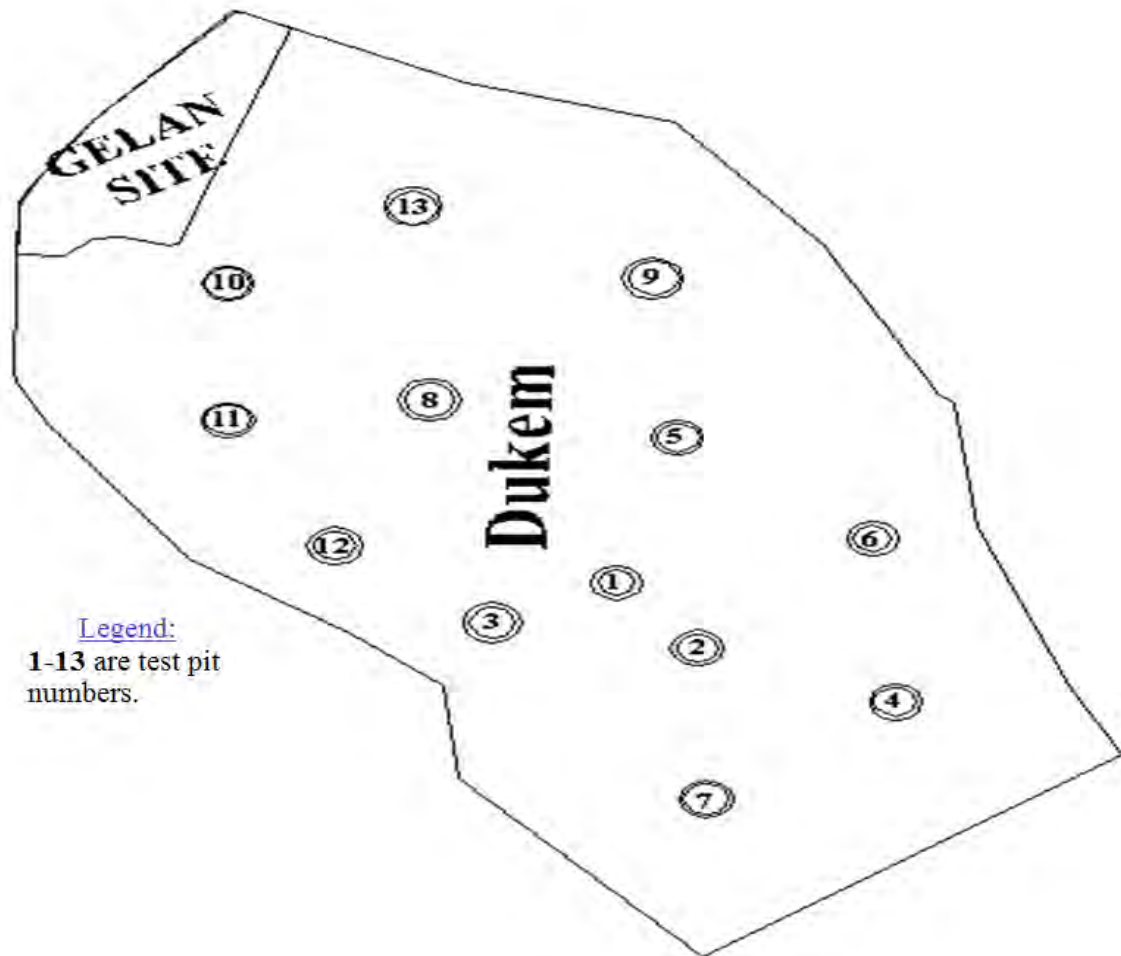


Fig 3.1 Locations of test pits.

The disturbed samples are easily taken by digging the soil with hand tools. Whereas undisturbed samples collected by the help of hydraulic jack to avoid disturbance.

3.2 Laboratory work

After the representative soil samples are collected, the following laboratory tests were conducted.

- ❖ Water content
- ❖ Dry density
- ❖ Specific gravity
- ❖ Atterberge limits (LL, PL, PI & SL)
- ❖ Sieve and Hydrometer analysis
- ❖ Free swell test
- ❖ Swell consolidation tests

The significances and method of conducting each test are presented as in Table 3.3 below.

Table 3.3 Laboratory tests and their significance

Test type	Test method	Sample type	Significance
Water content (ω _n)	ASTM [D2216-98]	Undisturbed	<ul style="list-style-type: none"> ➤ For many materials, it is one of the most significant index properties used in establishing a correlation between soil behavior and its index properties. ➤ In fine-grained (cohesive) soils, the consistency of a given soil type depends on its water content. The water content of a soil, along with its liquid and plastic limits is used to express its relative consistency or liquidity index.
Specific gravity (G _s)	ASTM [D854-98]	Disturbed	<ul style="list-style-type: none"> ➤ Used in hydrometer test results calculations. ➤ Used in preliminary soil classification.

Test type	Test method	Sample type	Significance
Liquid limit(LL) and plastic limit (PL)	ASTM [D4318-98]	Disturbed	<ul style="list-style-type: none"> ➤ Used as an integral part of several Engineering soil classification systems to characterize the fine-grained fractions of soils and to specify the fine-grained fraction of construction materials. Also used extensively, either individually or together, with other soil properties to correlate with engineering behavior such as shrink-swell, shear strength etc. ➤ Can be used with the natural water content of the soil to express its relative consistency or liquidity index and can be used with the percentage finer than 2-μm size to determine its activity number.
Shrinkage limit(SL)	ASTM [D427-98]	Disturbed	<ul style="list-style-type: none"> ➤ The term shrinkage limit, expressed as water content in percent, is typically assumed to represent the amount of water required to fill the voids of a given cohesive soil at its minimum void ratio obtained by drying (usually oven). Thus, the concept shrinkage limit can be used to evaluate the shrinkage potential or possibility of development, or both, of cracks in earthworks involving cohesive soils.
Sieve analysis	ASTM [D422-63] (wet method)	Disturbed	<ul style="list-style-type: none"> ➤ The distribution of particle sizes larger than 75 μm (retained on the No. 200 sieve) determined by sieving. ➤ Grain size analysis provides the grain size distribution, affects the engineering properties of soil, and it is required in classifying the soil.

Test type	Test method	Sample type	Significance
Hydrometer	ASTM [D422-63]	Disturbed	<ul style="list-style-type: none"> ▶ Using this test, soils particle having a diameter less than 75μm classified into silt and clay. The amount of clay in a given soil affects the engineering properties of the soil.
Dry density	ASTM [D2937-94]	Undisturbed	<ul style="list-style-type: none"> ▶ The swelling pressure of an expansive soil increases with increasing dry density for constant moisture content. The reason is that higher densities result in closer particles spacing, therefore causing greater particle interaction. ▶ As swelling pressure is the built-in property of expansive soil and will not affected by placement condition or environmental condition, only initial dry density and the amount and the type of clay mineral affect the swelling pressure.
Free swell	BS-Standard	Disturbed	<ul style="list-style-type: none"> ▶ Used to indicate the expansiveness of a given soil. ▶ Most commonly used simple tests for estimating soil swelling potential
Swell Consolidation test	ASTM [D4546-96]	Undisturbed	<ul style="list-style-type: none"> ▶ The relative swell/settlement potential of soil determined from this test method can be used to develop estimates of heave or settlement for given final moisture and loading condition. ▶ Soils containing montmorillonites (smectite) are likely to have a significant potential for swell and are commonly tested by this test methods.

3.3 Materials

In order to achieve the objectives of this research, different laboratory and field materials are used. These materials are

- The consolidation test equipment and its accessories
- Sampling tools for disturbed and undisturbed samples
- Hydrometer, sieves, balance, cans, picnometers, flat glass, Casagrand apparatus, oven dry, computer etc.

3.4 Computer analysis

The test results were analyzed by using the basic Microsoft office excels. Also computer software SPSS 15.0 was used to develop a correlation between index properties and swelling pressure of expansive soils.

Chapter 4

Laboratory test results and discussions

4.1 Laboratory test results

To conduct laboratory tests, both disturbed and undisturbed soil samples were collected from different locations in the town. 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 Fig 3.1.

Table 4.1 Areas, test pits designation and depths where samples were collected.

Area name	Samples designation	Color	Depth ,below ground Level (m)
Dukem primary school (1)	T.P11	Black	1.00
	T.P12	Grey	1.45
	T.P 13	Dark brown	2.62 (only disturbed)
Stadium (2)	T.P21	Black	1.00
	T.P22	Grey	2.43
Al-mehdi industry (3)	T.P31	Grey	1.05
	T.P32	Light black	2.00
	T.P33	Brown	2.40(only disturbed)
Eastern industrial zone (4)	T.P41	Black	1.05
	T.P42	Grey	2.80
Technical school (5)	T.P51	Black	1.05
	T.P52	Grey	2.85
Atlabachew Real state (6)	T.P61	Black	1.2(only disturbed)
	T.P62	Brown	2.57(only disturbed)
Kotch (East Africa Tiger brand)(7)	T.P71	Black	1.00
	T.P72	Brown	2.43

Area name	Samples designation	Color	Depth ,below ground Level (m)
Asse Marble factory (8)	T.P81	Black	1.45
	T.P82	Gray	2.60
Right side of medhaniallem church (9)	T.P91	Yellowish	1.45
	T.P92	Dark yellow	2.58
Elesewdy cable factory (10)	T.P10-1	Black	1.00
	T.P10-2	Dark brown	1.95(only disturbed)
Dalota infront of high tension (11)	T.P11-1	Black	1.08(only disturbed)
Dalota around dukebbm boarder (12)	T.P12-1	Dark brown	1.45

4.1.1 Laboratory tests on disturbed soil sample

Disturbed soil samples are used to determine the index property of the soil. Index property is a property, which helps in distinguishing the characteristics of a soil. Two main categories of Index properties are soil grain property and soil aggregate property. 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.

Index property tests are the most commonly applied methods in all soil testing laboratories and consists of:

- ❖ Grain size analysis: - helps to determine the amount of colloidal sized particles existing in a soil. The term colloid describes a particle whose behavior is controlled by surface force (i.e electrostatic and adsorptive force) rather than by gravitational force and smaller than 0.001 mm in diameter. These colloidal particles greatly influence the plasticity characteristics and volume change behavior of the soil
- ❖ Consistency test:-which include liquid limit, plastic limit and shrinkage limit tests.
- ❖ Free swell and Vertical swell, under a setting load (7kPa) in a consolidometer ring.

Using the ASTM procedures, liquid limit, plastic limit, shrinkage limit, specific gravity, sieve analysis, free swell and hydrometer tests are conducted on disturbed soil samples. Also Activity and plasticity index is calculated using the following formulas respectively, $A_c = PI / (\text{percentage by weight finer than } 2\mu\text{m})$ and $PI = LL - PL$. The results are presented in Table 4.2.

Table 4.2 Laboratory test results on disturbed soil samples.

Test pit	Liquid Limit (LL)%	Plastic limit (PL)%	shrinkage limit (SL)%	Plasticity Index (PI)	Specific gravity (Gs)	Clay content (%)	Free swell (%)	Activity
T.p11	91.70	40.01	11.58	51.68	2.70	61.04	121.00	0.85
T.p12	106.44	38.74	12.34	67.70	2.74	44.50	116.00	1.52
T.P 13	69.98	32.50	16.24	37.47	2.74	38.30	72.00	0.97
T.p21	108.68	38.37	11.74	70.31	2.74	57.44	135.00	1.23
T.p22	87.23	43.57	13.33	43.65	2.73	50.49	100.00	0.87
T.p31	72.55	28.95	16.94	43.59	2.64	43.37	76.00	1.00
T.p32	73.29	29.69	15.31	43.60	2.71	29.92	82.00	1.47
T.P33	56.93	24.73	14.12	32.20	2.72	34.87	65.00	0.92
T.p41	96.08	35.77	10.59	60.30	2.79	56.61	120.00	1.06
T.p42	98.57	40.79	11.54	57.77	2.76	46.10	114.00	1.24
T.P51	95.38	37.28	9.00	58.09	2.79	54.86	109.00	1.05
T.p52	83.41	36.93	14.29	46.47	2.66	53.25	89.00	0.88
T.p61	90.34	34.74	12.60	55.59	2.74	69.94	152.00	0.79
T.p62	87.43	34.39	13.83	53.04	2.71	67.68	151.00	0.78
T.p71	109.04	39.50	13.97	69.54	2.74	70.40	200.00	0.98
T.p72	117.64	42.92	14.15	74.72	2.74	62.42	170.00	1.19
T.p81	96.31	41.36	12.81	54.95	2.71	61.82	189.00	0.88
T.p82	106.61	40.31	13.46	66.30	2.70	72.21	170.00	0.91
T.p91	65.16	32.12	22.94	33.04	2.61	26.84	93.00	1.23

Test pit	Liquid Limit (LL)%	Plastic limit (PL)%	shrinkage limit (SL)%	Plasticity Index (PI)	Specific gravity (Gs)	Clay content (%)	Free swell (%)	Activity
T.p92	84.17	44.71	28.70	39.46	2.58	27.34	88.00	1.44
T.p10-1	124.56	45.07	13.66	79.49	2.68	79.10	250.00	1.00
T.p10-2	118.81	44.29	14.08	74.51	2.70	81.48	248.00	0.91
T.P11-1	112.80	43.47	11.14	69.32	2.69	72.03	170.00	0.96
T.p12-1	109.92	41.86	13.72	68.05	2.72	74.22	210.00	0.91

4.1.2 Laboratory test results on undisturbed sample

Based on the result obtained from the index tests, the location of undisturbed sample was selected for the locations where the soil shows more expansiveness and uniqueness. Using the ASTM procedures, water content, dry density and swelling pressure tests are conducted on undisturbed soil samples. The result is presented in table 4.3 below.

Table 4.3 Laboratory test results on undisturbed soil samples.

Test pit	Color	Water content (w) %	Dry density (γ_d) kg/m ³	Swelling pressure (Sp)kPa
T.p11	Black	31.28	1255.78	351.91
T.p12	Grey	36.95	1112.77	12.93
T.P 21	Black	38.43	1127.20	0.00
T.P 21R	Black	22.53	1386.38	523.95
T.p22	Grey	36.51	1131.06	7.91
T.p31	Grey	21.72	1343.24	72.24
T.p32	Light black	24.82	1405.46	55.27
T.p41	Black	30.66	1303.00	149.84
T.p42	Grey	40.00	1130.81	0.00

Test pit	Color	Water content (w) %	Dry density (γ_d) kg/m ³	Swelling pressure (Sp)kPa
T.p42R	Grey	26.38	1477.41	563.47
T.P51	Black	34.83	1305.60	150.44
T.p52	Grey	35.77	1188.46	82.25
T.p71	Black	33.70	1322.94	372.81
T.p72	Brown	33.09	1224.40	380.00
T.p81	Black	29.27	1326.03	378.95
T.P82	Grey	39.54	1129.05	1.00
T.P82R	Grey	27.25	1424.44	580.78
T.p91	Yellowish	24.67	1270.02	107.10
T.p92	dark yellow	28.91	1175.30	231.58
T.p10-1	Black	38.46	1255.88	507.00
T.p12-1	dark brown	34.28	1271.43	387.85

❖ R: - Indicate the sample is remolded sample from disturbed one.

From the undisturbed soil test value, one can observe that when the initial water content is approximately equal to the plastic limit the swelling pressure approach to zero. This shows the soil is fully saturated. 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. Also, some samples show, with approximately the same dry density and water content; they have different swelling pressure. This is due to the amount of Montmorillonite available in the sample.

4.2 Discussions on the results

The profile of most of the test pits show the grey or dark brown color soil are overlain by black expansive soil. The average depth for the boundary between the grey or dark brown and black expansive soils is 1m to 1.50m.

According to the classification system stated in Chapter 2, the soils are classified as follow.

- ❖ Except test pit 3 and test pit 9 all the samples test results lie in rang of Ethiopian expansive soils properties given by A. Teffera and L. Mesfin.
- ❖ According to AASHTO classification, except test pit 3 and test pit 9 all the samples are grouped in A-7-5. But test pit 3 and test pit 9 are grouped in A-7-2. 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. Also subgroup A-7-2 has volume change but less than subgroup A-7-5.
- ❖ Based on the Unified soil classification systems, most of the samples are grouped in CH (Fat clay). The remaining samples are grouped as SC (clayey sand), SM (silty sand), and GC (clayey gravel). In this classification CH and OH groups have high volume change and the remaining (SM, SC and GC) groups have moderate expansion.
- ❖ U.S.B.R Classification method shows the samples have very high to high degree of expansion or swell.
- ❖ Seed, Woodward and Lundgreen [18] use plasticity index as a tool to indicate the swelling characteristics of a soil. Based on this classification, except test pit 9 which has high Swell Potential, all other samples have very high Swell Potential.
- ❖ Based on Chen method of soil classification, the samples have medium to very high degree of expansion.

Generally, from the above discussion, the soils are mostly fat clay soil and have very high swelling potential. Because the town is surrounded by mountains and the fine grained (clay and silt) soils are easily transported to the center of the town and deposited for a long time. This makes the town soil type become clay soil. Also the deposited soil stays in one area for a long time in different environmental condition. This promotes the formation of montmorilonite. The presence of montmorilonite in the soil increases the swelling potential of the soil.

CHAPTER 5

Examining Existing Swelling Pressure Prediction Models and Development of New Models

5.1. Swelling Pressure Prediction Models in General

To design a structure on expansive soil, it is essential to determine the swelling pressure. The most reliable method for the estimate of swelling pressure would involve utilizing odometer test on undisturbed samples.

The evaluation of swell pressure of a soil using undisturbed samples is a difficult and expensive process. But such estimate can also be derived from soil properties that are easily determined with a reasonable degree of reliability using simple routine tests. To facilitate this, empirical models had been developed by different researchers to predict swell behavior of a soil. 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. The formation and development of soil structure have 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.

Many swelling pressure prediction models have been established from which swelling pressure can be estimated based on index test and the physical state of the soil. Most of them are developed for soil found in other parts of the world.

5.2. Swelling Pressure Prediction Models Developed for Soils found in Ethiopia.

As mentioned previously, there are different empirical equations developed to determine the swelling behavior of a soil found in Ethiopia. Some of them are presented below.

❖ Daniel Teklu (2003)

From multiple regression analysis he recommended the following two equations for soil found in Addis Ababa.

$$\text{Log Sp} = -5.00 - 0.0002064 \text{ LL} + 0.003477\text{PI} + 0.005827 \gamma_d \dots \text{Eqn 5.1}$$

$$\text{Log Sp} = -9.384 + 0.002748\text{W} + 0.006307\text{PI} + 0.008359 \gamma_d \dots \text{Eqn 5.2}$$

Where: - LL= Liquid Limit (%)

PI=Plasticity index (%)

γ_d =Dry density (kg/m²)

W=Natural water content (%)

Sp=Swelling pressure (kPa)

❖ Dagmawe Negussie (2007)

He recommended the following two equations for soil found in Bahir-dar.

$$\text{Log Sp} = 7.042 - 1.926 * \gamma_{dry} - 0.046 * w - 0.609 * A_c \dots \text{Eqn 5.3}$$

$$\text{Log Sp} = 7.018 - 1.924 * \gamma_{dry} - 0.042 * w - 0.008 * W_l + 0.003 * \text{CEC} \dots \text{Eqn 5.4}$$

Where: - γ_{dry} =dry density (gm /cc)

CEC= Cation Exchange Capacity (meq/100gm)

w=Natural water content (%)

w_l or LL= Liquid Limit

A_c= Activity

Sp=swelling pressure (kPa)

5.3. Some of Swelling Pressure Prediction Models Developed for Soil Found in other Countries.

The following models are tested for their validity in our environmental and climatic condition. They are selected for their simplicity, wide acceptance and practical significances to field application [10].

❖ Vijayvergiya and Ghazzaly (1973)

$$\text{Log Sp} = (0.4 w_l - w + 23.6) / 12 \dots \dots \dots \text{Eqn 5.5}$$

$$\text{Log Sp} = (6.242 \gamma_d + 0.65 w_l - 100) / 19.5 \dots \dots \dots \text{Eqn 5.6}$$

❖ Komornik and Davvid (1969)

$$\text{Log Sp} = 0.132 + 0.0208(\omega) + 0.0006688(\gamma_d) - 0.0269(w) \dots \dots \dots \text{Eqn 5.7}$$

In the above equations

w_l = Liquid limit (%)

Sp = Swelling pressure (kPa)

γ_d = Dry density (g/cm³) for equation Eqn 5.7.

γ_d = Dry density (kN/m³) for equation Eqn 5.6.

ω = Moisture content (%)

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. At this point it is worthwhile to test these equations for the soil of the study area and to examine the outcome. The results are shown in table 5.1.

Table 5.1 Comparison of values calculated using previously developed equations with the measured values.

	measured(Sp) kPa	calculated Sp (kPa) values using previously developed equations					
		Daniel teklu		dagmawi	Vijayvergiya and Ghazzaly		Komornik and Davvid
Test pit		Eqn 5.1	Eqn 5.2	Eqn 5.3	Eqn 5.5	Eqn 5.6	Eqn 5.7
T.p11	351.91	300.79	33.50	462.55	260.69	74.47	15.79
T.p12	12.93	49.83	2.79	185.48	272.51	82.11	22.53
T.P 21R	523.95	1997.45	513.00	385.41	5146.31	704.66	61.27
T.p22	7.91	53.02	2.79	450.09	67.78	21.43	9.22
T.p31	72.24	919.83	150.96	693.57	375.29	32.22	11.41
T.p32	55.27	2118.97	509.93	198.60	219.24	53.50	9.76
T.p41	149.84	605.96	93.84	299.51	410.99	146.65	20.25
T.p42R	563.47	6158.22	2527.25	166.99	1130.52	626.42	29.74
T.P51	150.44	616.66	98.09	191.13	175.04	141.57	15.12
T.p52	82.25	117.37	8.74	372.34	58.35	24.22	8.04
T.p71	372.81	847.44	160.59	219.91	621.10	458.21	31.22
T.p72	380.00	234.49	25.88	270.73	1350.58	434.79	48.94
T.p81	378.95	790.64	134.07	398.28	546.72	176.32	22.32
T.p82R	580.78	3226.96	1037.65	305.88	1775.29	792.18	41.44
T.p91	107.10	317.57	32.23	514.50	120.91	10.76	6.67
T.p92	231.58	92.97	5.87	371.09	230.85	23.35	12.76
T.p10-1	507.00	370.41	52.59	174.43	818.64	928.25	48.86
T.p12-1	387.85	419.37	58.53	286.76	593.50	337.72	31.40

From the above table, one can observe that most of the equations do not predict the swelling pressure of the soil under investigation except equation Eqn 5.6 developed by Vijayvergiya and Ghazzaly, which predicts closely for those samples that have relatively high density.

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.

5.4. Development of New Swelling Pressure Prediction Models

To predict the swelling behavior of the study area, new empirical equations are needed. To develop new empirical equations, 15 samples were taken out of which 3 samples are prepared from disturbed samples. Several functions [Appendix B] composed of dry density; Atterberg limits and initial moisture content in different combinations were tested using the SPSS 15 computer program. The effect of dry density is expressed by directly involving dry density in the developed relations. Also the type and amount of clay present in the soil may be obtained by considering Atterberg limit values in the equation.

Out of these equations, 9 equations with higher R^2 values were selected and using these equations the swelling behavior of the soil of the study area were calculated. Then a graphs are plotted which shows the measured value against the predicted or calculated value. Also, the developed equations were tested for three samples, which are used as a control to test the relations. Finally, using different selection criteria, one equation is selected which predicted the measured value better than the others. The input and necessary outputs of the software are presented in Table 5.2 below.

Table 5.2 Input data for SPSS 15 computer program

Test pit	Color	Liquid limit (LL) %	Plastic limit (PL) %	Shrinkage limit (Sl) %	Plasticity index (PI) %	Water content (w) %	Dry Density (γ_d) kg/m ³	Swelling pressure (Sp)kPa
T.p11	Black	91.70	40.01	11.58	51.68	31.28	1255.78	351.91
T.P 21R	Black	108.68	38.37	11.74	70.31	22.53	1386.38	523.95
T.p22	Grey	87.23	43.57	13.33	43.65	36.51	1131.06	7.91

Test pit	Color	Liquid limit (LL) %	Plastic limit (PL) %	Shrinkage limit (Sl) %	Plasticity index (PI) %	Water content (w) %	Dry Density (γ_d) kg/m ³	Swelling pressure (Sp)kPa
T.p31	Grey	72.55	28.95	16.94	43.59	21.72	1343.24	72.24
T.p32	light black	73.29	29.69	15.31	43.60	24.82	1405.46	55.27
T.p41	Black	96.08	35.77	10.59	60.30	30.66	1303.00	149.84
T.p42R	Grey	98.57	40.79	11.54	57.77	26.38	1477.41	563.47
T.P51	Black	95.38	37.28	9.00	58.09	34.83	1305.60	150.44
T.p52	Grey	83.41	36.93	14.29	46.47	35.77	1188.46	82.25
T.p72	brown	117.64	42.92	14.15	74.72	33.09	1224.40	380.00
T.p81	Black	96.31	41.36	12.81	54.95	29.27	1326.03	378.95
T.p82R	Grey	106.61	40.31	13.46	66.30	27.25	1424.44	580.78
T.p91	Yellowish	65.16	32.12	22.94	33.04	24.67	1270.02	107.10
T.p92	Darkyellow	84.17	44.71	28.70	39.46	28.91	1175.30	231.58
T.p10-1	Black	124.56	45.07	13.66	79.49	38.46	1255.88	507.00

Table 5.3 Input data for the control sample

Test pit	Color	Liquid limit (LL)%	Plastic limit (PL)%	Shrinkage limit (Sl)%	Plasticity index (PI) %	Water content (w) %	Dry Density (γ_d) kg/m ³	Swelling pressure (Sp) kPa
T.p12	Grey	106.44	38.74	12.34	67.70	36.95	1112.77	12.93
T.p71	Black	109.04	39.50	13.97	69.54	33.70	1322.94	372.81
T.p12-1	Darkbrown	109.92	41.86	13.72	68.05	34.28	1271.43	387.85

The following possible empirical formulas (Table 5.4) are developed by taking one or more of the important parameters; liquid limit, plastic limit, shrinkage limit, plasticity index, natural moisture content and dry density in different combinations.

Table 5.4 Newly developed possible empirical equations.

Equations	n	R ²	Eqn. n o
$Sp=1.044*\gamma_d-9.780w+6.484*LL+19.953*PL+4.602*SL-2229.794$	15	0.905	Eqn 1
$Sp=0.896*\gamma_d-13.331w+5.858*LL+22.374*PL-1900.052$	15	0.900	Eqn 2
$Sp=1.489*\gamma_d-5.759w+35.140*PL-2839.779$	15	0.828	Eqn 3
$Sp=1.639*\gamma_d+32.676*PL-3110.940$	15	0.819	Eqn 4
$Sp=0.877*\gamma_d+8.858*LL-1689.305$	15	0.757	Eqn 5
$Sp=1.415*\gamma_d+6.259*LL+17.225*PL+9.396*SL-2946.915$	15	0.891	Eqn 6
$Sp=1.093*\gamma_d+10.711*LL+13.727*SL-2344.507$	15	0.836	Eqn 7
$Sp=1.051*\gamma_d+16.489*SL+12.022*PI+4.704*w-2130.184$	15	0.721	Eqn 8
$Sp=1.373*\gamma_d+3.936*LL+21.922*PL-2719.088$	15	0.858	Eqn 9

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

Table 5.5 Calculated swelling pressure values using newly developed equations.

Test pit	Measured Sp, kPa	Calculated swelling pressure values using new equation								
		Eqn 1	Eqn 2	Eqn 3	Eqn 4	Eqn 5	Eqn 6	Eqn 7	Eqn 8	Eqn 9
T.p11	351.91	221.59	240.52	256.01	254.81	224.33	202.12	169.36	149.29	243.25
T.P 21R	523.95	521.53	536.88	443.10	415.12	489.23	466.31	496.08	471.80	453.33
T.p22	7.91	90.36	112.57	165.41	166.84	75.31	75.41	9.06	-25.06	132.52
T.p31	72.24	86.19	86.70	52.69	36.80	131.36	65.82	133.30	187.22	45.51
T.p32	55.27	132.91	122.01	153.43	162.90	192.53	155.95	186.95	240.44	150.06
T.p41	149.84	216.21	221.91	180.94	193.69	304.53	214.00	254.26	283.25	232.39

Test pit	Measured Sp, kPa	Calculated swelling pressure values using new equation								
		Eqn 1	Eqn 2	Eqn 3	Eqn 4	Eqn 5	Eqn 6	Eqn 7	Eqn 8	Eqn 9
T.p42R	563.47	560.70	562.01	641.52	643.44	479.52	571.66	484.53	431.65	591.60
T.P51	150.44	196.46	198.40	213.94	247.35	300.58	224.38	227.74	252.73	266.34
T.p52	82.25	4.74	2.97	21.76	43.87	91.83	27.41	44.18	81.66	50.69
T.p72	380.00	409.33	405.49	301.25	298.55	426.62	394.39	448.18	444.00	366.14
T.p81	378.95	377.02	387.43	419.48	413.90	326.78	365.08	312.38	273.14	387.34
T.p82R	580.78	548.35	539.39	540.78	540.93	504.36	556.84	539.19	514.24	540.02
T.p91	107.10	23.75	9.31	37.87	20.17	1.71	26.83	56.49	96.18	-14.73
T.p92	231.58	284.48	261.07	314.86	276.33	87.08	282.85	235.76	188.85	206.07
T.p10-1	507.00	475.06	450.59	392.61	420.31	515.49	514.61	549.96	551.65	483.65

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

Test pit	Measured Sp, kPa	Calculated Using Possible Equations								
		Eqn 1	Eqn 2	Eqn 3	Eqn 4	Eqn 5	Eqn 6	Eqn 7	Eqn 8	Eqn 9
T.p12	12.93	90.68	94.89	-34.03	-20.93	229.52	77.31	181.31	230.53	77.19
T.p71	372.81	381.41	358.77	324.29	348.31	436.86	419.36	461.26	485.14	392.61
T.p12-1	387.85	373.54	362.75	327.16	341.0	399.46	390.31	410.96	411.85	377.09

The following graphs are plotted to investigate the approximation accuracy of the newly developed formulas. The measured and calculated values are plotted (Fig 5.1 to Fig 5.5) trend lines are drawn to observe the gap between the measured and the calculated values.

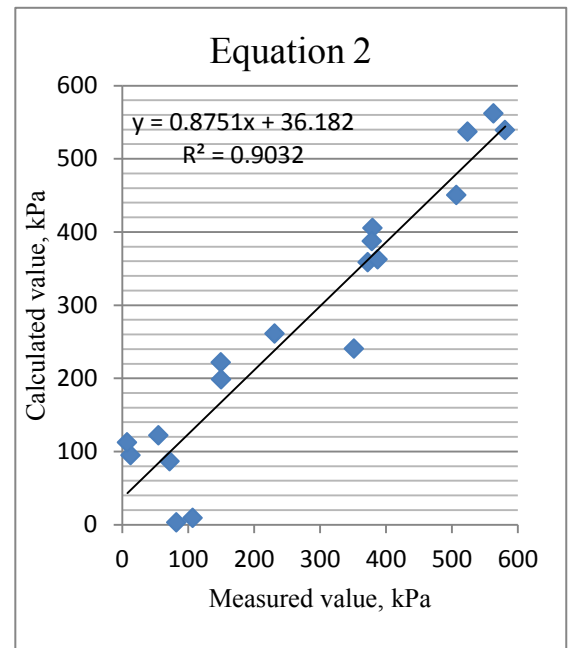
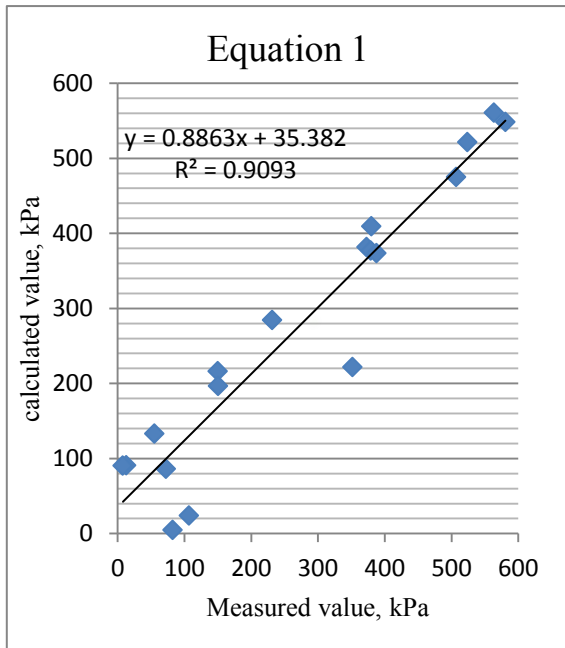


Fig 5.1 Measured versus predicted swelling pressure for equation 1 and 2.

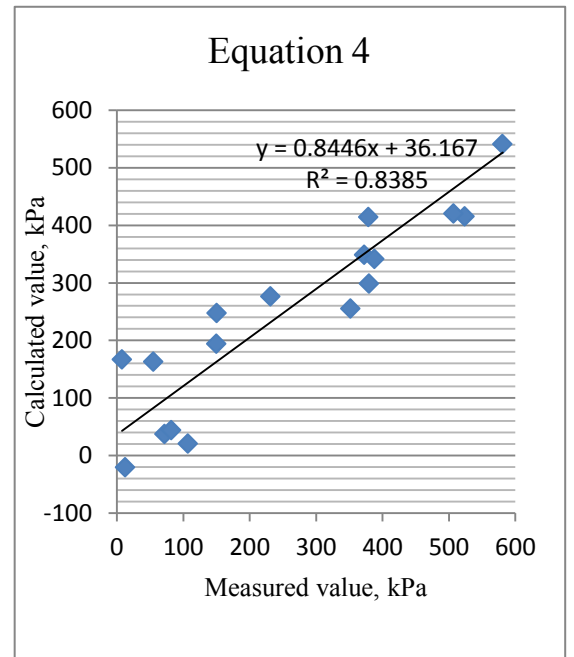
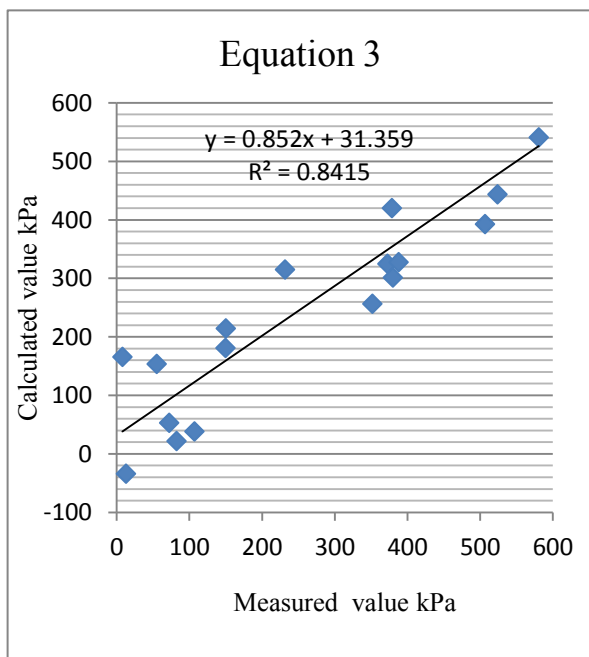


Fig 5.2 Measured versus predicted swelling pressure for equation 3 and 4.

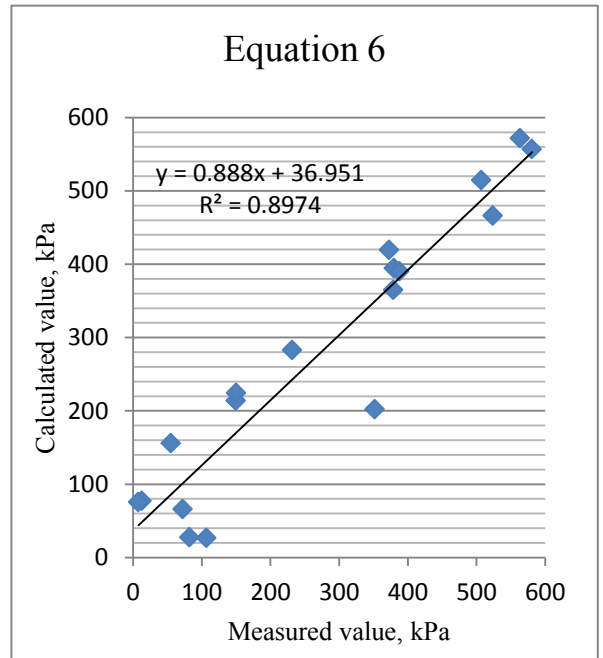
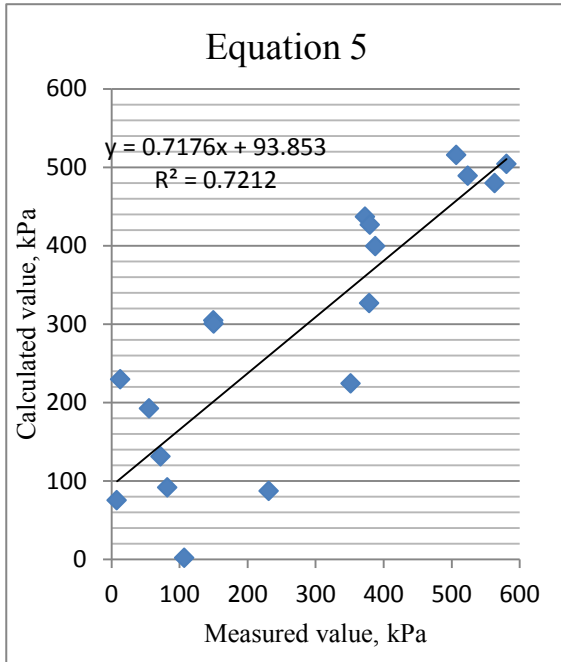


Fig 5.3 Measured versus predicted swelling pressure for equation 5 and 6.

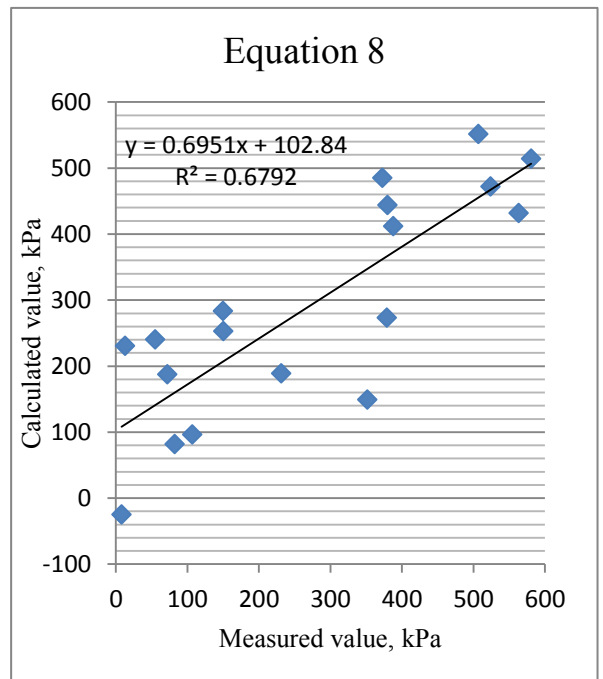
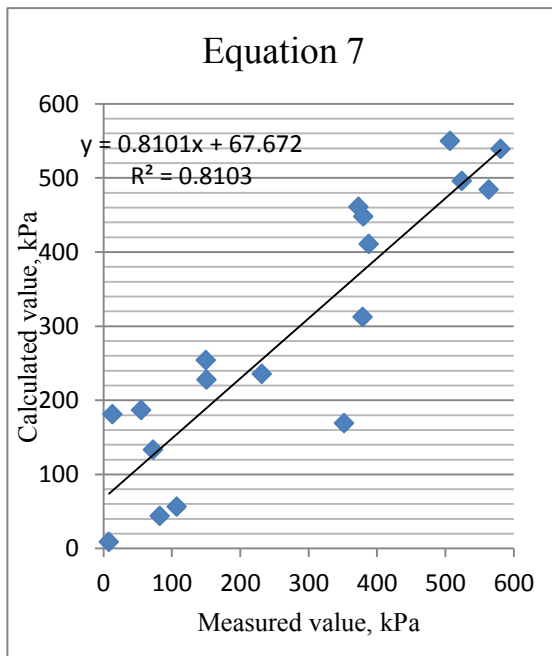


Fig 5.4 Measured versus predicted swelling pressure for equation 7 and 8.

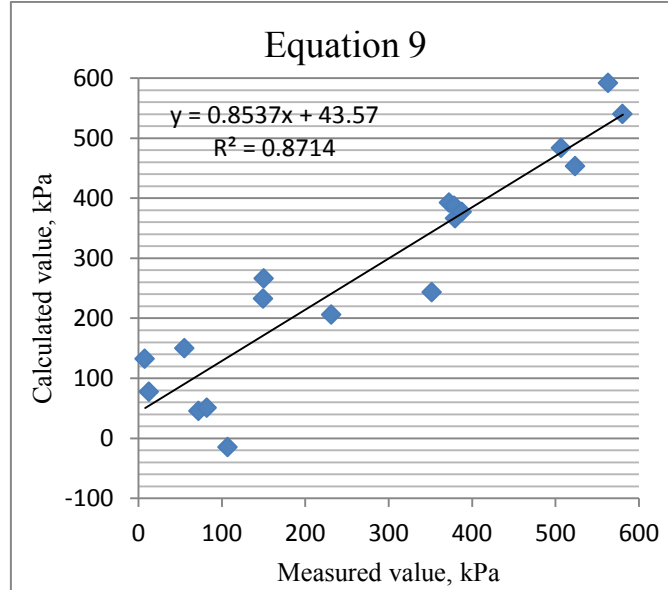


Fig 5.5 Measured versus predicted swelling pressure for equation 9.

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 value of R^2 for the measured versus calculated swelling pressure graph should have relatively higher value and approaches to one.
- ❖ The soil under investigation is found to be sensitive to dry density. So that, this important soil parameter should be involved in the equation.
- ❖ The weight given to the dry density should be taken in to consideration. This means if one equation has relatively high dry density multiplication coefficient than the others, this equation will be preferable.
- ❖ For simplicity the number of independent variables or parameters involved in the equation should be less.
- ❖ The equation should give approximately the same swelling pressure value compared with the measured one for the control samples.

When one evaluate the equations based on the above considerations, all the equations have good regression analysis and measured versus calculated swelling pressure graph R^2 values. Also, dry density is involved in all the equations. The major difference between them is the weight given to the dry density and the number of independent variables or parameters involved in the equation. Accordingly, equation number 4 fulfills the entire requirement.

Note that: - Even if equation number 4 fulfills the entire requirements, the remaining equations also predict the swelling pressure of the study area with various degrees of accuracy.

Chapter 6

Conclusion and Recommendation

1. Most of the study area is covered by 1.0m to 1.50m thick black clay soil. Based on different soil classification system stated in Chapter 2 the study area soil type is fat clay soil. This soil has very high swelling potential. Therefore, care should be taken to design light weight structures on this area.
2. For different clay content, in-situ dry density and water content the swelling pressure of expansive soils found in Dukem ranges between 7.91kPa to 580kPa.
3. Evaluation of the previously developed equations with the present study area showed that, specific prediction model is necessary for specific areas in order to get fair evaluations.
4. The Regression Analysis showed that there is a relationship between Index Properties and Swelling Characteristics of Expansive Soil. Specially, dry density, in combination with other parameters is a powerful variable for prediction of swelling characteristics of soils found in Dukem.
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 4 ($Sp=1.639*\gamma_d+32.676*PL-3110.940$) is recommended.

Suggestion for Future Works

- ❖ The equations developed may be further improved by increasing the number of samples.
- ❖ The shear strength characteristics of the study area not yet investigated.
- ❖ The study area is very close to the East Africa Rift valley. So the dynamic property, e.g. shear modulus and damping ratio, etc... can be studied.
- ❖ During this study, it was observed that structures constructed in Dukem town settle significantly. Hence, it is interesting to investigate the consolidation and settlement characteristics of these soils.

References

1. Alemayehu, T. and L. Mesfin, 1999, Soil Mechanics, AAU Printing Press.
2. Alemayehu, T. and Y. Solomon, 1963, Investigation on the Expansive of Addis Ababa. Journal of the Ethiopia Association of Engineers and Architects. Vol. **7**, pp 1-2.
3. ASTM, 1996, American Society for Testing and Material, Annual Book of ASTM Standards.
4. Ayenew, Z., 2004, Investigation into Shear Strength Characteristics of Expansive Soil of Ethiopia, Unpublished M.Sc Thesis, Addis Ababa University.
5. Bowles J.E., 1996, Foundation Analysis and Design, Fifth Edition, the Mc Graw-Hill Companies Inc.
6. Chen, F.H., 1988, 1975 and 1966, "Foundation on Expansive Soils," Elsevier scientific publishing company, New York.
7. Dagmawe, N., 2007, In-depth Investigation of Relationship between Index Property and Swelling Characteristic of Expansive Soil in Bahir-Dar, Unpublished M.Sc Thesis, Addis Ababa University.
8. Daniel T., 2003, Examining the Swelling Pressure of Addis Ababa Expansive Soil, Unpublished M.Sc Thesis, Addis Ababa University.
9. Das, S.K. and A.K. Sabat, 2008, Swelling Pressure of Soil: Artificial Intelligence Technique Approaches. Research paper on 12th International Conference of IACMAG.
10. El-Sohby, M.A and S.O. Mazen, 1987, "On the Prediction of Swelling Pressure and Deformation Behavior of Expansive Soils," 9th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Lagose.
11. Getaneh, B., 2005, Investigation the Index Properties and Swelling Characteristics of Expansive Soil of Bahir-dar. Unpublished M.Sc Thesis, Addis Ababa University.
12. Holtz, W.G. and H.J. Gibbs, 1956, Engineering Properties of Expansive Clays. Translation ASCE, Vol. 121.

13. John, D.N. and J.M., Debra, 1992, 'Expansive Soils-Problems and Practice in Foundation and Pavement Engineering', John Wiley & Sons. Inc., New York.
14. Komornik, A. and D. David, 1969, 'Prediction of Swelling Pressure of Clays,' ASCE, Vol 95, No Sm1, proc. Paper 6358, pp 209-232.
15. Lambe T.W., 1951, 'Soil Testing for Engineers,' New York.
16. Mckeen, R.G., 1976, 'Design and Construction of Airport Pavements on Expansive Soils,' Report no FAA-RD-76-66, U.S Department of Transportation Federal Aviation Administration Systems Research and Development Services, Washington, D.C.
17. Mitchell, J.K, 1976, Fundamentals of Soil Behavior, the Mc Graw-Hill Companies Inc.
18. Seed, H.B, Woodward, R.J. and R. Lundgren, 1962, Prediction of Swelling Potential for Compacted Clays. Proceedings ASCE, Vol 88, No. SM3.
19. Snethen, R., 1975, 'A Review of Engineering Experience with Expansive Soil in Highway Sub-grads,' U.S Army Engineering Waterways Experiment Station.

Appendix A

Laboratory Test results

Representative Sieve and hydrometer analysis

Parameters and formulas used

Ra= actual hydrometer reading

L= Effective length from table A.2

K= Constant from table A.1

D =diameter of particle, mm= $K*[L/T]$, Where T-Time in minute

Rc = R actual - zero correction

Zero correction = Determined from laboratory test

$P = [(100\ 000/W) * G / (G - G1)] (R - G1)$

Where, P= % pass for hydrometer analysis only

G = specific gravity of the soil particles, and

G1 = specific gravity of the liquid in which soil particles are suspended.

Pa= % finer for combined analysis

Table A.1 Values of K for Use in Equation for Computing Diameter of Particle in Hydrometer Analysis

Temperature, ° C	Specific Gravity of Soil Particles								
	2.45	2.50	2.55	2.60	2.65	2.70	2.75	2.80	2.85
16	0.01510	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	0.1323	0.01305
20	0.01456	0.01431	0.01408	0.01386	0.01365	0.01344	0.01325	0.01307	0.01289
21	0.01438	0.01414	0.01391	0.01369	0.01348	0.01328	0.01309	0.01291	0.01273
22	0.01421	0.01397	0.01374	0.01353	0.01332	0.01312	0.01294	0.01276	0.01258
23	0.01404	0.01381	0.01358	0.01337	0.01317	0.01297	0.01279	0.01261	0.01243
24	0.01388	0.01365	0.01342	0.01321	0.01301	0.01282	0.01264	0.01246	0.01229
25	0.01372	0.01349	0.01327	0.01306	0.01286	0.01267	0.01249	0.01232	0.01215
26	0.01357	0.01334	0.01312	0.01291	0.01272	0.01253	0.01235	0.01218	0.01201
27	0.01342	0.01319	0.01297	0.01277	0.01258	0.01239	0.01221	0.01204	0.01188
28	0.01327	0.01304	0.01283	0.01264	0.01244	0.01255	0.01208	0.01191	0.01175
29	0.01312	0.01290	0.01269	0.01249	0.01230	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.2 Values of Effective Depth (L), Based on Hydrometer and Sedimentation Cylinder of Specified Sizes.

Hydrometer 151H		Hydrometer 152H			
Actual Hydrometer Reading	Effective Depth, L, cm	Actual Hydrometer Reading	Effective Depth, L, cm	Actual Hydrometer Reading	Effective Depth, L, cm
1.000	16.3	0	16.3	31	11.2
1.001	16.0	1	16.1	32	11.1
1.002	15.8	2	16.0	33	10.9
1.003	15.5	3	15.8	34	10.7
1.004	15.2	4	15.6	35	10.6
1.005	15.0	5	15.5		
1.006	14.7	6	15.3	36	10.4
1.007	14.4	7	15.2	37	10.2
1.008	14.2	8	15.0	38	10.1
1.009	13.9	9	14.8	39	9.9
1.010	13.7	10	14.7	40	9.7
1.011	13.4	11	14.5	41	9.6
1.012	13.1	12	14.3	42	9.4
1.013	12.9	13	14.2	43	9.2
1.014	12.6	14	14.0	44	9.1
1.015	12.3	15	13.8	45	8.9
1.016	12.1	16	13.7	46	8.8
1.017	11.8	17	13.5	47	8.6
1.018	11.5	18	13.3	48	8.4
1.019	11.3	19	13.2	49	8.3
1.020	11.0	20	13.0	50	8.1
1.021	10.7	21	12.9	51	7.9
1.022	10.5	22	12.7	52	7.8
1.023	10.2	23	12.5	53	7.6
1.024	10.0	24	12.4	54	7.4
1.025	9.7	25	12.2	55	7.3
1.026	9.4	26	12.0	56	7.1
1.027	9.2	27	11.9	57	7.0
1.028	8.9	28	11.7	58	6.8
1.029	8.6	29	11.5	59	6.6
1.030	8.4	30	11.4	60	6.5
1.031	8.1				
1.032	7.8				
1.033	7.6				
1.034	7.3				
1.035	7.0				
1.036	6.8				
1.037	6.5				
1.038	6.2				

Test Pit T.P11

Gs =2.706

Zero correction =+0.0025

Table A.3 Hydrometer analysis for test pit T.P11.

Elapsed time ,min	Temp. C°	Ra	L from table	K from table	D = k[L/T]in mm	R _C	P	Pa
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.000	18.900	1.030	8.400	0.014	0.028	1.028	87.239	81.309
4.000	18.900	1.030	8.400	0.014	0.020	1.028	87.239	81.309
8.000	19.300	1.029	8.600	0.014	0.014	1.027	84.067	78.352
15.000	19.300	1.028	8.900	0.014	0.010	1.026	80.894	75.395
30.000	20.100	1.027	9.220	0.013	0.007	1.024	77.405	72.143
60.000	20.100	1.025	9.580	0.013	0.005	1.023	72.646	67.708
120.000	21.000	1.025	9.730	0.013	0.004	1.022	71.060	66.230
240.000	22.400	1.023	10.120	0.013	0.003	1.021	66.302	61.795
1545.000	22.100	1.023	10.260	0.013	0.001	1.020	64.398	60.021

Table A.4 Sieve analysis for test pit T.P11.

Sieve Opening (mm)	Wt. Retained Out Of 500g	% Retained	Cum. % Retained	% Finer
19	0	0.000	0.000	100.000
9.5	3.2609	0.652	0.652	99.348
4.75	7.2904	1.458	2.110	97.890
2.36	6.1151	1.223	3.333	96.667
2	1.2178	0.244	3.577	96.423
1.18	2.2869	0.457	4.034	95.966
0.6	2.6089	0.522	4.556	95.444
0.425	1.0965	0.219	4.775	95.225
0.3	1.3053	0.261	5.036	94.964
0.15	4.009	0.802	5.838	94.162
0.075	4.8	0.960	6.798	93.202

Test Pit T.P61

Zero correction = -0.0001

Gs = 2.75

Table A.5 Hydrometer analysis for test pit T.P61.

Elapsed time ,min	Temp. C°	Ra	L from table	K from table	D = k[L/T]in mm	R _C	P	Pa
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.000	19.600	1.031	8.100	0.013	0.027	1.031	97.743	94.821
4.000	19.800	1.030	8.340	0.013	0.019	1.030	95.229	92.382
8.000	19.500	1.029	8.540	0.013	0.014	1.029	92.400	89.638
15.000	20.100	1.029	8.750	0.014	0.010	1.029	89.886	87.199
30.000	19.900	1.027	9.140	0.013	0.007	1.027	85.800	83.235
60.000	20.500	1.026	9.380	0.014	0.005	1.026	82.343	79.881
120.000	21.400	1.025	9.760	0.013	0.004	1.025	78.257	75.918
240.000	22.500	1.023	10.140	0.013	0.003	1.023	73.543	71.344
1440.000	20.200	1.022	10.410	0.014	0.001	1.022	70.400	68.296

Table A.6 Sieve analysis for test pit T.P61

Sieve Opening (mm)	Wt. Retained out of 500g	% retained	Cum. % Retained	% Finer
19	0	0.000	0.000	100.000
9.5	0	0.000	0.000	100.000
4.75	1.1122	0.222	0.222	99.778
2.36	2.7947	0.559	0.781	99.219
2	0.3969	0.079	0.861	99.139
1.18	1.0465	0.209	1.070	98.930
0.6	1.5324	0.306	1.377	98.623
0.425	0.8968	0.179	1.556	98.444
0.3	0.9571	0.191	1.747	98.253
0.15	2.765	0.553	2.300	97.700
0.075	3.4446	0.689	2.989	97.011

TEST PITE T.P 91

Zero correction = -0.001

Gs =2.61

Table A.7 Hydrometer analysis for test pit T.P91.

Elapsed time ,min	Temp. C°	Ra	L from table	K from table	D = k[L/T]in mm	R _c	P	Pa
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.000	20.600	1.028	8.900	0.014	0.029	1.028	91.107	82.588
4.000	20.500	1.026	9.400	0.014	0.021	1.026	84.622	76.710
8.000	20.600	1.023	10.200	0.014	0.015	1.023	74.896	67.893
15.000	21.100	1.022	10.500	0.014	0.011	1.022	71.653	64.954
30.000	21.200	1.018	11.480	0.014	0.008	1.018	59.009	53.491
60.000	21.300	1.015	12.420	0.014	0.006	1.015	47.661	43.205
120.000	21.900	1.013	12.900	0.014	0.004	1.013	42.473	38.502
240.000	22.700	1.011	13.430	0.013	0.003	1.011	35.665	32.330
1440.000	21.100	1.008	14.200	0.014	0.001	1.008	26.262	23.807

Table A.8 Sieve analysis for test pit T.P91.

sieve opening (mm)	wt. retained out of 500g	% retained	cum. % retained	% finer
19	0	0.000	0.000	100.000
9.5	2.7628	0.553	0.553	99.447
4.75	2.8097	0.562	1.115	98.886
2.36	1.7458	0.349	1.464	98.536
2	0.4604	0.092	1.556	98.444
1.18	2.0697	0.414	1.970	98.030
0.6	7.036	1.407	3.377	96.623
0.425	5.3236	1.065	4.442	95.558
0.3	5.2045	1.041	5.483	94.518
0.15	10.0334	2.007	7.489	92.511
0.075	9.3048	1.861	9.350	90.650

Test Pit T.P 12-1

Zero correction = -0.001

G_s=2.72

Table A.9 Hydrometer analysis for test pit T.P12-1.

Elapsed time ,min	Temp. C°	R _a	L from table	K from table	D = k[L/T]in mm	R _c	P	Pa
0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
2.000	20.500	1.031	7.860	0.013	0.026	1.032	99.628	90.637
4.000	20.300	1.031	8.100	0.013	0.019	1.031	98.363	89.486
8.000	20.600	1.030	8.340	0.013	0.014	1.030	95.833	87.184
15.000	20.500	1.030	8.500	0.013	0.010	1.030	93.619	85.170
36.000	21.200	1.029	8.750	0.013	0.006	1.029	90.456	82.293
60.000	20.900	1.028	8.930	0.013	0.005	1.028	88.558	80.566
120.000	22.100	1.026	9.340	0.013	0.004	1.026	83.498	75.963
240.000	22.600	1.026	9.400	0.013	0.003	1.026	82.549	75.099
1469.000	20.400	1.025	9.640	0.013	0.001	1.025	80.019	72.797

Table A.10 Sieve analysis for test pit T.P12-1.

Sieve Opening (mm)	Wt. Retained out of 500g	% Retained	Cum. % Retained	% Finer
19.000	0.000	0.000	0.000	100.000
9.500	0.000	0.000	0.000	100.000
4.750	17.567	3.513	3.513	96.487
2.360	14.621	2.924	6.437	93.563
2.000	1.768	0.354	6.791	93.209
1.180	3.062	0.612	7.403	92.597
0.600	2.417	0.483	7.887	92.113
0.425	0.851	0.170	8.057	91.943
0.300	0.755	0.151	8.208	91.792
0.150	1.804	0.361	8.569	91.431
0.075	2.279	0.456	9.024	90.976

Combined sieve-hydrometer analysis

Table A.11 Combined sieve-hydrometer analysis for selected representative test pits.

TEST PITS							
T.P11		T.P61		T.P91		T.P12-1	
Sieve Opening (mm)	% Finer	Sieve Opening (mm)	% Finer	Sieve Opening (mm)	% Finer	Sieve Opening (mm)	% Finer
19.000	100.000	19.000	100.000	19.000	100.000	19.000	100.000
9.500	99.348	9.500	100.000	9.500	99.447	9.500	100.000
4.750	97.890	4.750	99.778	4.750	98.886	4.750	96.487
2.360	96.667	2.360	99.219	2.360	98.536	2.360	93.563
2.000	96.423	2.000	99.139	2.000	98.444	2.000	93.209
1.180	95.966	1.180	98.930	1.180	98.030	1.180	92.597
0.600	95.444	0.600	98.623	0.600	96.623	0.600	92.113
0.425	95.225	0.425	98.444	0.425	95.558	0.425	91.943
0.300	94.964	0.300	98.253	0.300	94.518	0.300	91.792
0.150	94.162	0.150	97.700	0.150	92.511	0.150	91.431
0.075	93.202	0.075	97.011	0.075	90.650	0.075	90.976
0.028	81.309	0.027	94.821	0.029	82.588	0.026	90.637
0.020	81.309	0.019	92.382	0.021	76.710	0.019	89.486
0.014	78.352	0.014	89.638	0.015	67.893	0.014	87.184
0.010	75.395	0.010	87.199	0.011	64.954	0.010	85.170
0.007	72.143	0.007	83.235	0.008	53.491	0.006	82.293
0.005	67.708	0.005	79.881	0.006	43.205	0.005	80.566
0.004	66.230	0.004	75.918	0.004	38.502	0.004	75.963
0.003	61.795	0.003	71.344	0.003	32.330	0.003	75.099
0.001	60.021	0.001	68.296	0.001	23.807	0.001	72.797

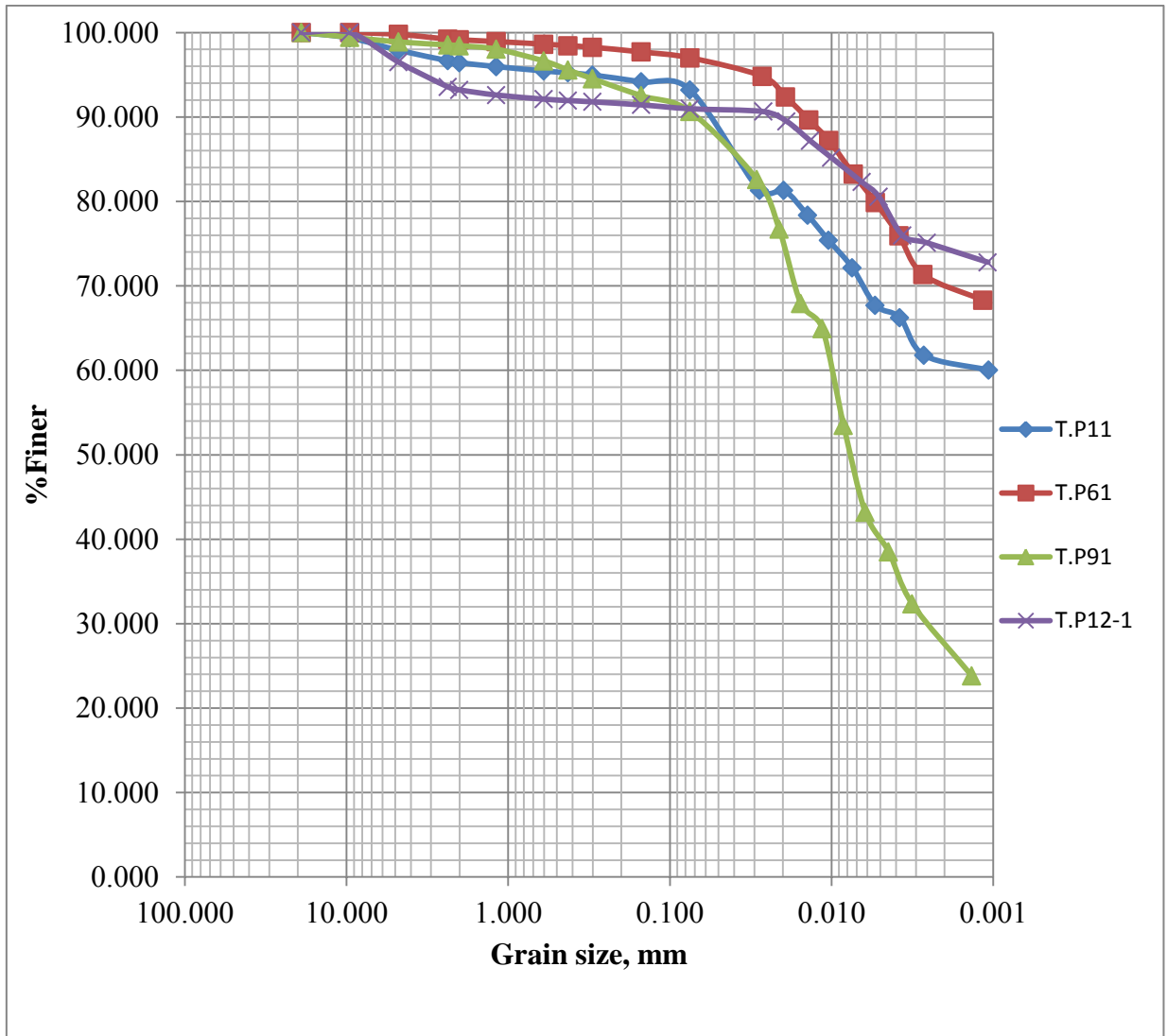


Fig A.1 combined sieve-hydrometer analysis graph for selected representative test pits.

Representative Liquid limit and plastic limit tests

Parameters and formulas used

Mass of water= (mass of can +Wet soil) - mass of can

Mass of dry soil= (mass of can +Wet soil) - mass of can

Water content, %= Mass of water *100/ Mass of dry soil

Liquid limit = water content, % at no of blows equal to 25.

Plastic limit=average water content of plastic limit test trials

Table A.12 Liquid limit and plastic limit for test pit (TP11)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.p11					
Trial number	1	2	3	1	2	3
Can no, g	A-19	12	79	D-24	59	D-5
mass of can, g	15.5704	15.8537	15.5022	15.4155	15.2951	15.7065
mass of can +Wet soil, g	40.2575	42.3608	37.8311	21.685	20.4227	22.8613
mass of can +dry soil, g	28.5261	29.5599	27.1625	19.8404	18.9934	20.8277
mass of water, g	11.7314	12.8009	10.6686	1.8446	1.4293	2.0336
mass of dry soil, g	12.9557	13.7062	11.6603	4.4249	3.6983	5.1212
water content,%	90.5501	93.39496	91.49507	41.68682	38.64749	39.70944
number of blows	30	19	26			
Result	91.7041			40.0146		

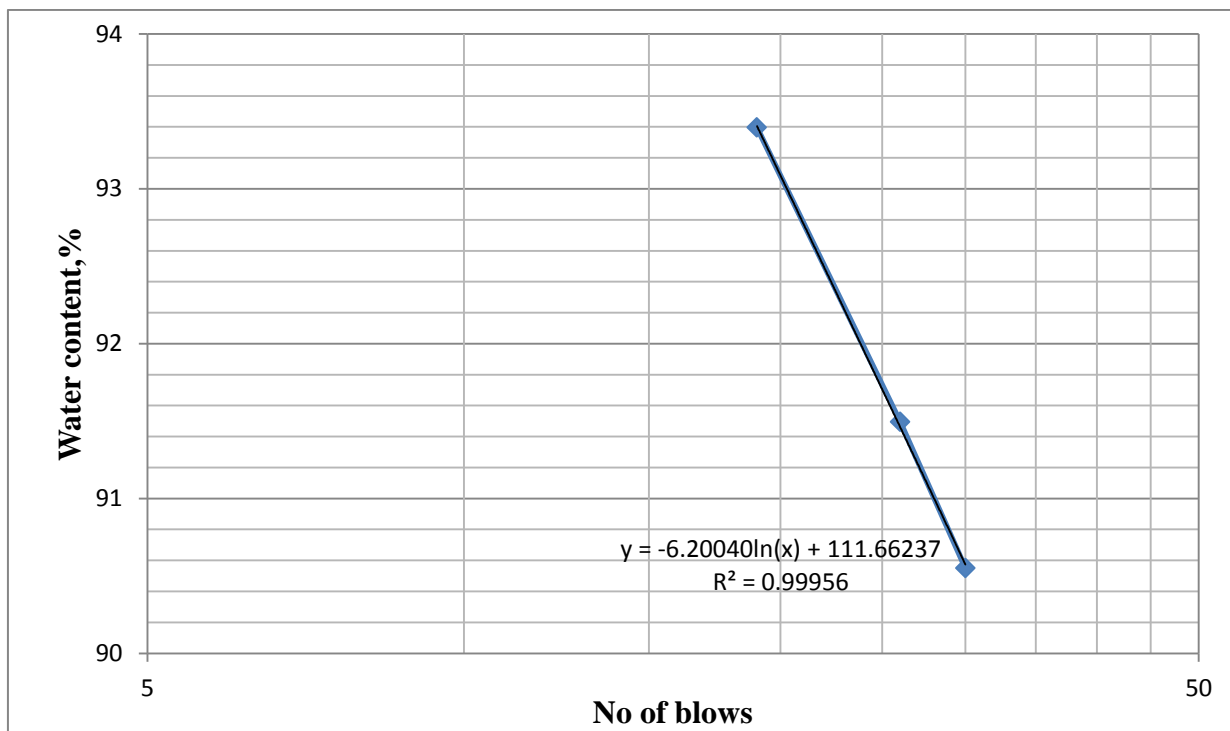


Fig A.2 water content v_s log no of blows graph for test pit (TP11)

Table A.13 Liquid limit and plastic limit for test pit (TP13)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.P13					
Trial number	1	2	3	1	2	3
Can no, g	D-5	31	47	A-1	33	81
mass of can, g	15.6957	15.4269	15.6712	15.5928	14.0961	15.667
mass of can +Wet soil, g	47.8381	46.8019	47.642	24.0197	23.4057	24.3343
mass of can +dry soil, g	34.4969	33.9284	34.5994	21.882	21.1288	22.2753
mass of water, g	13.3412	12.8735	13.0426	2.1377	2.2769	2.059
mass of dry soil, g	18.8012	18.5015	18.9282	6.2892	7.0327	6.6083
water content, %	70.9593	69.58084	68.90565	33.99001	32.3759	31.15779
number of blows	19	27	31			
result	69.8439			32.5079		

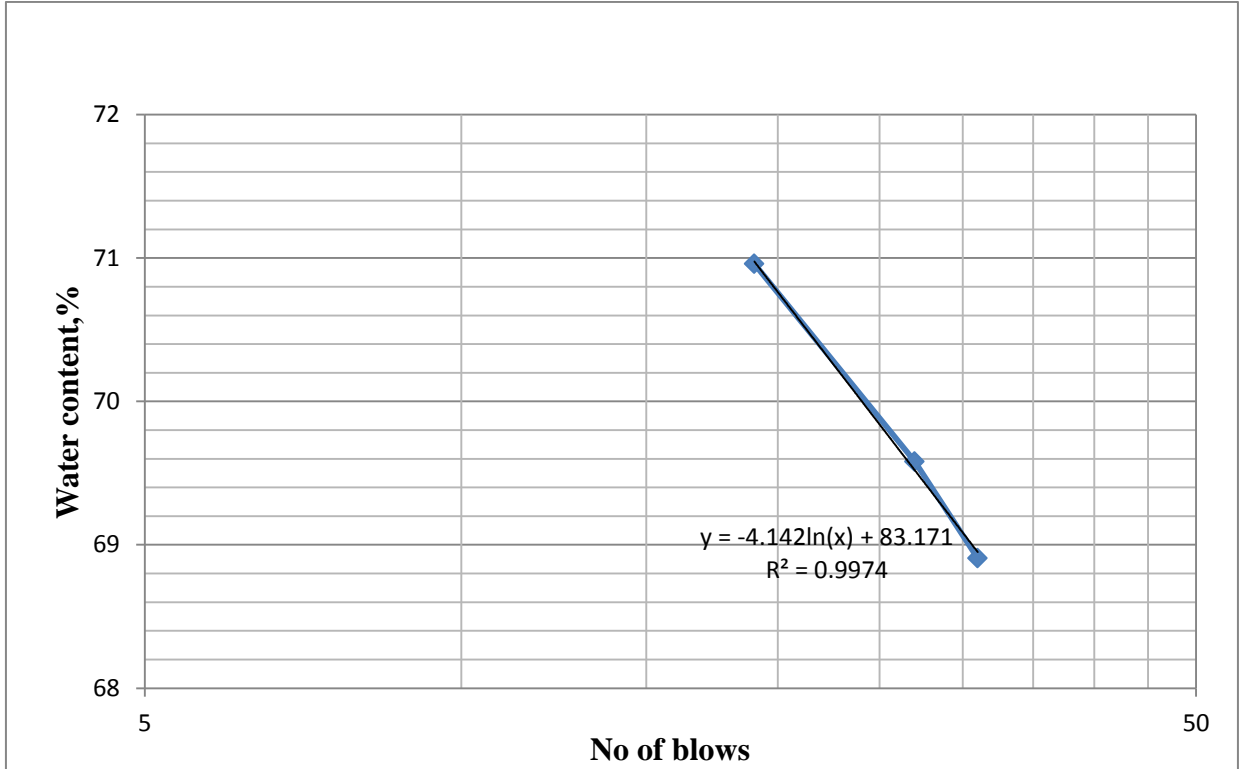


Fig A.3 water content v_s log no of blows graph for test pit (TP13)

Table A.14 liquid limit and plastic limit for test pit (TP32)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.P32					
Trial number	1	2	3	1	2	3
Can no, g	33	D-24	70	C-8	D-25	15
mass of can, g	14.0617	15.408	15.716	13.6893	15.8717	15.4814
mass of can +Wet soil, g	37.3056	38.1925	40.7276	19.7013	22.3553	22.095
mass of can +dry soil, g	27.1573	28.5098	30.3576	18.3366	20.848	20.5913
mass of water, g	10.1483	9.6827	10.37	1.3647	1.5073	1.5037
mass of dry soil, g	13.0956	13.1018	14.6416	4.6473	4.9763	5.1099
water content, %	77.4939	73.9035	70.8255	29.3654	30.2895	29.4271
number of blows	16	24	32			
Result	73.2954			29.6941		

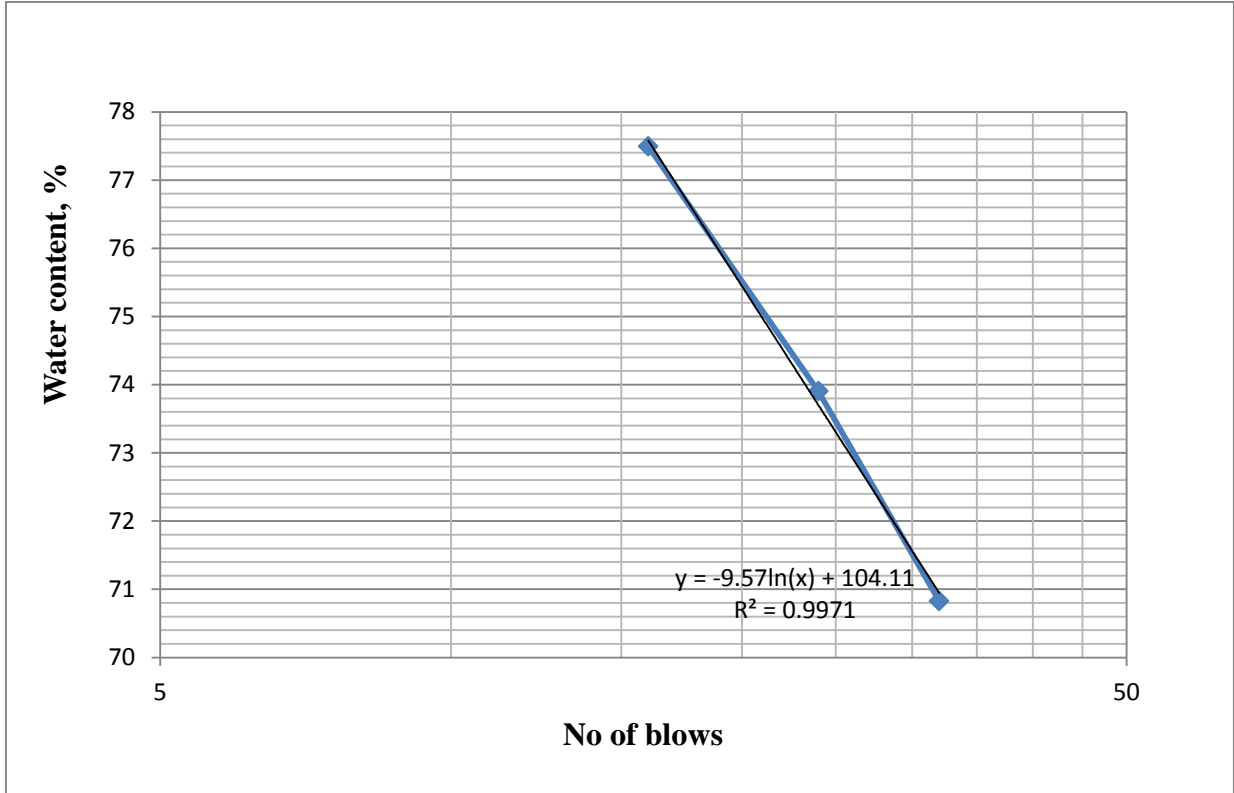


Fig A.4 water content v_s log no of blows graph for test pit (TP32)

Table A.15 Liquid limit and plastic limit for test pit (TP82)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.P82					
Trial number	1	2	3	1	2	3
Can no, g	74	72	51	54	H-3	24
mass of can, g	15.849	15.6861	15.8272	15.8422	15.0743	15.6566
mass of can +Wet soil, g	35.7974	33.1026	35.3336	21.6241	21.1424	22.5168
mass of can +dry soil, g	25.5828	24.1244	25.0978	19.9645	19.408	20.534
mass of water, g	10.2146	8.9782	10.2358	1.6596	1.7344	1.9828
mass of dry soil, g	9.7338	8.4383	9.2706	4.1223	4.3337	4.8774
water content,%	104.9395	106.3982	110.4114	40.2590	40.0212	40.6528
number of blows	35	26	12			
Result	106.6194			40.3110		

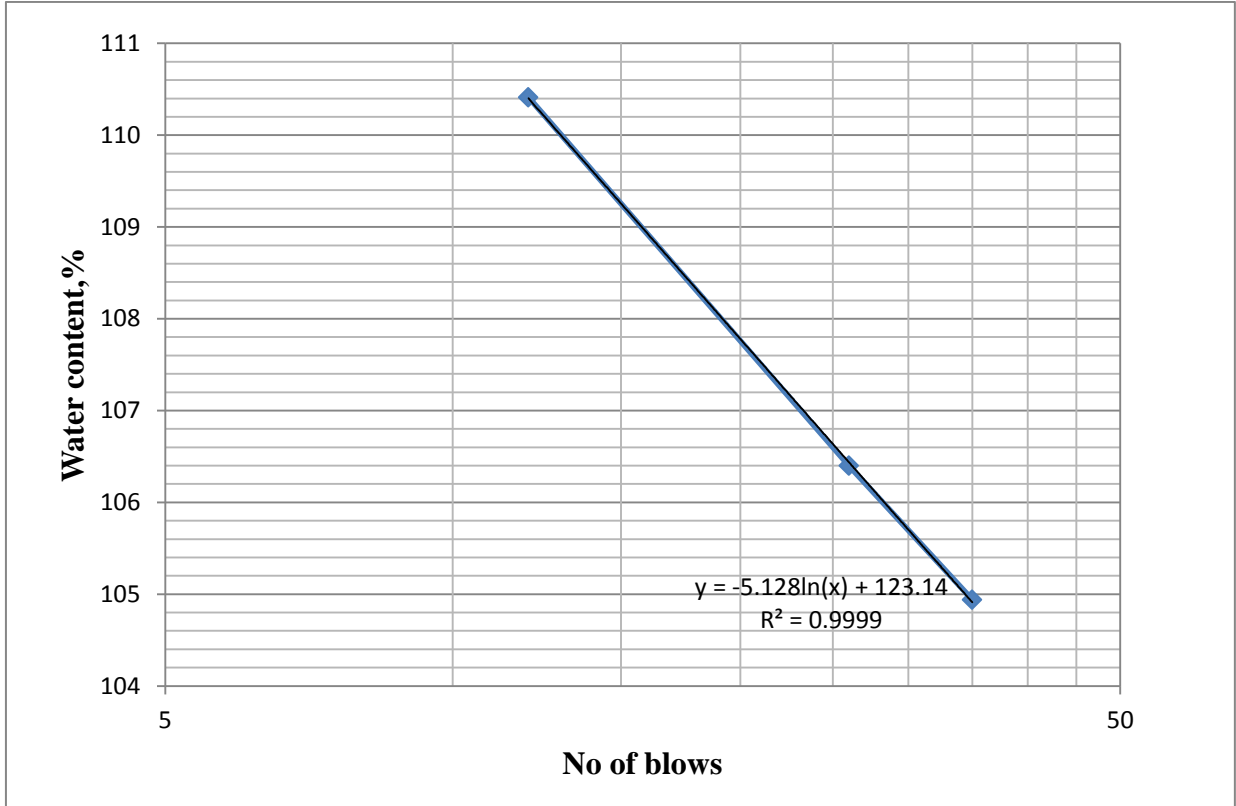


Fig A.5 water content v_s log no of blows graph for test pit (TP82)

Table A.16 Liquid limit and plastic limit for test pit (TP10-2)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.P10-2					
Trial number	1	2	3	1	2	3
Can no, g	100	2	26	47	A-1	85
mass of can, g	15.4412	15.626	15.6972	15.6792	15.7725	15.837
mass of can +Wet soil, g	38.17	37.3496	42.8262	21.4345	20.0074	20.2854
mass of can +dry soil, g	25.9123	25.4288	28.0438	19.6841	18.7018	18.9131
mass of water, g	12.2577	11.9208	14.7824	1.7504	1.3056	1.3723
mass of dry soil, g	10.4711	9.8028	12.3466	4.0049	2.9293	3.0761
water content,%	117.0622	121.6061	119.7285	43.7064	44.5703	44.6116
number of blows	31	18	22			
result	118.8155			44.2962		

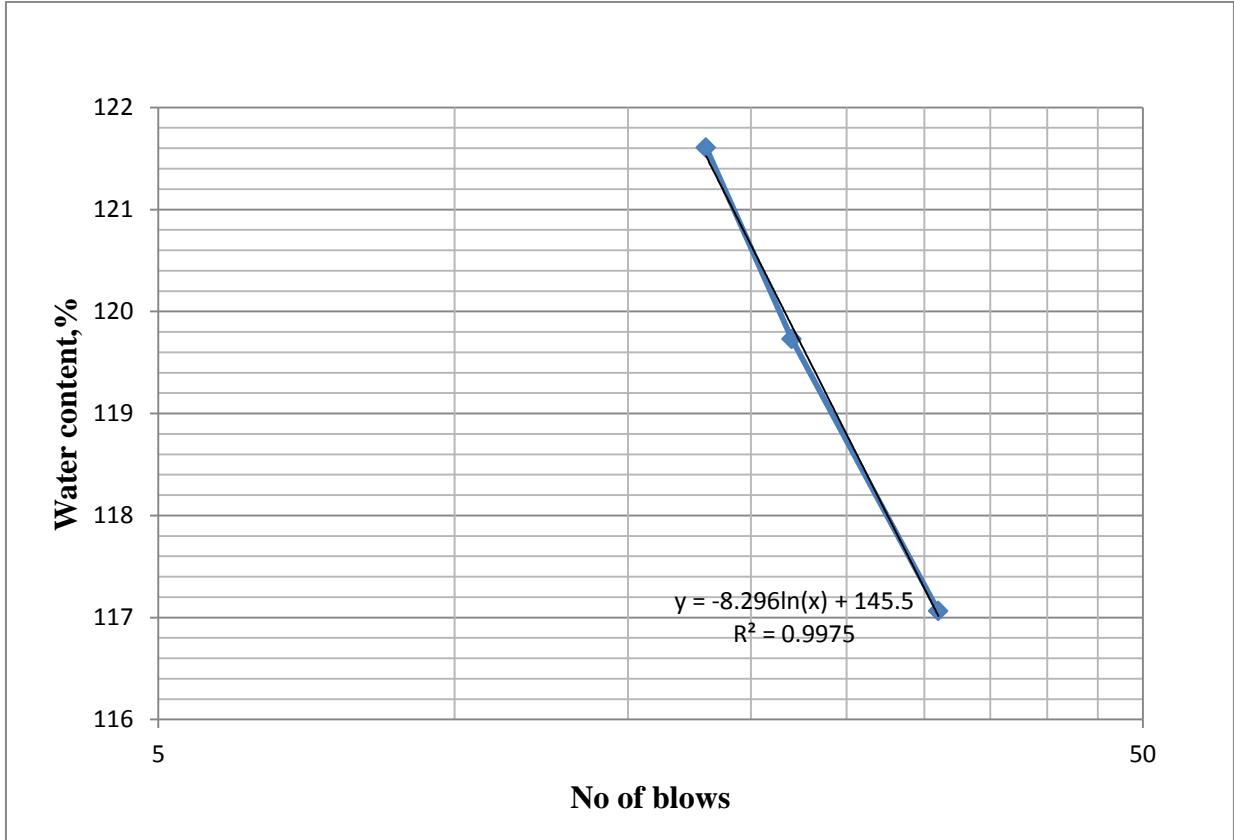


Fig A.6 water content v_s log no of blows graph for test pit (TP10-2)

Table A.17 Liquid limit and plastic limit for test pit (TP11-1)

	LIQUID LIMIT			PLASTIC LIMIT		
	Test pit T.P11-1					
Trial number	1	2	3	1	2	3
Can no, g	A-200	2	85	74	A-22	101
mass of can, g	15.6094	15.6226	15.8285	15.8525	15.5147	11.6099
mass of can +Wet soil, g	41.6201	40.5417	38.9277	22.1313	21.6883	17.3554
mass of can +dry soil, g	27.8338	27.4464	26.3959	20.2116	19.8115	15.6357
mass of water, g	13.7863	13.0953	12.5318	1.9197	1.8768	1.7197
mass of dry soil, g	12.2244	11.8238	10.5674	4.3591	4.2968	4.0258
water content, %	112.7769	110.7537	118.5892	44.0389	43.6790	42.7169
number of blows	24	30	15			
result	112.8048			43.4783		

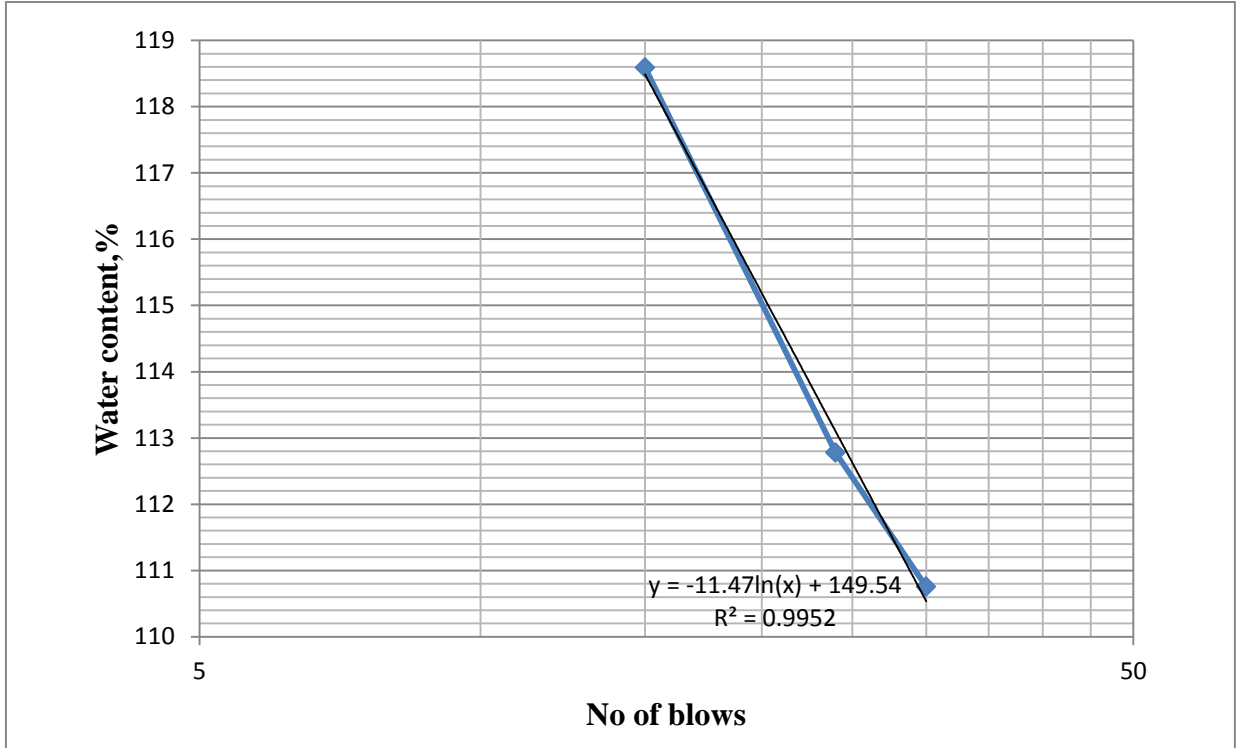


Fig A.7 water content v_s log no of blows graph for test pit (TP11-1)

Free swell

Formula used

Free swell % = (Final Volume – Initial Volume)/Initial Volume

Table A.18 Free swell test for all test pits.

Test Pit	Initial Volume (ml)	Final Volume (ml)	Free Swell (%)
T.p11	10	22.1	121
T.p12	10	21.6	116
T.p13	10	17.2	72
T.p21	10	23.5	135
T.p22	10	20.0	100
T.p31	10	17.6	76
T.p32	10	18.2	82
T.p33	10	16.5	65
T.p41	10	22.0	120
T.p42	10	21.4	114
T.P51	10	20.9	109
T.p52	10	18.9	89
T.p61	10	25.2	152
T.p62	10	25.1	151
T.p71	10	30.0	200
T.p72	10	27.0	170
T.p81	10	28.9	189
T.p82	10	27.0	170
T.p91	10	19.3	93
T.p92	10	18.8	88
T.p10-1	10	35.0	250
T.p10-2	10	34.8	248
T.P11-1	10	27.0	170
T.p12-1	10	31.0	210

SHRINKAGE LIMITE

Parameters and formulas used

Mt= mass of empty shrinkage limit can

Mv= mass of can + mercury

Mn= mass of mercury =Mv-Mt

Mw= mass of can + wet soil

Md= mass of can + oven dry soil

Mf= mass of mercury displaced by the soil

M= mass of wet soil= Mw-Mt

Mo= mass of oven dry soil= Md-Mt

w= (M-Mo)*100/Mo

V= Mn/13.55. Where 13.55= density of mercury

Vo =Mf/13.55.

Sl = (w-((V-Vo)/Mo)*100)

Table A.19 Shrinkage limits test results for all test pits.

Test Pit	Can no	Mt	Mv	Mn	Mw	Md	Mf	M	Mo	w	V	Vo	S.L	Avg. S.L
T.P11	C-5	19.63	224	204.36	41.51	30.55	73.047	21.87	10.92	100.32	15.08	5.39	11.58	11.58
T.P12	1-G	17.41	231	213.59	40.26	28.59	74.189	22.85	11.18	104.34	15.76	5.47	12.34	12.34
T.P13	E-5	17.32	228	210.68	42.38	32.03	102.86	25.06	14.71	70.319	15.54	7.59	16.24	16.24
T.P21	M3	24.68	642	617.31	91.26	57.93	218.63	66.58	33.25	100.22	45.55	16.1	11.74	11.74
T.P22	M10	20.00	198	177.99	39.68	30.30	69.501	19.68	10.30	91.059	13.13	5.12	13.33	13.33
T.P31	25	24.62	634	609.37	95.96	64.92	281.31	71.33	40.29	77.021	44.97	20.7	16.94	16.94
T.P32	M10	19.99	198	178.01	40.65	31.90	84.164	20.66	11.91	73.464	13.13	6.21	15.31	15.31
T.P33	25	24.59	637	612.40	97.10	68.30	305.84	72.51	43.71	65.879	45.19	22.5	14.12	14.12

Test Pit	Can no	Mt	Mv	Mn	Mw	Md	Mf	M	Mo	w	V	Vo	S.L	Avg. S.L
T.P41	16	24.64	658	633.35	93.07	59.71	231.78	68.42	35.07	95.087	46.74	17.1	10.59	10.59
T.P 42	4	24.33	638	613.66	90.34	58.40	225.74	66.00	34.06	93.778	45.28	16.6	9.734	11.54
	E-5	17.30	229	211.70	39.98	28.46	75.740	22.68	11.16	103.25	15.62	5.59	13.35	
T.P51	D	24.06	638	613.93	89.09	56.91	218.09	65.02	32.85	97.927	45.30	16.0	9.005	9.005
T.P52	C-5	19.66	223	203.33	42.44	31.78	82.349	22.77	12.11	88.007	15.00	6.07	14.29	14.29
T.P61	A	24.28	642	617.71	91.92	59.26	233.39	67.63	34.97	93.390	45.58	17.2	12.29	12.60
	25	24.58	634	609.41	90.62	57.86	223.77	66.03	33.28	98.431	44.97	16.5	12.91	
T.P62	E-5	17.29	230	212.70	41.28	30.03	84.179	23.99	12.74	88.278	15.69	6.21	13.83	13.83
T.P71	1-G	17.42	231	213.58	40.38	28.56	74.299	22.96	11.14	105.99	15.76	5.48	13.78	13.97
	27	24.60	652	627.39	91.31	56.28	213.49	66.70	31.67	110.60	46.30	15.7	14.15	
T.P72	D	24.08	635	610.91	89.31	55.09	206.68	65.22	31.00	110.36	45.08	15.2	14.15	14.15
T.P81	1-G	17.39	232	214.60	40.43	28.69	74.713	23.03	11.29	103.84	15.83	5.51	12.47	12.81
	A	24.26	639	614.73	90.10	56.06	210.08	65.84	31.79	107.08	45.36	15.5	13.15	
T.P82	A	24.28	637	612.71	90.38	56.41	211.02	66.10	32.13	105.72	45.21	15.5	13.46	13.46
T.P91	M3	24.68	641	616.31	97.04	66.67	335.34	72.35	41.98	72.329	45.48	24.7	22.94	21.51
	M3	24.68	641	616.32	89.53	58.90	294.43	64.85	34.22	89.490	45.48	21.7	20.08	
T.P92	27	24.63	653	628.36	95.58	63.64	347.41	70.94	39.01	81.849	46.37	25.6	28.70	28.70
T.P10-1	4	24.37	636	611.62	88.72	53.36	191.90	64.35	28.99	121.95	45.13	14.1	15.11	13.66
	16	24.65	653	628.34	88.70	52.55	184.61	64.05	27.89	129.59	46.37	13.6	12.21	
T.P10-2	16	24.71	650	625.28	89.71	54.00	193.81	65.00	29.29	121.93	46.14	14.3	13.21	14.08
	C-5	19.65	223	203.34	40.43	28.58	60.907	20.77	8.928	132.70	15.00	4.49	14.96	
T.P11-1	27	24.60	655	630.39	89.44	53.96	194.03	64.83	29.35	120.84	46.52	14.3	11.14	11.14
T.P12-1	M-1	19.97	199	179.03	38.88	28.80	58.38	18.91	8.835	114.11	13.21	4.30	13.33	13.72
	D	24.05	633	608.94	87.93	53.33	196.03	63.87	29.27	118.21	44.94	14.4	14.11	

Specific gravity

Parameters and formulas used

Mf=mass of pycnometer

Mb=mass of pycnometer + water + soil at Tb

Mc=mass of pycnometer +oven-dry soil

Mo=mass of oven-dry soil=Mc-Mf

Ta=temperature of water

Tb=temperature of Mb

Ma (at Tb) = [(D at Tb/D at Ta)*(Ma-Mf)] +Mf

D at Tb =density of water at a temperature Tb (from table A.20)

D at Ta =density of water at a temperature Ta (from table A.20)

G at Tb =Mo/ [Mo+ (Ma at Tb -Mb)]

G at 20 Co= K*G at Tb

k =D at Tb /D at 20C° (or from table A.20)

Table A.20 Density of Water and Correction Factor K for Various Temperatures

Temperature, °C	Density of Water (g/mL)	Correction Factor <i>K</i>
16.0	0.99897	1.0007
16.5	0.99889	1.0007
17.0	0.99880	1.0006
17.5	0.99871	1.0005
18.0	0.99862	1.0004
18.5	0.99853	1.0003
19.0	0.99843	1.0002
19.5	0.99833	1.0001
20.0	0.99823	1.0000
20.5	0.99812	0.9999
21.0	0.99802	0.9998
21.5	0.99791	0.9997
22.0	0.99780	0.9996
22.5	0.99768	0.9995
23.0	0.99757	0.9993
23.5	0.99745	0.9992
24.0	0.99732	0.9991
24.5	0.99720	0.9990
25.0	0.99707	0.9988
25.5	0.99694	0.9987
26.0	0.99681	0.9986
26.5	0.99668	0.9984
27.0	0.99654	0.9983
27.5	0.99640	0.9982
28.0	0.99626	0.9980
28.5	0.99612	0.9979
29.0	0.99597	0.9977
29.5	0.99582	0.9976
30.0	0.99567	0.9974

Table A.21 Specific gravity test analysis for all test pits.

Test pit	Pyc no	Mf	MC	Ma	Mb	Mo	Ta	Tb	D at Ta	D at Tb	Ma (at Tb)	G at Tb	k	G at 20 C°	Averg. G
T.P11	P6	48.76	72.53	148.17	163.13	23.77	18.6	20.7	0.9985	0.9981	148.12	2.71	0.9999	2.71	2.70
	P81	48.52	71.58	147.99	162.46	23.05	18.1	21.1	0.9986	0.9980	147.93	2.70	0.9998	2.70	
T.P12	P11	49.44	73.51	149.05	164.29	24.07	17.9	20.1	0.9986	0.9982	149.01	2.73	1.0000	2.73	2.74
	P10	45.77	67.67	145.18	159.06	21.90	18.2	20.6	0.9986	0.9981	145.14	2.74	0.9999	2.74	
T.P13	P3	45.82	69.48	145.31	160.29	23.65	18.2	20.6	0.9986	0.9981	145.26	2.74	0.9999	2.74	2.74
	P11	49.42	70.03	148.89	161.91	20.60	17.6	21.1	0.9987	0.9980	148.82	2.74	0.9998	2.74	
T.P21	P10	45.62	68.42	145.26	159.69	22.80	18.2	20.3	0.9986	0.9982	145.22	2.73	0.9999	2.73	2.74
	P3	45.77	68.89	145.33	160.04	23.11	19.0	20.0	0.9984	0.9982	145.31	2.75	1.0000	2.75	
T.P22	P1	45.32	73.21	144.58	162.30	27.89	18.2	20.6	0.9986	0.9981	144.53	2.75	0.9999	2.75	2.73
	P13	49.16	73.25	148.63	163.83	24.09	17.9	20.1	0.9986	0.9982	148.59	2.72	1.0000	2.72	
T.P31	P3	45.85	74.90	145.33	163.36	29.05	18.6	20.7	0.9985	0.9981	145.29	2.64	0.9999	2.64	2.64
	P1	45.30	69.05	144.72	159.41	23.75	18.0	21.0	0.9986	0.9980	144.66	2.64	0.9998	2.64	
T.P32	P20	45.47	69.06	144.85	159.61	23.58	18.1	21.1	0.9986	0.9980	144.79	2.69	0.9998	2.69	2.71
	P9	49.62	71.26	148.92	162.65	21.63	20.0	21.0	0.9982	0.9980	148.90	2.74	0.9998	2.74	

Test pit	Pyc no	Mf	MC	Ma	Mb	Mo	Ta	Tb	D at Ta	D at Tb	Ma (at Tb)	G at Tb	k	G at 20 C°	Averg. G
T.P3 3	P8	49.72	74.50	149.10	164.81	24.78	18.2	20.9	0.9986	0.9980	149.05	2.74	0.9998	2.74	2.72
	P4	54.76	76.97	154.00	167.97	22.20	20.2	21.5	0.9982	0.9979	153.97	2.70	0.9997	2.70	
T.P4 1	P32	49.67	73.59	149.14	164.48	23.91	18.5	20.5	0.9985	0.9981	149.10	2.80	0.9999	2.80	2.79
	P20	45.43	69.81	144.73	160.44	24.38	18.3	20.6	0.9986	0.9981	144.68	2.82	0.9999	2.82	
	P13	49.20	74.94	148.61	164.94	25.73	18.4	20.5	0.9985	0.9981	148.57	2.74	0.9999	2.74	
T.P4 2	P81	48.59	75.02	148.07	164.90	26.43	18.5	20.7	0.9985	0.9981	148.02	2.76	0.9999	2.76	2.76
	P8	49.61	74.51	149.26	165.12	24.90	18.9	21.5	0.9985	0.9979	149.20	2.77	0.9997	2.77	
T.P5 1	P4	54.64	78.43	154.02	169.24	23.78	18.9	21.5	0.9985	0.9979	153.97	2.79	0.9997	2.79	2.79
	P1	45.12	69.87	144.63	160.52	24.74	18.2	20.6	0.9986	0.9981	144.58	2.80	0.9999	2.80	
	P11	49.36	75.24	148.91	165.44	25.87	18.8	21.4	0.9985	0.9979	148.86	2.78	0.9997	2.78	
T.P5 2	P9	49.43	74.95	148.97	165.11	25.52	18.8	21.5	0.9985	0.9979	148.92	2.73	0.9997	2.73	2.66
	P6	48.67	72.50	148.36	162.91	23.82	18.4	21.5	0.9985	0.9979	148.29	2.58	0.9997	2.58	
T.P6 1	P32	49.64	74.48	148.95	164.74	24.83	21.6	23.5	0.9979	0.9975	148.91	2.75	0.9992	2.75	2.74
	P3	45.96	69.31	145.16	159.97	23.35	22.6	24.0	0.9977	0.9973	145.12	2.74	0.9991	2.74	
T.P6 2	P20	45.47	68.02	144.78	158.89	22.55	20.7	23.4	0.9981	0.9975	144.72	2.69	0.9992	2.69	2.71
	N3	48.31	73.56	147.90	163.86	25.24	22.2	24.4	0.9978	0.9972	147.85	2.73	0.9990	2.73	
T.P7 1	P13	49.23	76.21	148.47	165.63	26.98	22.0	23.6	0.9978	0.9974	148.43	2.76	0.9992	2.75	2.74
	P6	48.79	74.53	148.20	164.49	25.74	22.5	24.0	0.9977	0.9973	148.16	2.73	0.9991	2.73	
T.P7 2	P81	48.55	72.28	147.99	163.04	23.72	21.4	23.8	0.9979	0.9974	147.93	2.75	0.9991	2.74	2.74
	N1	49.43	74.84	149.05	165.14	25.40	22.0	24.1	0.9978	0.9973	149.00	2.74	0.9991	2.73	
T.P8 1	N2	50.02	73.98	149.56	164.66	23.96	21.4	23.0	0.9979	0.9976	149.52	2.71	0.9993	2.71	2.71
	P1	45.32	67.73	144.57	158.71	22.41	22.3	23.2	0.9977	0.9975	144.55	2.71	0.9993	2.71	
T.P8 2	P10	45.83	70.64	145.13	160.72	24.81	20.5	23.3	0.9981	0.9975	145.06	2.71	0.9992	2.70	2.70
	P8	49.86	74.23	149.09	164.39	24.36	21.2	24.4	0.9980	0.9972	149.01	2.71	0.9990	2.71	
T.P9 1	P3	45.87	71.26	145.29	160.85	25.39	20.9	22.9	0.9980	0.9976	145.25	2.59	0.9993	2.59	2.61
	P1	45.29	70.29	144.66	160.14	25.00	21.8	23.1	0.9978	0.9975	144.63	2.63	0.9993	2.63	
T.P9 2	P81	48.61	72.23	148.01	162.50	23.61	22.5	23.8	0.9977	0.9974	147.98	2.59	0.9991	2.59	2.58
	P20	45.35	69.12	144.71	159.20	23.77	21.7	23.8	0.9979	0.9974	144.66	2.57	0.9991	2.57	
T.P1 0-1	P13	49.18	72.98	148.57	163.39	23.80	24.4	24.6	0.9972	0.9972	148.57	2.65	0.9990	2.64	2.68
	P6	48.88	70.74	148.22	162.05	21.85	22.1	23.2	0.9978	0.9975	148.19	2.73	0.9993	2.72	
T.P1 0-2	P8	49.79	74.45	149.16	164.64	24.66	19.6	22.2	0.9983	0.9978	149.11	2.70	0.9996	2.70	2.70
	N1	50.10	74.19	149.65	164.82	24.08	20.5	22.5	0.9981	0.9977	149.61	2.71	0.9995	2.71	
T.P1 1-1	N3	49.70	73.79	149.12	164.13	24.09	20.8	24.2	0.9981	0.9972	149.03	2.67	0.9991	2.67	2.69
	P32	49.69	73.63	149.02	164.05	23.94	21.6	24.6	0.9979	0.9972	148.95	2.70	0.9990	2.70	
T.P1 2-1	P10	45.76	70.44	145.07	160.69	24.67	21.6	23.0	0.9979	0.9976	145.04	2.73	0.9993	2.73	2.72
	N2	48.46	72.85	147.89	163.25	24.39	20.8	23.4	0.9981	0.9975	147.84	2.71	0.9992	2.71	

Representative Water content test Results

Parameters and formulas used

Mass of water= (mass of can + wet soil)-(mass of can +dry soil)

Mass of dry soil= (mass of can +dry soil)-(mass of can)

Mass of water= (mass of can +Wet soil)-(mass of can)

Water content, % = Mass of water*100/ Mass of dry soil

Average water content, % = (Σ Water content, %)/total number of trials

Table A.22 Determination of water content for test pit TP11

	Test Pit T.P 11		
Trial number	1	2	3
Can no, g	A-29	59	33
mass of can, g	15.342	15.303	14.087
mass of can +Wet soil, g	44.489	46.488	39.062
mass of can +dry soil, g	37.405	39.205	33.110
mass of water, g	7.085	7.283	5.951
mass of dry soil, g	22.063	23.902	19.024
water content,%	32.110	30.470	31.284
Average water content,%	31.288		

Table A.23 Determination of water content for test pit TP51

	Test Pit T.P 51		
Trial number	1	2	3
Can no, g	40	D-22	107
Mass of can, g	15.320	15.746	15.811
Mass of can +Wet soil, g	49.103	50.152	55.174
Mass of can +dry soil, g	40.378	41.379	44.871
Mass of water, g	8.725	8.774	10.303
Mass of dry soil, g	25.058	25.632	29.061
Water content,%	34.821	34.229	35.453
Average water content,%	34.834		

Table A.24 Determination of water content for test pit TP81

	Test Pit T.P 81		
Trial number	1	2	3
Can no, g	30	DEF	76
Mass of can, g	15.666	15.605	15.538
Mass of can +Wet soil, g	48.732	49.308	54.524
Mass of can +dry soil, g	41.236	41.601	45.792
Mass of water, g	7.495	7.707	8.731
Mass of dry soil, g	25.571	25.997	30.255
Water content,%	29.313	29.647	28.860
Average water content,%	29.273		

Table A.25 Determination of water content for test pit TP82

	Test Pit T.P 82		
Trial number	1	2	3
Can no, g	107	A-22	C-15
Mass of can, g	15.816	15.517	13.923
Mass of can +Wet soil, g	55.511	54.445	50.702
Mass of can +dry soil, g	46.973	46.170	42.798
Mass of water, g	8.538	8.275	7.904
Mass of dry soil, g	31.157	30.654	28.876
Water content,%	27.403	26.996	27.371
Average water content,%	27.257		

Table A.26 Determination of water content for test pit TP91

	Test Pit T.P 91		
Trial number	1	2	3
Can no, g	33	24	67
Mass of can, g	15.743	15.644	15.495
Mass of can +Wet soil, g	50.695	46.127	47.236
Mass of can +dry soil, g	43.726	40.103	40.990
Mass of water, g	6.968	6.024	6.245
Mass of dry soil, g	27.983	24.459	25.496
Water content,%	24.902	24.629	24.495
Average water content,%	24.675		

Table A.27 Determination of water content for test pit TP12-1

	Test Pit T.P 12-1		
Trial number	1	2	3
Can no	36	91	44
Mass of can, g	5.309	5.312	5.261
Mass of can +Wet soil, g	45.082	49.234	48.061
Mass of can +dry soil, g	34.964	37.851	37.258
Mass of water, g	10.118	11.384	10.803
Mass of dry soil, g	29.655	32.538	31.998
Water content,%	34.120	34.986	33.762
Average water content,%	34.289		

Representative Bulk and dry densities test Results

Parameters and formulas used

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

Bulk density= Mass of soil/ Volume of the ring

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

Table A.28 Bulk and dry density analysis for selected representative samples.

Test pits						
	TP11	TP52	TP81	TP82	TP91	TP12-1
Mass of ring, g	71.193	70.614	71.198	71.723	70.512	71.683
Mass of ring +soil, g	135.938	133.981	138.513	142.907	132.690	138.733
Mass of soil, g	64.746	63.367	67.315	71.184	62.179	67.049
Volume of the ring, cm ³	39.270	39.270	39.270	39.270	39.270	39.270
Bulk density g/cm ³	1.649	1.614	1.714	1.813	1.583	1.707
Water content, %	31.288	34.834	29.273	27.257	24.675	34.289
Water content, in decimal	0.313	0.348	0.293	0.273	0.247	0.343
Dry density, g/cc	1.256	1.197	1.326	1.424	1.270	1.271
Dry density, kg/m ³	1255.810	1196.746	1326.005	1424.423	1269.987	1271.431

Swelling pressure test results

Parameters and formulas used

1. Initial dimensions of the specimen

Initial height of the specimen, $H_0=2\text{cm}$

Initial diameter of the specimen, $D_0=5\text{cm}$

Initial cross-sectional area of the specimen, $A= 19.635\text{cm}^2$

Initial volume of the specimen, $V=39.27\text{cm}^3$

2. Applied pressure

$$P = (p/A) * C$$

Where P=Applied pressure

P= Applied load

A=Cross-sectional area of the specimen

C=100 (lever arm multiplier)

3. The change in height of the specimen (Swell height)

$$DH = (\text{corresponding dial reading} - \text{initial dial reading}) * \text{calibration factor}$$

4. Total height of the specimen, H=initial height of the specimen at the start of the test Plus change in height of the specimen after swelling for each applied load

Swelling pressure test for sample 1 (TP11) Black

1. Location of the sample

Primary school

2 Sample descriptions

Initial moisture content=31.29%

Dry density=1.26 g/cc

3. Initial dial reading=8

Table A.29 swelling pressure test analysis for test pit TP11

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell, %
0.140	7.000	6.084	21.916	1.916	9.582
2.140	107.000	6.800	21.200	1.200	5.999
4.140	207.000	7.361	20.639	0.639	3.193
7.038	351.918	8.000	20.000	0.000	0.000
8.140	407.000	8.175	19.825	-0.175	-0.875

Swelling pressure test for sample 5 (TP51) Black

1. Location of the sample

Technical school

2 Sample descriptions

Initial moisture content=34.83%

Dry density=1.31 g/cc

3. Initial dial reading=10

Table A.30 Swelling pressure test analysis for test pit TP51

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell, %
0.100	5.000	9.122	20.878	0.878	4.388
1.100	55.000	9.461	20.539	0.539	2.695
2.100	105.000	9.768	20.232	0.232	1.161
3.000	150.438	10.000	20.000	0.000	0.000
4.100	205.000	10.234	19.766	-0.234	-1.171

Swelling pressure test for sample 8 (TP81), Black

1. Location of the sample

Asse Marble factory

2 Sample descriptions

Initial moisture content=29.27%

Dry density=1.33 g/cc

3. Initial dial reading=10

Table A.31 Swelling pressure test analysis for test pit TP81

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell,%
0.140	7.000	8.366	21.634	1.634	8.171
2.140	107.000	8.796	21.204	1.204	6.020
4.140	207.000	9.331	20.669	0.669	3.345
7.140	357.000	9.917	20.083	0.083	0.416
7.579	378.952	7.000	23.000	3.000	0.000
7.890	387.500	10.024	19.976	-0.024	-0.119

Swelling pressure test for sample 8 (TP82) Gray

1. Location of the sample

Asse Marble factory

2 Sample descriptions

Remolded

Initial moisture content= 27.26%

Dry density=1.42 g/cc

3. Initial dial reading=6

Table A.32 Swelling pressure test analysis for test pit TP82

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell,%
0.100	5.000	4.646	21.354	1.354	6.771
6.100	305.000	5.316	20.684	0.684	3.421
9.100	455.000	5.680	20.320	0.320	1.601
11.100	555.000	5.928	20.073	0.073	0.363
11.616	580.780	6.000	20.000	0.000	0.000
12.100	605.000	6.063	19.937	-0.063	-0.316

Swelling pressure test for sample 9 (TP91) yellowish

1. Location of the sample

Right side of medhanialem church

2 Sample descriptions

Initial moisture content= 24.68%

Dry density=1.27 g/cc

3. Initial dial reading=7

Table A.33 Swelling pressure test analysis for test pit TP91

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell,%
0.140	7.000	6.511	20.489	0.489	2.445
1.140	57.000	6.804	20.196	0.196	0.980
2.140	107.000	6.998	20.002	0.002	0.010
2.142	107.100	7.000	20.000	0.000	0.000
2.390	112.500	7.028	19.972	-0.028	-0.140

Swelling pressure test for sample 12 (TP12-1) yellowish

1. Location of the sample

Dalota

2 Sample descriptions

Initial moisture content= 34.29%

Dry density=1.27 g/cc

3. Initial dial reading=5

Table A.34 Swelling pressure test analysis for test pit TP12-1

Applied load (kg)	Pressure (kPa)	Dial reading	Height after swell (mm)	Swell height (mm)	Percent swell, %
0.100	5.000	4.739	22.261	2.261	11.305
2.100	105.000	5.754	21.246	1.246	6.231
4.100	205.000	6.272	20.728	0.728	3.641
7.100	355.000	6.807	20.193	0.193	0.966
7.757	387.850	7.000	20.000	0.000	0.000
7.800	390.000	7.012	19.988	-0.012	-0.060

Appendix B

SPSS 15 Regression Analysis Results

B.1 Regression analysis for Equation 1

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	shrinkage limit (SL), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL) , Water content %(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.951(a)	.905	.852	78.335483667783500

a Predictors: (Constant), shrinkage limit (SL), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL) , Water content(w)%

ANOVA (b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	524151.689	5	104830.338	17.083	.000(a)
	Residual	55228.032	9	6136.448		
	Total	579379.721	14			

a Predictors: (Constant), shrinkage limit (SL), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL) , Water content(w) %

b Dependent Variable: Swelling pressure

Coefficients (a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2229.794	778.826		-2.863	.019
	Dry density(γ_d)	1.044	.421	.504	2.478	.035
	Water content %	-9.780	8.550	-.252	-1.144	.282
	Liquid limit (LL)	6.484	2.435	.530	2.663	.026
	Plastic limit (PL)	19.953	7.944	.502	2.512	.033
	shrinkage limit (Sl)	4.602	6.815	.114	.675	.516

a Dependent Variable: Swelling pressure

B.2 Regression Analysis for Equation 2

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	Plastic limit (PL), Dry density(γ_d), Water content %, Liquid limit (LL)(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.949(a)	.900	.860	76.174953916975800

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d), Water content %, Liquid limit (LL)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	521353.485	4	130338.371	22.462	.000(a)
	Residual	58026.236	10	5802.624		
	Total	579379.721	14			

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d), Water content %, Liquid limit (LL)

b Dependent Variable: Swelling pressure

Coefficients (a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-1900.052	589.998		-3.220	.009
	Dry density(γ_d)	.896	.350	.433	2.558	.028
	Water content %	-13.331	6.556	-.343	-2.033	.069
	Liquid limit (LL)	5.858	2.190	.479	2.676	.023
	Plastic limit (PL)	22.374	6.893	.563	3.246	.009

a Dependent Variable: Swelling pressure

B.3 Regression analysis for Equation 3

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	Plastic limit (PL), Dry density(γ_d), Water content %(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.910(a)	.828	.781	95.139212109868200

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d), Water content %

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	479813.555	3	159937.852	17.670	.000(a)
	Residual	99566.166	11	9051.470		
	Total	579379.721	14			

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d), Water content %

b Dependent Variable: Swelling pressure

Coefficients (a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2839.779	592.092		-4.796	.001
	Dry density(γ_d)	1.489	.339	.719	4.396	.001
	Water content %	-5.759	7.386	-.148	-.780	.452
	Plastic limit (PL)	35.140	6.214	.884	5.655	.000

a Dependent Variable: Swelling pressure

B.4 Regression analysis for Equation 4

Variables Entered/Removed (b)

Model	Variables Entered	Variables Removed	Method
1	Plastic limit (PL), Dry density(γ_d) (a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.905(a)	.819	.788	93.572082609730500

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d)

ANOVA (b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	474310.905	2	237155.453	27.086	.000(a)
	Residual	105068.816	12	8755.735		
	Total	579379.721	14			

a Predictors: (Constant), Plastic limit (PL), Dry density(γ_d)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-3110.940	471.297		-6.601	.000
	Dry density(γ_d)	1.639	.274	.792	5.978	.000
	Plastic limit (PL)	32.676	5.263	.822	6.209	.000

a Dependent Variable: Swelling pressure

B.5 Regression analysis for Equation 5

Variables Entered/Removed (b)

Model	Variables Entered	Variables Removed	Method
1	Liquid limit (LL) , Dry density(γ_d) (a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.870(a)	.757	.717	108.306810515227200

a Predictors: (Constant), Liquid limit (LL) , Dry density(γ_d)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	438615.339	2	219307.669	18.696	.000(a)
	Residual	140764.382	12	11730.365		
	Total	579379.721	14			

a Predictors: (Constant), Liquid limit (LL) , Dry density(γ_d)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-1689.305	404.936		-4.172	.001
	Dry density(γ_d)	.877	.296	.423	2.964	.012
	Liquidlimit (LL)	8.858	1.746	.724	5.073	.000

a Dependent Variable: Swelling pressure

B.6 Regression analysis for Equation 6

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	shrinkage limit (SI), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL)(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.944(a)	.891	.847	79.534305913043900

a Predictors: (Constant), shrinkage limit (SI), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	516122.663	4	129030.666	20.398	.000(a)
	Residual	63257.058	10	6325.706		
	Total	579379.721	14			

a Predictors:(Constant),shrinkage limit (SI), Plastic limit (PL), Dry density(γ_d), Liquid limit (LL)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2946.915	469.163		-6.281	.000
	Dry density(γ_d)	1.415	.273	.683	5.190	.000
	Liquid limit (LL)	6.259	2.464	.512	2.540	.029
	Plastic limit (PL)	17.225	7.693	.433	2.239	.049
	shrinkage limit (SI)	9.396	5.456	.233	1.722	.116

a Dependent Variable: Swelling pressure

B.7 Regression analysis for Equation 7

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	shrinkage limit (SI), Dry density(γ_d), Liquid limit (LL)(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.914(a)	.836	.791	92.915066269171100

a Predictors: (Constant), shrinkage limit (SI), Dry density(γ_d), Liquid limit (LL)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	484414.416	3	161471.472	18.704	.000(a)
	Residual	94965.305	11	8633.210		
	Total	579379.721	14			

a Predictors: (Constant), shrinkage limit (Sl), Dry density(γ_d), Liquid limit (LL)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2344.507	449.001		-5.222	.000
	Dry density(γ_d)	1.093	.271	.528	4.040	.002
	Liquid limit (LL)	10.711	1.700	.876	6.299	.000
	shrinkage limit (Sl)	13.727	5.960	.340	2.303	.042

a Dependent Variable: Swelling pressure

B.8 Regression analysis for Equation 8

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	Water content %, shrinkage limit (Sl), plastic index (PI), Dry density(γ_d) (a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.849(a)	.721	.609	127.147643375623400

a Predictors: (Constant), Water content %, shrinkage limit (Sl), Plastic index(PI), Dry density(γ_d)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	417714.489	4	104428.622	6.460	.008(a)
	Residual	161665.232	10	16166.523		
	Total	579379.721	14			

a Predictors: (Constant), Water content %, shrinkage limit (Sl), Plastic index(PI), Dry density(γ_d)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2130.184	1263.529		-1.686	.123
	Dry density(γ_d)	1.051	.684	.508	1.537	.155
	shrinkage limit (Sl)	16.489	10.045	.409	1.642	.132
	Plastic index (PI)	12.022	3.311	.804	3.631	.005
	Water content %	4.704	12.678	.121	.371	.718

a Dependent Variable: Swelling pressure

B.9 Regression analysis for Equation 9

Variables Entered/Removed(b)

Model	Variables Entered	Variables Removed	Method
1	Liquid limit (LL) , Dry density(γ_d), Plastic limit (PL)(a)		Enter

a All requested variables entered.

b Dependent Variable: Swelling pressure

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.927(a)	.858	.820	86.349553977626500

a Predictors: (Constant), Liquid limit (LL) , Dry density(γ_d), Plastic limit (PL)

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	497361.021	3	165787.007	22.235	.000(a)
	Residual	82018.700	11	7456.245		
	Total	579379.721	14			

a Predictors: (Constant), Liquid limit (LL) , Dry density(γ_d), Plastic limit (PL)

b Dependent Variable: Swelling pressure

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta	B	Std. Error
1	(Constant)	-2719.088	488.697		-5.564	.000
	Dry density (γ_d)	1.373	.295	.663	4.658	.001
	Plastic limit (PL)	21.922	7.810	.552	2.807	.017
	Liquid limit (LL)	3.936	2.239	.322	1.758	.106

a Dependent Variable: Swelling pressure

DECLARATION

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

Name: Ashenafi Tamrat

Signature: _____

Place: Faculty of Technology, Addis Ababa institute of Technology, Addis Ababa.

Date: August, 2013