ADDIS ABABA UNIVERSITY

School of Earth and Planetary Sciences

College of Natural Sciences

Chemical Stabilization of Expansive Sub-grade Soil Performance Evaluation on Selected Road Section in Northeastern Addis Ababa

A Thesis

Submitted to

The School of Graduate Studies

of Addis Ababa University

In Partial Fullfillment of the requirements for the Degree of Masters in Engineering Geology

Habtamu Solomon

March 2011

A Thesis

On

Chemical Stabilization of Expansive Sub-grade Soil Performance Evaluation on Selected Road Section in Northeastern Addis Ababa

Submitted to

The School of Graduate Studies
of Addis Ababa University

In Partial Fullfillment of the requirements for the Degree of Masters in Engineering Geology

By

Habtamu Solomon

ADDIS ABABA UNIVERSITY
School of Earth and Planetary Sciences
College of Natural Sciences

March 2011

Addis Ababa University
School of Earth and Planetary Science
College of Natural Science

Chemical Stabilization of Expansive Sub-grade Soil Performance Evaluation on a Selected Road Section in Northeastern Addis Ababa

By
Habtamu Solomon
Engineering Geology Programme

Approved by board of Examiners	SIGNATURE
Dr. Tigistu Haile Chairman	______________________
Dr. Tarun Kumar Raghuvanshi Advisor	______________________
Dr. Addis Alem Zeleke Examiner	______________________
Ato. Tadese Hailemariam Examiner	______________________

DECLARATION

I hereby declare that the thesis is my original work under the supervision of Dr. Tarun Kumar Raghuvanshi, School of Earth and Planetary sciences, Addis Ababa University during the year 2011 as part of Master of Science Program in Engineering Geology. I further declare that this work has not been submitted to any other University or institution for the award of any degree or diploma and all sources of materials used for the thesis have duly acknowledged.

Habtamu Solomon

Signature ______________________________

Place and date of submission: School of Graduate Studies, Addis Ababa University

March 2011

Acknowledgements

I extend my sincere and special thanks to my advisor, Dr Tarun Kumar Raghuvanshi, for his guidance and constant encouragement throughout this research study. As an advisor, he provided the impetus and guidance for this study. His support and patience throughout this research is sincerely appreciated.

I am grateful to Addis Ababa Roads Authority (AACRA) and Gondwana Engineering PLC from where I received soil mechanics laboratory services. I am also grateful to Anyways Company Ltd and DAKASOS Senkele Lime Factory for providing me the stabilizer chemical agents used in the present study.

Words cannot express my feelings which I have for my family: father, mother, brothers and sisters. I am highly indebted to them for their blessing, guidance, advice, encouragement, support and all the way helped me to concentrate on my studies.

And finally I would like to extend my special thanks to my friends Genenew, Tesfahun, Hailu Tsegaye, Bizuwerk Shawl, Melaku Abay, Solomon, Haimanot Zena, Abiy Tamrat and many others for their constant encouragement and help.

(Habtamu Solomon)

Table of Contents

List of Figures

List of Tables

Abstract

Expansive soils are characterized by volume change due to variation in moisture content. The cyclic wetting and drying processes causes vertical movements in expansive soils and these movements lead to failure of pavements. These soils have very low load bearing capacity too when wet. These problematic expansive soils, therefore, when encountered as sub-grade should be avoided or treated properly. The removal of expansive soils and replacement with suitable fill material is an appropriate method in areas like Addis Ababa in most cases where there is suitable fill material available nearby. At places, however, its feasibility depends on the availability of suitable fill material within economic distances and the thickness of the poor sub-grade soil to be replaced. Chemical stabilization is another alternative being applied worldwide even if the method is at a conceiving stage in Ethiopia. In recent years there are tendencies to use lime and other chemicals to stabilize sub-grade and sub base materials by Ethiopian Road Authority (ERA) and Addis Ababa City Roads Authority (AACRA). In the present study, hence, the performance of a locally manufactured hydrated lime and an imported industry product Anyway Natural Soil Stabilizer (ANSS) were evaluated based on laboratory test results on expansive sub-grade soils collected from Gerji area. The sub-grade soil was first characterized based on Atterberg limits, linear shrinkage, CBR and percent swell of CBR. The test results showed that the sub-grade soil is classified as A-7-5 in the AASHTO and MH in USCS systems. These soils have very low load bearing capacity and are highly expansive nevertheless of the mineralogy of the sub-grade soil samples have no montimorillonite, as expected in such soils. Two soil layers on colour variations were observed in the field: the upper dark gray clay soil and the lower light gray clay soil. The effects of the chemicals were then evaluated on two soil samples. The improvement of the sub-grade soil samples increased with increasing both dosages as well as curing periods. In general terms, increasing the dosage has more significant effect than that of increasing the curing period and 4% of either chemical has resulted in adequate improvements of the sub-grade soil. In most cases the performance of hydrated lime is better than that of ANSS and the improvement of the dark gray clay soil is better than the light gray clay soil.

Chapter I Introduction

1.1. Preamble

The origin of expansive soils is related to a complex combination of conditions and processes that result in the formation of clay minerals having a particular chemical makeup which, when in contact with water, will expand. All clay soils are not expansive and the degree of expansion varies with the type of clay mineral predominantly present in the soil mass. The presence of montmorillonite in these soils imparts them high swell-shrink potentials. These soils are very hard when dry, but lose strength completely when wet (Chen, 1988).

Expansive soils are distributed all over the world. Argentina, Australia, Canada, China, USA, India, Sudan, Ethiopia, Ghana, Iran, Turkey, South Africa, Tanzania, Spain are among the countries in which expansive soils are reported. However, as development proceeds additional areas covered with significant expansive soils have been discovered with time (Chen, 1988; McKeen, 1976). The formation of these soils requires specific conditions as described by Rollings et al. (2002) and Chen (1988) which include:

- Suitable parent material rich in calcium and magnesium to form smectite clay minerals, commonly basic igneous rocks such as basalt or gabbro.
- High temperatures and sufficient rainfall for weathering but not enough to leach base materials from the soil, commonly a semi-arid to dry tropical or subtropical climates.
- Seasonal dry periods to allow clay crystals to form.
- Impeded drainage to slow leaching and loss of weathering products.
- High pH environment.

Expansive soils (alternatively called black cotton soils or vertisols in the present study) are generally found on sedimentary plains as a result of thousands of years eroding the clay content from the surrounding hills and also on level land on plateaus as well as in depressions. Smaller areas of expansive soils are found on hill slopes and piedmont plains. However, due to leaching of bases and silica lateritic soils are predominant around hill slopes (Thagesen et al, 2004).

Expansive soils form a major soil group in Ethiopia and occur in the high lands mostly in the western, central and southwestern part of the country and in most cases the major clay mineral component is montmorillonite. The road sector in Ethiopia is suffering from the high shrink-swell behavior of this expansive soil. Many damages occur each year and road construction over such expansive soil creates serious problems including increasing cost of construction and maintenance (MoWUD, 2009).

As a result of cyclic wetting and drying processes due to seasonal climatic changes, vertical movements take place in the expansive soil mass. All these movements lead to failure of pavements, in the form of settlement, heavy depression, cracking and unevenness. The expansive sub-grade soil when wet has a tendency to up heave into the upper layers of the pavement, especially when the sub-base consists of stone soling with lot of voids. Gradual intrusion of wet soil invariably leads to failure of the road. The physical properties of expansive soils vary from place to place. In general, these soils have very low load bearing capacity and high swelling and shrinkage characteristics. Roads laid on such sub-grade soils develop undulations at the road surface due to loss of strength of the sub-grade through softening during rainy seasons (Seehra, 2008).

Expansive soils are costing a lot worldwide, most of these damages occur to transportation facilities such as highways, railroads, runways, canals, pedestrian walkways among others. The swelling potential of expansive clay can be minimized or completely eliminated either by pre-wetting, compaction, soil replacement, chemical stabilization or isolation of the clay from moisture. The current highway practice in resolving expansive soil problem is the removal of the undesirable soil and replacement with non expansive soil. Chemical stabilization and geo-membranes are also in use extensively in countries such as USA, Canada, India and China (Chen, 1988). Stabilization of the sub-grade material will allow for the design of a thinner overall pavement or alternatively extended life and reduction in required maintenance.

1.2. Problem Statement

Addis Ababa city, particularly the relatively low lying flat land area in the central and southern part, is dominated by expansive soils. These expansive soils mapped as black cotton soil by Kebede Tsehayu and Tadese Hailemariam (1990) has been the major problem in the construction sector of the city. Cracks are visible on buildings with shallow foundations due to shrink swell and differential settlement property of the expansive soils. Roads usually deteriorate quickly even before their design period.

The observable drainage problems especially in the flat lying areas of the city where expansive soils are predominating made the problem worse. Various problems are associated with inadequate drainage facilities which include bearing capacity reduction of sub-grade, pavement failures like potholes, rutting, waviness and corrugation in flexible pavements, reduction of strength of pavement materials such as stabilized soil and bituminous surfacing, damages to shoulder and pavement edges and considerable erosion of soil from sub strata, slopes, cut and hill sides by surface water (Rao, 2007).

Addis Ababa City Roads Authority has been doing much to alleviate problems caused by expansive soils by conventional method of removing the unsuitable expansive soil and replacing it with better quality fill material and constructing thicker pavements to account for the lower load bearing capacity of the expansive soil. In recent years the City Roads Authority has started stabilizing expansive soil with chemical additives on trial road sections since the conventional method of replacing expansive sub-grade soil with suitable fill material is found to be more costly, time taking and machinery intensive. Accordingly, the authority has contracted foreign chemical additive supplying companies to undertake stabilization of expansive sub-grade soil on trial road sections in the City. The Ethiopian Roads Authority has also doing on sub-grade and sub base stabilization with lime on some roads such as Ambo-Gedo road section. This shows that the problem due to expansive soils is serious in the road sector development activity in the city as well as in the country. Such prevailing conditions in the road development sector have initiated to search and evaluate for the various alternatives which enables to improve the engineering characteristics of the expansive sub-grade soil. To this effect, therefore, the following tasks were conducted:

- Identification of the mineralogical and chemical composition of the expansive soil so as to know the extent of expansiveness of the sub-grade soil on the selected trial road section
- Investigation of the physical and engineering characteristics of the expansive sub-grade soil and classify the soil group
- Investigation of the drainage properties of the area along the selected trial road section
- Suggest alternative feasible improvement techniques of the expansive sub-grade soil
- Draw conclusions and recommendation so as to use the most effective method of improvement techniques based on engineering performance and feasibility.

1.3. Origin and Distribution of Expansive Soils

Chen (1988) described that the origin of expansive soils is related to a complex combination of conditions and processes that result in the formation of clay mineral having a particular chemical makeup. These clay particles result from the alteration of parent rock materials

(Chen, 1988; McKeen, 1976). Alteration takes place by several processes which include weathering, diagenesis, hydrothermal action and post depositional alteration.

Montimorillonite, illite and kaolinite are the three most common groups of clay minerals and the clay mineral that is mostly responsible for high expansiveness belongs to the montmorillonite group (Chen, 1988). However, Gourley and Schreiner (1993) pointed out that kaolinite, illite and a mixed layer of montmorillonite with others could swell. Actually clays are rarely found separately; they are usually mixed with other clays and also crystals of carbonates, feldspars, micas and quartz.

Donaldson (1969, as cited in Chen, 1988) has classified the parent materials that can be associated with expansive soils into two groups. According to his study, the basic igneous rocks rich in the basic minerals pyroxene, amphibole, biotite and olivine such as basalts, gabbros and volcanic glass comprise the first group where as the sedimentary rocks shales and clay stones that contain montimorilonite as a constituent and those limestone and marls rich in magnesium comprise the second group.

Twenfel (1950) showed that alkaline environment and the absence of leaching; the presence of ferromagnesian minerals in parent rocks and the presence of bases favor the formation of the expansive montimorillonite clay. Prolonged leaching in tropical conditions with ferric iron parent rock favors formation of kaolinite and the presence of potash in the parent material under these conditions favors the formation of illite.

Expansive soils are distributed all over the world (Chen, 1988; McKeen, 1976). The distribution is generally a result of geologic history, sedimentation and local climatic conditions. The authors indicated that the areas with the most severe problems from expansive soils are those with semi arid and arid climates of the tropical region that produce desiccation. African black clay soils causing the most severe problems have formed over basic volcanic rocks, which are geologically, relatively recent in their origin. Sudan, Ethiopia, Ghana, South Africa, Nigeria are among the countries in Africa where black cotton soil is a problem (Morin, 1971).

A study by Morin and Parry (1971) shows that black clay soils in Ethiopia have formed over Tertiary to Recent basaltic rocks. These soils are found in areas with poor drainage and low to moderate rainfall and contain Montmorillonite as the principal clay mineral with accessory Kaolinite and Halloysite. According to the same authors, the black clay soils are principally residual, derived from the weathering of basic volcanic rocks, which cover much of the Ethiopian plateau. The transition from rock to soils is extremely abrupt almost everywhere.

In Ethiopia these expansive soils (vertisols) occupy 116,785sq.km which accounts to about 10.5% of the total area of the country (Alemayehu Mengistu, 2006). The largest extents of Vertisols are found on the volcanic plateaus. Vertisols are also found on colluvial slopes in the central highlands, on the colluvial slopes and alluvial plains along the Sudanese border and on the vast limestone plateaus of central Hararghe. It is also found in sites such as granitic colluvium in basins with seasonal drainage deficiencies in southern Sidamo. Sandstone colluvium is found in valleys in Tigray and the flood plains of the Wabe Shebele and Fafen rivers in the Ogaden (Srivastava et al., http://www.fao.org/Wairdocs/ILRI/x5456E/x5456e04.htm).

Kebede Tsehayu and Tadese Hailemariam (1990) mapped the engineering geological map of Addis Ababa. According to this study, the majority of the central and southern parts of Addis Ababa which are relatively low lying and flat areas are dominated by black cotton soils which are lacustrine in its origin.

1.4. Objectives of the Study

1.4.1. General Objective

The main objective of this research is to evaluate the performance of selected methods of stabilization on expansive sub-grade soil. The effects of stabilization on the soils of Addis Ababa collected from a selected trial road section is tested and evaluated based on engineering performance and feasibility. To accomplish the research successfully an integrated method of literature review, physical observation, sub-grade soil sampling, laboratory testing, analysis and interpretation of the test results were conducted.

1.4.2. Specific Objectives

The specific objectives of the present research work are;

- To identify the mineralogy of the sub-grade soil of Addis Ababa along the selected trial road section
- To characterize the sub-grade soil of the selected trial road section
- To identify problems associated with expansive sub-grade soils
- To assess the various methods of sub-grade soil stabilization techniques

- To investigate and evaluate the effects and performance of selected chemical stabilizing agents on sub-grade soil of the selected trial road section

1.5. Methodology of the Study

The research was conducted using literature review on expansive soils, field observations, collection of samples for laboratory testing and analysis of the laboratory test results. Laboratory tests were conducted on soil samples before and after mixing with the selected stabilizing chemical agents. A site where soil samples for laboratory testing were collected is selected at the Northeastern part of Addis Ababa Metropolitan. The selected trial road section is 1.2 km which is contracted to Anyway Company Ltd for stabilization of the expansive sub-grade soil.

The effects and performance of selected chemical stabilizers on the expansive sub-grade soil of the selected road section were tested in the laboratory. For this ANSS an imported chemical produced by Anyway Company Ltd and a locally produced hydrated lime obtained from DAKASOS Senkele Lime Factory were selected.

The literature review was undertaken in order to provide a framework and understanding regarding expansive soils and problems associated with such sub-grade soil. Emphasis was given to review previous works on treatment of expansive sub-grade soils particularly to chemical stabilization techniques. Literature sources include maps and reports, books, journals and on-line materials available on internet. Laboratory test results of sub-grade soils of different roads in and outside Addis Ababa has been presented for comparison with the sub-grade soil of the trial road section under study. Experiences of other countries with similar physical characteristics to Ethiopia have been referred in some parts of the study to build up a picture on the procedures and methods adopted in dealing with expansive soils and chemical stabilization.

In the field data were collected by physical observation and measurements. The trial road section where soil samples were collected has been mapped. Representative samples were collected for laboratory testing and the coordinates of all sample points have been registered and mapped. Samples were collected at regular intervals of about 200m and at different depths ranging from 1.2 m to 2 m for index tests and soil classification and to check whether the characteristics of the soil profile is homogeneous along the trial road section and with depth (Fig. 3.2).

After classification of the sub-grade soil two representative samples were collected for detailed laboratory testing which include mineralogical, chemical composition, index and engineering property tests to characterize the sub-grade soil and study the effects and performance of chemical stabilization on the sub grade soil. In addition to these two soil samples collected, later the previous samples used for classification purpose were also used to characterize the sub-grade soil when applicable.

The laboratory tests conducted before stabilization on natural soil samples include:

- X-Ray Diffraction (XRD)
- X-Ray Fluorescence (XRF)
- Hydrometer analysis
- Specific gravity
- PH
- Atterberg limits
    - liquid limit,
    - plastic limit,
    - plasticity index
- Linear Shrinkage
- California Bearing Ratio (CBR)
- Proctor test
    - Optimum Moisture Content (OMC)
    - Maximum Dry Density (MDD)
- Percent swell of CBR

The engineering properties of the soil samples after stabilization were tested at different percentages of chemical stabilizers and with 7, 14 and 28 days of curing periods.

For ANSS industrial product stabilizer the proportion was taken as 2%, 4% and 6% according the supplier's user manual and previous experiences where as for the locally produced hydrated lime the lowest percent of lime required for stabilization was first determined by PH test according to ASTM D 6276 which is also known as the "Eades-Grim" test.

Laboratory tests conducted on stabilized hydrated lime-soil and ANSS-soil mixtures include:

- Initial lime demand (Eades-Grim) test for lime-soil mixture

- Atterberg limits
    - liquid limit,
    - plastic limit,
    - plasticity index
- Linear Shrinkage
- California Bearing Ratio (CBR)
- Proctor test
    - Optimum Moisture Content (OMC)
    - Maximum Dry Density (MDD)
- Percent swell of CBR

The test results are evaluated providing prime consideration to the effects of the chemicals on engineering properties of the sub-grade soil. The results of the tests from the natural un-stabilized and stabilized specimens have been compared. Finally, improvements in the engineering properties of the samples have been analyzed and interpreted. This data together with data obtained from literature and other secondary sources have been compiled and based on the results obtained appropriate conclusions and recommendations have been made.

1.6. Significance of the Research

The research was conducted to identify and characterize the sub-grade soil in order to come up with appropriate improvement methods. Proper treatment of sub-grade soils helps to improve susceptibility problem of the sub-grade to water and increase stability and durability of pavement and long life of the road lying on such sub-grade.

The research, even if conducted with a small number of samples, will provide indicative information on the mineralogy of the expansive soil of Addis Ababa area and provides a thorough knowledge of the different chemical stabilization methods which can overcome the problems arising from expansive clay soils for road sub-grade preparation. The research also provides information about the better method of sub-grade preparation on expansive soils with similar mineralogy to other road sections in Addis Ababa area.

The research work improves the knowledge of expansive soils in the country and will be indicative of the better method of improvement of such soils for sub-grade preparation particularly in the road construction sector.

1.7. Limitations of the Study

The study is conducted on a selected road section of 1.2km in length and soil samples along this road section have been taken for laboratory testing and analysis. All tests included for analysis of sub-grade soil of the trial road section are conducted for the purpose of the present research work. Nevertheless the research work has some limitations.

The tests were conducted on small number of samples and hence the results are indicative rather than definitive. Furthermore, only selected tests which are very important to achieve the objectives of the research have been included. Due to lack of sufficient laboratory equipment and personnel at AACRA laboratory the laboratory tests has taken longer periods and obliged to undertake some of the tests at Gondwana Engineering PLC Laboratory.

During the initial stages of the study it was planned to conduct durability test on chemical stabilizer agent-soil mixture samples to see the performance of the chemical stabilizers when exposed to environmental conditions of drying and wetting. Though the test is simple it was not conducted due to unavailability and unfamiliarity of such tests in the various governmental and private laboratories in Addis Ababa.

The trial road section is selected to use the resources available from an ongoing project such as laboratory facility and chemicals, easy access of samples and other relevant data of the area. However, since the road section is found in a built-up area there was difficulty to take samples at any spot before the commencement of the project and this creates delay during the initial stages of the research work.

1.8. Scheme of Presentation

The present research is conducted using literature review on expansive sub-grade soils and improvement methods, field observation and measurement and sampling of sub-grade soil, laboratory testing and analysis on a trial road section in the northeastern part of Addis Ababa in Gerji area. So as to present the results of the research in a more systematic manner, it is divided into seven chapters and the scheme of presentation is as follows:

Chapter 1 comprises the introduction part, which include the background of the study, problem statement, origin and distribution of expansive soils, objectives of the study, methodology, scope of the study, significance of the research, limitations and scheme of presentation.

Chapter 2 presents the literature review. The literature review comprises a brief description of previous works relevant to the present research in order to provide framework of the problem statement. It includes mineralogy and identification of expansive soils, characteristics of expansive soils, problems associated with expansive sub-grade Soils, improvement methods of expansive soil for sub-grade and previous works relevant to the present research.

Chapter 3 presents a description of the study area including geographical location, climate, geology, physiographic and drainage conditions, soils, hydrogeology and seismology of the research area.

Chapter 4 presents the characterization of the sub-grade soil. It describes the classification of the sub-grade soil. It presents the mineralogy and chemical composition, gradation, plasticity index, moisture content and dry density characteristics, strength and percent swell and over all characterization of the sub-grade soil.

Chapter 5 presents chemical stabilization of sub-grade soils. It provides chemical stabilizer agent-soil mixture characteristics test result on plasticity index, linear shrinkage, moisture content and dry density characteristics, strength and percent swell.

Chapter 6 presents the interpretation and discussion of the test results, comparison of the test results, comparison with other similar test results and comparison of the results with other treatment method based on feasibility.

Chapter 7 presents the overall conclusions and recommendations that can be made out of the present research work.

Chapter II Literature Review

2.1. Preamble

During the present study exhaustive literature review was undertaken in order to provide a framework and understanding regarding mineralogy, identification and characteristics of expansive soils, problems associated with such sub-grade soils and treatment methods that enable to overcome the adverse effects of these soils. Emphasis was given to the review of previous works on treatment methods of expansive sub-grade soils with particularly concern to chemical stabilization techniques.

In the present study different literature sources were used. These include maps and reports, books, journals and on-line materials available on the internet. Previous studies and practical works conducted in Ethiopia that are of similar nature to the present research were assessed and included as part of the literature review.

Experiences and manuals of other countries with similar physical characteristics to Ethiopia have also been referred and has been tried to accommodate in the literature review.

2.2. Mineralogy of Expansive Soils

Expansivity of soils is due to the presence of clay minerals. Clay particles have sizes of 0.002mm or less. However, according to Chen (1988) the grain size alone does not determine clay minerals and he emphasized that the most important property of fine grained soils is their mineralogical composition.

Clay minerals are crystalline hydrous alumino-silicates derived from parent rock by weathering. The basic building blocks of clay minerals are the silica tetrahedron and the alumina octahedron and combine into tetrahedral and octahedral sheets to form the various types of clays (Chen 1988; Murray, 2007; Nelson, 2010). Kaolinite, illite and montimorillonite (smectite) are the common groups of clay minerals most important in engineering studies (Chen, 1988, Nelson, 2010).

Kaolinite is a typical two-layer mineral having a tetrahedral and an octahedral sheet joined to form a 1-1 layer structure held by a relatively strong hydrogen bond. Kaolinite does not absorb water and hence does not expand when it comes in contact with water (Murray, 2007;

Nelson, 2010). However, Gourley et al (1971) in their study indicated the swelling property of kaolinite. Nelson (2010) described that kaolinite is formed by weathering or hydrothermal alteration of rocks rich in feldspar in low PH condition to favor the leaching out of ions like sodium, potassium, calcium, magnesium and iron. The montmorillonite group clays on the other hand have a 2-1 layer structure formed by an octahedron sandwiched between two tetrahedrons. This group of clays can have significant amounts of magnesium and iron substituting into the octahedral layers. The most important aspect of the montimorillonite group is the ability for water molecules to be absorbed between the layers, causing the volume of the minerals to increase when they come in contact with water (Nelson, 2010).

The illite clays have a structure similar to that of muscovite, but are typically deficient in alkalies, with less aluminum substitution for silicon. Calcium and magnesium can also sometimes substitute for potassium and illites are non-expanding clays (Murray, 2007). However, Gourley et al (1971) indicated the swelling property of illites which are formed from weathering of potassium and aluminum rich rocks under high pH conditions by alteration of minerals like muscovite and feldspar.

2.3. Identification of Expansive Soils

Expansive soils can be recognized by using mineralogical identification, indirect index property tests or direct expansion potential tests (Chen, 1988). Expansivity of a soil is governed by the type and proportion of clay minerals it contains. Knowing the type and proportion of the clay mineral in a soil gives a clue on the swelling potential (Chen, 1988).

However, Nelson (2010) pointed out that the extremely small size of clay grains makes the minerals difficult to distinguish in either hand specimen or in a petrographic microscope. He also indicated the absence of a single or simple procedure for the positive identification of clay minerals or for their quantification and recommended the application of several methods for even approximate identification and rough quantification.

Fell et al (2005) described the identification techniques of clay minerals in soils and recommended to apply at least two of them at a time. According to these authors, the mineralogical identification techniques X-ray diffraction, scanning electron microscope and differential thermal analysis and the indirect index property methods cassagrande's plasticity chart and the activity of the soil which is the ratio of the plasticity index and clay fraction are recommended to identify expansive soils.

Chen (1988) recommended the direct method of expansion potential measurement to recognize expansive soils since the test is simple to perform and does not require any costly laboratory equipment. According to him X-ray diffraction is principally used in determining the proportion of the various minerals present in colloidal clay and if supported by differential thermal analysis and scanning electron microscopic examination it provides good results.

Nevertheless of the fact that X-ray diffraction alone provide enough information, Chittoori (2008) and Pedarla (2009) in their study of durability of chemically stabilized soil preferred to use cation exchange capacity (CEC), specific surface area of soil samples and total potassium to know the dominating clay mineral in a soil sample since these methods are cheap and are not highly skill oriented.

Holtz and Gibbs (1956) demonstrated that the liquid limit and plasticity index are useful for determining the swelling characteristics of most of the clays and prepared a chart to assist the identification.

Ministry of Works and Unban Development of Ethiopia (2009) described that in Ethiopia all grayish and/or brownish clays with plasticity index greater than 25% can be identified as expansive. The classification or rating from low potential to high heave potential usually depends on the clay content and plasticity.

2.4. Characteristics of Expansive Soils

Soils usually encounter as sub-grade material during any road construction project and these sub-grade soils may vary from highly expansive to non expansive in nature. Therefore, these sub-grade soils should be adequately investigated since the stability and performance of the pavements are greatly influenced by the nature of sub-grade soil as it serves as foundations for pavements (Chen, 1988).

Little and Nair (2009) described the classification of soils into sub-grade and sub base materials based on fractions passing No. 200 sieve for stabilization purposes. According to these authors, a soil can be considered as a sub-grade if 25% or more passes through the No. 200 sieve, otherwise it may be classified as a base material. According to these researchers, an in situ coarse-grained soil with less than 25% fines, may be, by definition a native sub-grade even though it may achieve the required classification of a base. The properties of these sub-grade soils may vary from highly expansive to non expansive depending on its mineralogical constituents.

Rao (2007) pointed out the nature and characteristics of the expansive soils. Expansive soils absorb water heavily, swell, become soft and lose strength. These soils are easily compressible when wet and possesses a tendency to heave during wet condition and shrink in volume and develop cracks during dry seasons of the year. These soils are characterized by extreme hardness and cracks when dry.

Holland and Rechards (1982) outlined that the seasonal changes in volume of expansive soil is manifested by horizontal and vertical movements. The horizontal movements lead to fissure opening during drying and closing during wetting where as the vertical movements lead to cyclic changes in soil levels. The authors described that the magnitude of these movements decreases with depth where there is no seasonal moisture changes.

Seehra (2008) describe the variation of the physical properties of black cotton soils from place to place. According to him, about 40 to 60% of the black cotton soils have grain sizes less than 0.001 mm. These soils generally have higher liquid limit and plasticity index and extremely low CBR value. At the liquid limit, the volume change is of the order of 200 to 300% and results in swelling pressure as high as $8kg/cm^2$ to $10kg/cm^2$. Soaked laboratory CBR values of black cotton soils are generally found to be in the range of 2 to 4%. Laboratory results conducted on highly expansive soil samples taken from Dejen-Debre Markos and Addis Ababa-Tarmaber Road sections provided soaked CBR values range on average from 1 to 2% (Annexure 5). Due to very low CBR values of this soil, excessive pavement thickness is required for designing of flexible pavement which can cause costly construction of pavements.

Rao (2007) described expansivity of soils in relation to their free swell index (FSI). Soils are called highly expansive when the free swell index exceeds 50% and such soils undergo volumetric changes leading to pavement distortion, cracking and general unevenness due to seasonal wetting and drying.

2.5. Problems Associated With Expansive Sub-grade Soils

Gourley and Schriener (1993) described that damages caused by expansive soils is almost entirely restricted to light structures and is a particular problem with transportation facilities.

The problem heightens due to insufficient identification of expansive soils during the site investigation and testing stages on many projects.

Problems associated with expansive sub-grade soils arise mostly from the nature of the soil and drainage facilities available (Rao, 2007). Expansive soils have a low CBR value in the range of 2 to 4% that they have low strength to support the loads transmitted from the pavement structure and results in excessive deformation beyond permissible limits (Rao, 2007; Seehra, 2008). The low load bearing capacity of expansive soils is affected by many factors such as moisture content, degree of compaction, soil type etc. Volumetric changes of expansive soil which leads to pavement distortion, cracking and general unevenness due to seasonal wetting and drying are explained by Rao (2007). This soil absorbs water heavily, swell, become soft, easily compressible and lose strength greatly. It has a tendency to heave during wet condition; shrink and develop cracks during dry seasons of the year which makes expansive soils a problem to pavements.

Seehra (2008) and Rao (2007) described the effect of water to pavements. In their study they proved that water is the worst enemy of road pavement, particularly in expansive soil areas and Poor drainage facility and results in damages of pavements. Furthermore, Seehra (2008) described the paths that water enters in to pavements. Water penetrates into the road pavement through the top surface, side berms and from sub-grade due to capillary action. Therefore, the road surfacing must be impervious, side berms paved and sub-grade well treated to check capillary rise of water.

Bulman (1980) presented problems associated with black clay soils of Africa as sub-grade soil under paved roads. According to him the problems are not only because of its swelling characteristics due to moisture variations and a very low bearing strength when saturated but also difficulties during the construction stage that it is difficult to handle if too wet or too dry. He also indicated the difficulty to raise the moisture of such soils to optimum for compaction in arid climates and thus results in low densities in compacted fills under road pavements built on black clay soil.

The other problem of expansive soil is its susceptibility to erosion. Highly expansive clays, such as black cotton soils, when dry exhibit a sand like texture and are susceptible to erosion to a much greater extent than that normally anticipated from their plasticity and clay content (ERA, 2002).

Road Design manual of the Republic of Kenya (1987) has discussed in detail about problems associated with expansive clay. The problems are volume change due to moisture variation, load bearing capacity reduction and susceptibility to erosion.

The Tanzanian Pavement and Materials Design manual (1999) describes about problematic soils. The manual present descriptions of the problem related with expansive soils and advices investigators to identify and classify expansive soils. This includes:

- Routine investigations: are those carried out during surveys of all projects.
- Extended investigations including simple additional indicator testing in the laboratory when expansive soils are suspected.
- In-depth studies including specialized laboratory testing and is employed where the extended investigations have shown occurrence of expansive soils

2.6. Improvement of Expansive Sub-grade Soils

Expansive soils do not meet the requirements and may need improvements to their engineering properties in order to transform these inexpensive earth materials into effective construction materials. This is often accomplished by physical or chemical stabilization or modification of these problematic soils (Little and Nair, 2009).

Chen (1988) has also determined the availability of different methods to overcome the problems associated with these highly expansive sub-grade soils either by replacing, modifying (altering) or protecting the soil from moisture variation.

Gourley et al (1993) have forwarded various options that can be applied to treat expansive sub-grade soils in road engineering; the choice of which option or combination of options depends primarily on the size of the project and economic consideration. According to them the options to be considered are;

- Alter the route/alignment to avoid the expansive soil
- Remove the expansive soil and replace it with non-expansive material
- Design for low strength and allow for maintenance to repair heave deformation
- Provide non-expansive material as a cover or surcharge layer
- Control moisture movement
- Improve the expansive soil by stabilization

Chen (1988) recommended the replacement method as the best alternative to overcome economic problems considering the depth and width of replacement and availability of non expansive soil within economic distance. Whereas altering the properties of the existing expansive soils and making it suitable for a pavement sub-grade is another alternative practiced widely. Soil properties may be altered mechanically by compaction or by blending the soil with better soils or chemically by adding chemicals to the soil (McKeen, 1976, Chen, 1988, Little and Nair, 2009).

Little and Nair (2009) described that mechanical stabilization, or compaction, which results in the densification of soil by application of mechanical energy, is particularly effective for cohesion less soils where the soils are not subjected to significant moisture fluctuations. The effectiveness of compaction may also decrease with an increase of the fine grained soil smaller than 75μm. The authors recommend chemical stabilization for fine grained soils.

Chemical stabilization has been discussed by many authors (Chen, 1988; McKeen, 1976; Seehra, 2008; Little and Nair, 2009; Al-Rawas et al, 2006). Chemical stabilizers result in increased CBR and UCS values of the sub-grade soil. The liquid limit and plastic limit of the stabilized soil are improved, especially in the cases of highly plastic clays and silts. The hydration process results in a stabilized soil which exhibits greater shear strength, stiffness and bearing capacity.

Little and Nair (2009) classified chemical stabilizers as traditional stabilizers which include hydrated lime, Portland cement and Fly ash; Non-traditional stabilizers comprised of sulfonated oils, ammonium chloride, enzymes, polymers and potassium compounds; and By-product stabilizers which include cement kiln dust, lime kiln dust etc. The traditional chemical stabilizers are widely used and in some cases a combination of lime, cement and fly ash is used for better result and economic stabilization. The authors suggest worth considering the under listed criteria while selecting an additive for stabilization:

- Soil consistency and gradation
- Soil mineralogy and composition
- Desired engineering properties
- Purpose of treatment
- Mechanisms of stabilization
- Environmental conditions and engineering economics

These researchers, as preliminary criteria, used the index properties plasticity index (PI) and the percent passing the no. 200 sieve (percent smaller than 75µm) to select an appropriate stabilizer for a given soil (Fig. 2.1).

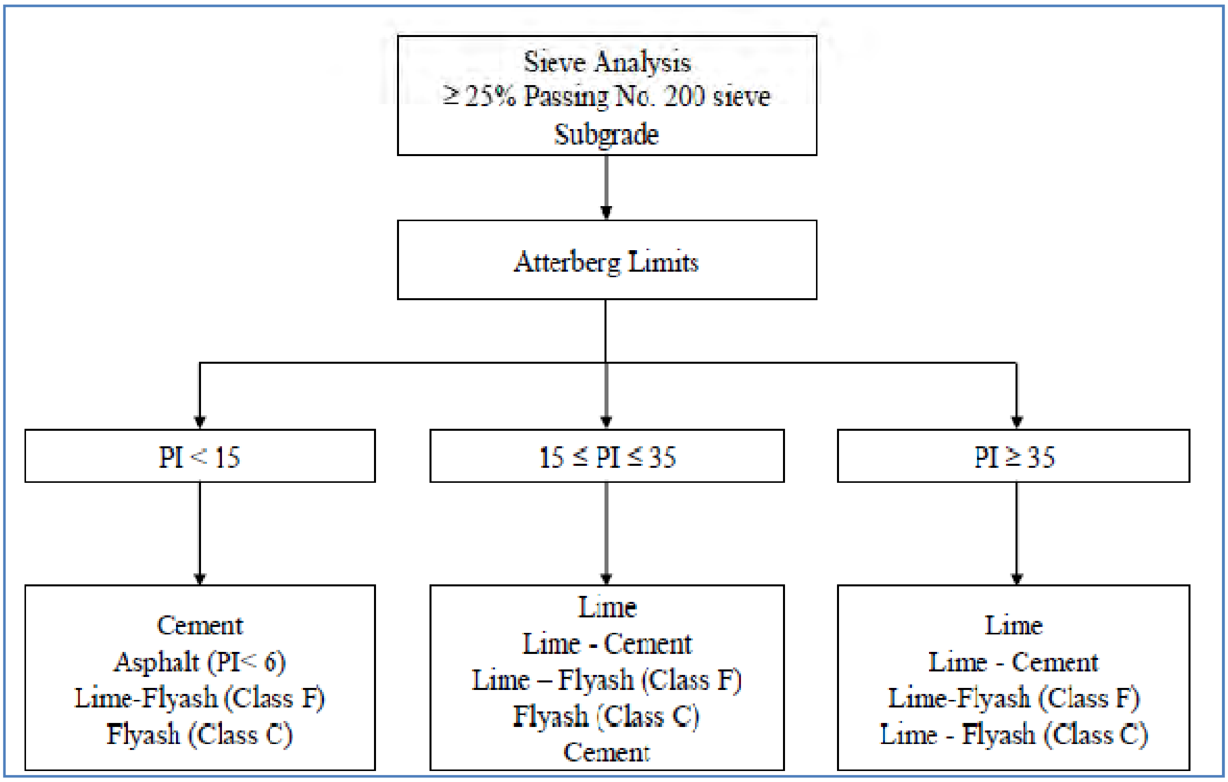


Fig 2.1 Decision Tree for Selecting Stabilizers for use in Sub-grade Soils (Adapted from Little and Nair, 2009)

Lime, cement and a combination of these two are commonly used in many countries. However, cement stabilization is more expensive than lime stabilization and difficult to use on fine grained clays. Cement is much more effective in granular soils (McKeen, 1976). Furthermore, Chen (1988) indicated that lime is increasingly used in the United States of America to stabilize expansive soils nevertheless of the success of lime treated sub-grade is questionable.

Bulman (1980) described chemical stabilization of black clay sub-grade soil in Africa. According to his study the great majority of African countries most commonly use cement for stabilization purpose and lime and bitumen are also used but to a much lesser extent. Bitumen is usually employed for stabilizing non-plastic sandy soils and thus finds its main application in desert areas. In his study he indicated that not only many natural gravels occurring in Africa can be stabilized with lime and the construction process is in several ways easier to carry out than when cement is used but also lime is the only feasible stabilizer for black cotton soils.

A study sponsored by the Nation Lime Association indicated that the effect of lime when added into soil can be drying, modification or stabilization (Little, 2006). According to this report lime stabilization occurs in soils containing a suitable amount of clay and the proper mineralogy to produce long-term strength; and permanent reduction in shrinking, swelling, and soil plasticity with adequate durability to resist the detrimental effects of cyclic wetting and drying and prolonged soaking.

Lime stabilization occurs over a longer time period of curing. The effects of lime stabilization are typically measured after 28 days or longer, but can be accelerated by increasing the soil temperature during the curing period (Little, 2006).

Little and Nair (2009) described the effectiveness of lime and cement for various soils. Lime is most effective for fine grained plastic soils where as cement stabilization is ideally suited for well graded aggregates with sufficient amount of fines.

Cement stabilization has similar effects as lime stabilization and cement stabilized soils have higher strength than lime stabilized soils. However, finer soils require greater amounts of cement, and very heavy clays may not be economically stabilized with cement alone. Cement contains the necessary ingredients for the pozzolanic reactions and therefore cement/soil mixtures harden faster than lime/soil mixtures, although both mixtures continue to gain strength with time (McKeen, 1976). According to McKeen (1976) strength and durability testing are the only reliable means of evaluating stabilized materials.

Normally, the strength of cement stabilized soil increases linearly with the amount of cement content, but at different rates for different soils whereas strength of lime stabilized soil increases with increasing lime content only up to a certain level; above a certain proportion of lime the strength of the stabilized soil will start to decrease (Thagesen et al., 2004).

Little and Nair (2009) also discussed stabilization of soil using fly ash. A wide range of aggregates can be suitably stabilized with fly ash including sands, gravels, crushed stones and several types of slag. Fly ash can be used effectively to stabilize coarse grained particles with little or no fines where in coarse grained materials it requires an activator that could be lime or cement to maximize the pozollanic reaction.

Thagesen et al (2004) pointed out an increasingly use of enzyme-based stabilizing agents for improving the properties of organic soils which are organic, non-toxic, eco-friendly bio-enzyme stabilizer used in reducing the swelling in expansive soils. Experiment conducted by Naagesh et al (2010) on soil specimens treated with bio enzyme exhibit lesser percent swell and swell pressure compared to untreated soil specimens and increasing the curing period of bio-enzyme treated specimens beyond 30days did not yield any further significant reduction in swell properties.

Literature shows that many companies produce stabilizers which can be either lime based, cement based, enzyme, polymer, etc. with varying degrees of effectiveness in different soil formations (Little and Nair, 2009).

Chittoori (2008) indicated the limitations of the current procedures for selecting the optimal additive content for stabilization. Sub-grade failure occurs either due to loss of stabilizer over time or a stabilizer being ineffective in some soils while other soils with the same index properties respond well to that stabilizer or the use of insufficient stabilizer.

Chittoori (2008) and Pedarla (2009) studied the performance of chemical stabilization in relation to clay mineralogy and durability. Both studies proved that soils containing montmorillonite as a dominant mineral were more susceptible to premature failures after chemical stabilization when they were exposed to volume changes caused by swell and shrink related volume changes. Furthermore, low amount of additive dosage can cause premature failures in the pavement structure. The researchers recommended considering stabilizer design by including clay mineralogy aspects in to the stabilizer design during additive selection and its dosage.

ERA Manual (2002) was reviewed to know about treatment of expansive soils. According to this manual the treatment measures to be applied on expansive soils for higher class roads of AADT design greater than 50 are;

i) Removal of Expansive Soil

   a) Where the finished road level is designed to be less than 2 m above ground level, remove the expansive soil to a minimum depth of 600 mm over the full width of the road, or
   b) Where the finished road level is designed to be greater than 2 m above ground level, remove the expansive soil to a depth of 600 mm below the ground level under the un-surfaced area of the road structure, or

c) Where the expansive soil does not exceed 1 m in depth, remove it to its full depth.

ii) Stockpile the excavated material on either side of the excavation for subsequent spreading on the fill slopes so as to produce as flat a slope as possible.

iii) The excavation formed as directed in paragraph (i) should be backfilled with a plastic non-expansive soil of CBR value 3 - 4 or better, and compacted to a density of 95% modified AASHTO.

iv) After the excavated material has been replaced with non-expansive material in 150 mm lifts to 95% modified AASHTO density, bring the road to finished level in approved materials, with a side slope of 1 : 2, and ensure that pavement criteria are complied with; the previously stockpiled expansive soil excavated as directed under (i) should then be spread over the slope.

v) Do not construct side drains unless they are absolutely essential to stop ponding ; where side drains are necessary, they should be as shallow as possible and located as far from the toe of the fill as possible.

vi) Ideally, construction over expansive soil should be done when the in-situ moisture content is at its highest, i.e. at the end of rainy season.

The manual also presents treatment operations to be applied on expansive soils for light traffic class roads of AADT design less than 50. These include:

i) Remove 150 mm of expansive topsoil and stockpile conveniently for subsequent use on shoulder slopes

ii) Shape road bed and compact to 90% modified AASHTO

iii) The excavation formed as directed in paragraph (i) should be backfilled with a plastic non-expansive soil of CBR value 3 - 4 or better, and compacted to a density of 95% modified AASHTO in each 150 mm layer; the sub-grade material may be plastic but non-expansive.

AACRA (2004) has also been reviewed and found to discus about the remedial measures for cut areas in swelling soil. These are:

(i) Sub-excavation of potential expansive soil: Dry, dense unweathered shale and dry dense clays are backfilled with impermeable soil at 95% MDD and OMC in accordance with AASHTO T180. This treatment should carry through the cut area and transitions from cut to fill until the depth of fill is approximately equal to the depth of treatment

(ii) Treatment of sub-grade: the depth of soil stabilization should be determined using the sub-grade information such as thickness and swelling potential of the swelling material. The amount of chemicals to be introduced will be determined by the trial mix results.

(iii) A combination of the above two methods: if swelling soil is the only available borrow source for the upper fill, treatment of the top few centimeters of the sub-grade by the chemicals should be considered. Moisture control during construction should be carefully observed. It is recommended that all swelling soils to be used as a fill be compacted to moisture contents at or above optimum moisture.

(iv) The other alternative to the swelling soil for embankment cut is by providing blanket layer to avoid/minimize the moisture variation.

2.7. Previous Works

There are no much studies and significant previous practical experience of chemical stabilization in Ethiopia. Practical experience that can be mention in Ethiopia are expansive sub-grade soil stabilization on trial road sections in Addis Ababa with RBI Grade 81 and ANSS and a pilot project of lime and cement stabilization of highly plastic granular material on Ambo-Gedo road section. Furthermore, more recently laboratory tests of hydrated lime-soil mixture were conducted on expansive soil samples taken from Dejen-Debre Markos road section for practical stabilization purposes.

Some related studies to the present work, however, were conducted in the past for academic purposes. The works of Aksum Tesfaye (2001), Daniel Nebro (2002) and Getnet Aschilegn (2008) are among the literatures referred during the present study. The study on sub base stabilization by Beniam Alemue (2010) on the above mention Ambo-Gedo road section is also worth mentioning.

Akxum Tesfaye (2001) conducted chemical treatment of black cotton soil using lime and cement to make it usable as a foundation material. For this study black cotton soil was collected from different parts of Addis Ababa. The laboratory tests conducted to attain the objectives of the study were attereberg limits, moisture-density relation and swell and swell pressure of soil-lime mixture. Even though he conducted few tests he reaches to a conclusion;

- The swelling potential of expansive soil with 6% lime falls within low limit and 15% cement falls within medium degree of expansion; but the swelling pressure was still higher
- Swelling pressure decreases with increasing lime or cement and molding water.
- Black Cotton soil compacted at lower water content swell more than the same soil compacted at higher water content. Black cotton soil exhibit higher swelling pressure when compacted to maximum dry density and lower swelling pressure when it was compacted below maximum dry density.
- Black cotton soil with compaction effort of 95% of maximum dry density and controlling moisture content to the wettest side of OMC, minimize the swelling pressure and swelling.

Daniel Nebro (2002) conducted Stabilization of potentially expansive sub-grade soil using lime and Con-Aid on samples taken from Addis Ababa-Jimma road section. Laboratory tests on atterberg limits, moisture-density relations and CBR were conducted to evaluate the performance of the two stabilizing agents. Based on the investigation, he conclude that the addition of 4% lime effectively increases the CBR and UCS and hence, 4% lime by oven dry weight can be taken as the optimum lime content. However, Con-Aid had no effect on the soaked CBR and CBR swell of the treated soil.

Getnet Aschilegn (2008) studied the stabilization of potentially expansive soils using an industry product RBI Grade 81 chemical. He collected two samples one light grey soil and another red clay soil and tested the effect of the chemical in different proportions and at different curing periods. The tests conducted to attain the objectives were atterberg limits, moisture-density relation, soaked CBR, UCS, swelling potential and percent swell. According to the results obtained 4% of the chemical is enough to improve the engineering properties of the soil and the effect of the chemical is found to be more on the light grey soil than the red clay soil.

Beniam Alemue (2010) studied stabilization of granular sub base material using Lime on Ambo-Gedo Road Project. He conducted atterberg limits, UCS and ITS tests and determined the initial lime requirement by PH test method. From the results obtained he concluded that addition of lime decreases the PI and increase the strength and overall effectively stabilized the granular sub base material.

2.8. Genesis of the Present Research Study

From literature review and past experience it has been learned that expansive soils are widely distributed in Ethiopia and are the most problematic soils for engineering works. These soils pose serious problems for roads construction and maintenance. Therefore, such soils should be investigated, adequately identified prior to road construction and proper treatment measure should be taken to avoid the problems. Although chemical stabilization is a common remedial measure practiced all around the world among the various methods, it is still in the conceiving stage in Ethiopian. The common practice followed to construct road over expansive soils has been replacement method and same has been mentioned in ERA (2002) Manual, as already discussed in previous section. Thus, to study the effectiveness of chemical stabilization on expansive sub-grade soils the present research problem was conceived.

The present study was conducted on expansive soils in the northeastern part of Addis Ababa on a trial road section in Gerji area where the soil samples were taken. Hydrated lime and ANSS were used to stabilize the soil samples and the effects of these stabilizers on the properties of the soil were evaluated. The hydrated lime used in the present study is locally produced from limestone found in Ambo area which makes the present study unique from other related studies. Whereas the ANSS is imported cement based chemical stabilizer and the main components that are used to formulate are a series of inorganic hydration activated powders. It is composed of cement, lime, several pozzolans, rate governing additives and a unique polypropylene fiber (Anyway Company Ltd, 2003).

In the present study the mineralogy and chemical composition was considered to characterize the sub-grade soils in addition to other index and physical tests. Furthermore, initial lime required to stabilize the sub-grade soil was determined by PH test. Natural and chemical treated soil samples were tested for atterberg limits, linear shrinkage, moisture-density conditions, CBR and percent swell of CBR tests and comparisons are made to evaluate the performance of the chemical stabilizers on soil samples.

Chapter III Description of the Study Area

3.1. Preamble

The formation of the different types of soils depends on the prevailing environmental factors of an area. The climatic conditions and the geologic and physiographic setup of an area have impact on the formation of expansive soils since these soils need specific conditions to be fulfilled. Accordingly a considerable part of central and southern Addis Ababa is occupied by expansive soils which are problematic when encountered as sub-grade.

This chapter deals with the description of climatic, physiographic, geologic and hydrogeologic conditions which influenced the formation of expansive soils in the project site and the surrounding area. This section also includes description of the seismic condition and soil type distribution of the study area and its surrounding. Finally a brief description of the project site condition is included.

3.2. Location of the Study Area

The study area is Addis Ababa, the capital city of Ethiopia, bounded approximately by the UTM coordinates 964000N, 1002000N and 456000E, 496000E. The city overlies at the western margin of the Main Ethiopian Rift and is a part of the western highland of Ethiopia. A trial road section of about 1.2km which connects Imperial Hotel-Gerji road and Mebrat Hail-Yerer Ber Road is selected in the northeastern part of the city in Gerji area (Fig.3.1).

3.3. Climate

Ethiopia is classified into five climatic zones (EMA, 1981). These include "Kur" (Alpine), above 3000m mean sea level; "Dega" (Temperate), 2300m to about 3000m; "Weina Dega" (Sub tropical), 1500m to about 2300m; "Kolla" (Tropical), 800m to about 1500m and "Bereha" (Desert), less than 800m. Most parts of Addis Ababa fall under the Weina Dega (Sub tropical) category.

3.3.1. Rainfall

The variation in the seasonal distribution of rainfall in Ethiopia can be attributed by the reference to the position of the Inter-Tropical Convergence Zone, the relationship between upper and lower air circulation, the effects of topography and the role of local convection currents and the amount of rainfall (Daniel, 1977).

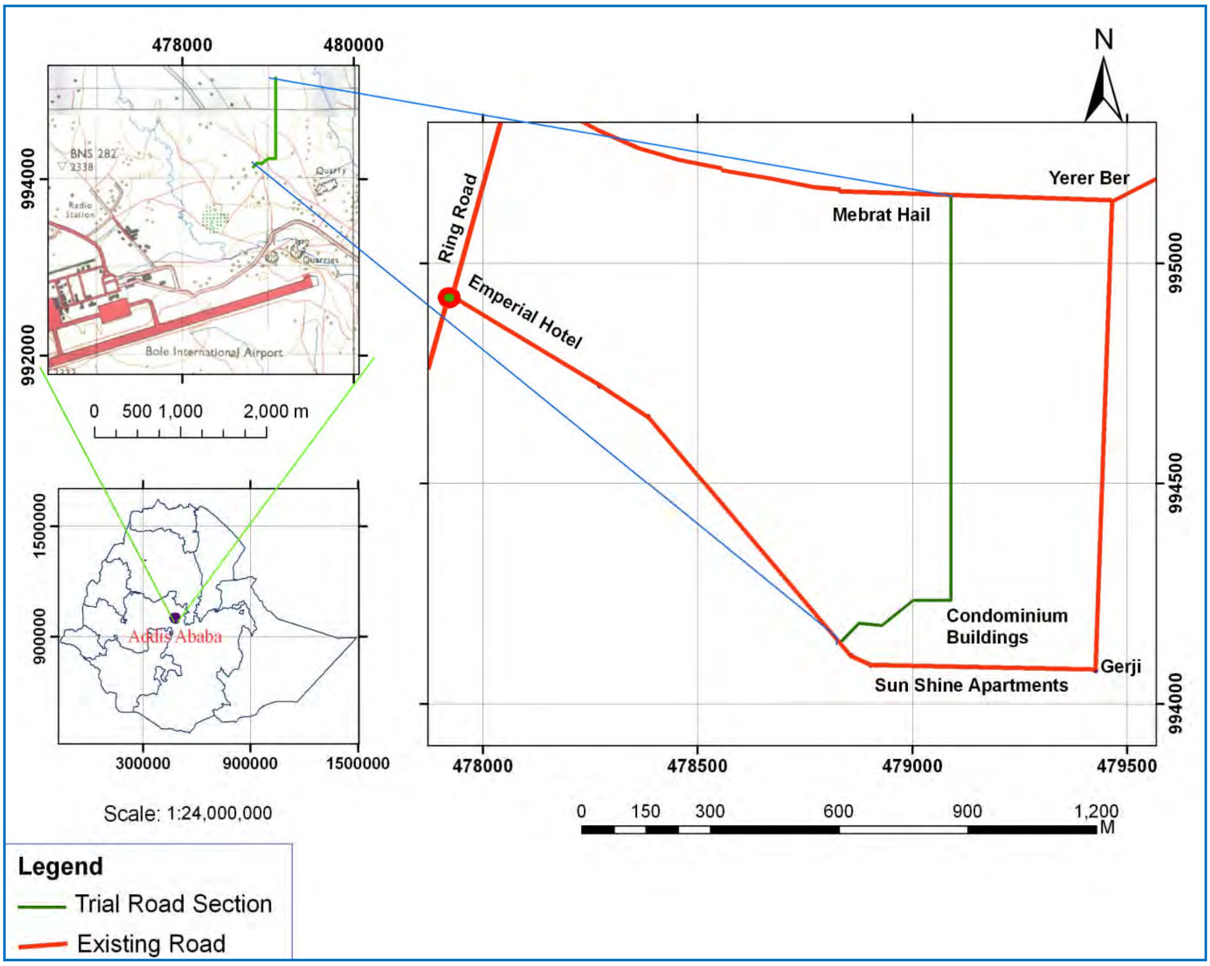


Fig. 3.1 Location of the Study Area

Monthly total rainfall records of three stations for the year from 1964 to 2004 for Addis Ababa Bole, from 1951 to 2004 for Akaki Beseka and from 1900 to 2004 for Addis Ababa observatory are utilized to analyze monthly mean rainfall and annual mean rainfall. The mean monthly and annual mean rainfall of National Meteorological Services Agency (NMSA) stations in Addis Ababa located at Addis Ababa Bole, Addis Ababa Observatory (Tekelehaimanot) and Akaki Beseka Stations are shown in Table 3.1. All stations are located at different elevations of 2350m, 2408m and 2000m a.s.l., respectively.

Table 3.1 Mean monthly and mean annual rainfall of Addis Ababa (Source: National Meteorological Services Agency)

Station	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Ann. Mean
A.A. Bole (1964-2004)	13.7	37.4	68.6	93	76.4	119	235.4	242.5	143.3	32.7	7.2	5	1074
Akaki Beseka (1951-2004)	14	36.8	67.5	91	67.1	123	264.1	283.9	131.1	24.5	3.8	3.1	1109
AA Observatory (1900-2004)	16.4	42.9	65.9	93.4	85.5	131	259	278.4	175.1	38.1	7.5	9	1201
Mean Monthly	14.7	39	67.3	92.5	76.3	124	252.8	268.3	149.8	31.8	6.2	5.7	1128

As indicated in Table 3.1 the precipitation occurs throughout the year and shows variation in amount from month to month. The monthly mean records of rainfall shown for each station indicates that the mean annual rainfall at Addis Ababa Bole, Addis Ababa Observatory (Teklehaimanot) and Akaki Beseka stations were 1074mm, 1201mm and 1109mm, respectively. Thus, the city receives mean annual rainfall of about 1128mm.

At all the stations the heaviest rainfall occurs during August where as the minimum rainfall occurs in December at Addis Ababa Bole and Akaki Beseka stations and in November at Addis Ababa Observatory. Furthermore, Addis Ababa Observatory which is located at a higher elevation than Addis Ababa Bole and Akaki Beseka stations, records greater amounts of mean annual rainfall. This shows that there is variation in the amount of rainfall within Addis Ababa with difference in altitude.

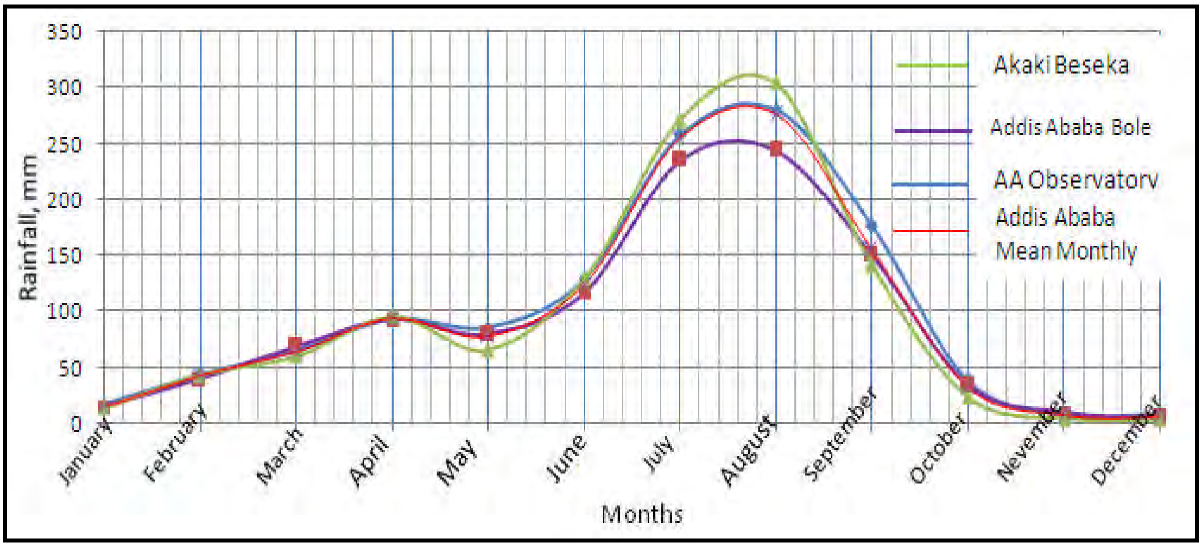


Fig. 3.2 Mean monthly rainfall of Addis Ababa based on Addis Ababa Observatory, Addis Ababa Bole and Akaki Beseka stations (Source: National Meteorological Services Agency)

"Rainy months" and "dry months" of any year is distinguished by calculating rainfall coefficient (RC). It is the ratio between the mean monthly rainfall and one twelfth of the annual mean (Tamiru Alemayehu et al, 2006). Rainy months have rainfall coefficient (RC) of above 0.6 where as those of dry months have less than 0.6 (Tamiru Alemayehu et al, 2006). The rainfall coefficient is shown in Table 3.2.

The rainy months of Ethiopia are classified into small rains with RC of 0.6 to 0.9 and big rains with RC of 1.0 and above. The big rainy months are further classified into three groups as moderate concentration with RC from 1.0 to 1.9, high concentration with RC from 2.0 to 2.9 and very high concentration of rainfall with RC from 3.0 and above (Daniel, 1977).

Table 3.2 Rainfall Coefficient at Addis Ababa Bole, Addis Ababa Observatory and Akaki Beseka Stations (Source: National Meteorological Services Agency)

Station	Jan.	Feb.	Mar	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.
A.A. Bole (1964-2004)	0.15	0.42	0.75	1.04	0.85	1.33	2.63	3.17	1.60	0.37	0.08	0.06
Akaki Beseka (1951-2004)	0.15	0.4	0.73	0.98	0.73	1.33	2.86	3.07	1.41	0.27	0.04	0.03
AA Observatory (1900-2004)	0.14	0.42	0.66	0.93	0.85	1.3	2.59	2.78	1.75	0.38	0.07	0.09

From Table 3.2 therefore, it is observed that the rainy months of Addis Ababa are from March to September and the dry months are from October to February. The small rain occurs from March to May as observed in Addis Ababa Observatory and Akaki Beseka Stations, while in Addis Ababa Bole Station it was observed in March and May. The big rain is from June to September as observed in Addis Ababa Observatory and Akaki Beseka stations, with moderate concentration in June and September. In Akaki Beseka Station high and very high concentration were recorded in July and August, respectively. In Addis Ababa Bole Station big rain with moderate concentration was recorded in April, June and September, high concentration in July and very high concentration in August.

3.3.2. Temperature

Latitude, altitude, winds and humidity, with varying magnitude have significant impacts on temperature conditions in Ethiopia. The overall temperature in Ethiopian highlands is lower than those in tropical lowlands. The average fall in temperature is 0.6^0C for every 100m rise in elevation. The average temperatures are typically tropical and fluctuate by 5^0C between the coldest and warmest months. The annual variation is from 2 to 6^0C in the Ethiopian highlands (Griffiths, 1972; as cited in Akundabweni, 1984). Highest temperature was observed for the months of March, April, May and June. While the months of October, November and December had the lowest temperatures.

The mean monthly maximum and minimum temperature records of Addis Ababa Observatory for the years between 1951 and 1998 were utilized to calculate monthly and annual averages. The computed average maximum and minimum temperature is presented in Table 3.3 below. Perusal to Table 3.3, the highest mean monthly maximum temperature occurs in the months of March with 24.6^0C and the lowest is in the month of August with 20.1^0C. While the mean monthly minimum temperature ranges for the lowest from 7.5^0C in December to the highest 11.7^0C in the month of March. Thus, the average temperature of Addis Ababa is 16^0C.

Table 3.3: Monthly and annual mean maximum and minimum temperatures of Addis Ababa (Source: National Meteorological Services Agency)

Description (^{0}C)	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual Mean
Average Maximum	23.3	24.1	24.6	23.9	24.6	22.9	20.3	20.1	21.1	22.4	22.6	22.8	22.7
Average Minimum	8.2	9.5	10.9	11.5	11.7	10.8	10.8	10.8	10.5	9.2	7.9	7.5	9.9

3.4. Physiography

Ethiopia can be divided into four major physiographic regions widely known as the Western plateau, Southern plateau, the Main Ethiopian Rift and Afar Depression (Mengesha Tefera et al., 1996).

Addis Ababa is located on a plateau with an elevation ranging from 2000 to 2800m a.s.l. on the shoulder of the western Main Ethiopian Rift (MER) escarpment. The morphology of Addis Ababa is a direct reflection of the different volcanic stratigraphic successions, tectonic activities and the action of erosion between successive lava flows (Tamiru Alemayehu et al., 2006). The physiographic map of Addis Ababa shows that the City is founded on an area with a well developed morphology. It is surrounded by high rising mountain systems in all directions and the center of the city lies on an undulating topography with some flat land areas. The urban area of the city is deeply dissected by numerous valleys formed by the river systems crossing the city from north to east.

Intoto mountain ridge forms the northern boundary of the city following the East-West trending Ambo-Kassam major fault system. The elevation of this ridge ranges from 2600 to 3200 m. The volcanic mountains; Mt. Wechecha in the west, Mt. Furi in the south-west and Mt. Yerer in the southeast are the high massive volcanic centers rising to elevations of 3385m, 2839m and 3100m a.s.l, respectively.

Undulating to flat topography is dominant within the city boundary. The presence of domes and river valleys create this undulating topography. Further south wards, the topography becomes very gentle and a very wide area falls under a smaller elevation range of 1960m and 2160m a.s.l (Fig. 3.4).

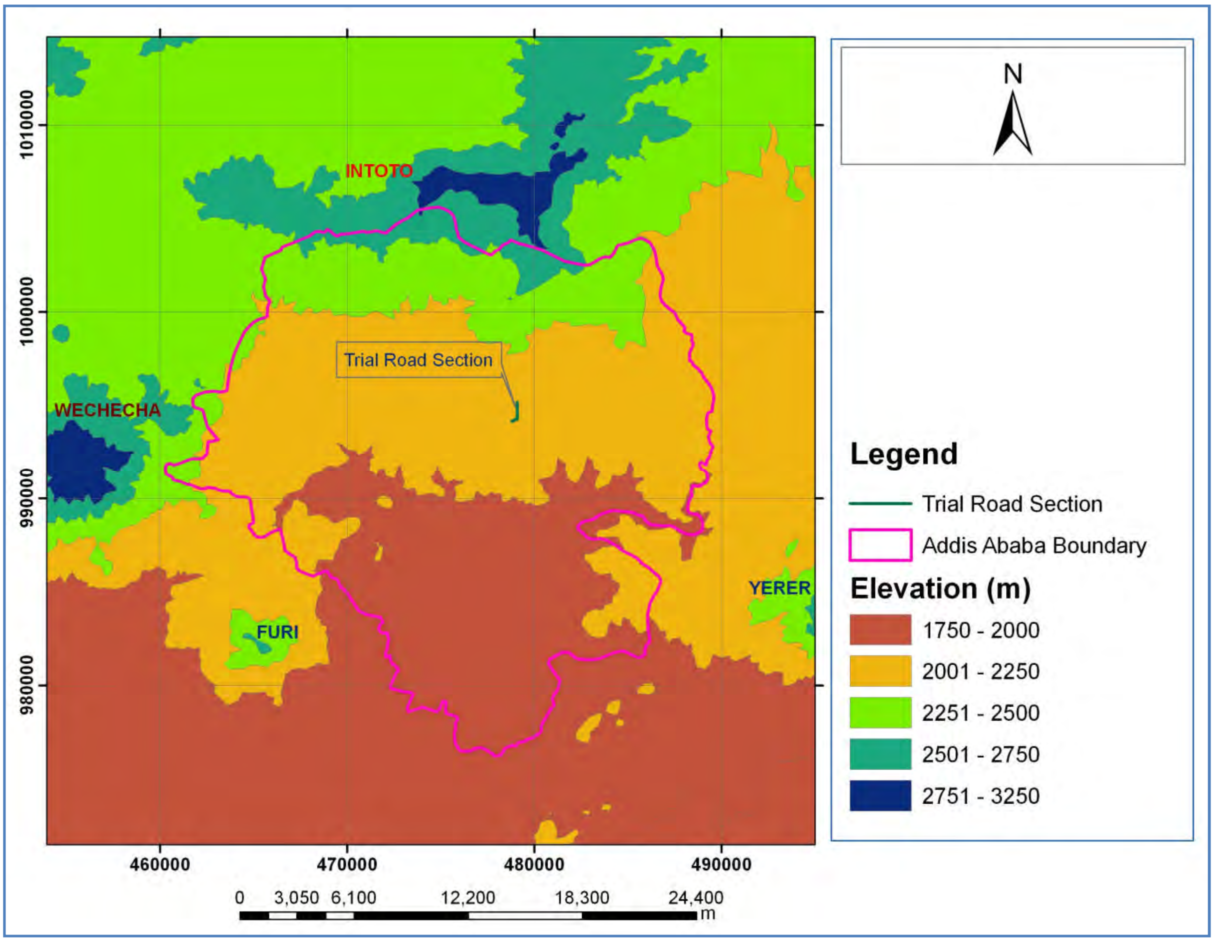


Fig 3.3 Physiographic map of Addis Ababa and the surrounding area

Addis Ababa lies within the Awash River Basin. The water divide between Awash Basin and Blue Nile Basin lies on the top of Intoto Ridge. The catchment area of Akaki River basin that totally includes Addis Ababa area is divided into two sub basins - the Big Akaki River (Eastern) sub basin and the Little Akaki River (Western) sub basin.

The streams of Addis Ababa drain towards south from Intoto ridge, south east from Mt. Wecheca and Mt. Furi and towards south west from Mt. Yerer and other elevated areas of the eastern outskirts of the city. The potential streams in the city are Little Akaki, Bantyiketu, Kurtume, Kebena, Ginifile, and Big Akaki. Other streams are intermittent in nature. Streams are dense with deep valleys on top of mountains such as Intoto ridge forming radial and dendritic drainage patterns (Fig. 3.4 and 3.5). In the southern part of the city the density of the streams is reduced and the main rivers show meandering type of flow. This is due to the decrease in the gradient of the valley floor. In general, streams are structurally controlled which is characterised by plains, rolling terrains and river gorges.

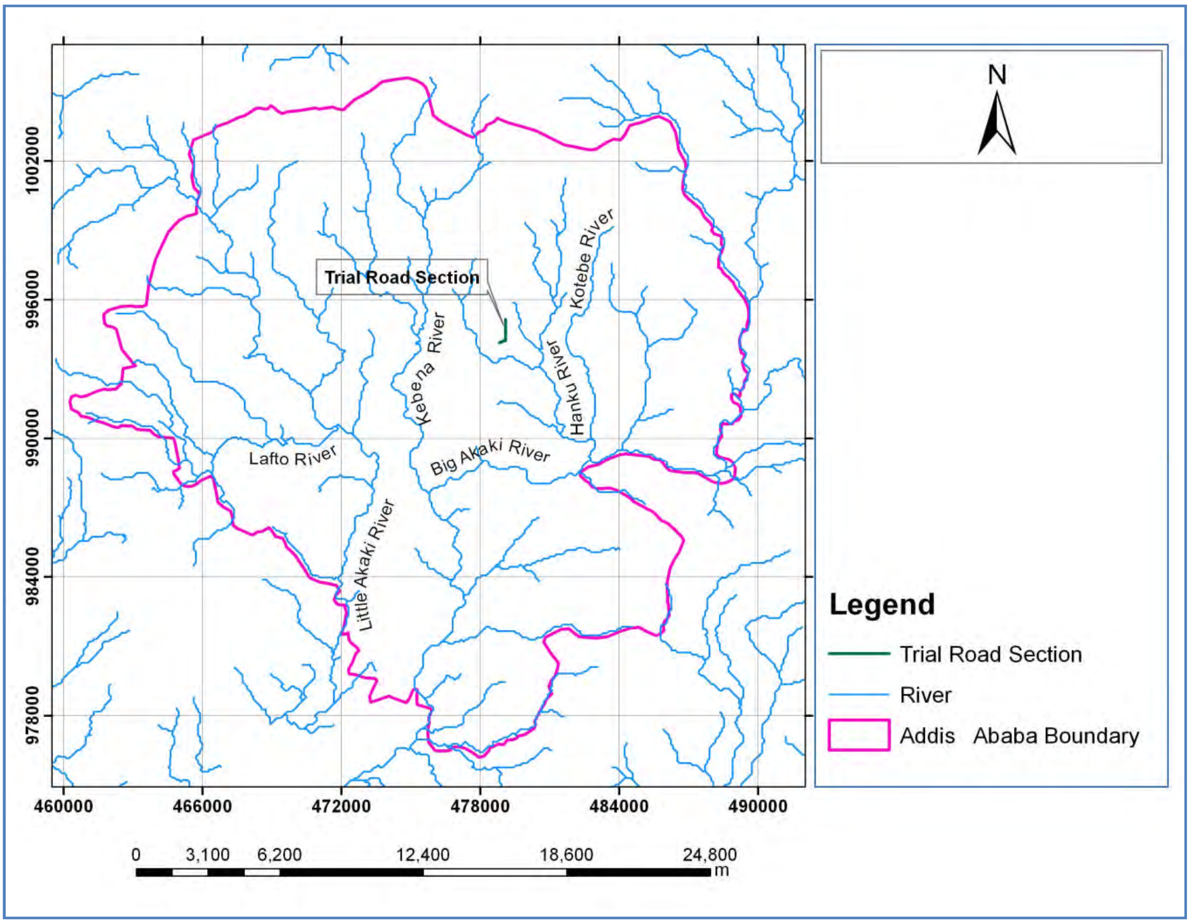


Fig 3.4 Drainage map of Addis Ababa and the surrounding area

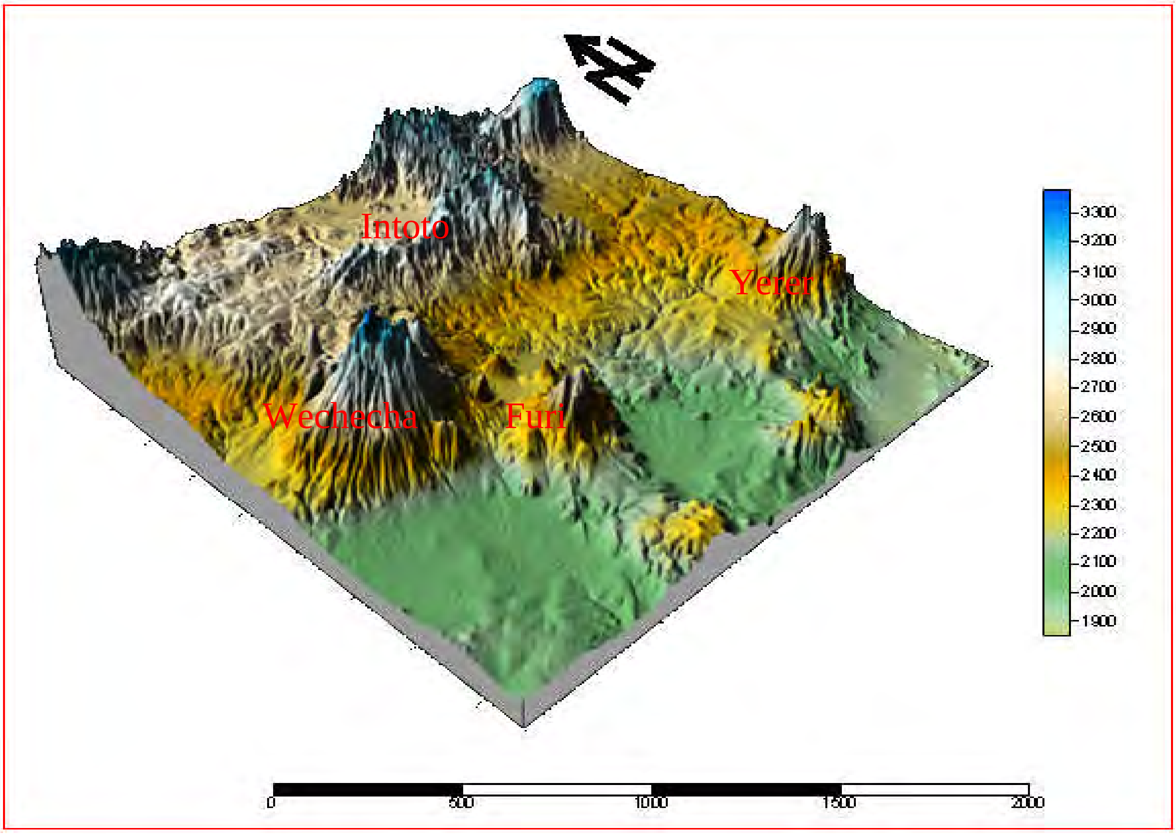


Fig 3.5 3D map of Addis Ababa and the surrounding area

3.5. Regional Geology

Extensive areas of the highlands of Ethiopia on both sides of the rift valley are covered by Tertiary (Trap series) volcanic rocks which are mainly basalts with subordinate acidic rocks. In the rift valley, subsequent to the formation of the rift valley, the Trap series were overlain by a variety of younger volcanic rocks of basalts, ignimbrites and rhyolites (Tesfaye Chernet, 1993). The Tertiary Ethiopian volcanism occurred in three main stages separated by periods of quiescence. These are; the pre-Oligocene stage (Ashanti formation), the Oligocene-Miocene stage (Aiba, Alaji and Tarmaber formations) and the Miocene- Pliocene stage (Fursa, Balchi and Bishoftu formations) (Zanettin et al, 1978).

Addis Ababa is located in the western margin of the Main Ethiopian Rift Valley. The margin is more recent, shows Mio-Pliocene volcanics and is characterized by normal faults down thrown towards the rift. The upper (outer) boundary of the margin is marked by the large fault running approximately east-west immediately north of the Addis Ababa-Ambo road. The lower boundary run northeast to southwest parallel to the principal systems of fissures of the rift-floor from Nazareth to awash Station (Zanettin et al. 1974).

3.6. Geology of Addis Ababa

Addis Ababa is located in the western margin of the Main Ethiopian Rift Valley. Many researchers have conducted the geological and stereographic sequences of Addis Ababa. Haileselassie Girmay and Getaneh Assefa (1989) established the straigraphy of Addis Ababa area based of K/Ar absolute age determination taken from different literature and field work. The suggested Miocene-Pleistocene volcanic succession from bottom to top is Alaji Basalts, Intoto Silicics, Addis Ababa Basalts, Nazareth Group and Bofa Basalts.

3.6.1. Alaji Basalts (end of Oligocene to Middle Miocene)

This unit is composed of basalts, which show variation in texture from highly porphyric to aphanitic. The unit is intercalated with gray and glassy welded tuff. The outcrops of Alaji basalts are situated in the North and Northeastern part of Addis Ababa. They form high topography and Rhyolites have more area extent than trachytes. Trachytes and rhyolites are contemporaneous in age. The Alaji basalt is underlain by tuffs and ignimbrites and is overlain by the Entoto Trachyites (Haileselassie Girmay and Getaneh Assefa, 1989).

3.6.2. Entoto Silicics (Early Miocene)

The unit is unconformably overlain by Addis Ababa basalt on the foothills of Entoto hills and is composed of rhyolites and trachytes with minor amount of welded tuff and obsidian (Hailesellase Girmay and Getaneh Asefa, 1989). The rhyolitic lava flows outcrop on the top and the foothills of the Entoto ridge, predominantly in the western side. It also outcrops in the eastern part of the town around Kokebe Tsebah School. The thickness is quite variable as it frequently forms dome structure. The thickness becomes maximum on the top of Entoto ridge and thin both towards the plateau and the plain east of Addis Ababa.

The rhyolites are overlain by porphyritic trachytes and underlain by a sequence of tuffs and Ignimbrites. Tuffs and Ignimbrites are welded and characterized by columnar jointing. The trachytic lava flows outcrop on the top of Entoto Ridge and its foothills. The trachyte and the alaji aphanitic basalts are separated by paleosoil indicating time gap.

3.6.3. Addis Ababa Basalts

Stratigraphically, this unit is underlain by the Entoto silicics and overlain by lower welded tuff of the Nazareth group. It is porphyritec in texture and mainly present in the central part of the city (Hailesellase Girmay and Getaneh Asefa, 1989). Olivine porphyritic basalts outcrop around Merkato, Teklehamanote and sidest Kilo. The Lower Welded tuff overlies both types of basalt nearby the building college, the kolfe Police School, the Kokebe Tseba School and Yeka Mariam church. On the other hand, only in the gorge of the Ketchene stream the olivine porphyritic basalt is overlain by the plagioclase porphyritic basalt.

3.6.4. Nazareth Group

The units identified in this group are lower welded tuff, aphanitic basalt and upper welded tuff. Welded tuffs have been related to Wachecha and Yerer Volcanisms. The group is underlain by Addis Ababa basalt and overlain by Bofa basalts. The rocks outcrop mainly south of Filwoha fault and extended towards Nazareth (Hailesellase Girmay and Getaneh Asefa, 1989). The units in this group are:

Lower Welded Tuff

It outcrops as small discontinuous body in Filwoha, western parts of Addis Ababa and Sululta. Generally it is overlain by the aphanitic basalt and underlain by the olivine and plagioclase porphyritic basalt. The age of this unit overlaps with the period of the activity of wechecha trachyte volcanoes.

Aphanitic Basalt

It covers the southern part of the city, especially the area of Bole International Airport and Lideta Old Airfield. The rock body shows vertical curved columnar jointing together with sub-horizonal sheet jointing. Along the course of Akaki River large amygdales of calcite occur in this basalt. Kaolinite lenses are present at the contact with the younger ignimbrite.

Upper Welded Tuff

It outcrops all over the southern part of the city including Bole, Nefas Silk and Railway Station; nevertheless it is also present in the central and northern part of the city. It is gray colored, vertically and horizontally jointed and composed of sanidine, anortoclase, rebekite, quartz, pumice and unidentified volcanic fragments (Hailesellasie Girmay and Getaneh Assefa, 1989). The welded tuff is underlain by aphanitic basalt and overlain by young olivine basalts.

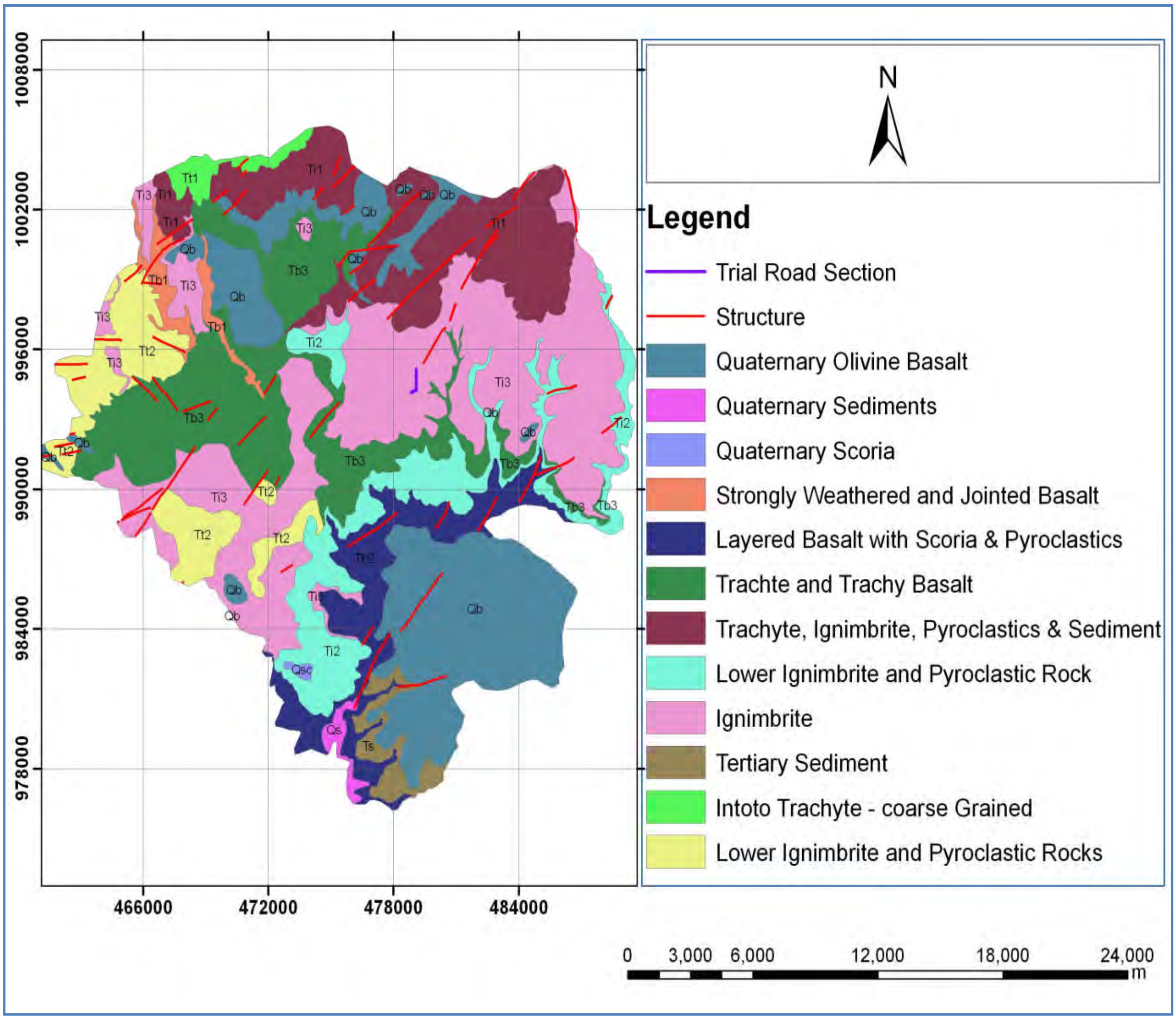


Fig. 3.6 Geological Map of Addis Ababa (Modified from Asegid Getahun, 2007)

3.6.5. Bofa Basalts

Bofa Basalts outcrop southward from Akaki River where they appear in the form of boulders reaching a thickness of 10 meters. They are restricted and dominated in the southeastern part of the city. This rock is characterized by big vesicles that are filled by calcite. This basalt is underlain by the tuffs which cover the welded tuff.

3.7. Soil

The soil development in Addis Ababa area is mostly due to the physical disintegration and chemical decomposition of volcanic rocks. The weathering products are either remain in places and form residual soils or transported and deposited in the low lying flat lands and depressions (Tamiru Alemayehu et al, 2006). The differences observed in the type and development of soils in the city depends mostly on the topography, parent rock and the degree of weathering. Although there is significant difference in the degree of weathering on the slopes, mostly soils are highly eroded and result in thin soil cover. In the localities where the topography is plain to gentle there is thick soil profile. The type of parent material and the length of time to which the parent material is subjected to weathering, control the variation in the thickness of soil. Thus, old basic and acidic rocks that outcrop in the central, western and southwestern parts of Addis Ababa are weathered and form thick soil profile. In places where young basalt and welded tuffs occur, the thickness of the soil cover is reduced.

The deterital materials that are derived from elevated areas of Entoto, Wechecha, Furi and Yerer are transported and deposited in the piedmont and along the stream courses of Addis Ababa. It covers most parts of Mekanisa, Ayere Tena, Kaliti, Akaki, Lideta, and Bole. The soil is black in color and the thickness varies from place to place primarily depending on the slope of the area. Kebede Tsehayu and Tadese Hailemariam (1990) classified the soil units of Addis Ababa based on their origin as alluvial, alluvial fan, colluvial, residual and lacustrine alternatively called black cotton soils (Fig.3.7).

The alluvial soils which include channel and terrace deposits are found in some places along Akaki River in the west and southwestern parts of Addis Ababa and along Kebena River north of Bole area. The alluvial soils consist of more or less stratified deposits of gravel and clay transported by streams. The study indicated that sample taken from terrace deposits near Bole consists of 46% silt, 34% clay and 20% sand and classified as ML in USCS system. Alluvial fan is deposited where there is a decrease in gradient from a hill to a plain along a river section. It is coarser near the mouth of the river and become finer outwards and found in the Intoto region dissected by deep gullies (Kebede Tsehayu and Tadese Hailemariam, 1990).

Residual soils developed in situ by the decomposition of rocks are mainly located in Gulele and Kolfe area. Sample tested provide grain size of 62% clay, 33% silt and 5% sand. In some localities reddish brown soil with a thickness of more than 10 meter is commonly seen.

Black cotton soils are found in Bole, Lideta and Mekanisa areas which are flat and relatively low lying (Kebede Tsehayu and Tadese Hailemariam, 1990). In the same study samples taken from Bole and Mekanisa area provided 76% clay, 22% silt and 2% sand and according to USCS it is MH (rarely CH).

Observations and tests show that the low lying flat areas around Addis Ababa are dominated by black cotton soils. These soils have extremely high plasticity and very high degree of swelling as compared to the other identified soil types found in Addis Ababa. The thickness of this soil varies at places from 2m to 10m. The highest thickness is found in Bole area and in Beklo Bet area it is about 5m thick (Kebede Tsehayu and Tadese Hailemariam, 1990).

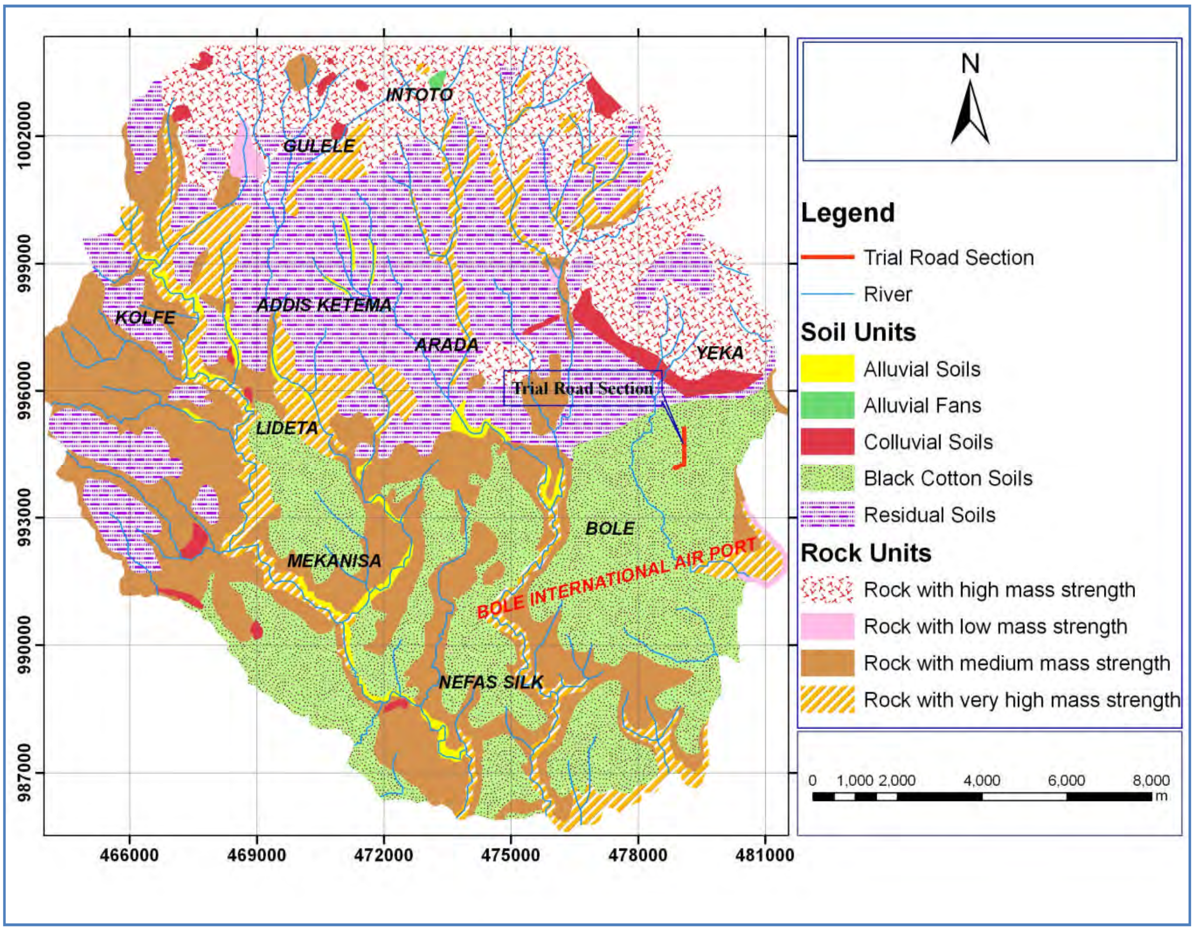


Fig 3.7 Engineering Geological Map of Addis Ababa (Kebede Tsehayu and Tadese Hailemariam, 1990)

In areas where there is great contrast in the topography colluvial soils are found. These are loose and incoherent deposits, consisting of fine to coarse grain particles. Colluvial soils are mainly located at the foot slopes of northeastern part of Entoto silicics and other few places (Kebede Tsehayu and Tadese Hailemariam, 1990).

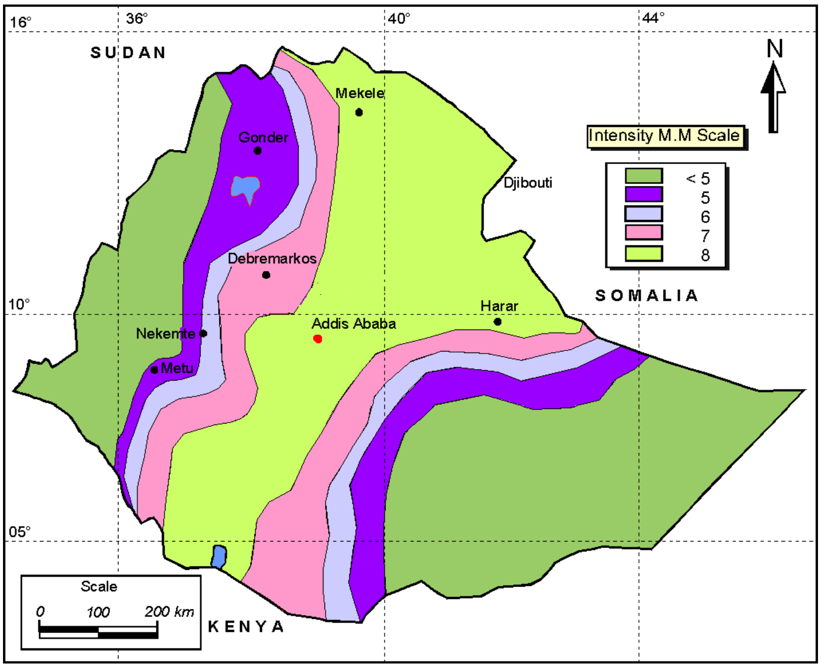
3.8. Hydrogeology

The major ground water aquifers in Addis Ababa are basalts, rhyolities, trachytes, scoria, trachy basalts, welded tuffs, unwelded tuffs and the unconsolidated materials of volcanic origin as depicted from boreholes previously drilled for water supply. The main aquifers in Addis Ababa area can be categorized in to three groups which include shallow aquifers of the weathered volcanic rocks and alluvial sediments along the river courses, deep aquifers of the fractured volcanic rocks that tap fresh ground water and thermal aquifers along Filwoha fault (Tamiru Alemayehu et al, 2006). These aquifers are characterized by fracture and inter granular porosity. Basalts are the major water bearing zone in the area due to its fracture porosity where as unconsolidated volcanics and alluvial sediments under favourable conditions stores water. The black cotton soils in the south of Addis Ababa act as impervious material (Tamiru Alemayehu et al., 2006).

Tamiru Alemayehu et al (2006) also determine the general direction of groundwater flow in Addis Ababa based on elevation of water level in boreholes drilled for water supply. According to this study the ground water movement direction is dominated by North-South and South-East flow. In some localities however the ground water flow direction changes, mostly towards the nearby streams and generally, the groundwater movement is sub-parallel to the surface water flow direction and more or less controlled by the topography of the area. The groundwater level in Bole Sub City around Imperial Hotel is about 20m below the ground level and the water level fluctuation is from 2m to 4m (Mesay Gashaw, 2008).

3.9. Seismicity

The seismicity of Ethiopia is controlled and influenced by the active Ethiopian Rift System which divides the country into two along the NE–SW direction (Tilahun Mamo, 2005). Earthquakes are intense and high in magnitude in the Afar triangle and Main Ethiopian Rift, becomes sparse and low in magnitude in the rift border faults and seismicity is less common in the south, a reflection of a difference in the stage of rift evolution (Keir et al, 2003).



Addis Ababa is located in a seismically active zone and it will have impact on road pavements and sub-grade soils (Fig.3.8). However, it requires consideration and a systematic study to know exactly the damage an earthquake can cause to these structures. Such study is beyond the scope of the present research.

Figure 3.8 Seismic risk map of Ethiopia 100 year return period, 0.99 probability (Laike Mariam Asfaw, 1986)

3.10. Project Site Description

The project area is located in Gerji northeast of Bole International Airport on plain land slightly sloping to the southeast and is already inhabited mainly by residential houses. The project is a road section about 1.2km in length connecting Imperial Hotel-Gerji road with Mebrat Hail-Yerer Ber road. The owner AACRA has contracted Anyway Company Ltd to stabilize the highly expansive sub-grade soil with the chemical ANSS and the authority has planned to undertake construction of road by own force.

There is a thick layer of soil mapped as black cotton soil by Kebede Tsehayu and Tadese Hailemariam (1990) which is a result of the prevailing climatic, geologic and physiographic condition of the surrounding area. This soil acts as impervious material to ground water flow (Tamiru Alematehu et al, 2006).

According to the geological map of Addis Ababa, the acidic volcanic rock ignimbrite underlies the soil deposit in the project area (fig 3.6). Ignimbrite rock exposure is also observed in a previous abandoned quarry nearby east of the project site. The soil, which is formed on ignimbrite rock, as observed to a shallower depth of up to 2.5m during sampling has two layers based on colour variations: the lower light gray soil and the upper dark gray soil. The change in colour between the two layers is not sharp but gradual. Furthermore, the XRD and XRF test results show that the two layers have similar mineralogy and chemical composition, which is more of acidic origin, with minor variation in proportion (Annexure 4, 5 and 6). This preliminary investigation shows that the soil is residual, a weathered product of the underlying ignimbrite rock. However, it needs further investigation as such study is beyond the scope of the present research.

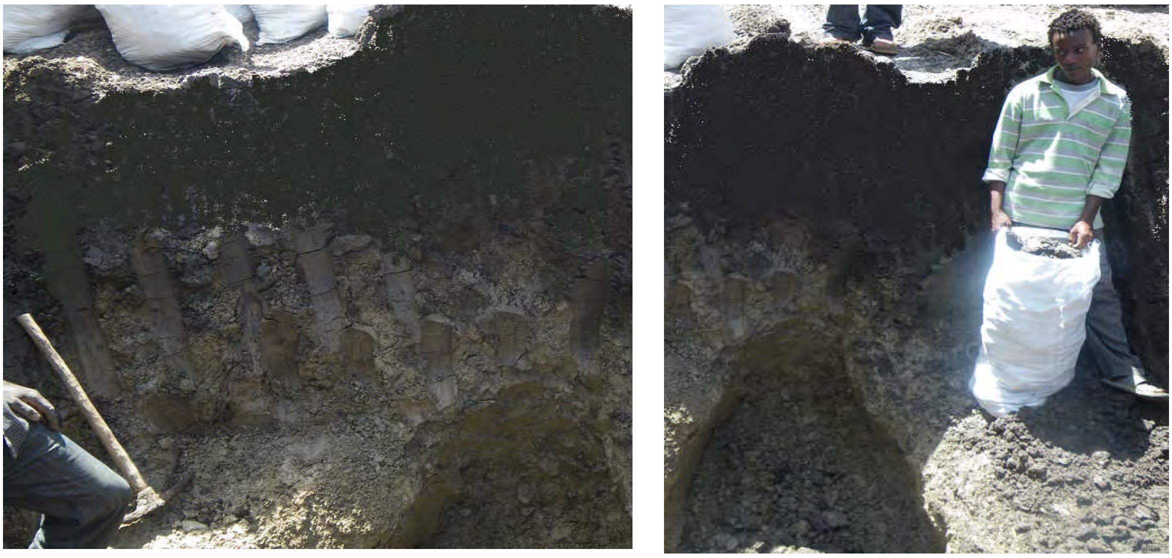


Fig 3.9 Dark gray and light gray clay soil layers observed at sampling pits

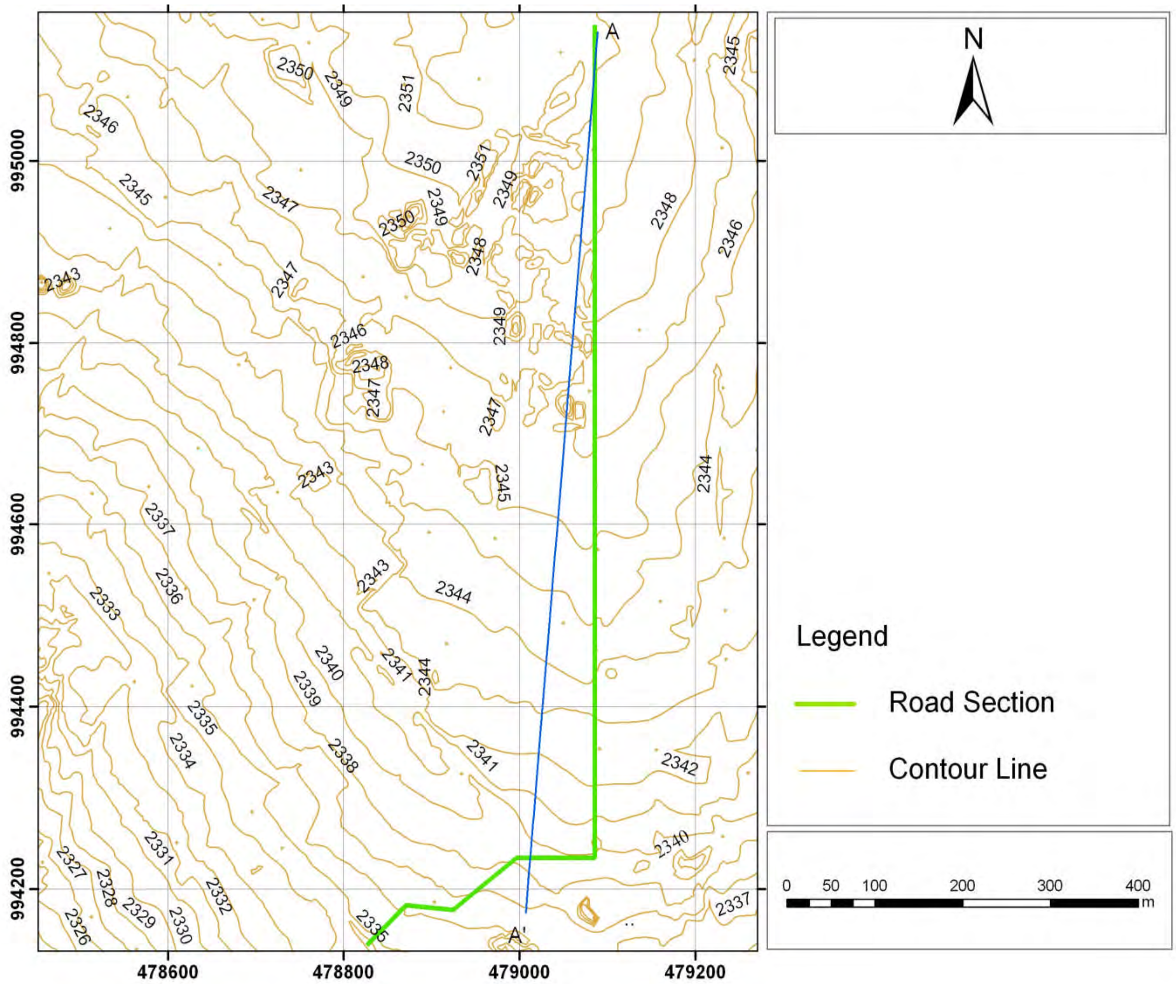


Fig. 3.10: Topographic map of the project site

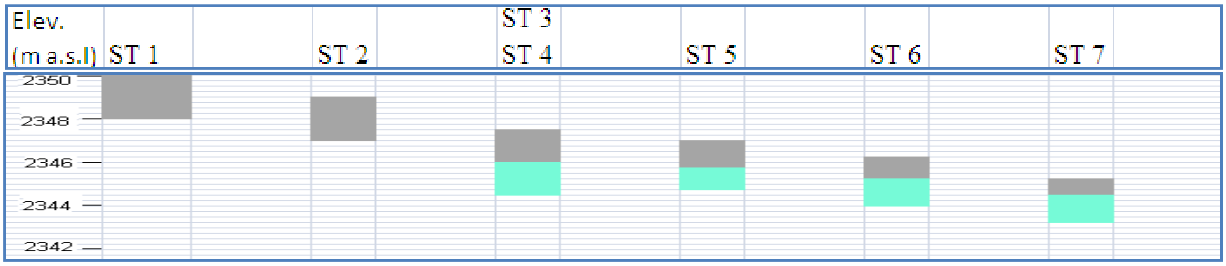


Fig 3.11 Sub-grade soil log at sampling stations along the trial road section

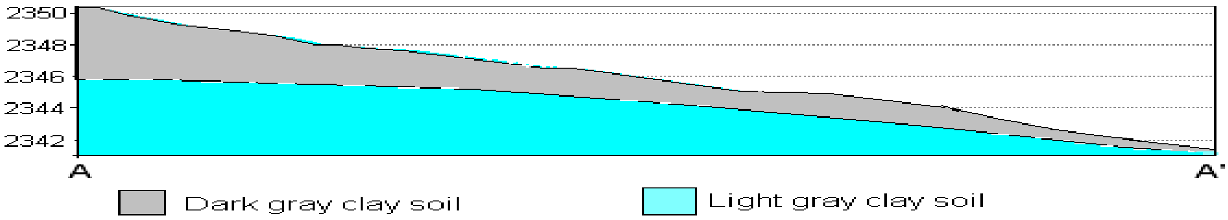


Fig 3.12 Soil profile of the project site through section A-A'

Borehole logs produced during the construction of the condominium houses in the project area shows that the thickness of the expansive soil layer in the area is about 8m. Furthermore, the ignimbrite rock is found below a depth of 8m from the ground surface (Annexure 10).

Due to the flatness of the area and impermeability of the expansive soil which results in poor drainage condition water lodging is a problem during rainy seasons of the year. The groundwater level around Imperial Hotel is about 20m below ground level and the water level fluctuation is from about 2m to 4m (Mesay Gashaw, 2008). However, at the present project site boreholes drilled to a depth of 20m doesn't struck groundwater (Annexure 10).

The project was selected to use the available resource obtained from an ongoing project such as to have an easy access and collection of soil samples and chemical agents, laboratory facility and other relevant data of the project area.

Chapter IV Characterization of Expansive Sub-grade Soil

4.1. Preamble

The stability and durability of pavements are largely dependent on the characteristics of the sub-grade underneath. In most cases soils form sub-grade of roads and usually in flat lying areas the thickness of the soil mass is considerable. This soil mass might vary from non expansive to highly expansive and when expansive soils are encountered in sub-grade it poses problems unless and otherwise proper improvement measures are not taken.

For proper treatment of expansive sub-grade soil it is important to adequately identify and understand its characteristics. Therefore, the investigation that should be conducted on such soils is a determining factor to select appropriate improvement methods and design the sub grade in a technically and economically feasible manner.

In the present study laboratory tests were conducted on natural untreated representative samples to characterize the sub-grade soil. To assist the laboratory testing and subsequent identification of the sub-grade soil, field investigation was undertaken during pitting and sampling. The field investigation included identification of soil based on observation of colour, soil texture, lithological position and thickness variations along the trial road section where the samples were collected. The laboratory tests conducted include grain size analysis, mineralogy, chemical composition, atterberg limits, linear shrinkage, moisture-density relation, CBR and percent swell of CBR. These tests were deemed enough to characterize the sub-grade soil for the present research work.

This section comprises a description of index, physico-chemical and engineering characteristics samples which were used to characterize the sub-grade soil.

4.2. Sub-grade Soil Investigation and Description

Field investigations of the sub-grade soil included field description of the soil and collection of representative soil samples at regular intervals for laboratory analysis.

Sampling of the sub-grade soil was conducted in two stages. The first stage of sampling was taken on 27/09/2010 and the second stage on 16/10/2010. The first series of samples were collected every 200m interval and within depth ranges of 1m to 2m for the purpose of classifying the sub-grade soil. Once the sub-grade soil was classified, the second series of samples were taken for characterization and detailed analysis of chemical stabilization. The second series of samples were taken based on the classification results of the sub-grade soil. The total number of samples taken during the first stage for soil classification purpose was 7. During the second stage of sampling 2 representative samples were taken one from each layer based on colour variation since all soil samples were categorized under the same class of A-7-5 (20) in AASHTO and MH in USCS soil classification systems.

During the first stage of sampling variations in colour, soil texture, lithological position, thickness of the sub-grade soil were noted and registered. This was mainly done to aid for the full understanding of the nature and type of the sub-grade soil mass. Location of sampling points is shown through Fig. 4.1.

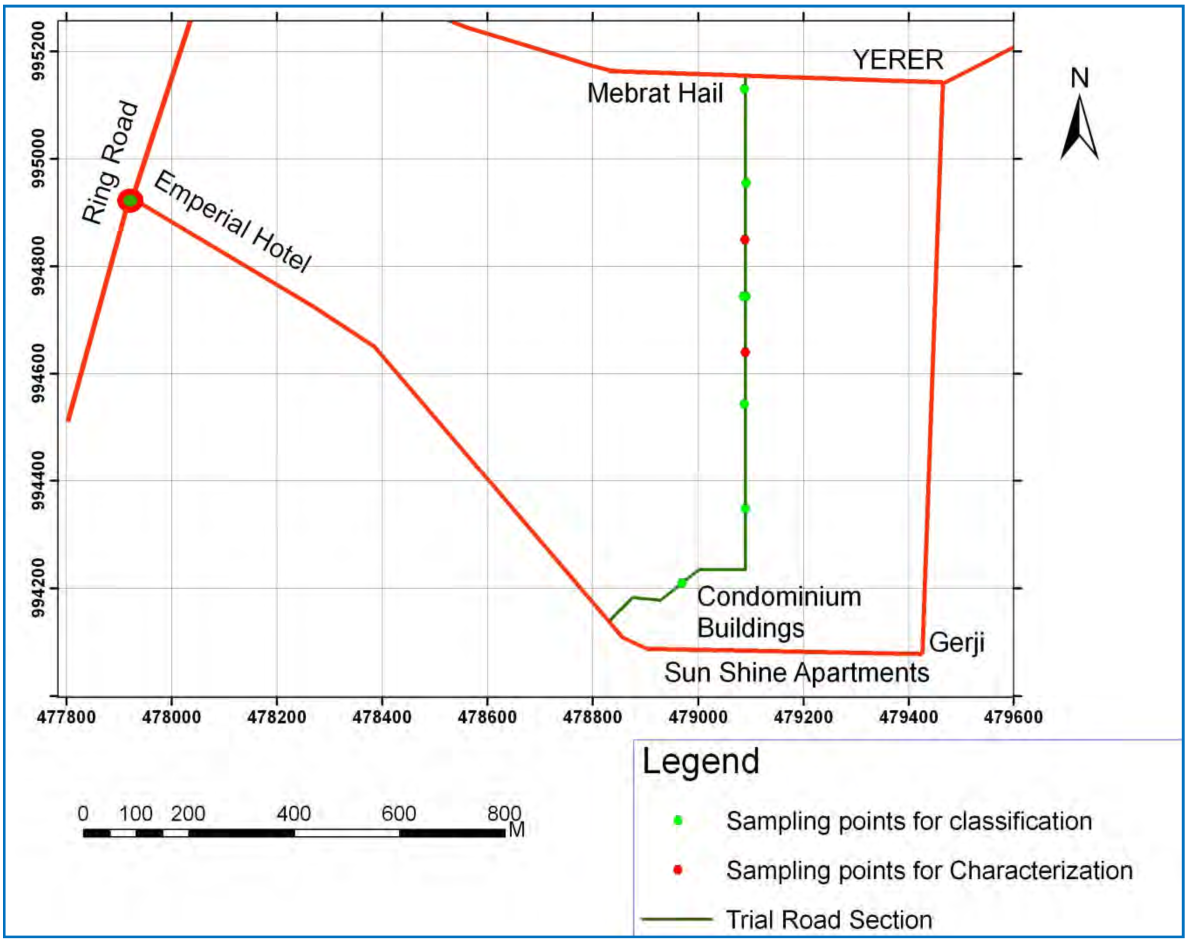


Fig. 4.1: Sampling locations for sub-grade soil classification and characterization

During the field investigation two soil layers with colour variation were observed: the upper dark grey clay soil and the lower light grey clay soil underneath. The change in colour is not sharp instead gradual. The soil mass is silty clay and feels plastic on wet condition. According to Kebede Tsehayu and Tadese Hailemariam (1990) the soil is mapped as black cotton soil (Fig. 2.7).

4.3. Laboratory Analysis of Samples

Tests for soil classification which include grain size distribution and atterberg limits tests were conducted on a total of seven samples which were collected along the road section. Further, after classifying the sub-grade soil, two representative soil samples were collected to characterize the sub-grade soil. The tests included hydrometer analysis, atterberg limits, linear shrinkage, mineralogy, chemical composition, moisture-density relation, CBR and percent swell of CBR to attain the objectives of the research.

4.4. Soil Classification

The most widely used soil classification systems for engineering purposes are American Association of State Highway and Transportation Officials (AASHTO) and Unified Soil Classification System (USCS). The AASHTO system of soil classification comprises seven groups of inorganic soils from A-l to A-7 with 12 subgroups in all. The system is based on particle-size distribution, liquid limit and plasticity index. On the other hand the Unified Soil Classification System is based on the recognition of the type and predominance of the constituents considering grain-size, gradation, plasticity and compressibility. It divides soil into three major divisions: coarse-grained soils, fine grained soils and highly organic soils. Field identification is accomplished by visual examination for the coarse-grained soils and a few simple hand tests for the fine-grained soils. In the laboratory, the grain-size curve and the Atterberg limits tests are used. The peaty soils are readily identified by color, odor, spongy feel and fibrous texture (Atkins, 2003).

4.4.1. Grain Size Distribution

Sieve analysis was carried out to determine the grain size distribution of sub-grade soil and used in the classification of the soil.

Accordingly, Wet sieve analysis was employed to determine the grain size distribution of sub-grade soil samples in accordance with AASHTO T-88 Test Method for Particle-Size Analysis of Soils. In addition hydrometer analysis was conducted for 5 samples to know the silt and clay fractions. The grain size distribution for the soil samples are presented in Table 4.1 and Fig. 4.2.

4.4.2. Atterberg Limits

The nature and response of sub-grade soils upon change to moisture content is determined by Atterberg limits test. This parameter is basic in the AASHTO and USCS soil classifications

Table 4.1: Grain Size Distribution of the Samples taken for Analysis

Sample No.	Sample Designation	Depth of sample(cm)	Description material	% passing				
				4.75	2.36	0.425	0.075	0.002
1	ST 1	140-180	Grey silty clay-Darkish	100	99.7	99.3	98.3	56.3
2	ST 2	100-150	Dark grey silty clay	100	99.2	98.4	95	57
3	ST 3	110-140	Dark grey silty clay	100	100	99.7	97.5	58.3
4	ST 4	140-180	Light grey silty clay	100	100	99.7	98.8	51.8
5	ST 5	100-120	Dark grey silty clay	100	99.4	99.3	97.5	47.5
6	ST 6	100-120	Dark silty grey clay	100	99.7	98.3	97.5	52
7	ST 7	120-160	**Grey silty clay-Darkish**	**100**	**99.8**	**99.3**	**98**	**57**

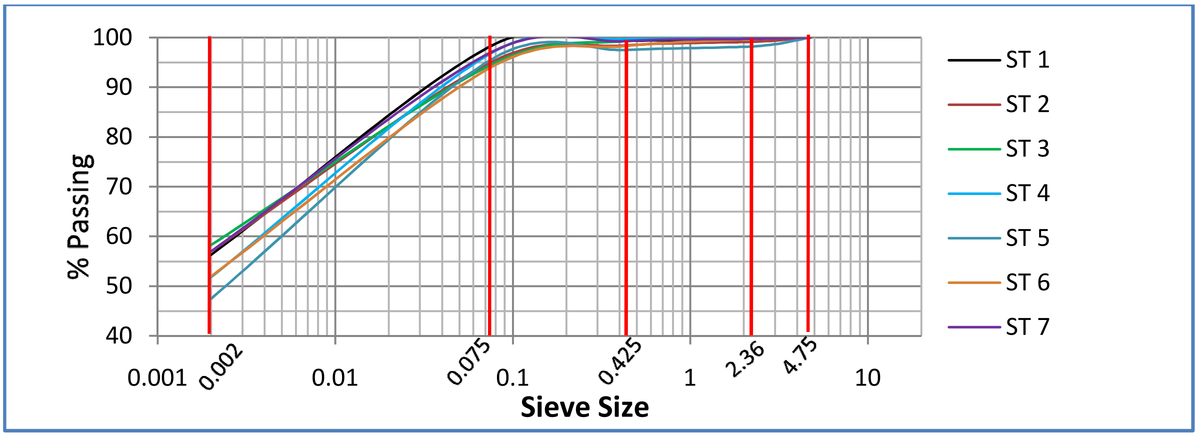


Fig 4.2: Grain Size Distribution Curves for the Soil Samples Tested

systems. The atterberg limit depends on the type of predominant clay mineral available in the soil mass. If the predominant clay is montmorillonite the liquid limit can reach or even exceed 100%. It is also expected that the Atterberg limit is less for illite dominated soil and even lesser for kaolinite dominated soils. In general, soils that exhibit plastic behavior over wide ranges of moisture content and that have high liquid limits have greater potential for swelling and shrinking (Nelson, 2010).

Group Index (GI) helps to further differentiate soils containing appreciable fine-grained materials. The GI is determined by the equation:

$$GI = (F - 35)\,[0.2 + 0.005\,(LL - 40)] + 0.01\,(F - 15)\,(PI - 10) \quad \text{………………….eq. 4.1}$$

Where; '*F*' is the percentage passing 0.075mm (No. 200) sieve expressed as a whole number. 'LL' is the liquid limit and '*PI*' is the plasticity index.

When the value is negative, the group index shall be taken as zero and when the value is greater than 20, the group index shall be reported as twenty. The group index is a means of rating the value of a soil as a sub-grade material within its own group. The higher the value of the group index, the poorer is the quality of the material within its own group. The Atterberg limits and the group index for the samples analyzed during the present study are shown in Table 4.2.

Table 4.2: Atterberg Limits and GI for the Soil Samples Tested for Soil Classification

Sample No.	Sample Designation	Depth of sampling (cm)	Description of material	Atterberg limit			GI
				LL	PL	PI	
1	ST 1	140-180	Grey silty clay-Darker	98	49	49	20
2	ST 2	100-150	Dark grey silty clay	103	52	51	20
3	ST 3	110-140	Dark grey silty clay	96	45	51	20
4	ST 4	140-180	Light grey silty clay	98	48	50	20
5	ST 5	100-120	Dark grey silty clay	99	49	50	20
6	ST 6	100-120	Dark grey silty clay	107	52	55	20
7	ST 7	120-160	Grey silty clay-Darker	95	42	45	20

Further, during the present study the samples tested for Atterberg limits were plotted over the Casagrande's plasticity chart. The perusal of results shows that all the soil samples tested are plotted below A Line (Fig. 4.3).

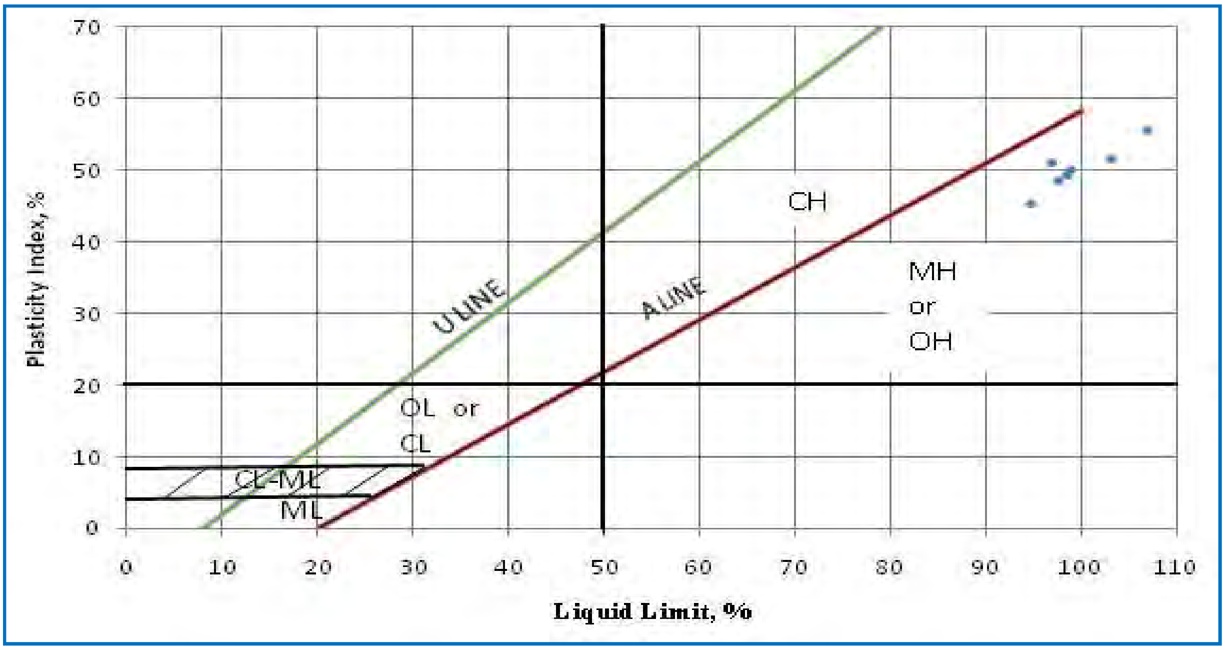


Fig 4.3: Plot of Samples on USCS Classification chart

The test results analysis in general shows that the sub-grade soil can be classified as A-7-5 (20) according to AASHTO and MH according to USCS soil classification system. The USCS classification chart under estimated the plasticity of the soil samples. For the characterization of the sub-grade soil the samples collected at the first stage of sampling for classification purpose are used as necessary in addition to the two samples collected at the second stage.

4.5. Mineralogy and Chemical Composition of Soil Samples

X-ray diffraction analysis was conducted on two selected soil samples to identify and quantitatively determine the mineralogy. The mineralogy of the samples and the corresponding proportion is indicated in Table 4.3.

Table 4.3: Mineralogy of Soil Samples for Sub-grade Based on XRD

Mineral	Light Grey Soil Sample	Dark Grey Soil Sample
Quartz low	70.2	57.7
Muscovite	3.3	13.9
Kaolinite	9.5	8.2
Microcline	17	20.2

The clay minerals were plotted on liquid limit plasticity chart (fig. 4.4)

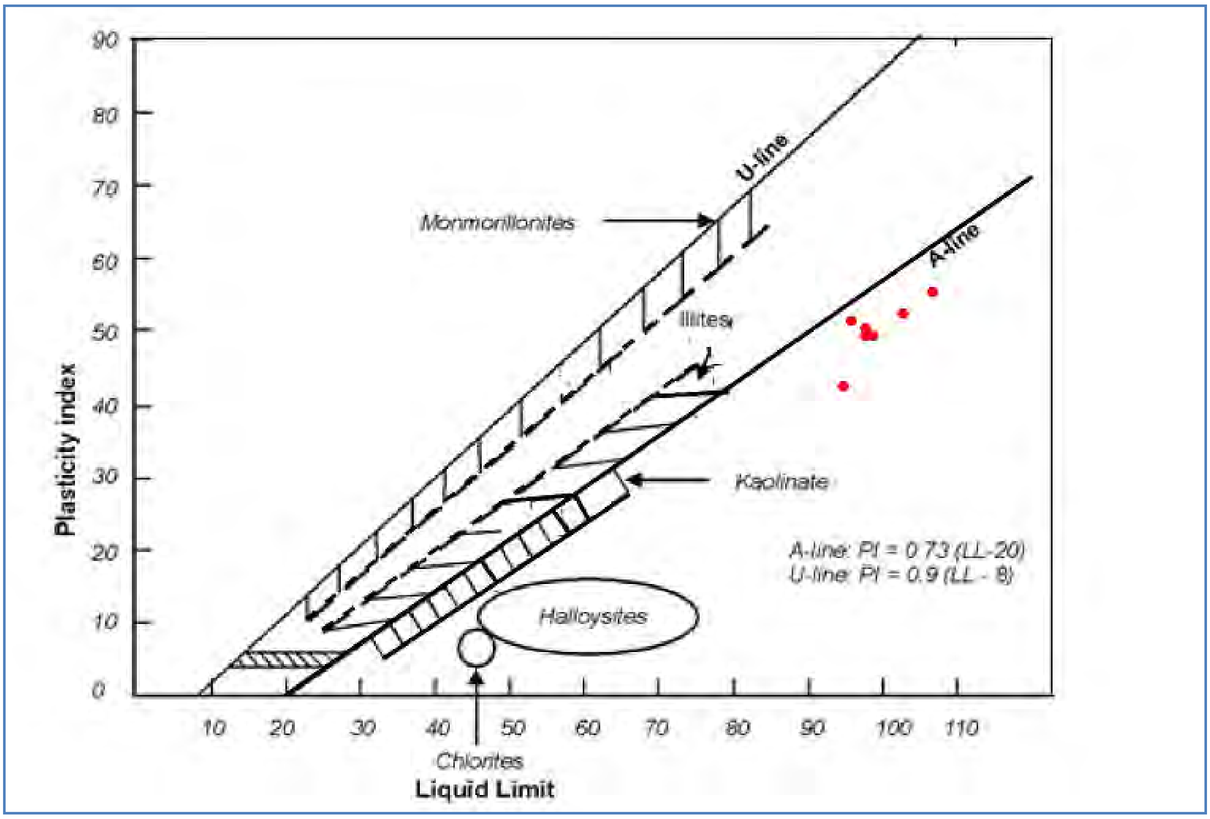


Fig 4.4: Plot of Clay Minerals on Liquid Limit Plasticity Index Chart

4.6. Potential Swell of Sub-grade Soil

One of the predominant properties of expansive soils is a measure of the potential swell and this parameter is important to classify sub-grade soils based on their degree of expansion. Potential swell can be measured either directly or indirectly.

The indirect methods involve the use of soil properties and classification schemes to estimate swell potential whereas the direct methods provide actual physical measurements of swelling (Chen, 1988).

4.6.1. Indirect Estimation of Potential Swell

Different methods have been evolved to identify expansive soils based on the percentage of clay content, shrinkage limit, plasticity index, liquid limit and shrinkage limit (Muntohar, 2006). In all the methods soils are classified into low, medium, high and very high degree of potential expansiveness (Table 4.5).

Table 4.4: Classification for degree of swelling potential (Source: Muntohar, 2006)

Degree of expansion	Chen (1983)	Seed et al. (1962)	Daksanamurthy and Raman (1973)	USBR (Holtz and Gibbs, 1956)
Very high	LL > 60	PI >35	LL > 70	CC > 28
High	40 < LL ≤ 60	20 < PI ≤ 35	50 < LL ≤ 70	20 < CC ≤ 31
Medium	30 ≤ LL ≤ 40	10 ≤ PI ≤ 20	35 < LL ≤ 50	13 ≤ CC ≤ 23
Low	LL < 30	<10	20 ≤ LL ≤ 35	CC < 13

- **Potential Swell Based on Plasticity Chart**

The plasticity chart alone, which plots plasticity index against liquid limit, helps to detect the swelling potential of soils by looking at where the soil samples fall in the chart. The swelling potential for any given plasticity index and liquid limit is indicated. For the present study, the samples tested for plasticity index were plotted on plasticity chart. As shown in Fig. 4.5 all the samples fall in the very high swelling potential region.

Holtz and Gibbs (1956) also demonstrated that the plasticity index and liquid limit are useful indices for determining the swelling characteristics of most of the clays. Soils with plasticity index that is above 35 and liquid limit greater than 70 have very high swell potential.

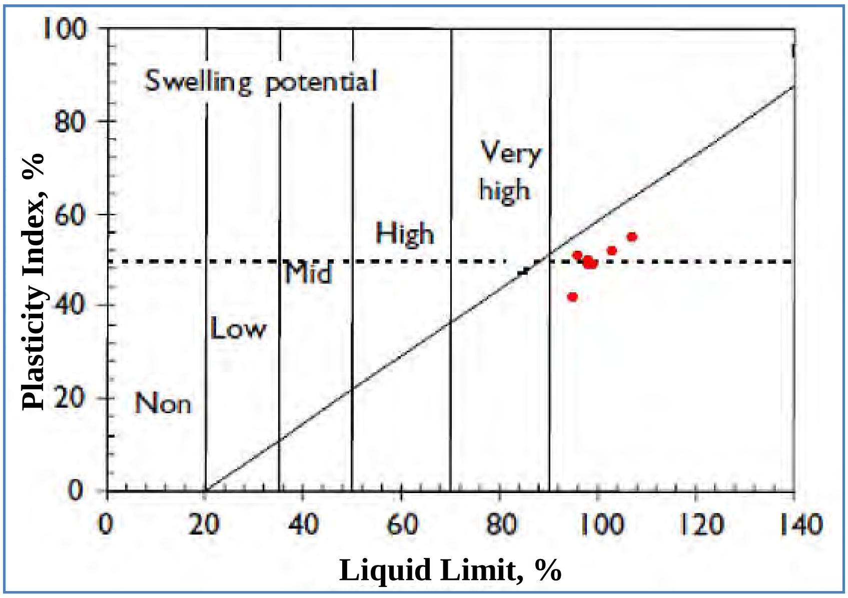


Fig 4.5 Potential Swell of Soil Samples Based on Plasticity Chart (Daksanamurthy, 1973)

- **Potential Swell Based on Clay Fraction**

Van Der Marwe (1964) used plasticity index and clay fraction to predict the potential swell of expansive soils. In his method expansiveness of soils is classified from low to very high and produced clay fraction versus plasticity chart. The sub-grade soil samples have been plotted on the Van Der Marwe's chart as seen in Fig 4.6 and found to be highly expansive.

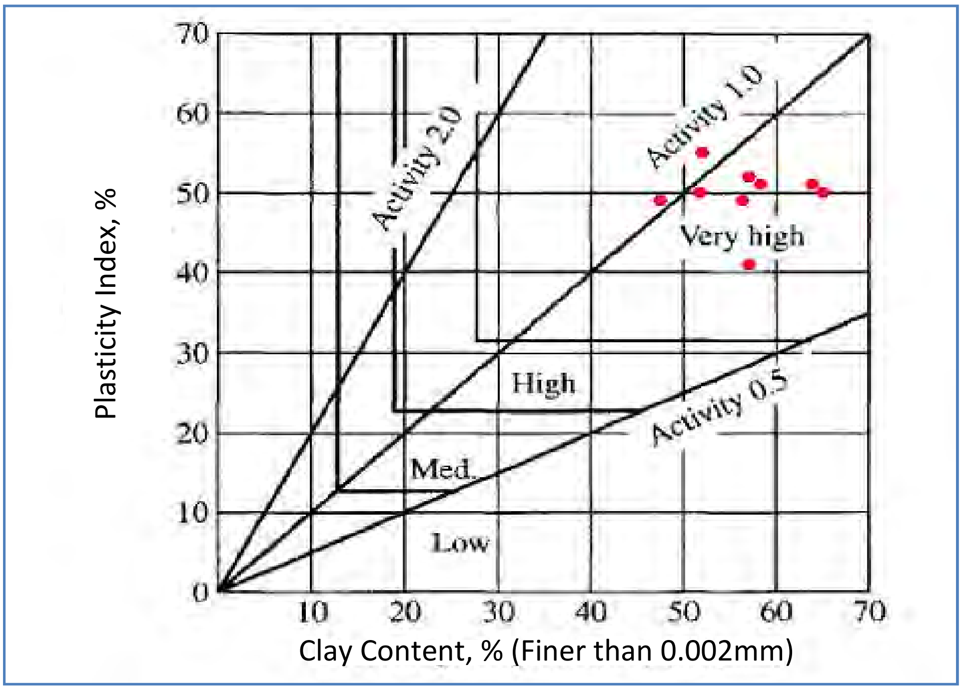


Fig 4.6 Plot using swelling potential classification chart proposed by Van Der Marwe (1964)

- **Potential Swell Based on Activity**

Seed et al (1962) proposed empirical relation that could enable to identify the swelling potential of soils and proposed a classification chart. The activity of clays is defined using the equation shown below:

$$A_C = \frac{PI}{C-5} \quad \text{...... Eq. (4.2)}$$

Where; PI is plasticity index and C is percentage of clay content finer than 0.002mm by weight.

Activity of the clay samples collected from the trial road section was calculated and plotted on clay content against activity chart as shown on Fig. 4.7. Almost all the samples are plotted to have very high swelling potential which is above 25%.

- **Estimation for Swelling Potential**

The degree of expansiveness is obtained by conducting shrinkage limit test and using the empirical relation given in the site investigation manual of Ethiopian Roads Authority, 2002 shown by eq. 4.3.

$$\epsilon_{ex} = 2.4\, w_p - 3.9\, w_s + 32.5 \quad \text{...... eq. 4.3}$$

Where; w_p is the PI x (% passing 425mm)/100 and w_s is the Shrinkage Limit x (% passing 425µm)/100

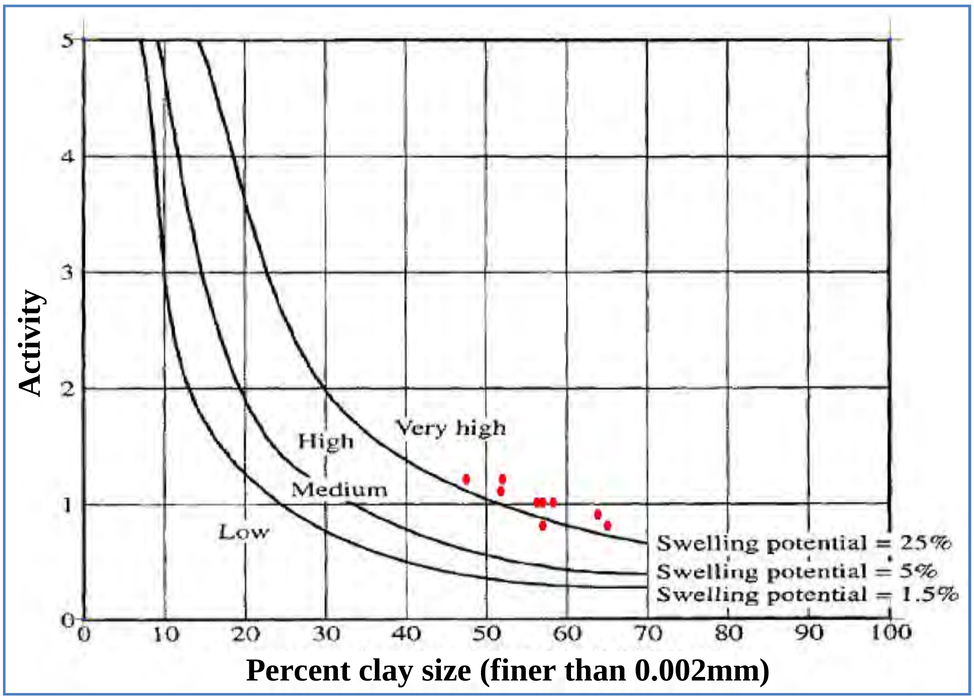


Fig 4.7: Plot of Samples Using Swelling Potential Classification Chart Proposed by Seed et al (1962)

Table 4.5: Expansive Soils Classification Based on ERA's Site Investigation Manual

Expansiveness ϵ_{ex}	**Classification**
< 20	Low
20-50	Medium
> 50	High

The expansiveness of the sub-grade soil samples tested is between 64 and 85 and according to the ERA Site Investigation Manual it lies under the high expansiveness class.

Indirect estimation of swelling potential given by Seed's model (Seed et al, 1962) is very simple and uses the plasticity index parameter only. The model is given by equations 4.4 and the category for swelling potential is shown in Table 4.7.

$$SP = 60K(PI)^{2.44} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \; eq.4.4$$

Where, SP is swelling potential, PI is plasticity index, K is a constants = 3.6×10^{-5}.

Table 4.6 Category for Swelling Potential Classification

USBR (Seed et al (1962)	**Expansiveness**
SP < 1.5	Low
1.5 ≤ SP <5	Medium
5 ≤ SP ≤ 15	High
SP > 25	Very High

As shown in Table 4.8 the estimated swelling potential according to Seed's model (Seed et al, 1962) ranges from 23 to 38 and hence in general the sub-grade soil has high expansiveness.

4.6.2. CBR Swell Tests

Readings of swelling value were taken before and after soaking of CBR for two samples and the swell percent calculated is presented in Annexure 1.

Table 4.7 Swell Potential Estimation of the Sub-grade Soil by Seed's Model

Sample No	Sample Designation	PI	SP
1	ST 1	52	33
2	ST 2	51	32
3	ST 3	53	35
4	ST 4	54	36
5	ST 5	55	38
6	ST 6	49	29
7	ST 7	45	23
8	Light Gray Clay	50	31
9	Dark Gray Clay	52	33

The results showed that the percent swell of CBR ranges between 10% and 11% with 10, 30 and 65 blows which is comparable to values obtained from laboratory tests of expansive soils found in different parts of Ethiopia (Annexure 5). The value is well above the permissible limit of 2%. Furthermore, the CBR swell shows irregularity; however, in general terms it increases with increased compaction efforts.

4.7. Moisture Density Relations of the Sub-grade Soil

Proctor tests were conducted on sub-grade soils of the trial road section to determine the relationship between the moisture content and dry density for a specific compaction effort. Modified compaction according to AASHTO T180 was applied and the results are annexed (Annexure 1).

The optimum moisture content is 28.5% and 31% and the maximum dry density is 1.42gm/cm^3 and 1.44gm/cm^3 for the dark grey clay soil and light grey clay soil, respectively. The result showed that the dark grey clay soil has slightly lower OMC and MDD than the light grey clay soil.

4.8. California Bearing Ratio (CBR)

Strength of the sub-grade soil along the trial road section has also been determined. A three point CBR test at 10, 30 and 65 blows were conducted according to AASHTO T193 and the CBR values at 95% MDD was determined (Annexure 1). The test result showed that the sub-grade soil has very low CBR value of 1% which does not satisfy the minimum requirements as sub-grade material.

4.9. Overall Characterization of sub-grade

The grain size analysis of the sub-grade soil samples shows that it has 1-3% sand, 28-35% silt and 47-65% clay. The sub-grade soil has found to be highly expansive with plasticity index varying between 45 to 55%. Therefore, these soils can be classified as A-7-5 in the AASHTO and MH in the USCS soil classification systems.

All the indirect methods and empirical relations as well as the percent swell test showed that the sub-grade soil is highly expansive. Such high expansivity of fine grained sub-grade soils are expected to be dominated by montimorillonite clay minerals. However, the XRD test result showed no significant montimorillonite clay mineral instead the less expansive kaolinite mineral is available. Muscovite which has similar expansiveness as illite is significantly made a proportion in the soil samples (Annexure 4 and 5).

The sub-grade soil has very low load bearing capacity in the order of 1% and very high swelling potential beyond the permissible limits. Such soils are potentially problematic and results in series damages to pavements constructed on them without appropriate treatment measures. Therefore, appropriate treatment methods should be conducted before any pavement structure is constructed over such poor sub-grade soils. The next chapter presents one of the treatment methods of expansive soils namely chemical stabilization which is based on laboratory test result.

Chapter V Chemical Stabilization of Sub-grade Soil

5.1. Preamble

Lime and cement are commonly used chemical additives for stabilization of expansive sub-grade soils. Lime is used to stabilize fine grained soils where as cement is effective for granular materials (Little and Nair, 2009). In the present study two chemical stabilizers namely a locally manufactured hydrated lime and imported cement based industrial product ANSS were used for the stabilization of the sub-grade soil. Laboratory tests were conducted on hydrated lime-soil and ANSS-soil mixtures to evaluate the performance of these chemical additives on the sub-grade soils at varying proportions and with different curing periods.

The initial lime consumption was determined according to ASTM D6276-99a (1999) also known as "Eades and Grim" test. Laboratory tests with hydrated lime proportions of 2%, 4%, 6% and 8% with 7, 14 and 28 days of curing periods were conducted. However, the proportion for ANSS was determined according to the information obtained from user guideline prepared by the supplier (Anyway Company Ltd, 2003). According to the guideline the standard methods, as suggested by ASTM, AASHTO, British Standard (BS) and standard specifications and test methods can be utilized. Accordingly, based on the guideline and the supplier experience ANSS proportions of 2%, 4% and 6% with 7, 14 and 28 days of curing periods were considered.

The performance of the locally manufactured hydrated lime and imported chemical powder ANSS on the expansive sub-grade soil under investigation was evaluated based on test results of atterberg limits (liquid limit, plastic limit and plasticity index), linear shrinkage, moisture-density relation of the sub-grade soil, CBR and percent swell of CBR.

5.2. Chemicals Used for Expansive Soil Stabilization

Literature shows that lime and cement are commonly used stabilizers worldwide (Chen, 1988; Little and Nair, 2009; McKeen, 1976). Currently, many stabilizing agents are available in the market which can be lime based, cement based, enzyme based or a combination of lime and cement as a main constituent.

According to Little and Nair (2009) chemical stabilizers are classified as traditional stabilizers such as hydrated lime, portland cement and fly ash; non-traditional stabilizers comprised of sulfonated oils, ammonium chloride, enzymes, polymers and potassium compounds; and by-product stabilizers which include cement kiln dust, lime kiln dust etc.

The traditional chemical stabilizers are widely used and in some cases a combination of lime, cement and fly ash is used for better result and economic stabilization. In general the effectiveness of the stabilizers as described by Little and Nair (2009) depends on:

- Soil consistency and gradation
- Soil mineralogy and composition
- Desired engineering properties
- Purpose of treatment
- Mechanisms of stabilization
- Environmental conditions and engineering economics.

5.3. Chemical Stabilizing Agent Selection

Chemical stabilization effects are site specific and require integration of standard test methods, analysis procedures and design steps to develop acceptable solutions. Chemical stabilizer interactions and the extent of improvement in soil properties vary with soil type. Hence developing a common procedure applicable for all types of stabilizers is not practical (Little and Nair, 2009).

A range of options are available for selecting soil stabilizer agents most of which are based on the soil classification following either the AASHTO or Unified soil classification system. A simple and currently accepted method of stabilizer selection is based on soil index properties; plasticity index and percent passing the no. 200 sieve (Little and Nair, 2009). Once the stabilizer agent is selected, detailed laboratory tests to determine strength and performance characteristics of soils are required.

5.4. Soil Sample Selection

For the present study the sub-grade soil was first classified based on samples collected from the trial road section with sampling interval of 200m and depth variation from 1m to 2m. The results showed that the sub-grade soil is homogeneous along the trial road section and with depth and classified within the same A-7-5 (20) on the AASHTO and MH on the USCS soil classification systems (Refer Tables 4.1 and 4.2 and figure 4.1). Two representative soil samples along the road section from different depths were hence collected to evaluate the effects of a locally manufactured hydrated lime and an imported chemical ANSS on such expansive sub-grade soil.

The percent pass 75µm sieve, plasticity index and classification of the two representative samples of the sub-grade soil under investigation are shown in Table 5.1.

Table 5.1 Percent pass 75µm, plasticity index and classification of the selected soil samples

Soil Sample	Depth, m	% pass no. 200 (75µm) sieve						Atterberg Limits			Classification	
		4.75	2.00	0.425	0.075	0.002	0.001	LL	PL	PI	AASHTO	USCS
Light Gray Clay	1.50-2.00	100	99.9	99.8	98.3	65.2	59.6	98	48	50	A-7-5(20)	MH
Dark Gray Clay	1.00-1.50	100	99.9	99.4	98.2	62.9	58.5	97	45	52	A-7-5(20)	MH

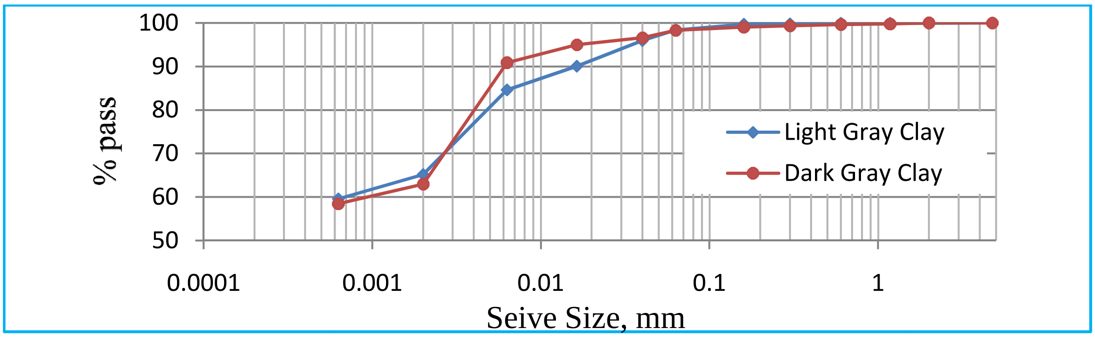


Fig 5.1: Grain size distribution curves for the soil samples tested

5.5. Properties of the Sub-grade Soil and Chemical Additives

Key characteristics were evaluated to determine the suitability of the sub-grade soil for stabilization with hydrated lime and ANSS. The suitability of hydrated lime is determined by the proportion of soil passing 75μm sieve and the plasticity of the soil. However, according to information obtained from a document prepared by the supplier the chemical composition of ANSS is formulated to be used for any type of soil ranging from fine grained to granular material (Anyway Company Ltd., 2003).

To evaluate the suitability of hydrated lime to stabilize the sub-grade soil AASHTO T27-99 (1999) and AASHTO T90 (1999) procedures were used. The tests showed that more than 25% pass 75μm sieve and the PI is greater than 10 and, therefore, hydrated lime is suitable to stabilize the sub-grade soil under investigation.

The physical, mineralogy and chemical composition of soils also affects the effectiveness of chemical stabilizers (Little and Nair, 2009). Laboratory analyses were, hence, conducted to determine the physical properties and mineralogy of the sub-grade soil samples and chemical composition of the soil samples and chemical additives.

The mineralogy of the natural soil samples were determined using X-ray powder diffraction technique at the Central Laboratory of Ministry of Mines and Energy. Soil mineralogy provides the basis for understanding the basic mechanisms of chemical stabilization. It also helps to identify the types of clay minerals in the soils in order to determine the ability of the soils to expand (Chittoori, 2008; Pedarla, 2009). The physical properties and mineralogy of the soil samples are presented in Table 5.2. (see also annexure 4 and 5)

Table 5.2 Physical properties and mineralogy of the soil samples

Physical Property	Light Gray Soil	Dark Grey Soil	Remark
Specific gravity	2.40	2.30	Tests conducted by Ministry of Mines and Energy Central Laboratory
Mineralogy			
• % Quartz low	70.2	57.7	
• % Muscovite	3.3	13.9	
• % Kaolinite	9.5	8.2	
• % Microcline	17	20.2	
Gradation			
• % Sand	1.20	1.60	
• % Silt	33.62	35.45	
• % Clay	65.18	62.95	
Colloid Content	> 59.56	> 58.49	
PH	7.44	6.8	
Modified Proctor Compaction Properties			
• OMC (%)	31	28.5	
• MDD (g/cm^3)	1.44	1.42	
Soil Classification			
• AASHTO	A-7-5	A-7-5	
• USCS	MH	MH	

X-ray fluorescence analysis was also conducted to determine the chemical composition of both natural sub-grade soil and chemical additives. Chemical composition of the natural sub-grade soil, hydrated lime and ANSS is shown in Table 5.3 (see also Annexure 6).

Table 5.3 Chemical composition of soil samples and chemical additives (laboratory test: Ministry of Mines and Energy Central Laboratory)

Mineral	Light grey clay soil	Dark grey clay soil	ANSS	Hydrated Lime
SiO_2	50.87	49.68	10.51	6.21
Al_2O_3	13.77	13.38	2.58	2.18
Fe_2O_3	10.89	11.56	1.82	3.57
CaO	1.57	1.49	35.47	59.47
MgO	1.68	1.70	2.12	3.91
Na_2O	0.29	0.28	0.25	0.61
K_2O	1.39	1.24	0.82	0.79
TiO_2	1.8159	1.5266	0.1717	0.3286
P_2O_5	0.045	0.047	0.118	0.208
MnO	0.1412	0.1536	0.0315	0.2785
SO_3	0.04	0.07	30.47	0.58

The chemical composition of the soil samples has slight differences. The proportion of SiO_2 and Al_2O_3 is a little more in the light gray clay soil where as Fe_2O_3 and MgO is more in the dark gray clay soil. Furthermore, the chemical analysis result shows that the concentration of SO_3 and MgO are well below 3% each and therefore are suitable for lime stabilization.

5.6. Initial Chemical Consumption Determination

Substantial long-term pozzolanic reaction for both hydrated lime and ANSS treated soil occur at higher PH conditions. Particularly for hydrated lime a PH of 12.4 is required to solubilize silicates and aluminates from the clay matrix and fine silt soil.

During the present study the initial consumption of lime was determined according to ASTM D6276 (Eades and Grim test).

However, the supplier of the chemical ANSS has not set any preliminary test which helps in determining the initial consumption. According to Anyway Company Ltd. (2003), the supplier of ANSS product, the stabilizer content required to produce a mixture conforming to specific index and engineering properties is determined by trial and previous experiences. Soil samples are prepared at three different stabilizer contents in increments of two percent by mass and tested for the parameters; atterberg limits, linear shrinkage, CBR and percent swell of CBR.

The PH test result provided the initial lime consumption for stabilization and was estimated to be 3.5% for both the dark grey clay soil and light grey clay soil. The dosages obtained by PH test have been checked by tests which include Atterberg limits, linear shrinkage, CBR and percent swell of CBR by applying hydrated lime proportions of 2%, 4%, 6% and 8%.

5.7. Test Results of Treated Soil Samples

During the present study tests were conducted to evaluate the improvements in plasticity index, linear shrinkage, moisture density relation, CBR and percent swell of sub-grade soil treated with lime and ANSS. The samples were prepared according to AASHTO T87-86(2000) standard procedure.

The soil samples were first air dried and properly pulverized. Atterberg limits and linear shrinkage tests were conducted on soil samples passing no 40 sieve where as other tests were conducted on soil samples passing no 4 sieve.

5.7.1. Moisture Density Relation

Air dried and pulverized soil passing no 4 sieve was used to determine moisture-density relation of the soil mixed with varying proportions of the chemical additives. The soil was mixed with ratios of 2%, 4%, 6% and 8% of hydrated lime and 2%, 4% and 6% of ANSS.

Further, modified proctor test was carried out according to AASHTO T180-97. Moisture content versus dry density graph was produced and optimum moisture content (OMC) and maximum dry density (MDD) were determined from the graph. The test results are shown in Table 5.4.

Table 5.4 Moisture density relation test result of hydrated lime and ANSS treated soil

Soil Type	Parameter	Natural Soil	Lime Treated Soil				ANSS Treated Soil		
			2%	4%	6%	8%	2%	4%	6%
Light Gray Soil	OMC, %	31	30	29	26	28	28.5	29	29
	MDD, g/ cm^3	1.44	1.45	1.47	1.48	1.44	1.43	1.44	1.5
Dark Gray Soil	OMC, %	28.5	28	27	27	23	27	26.5	26
	MDD, g/ cm^3	1.42	1.42	1.46	1.47	1.44	1.45	1.46	1.47

The addition of chemical stabilizers results in a slight change in the optimum moisture content and maximum dry density of the sub-grade soils. As observed from Table 5.4 in both soil samples the OMC has decreased where as that of the MDD has increased. The curves show the physical changes that occur during hydrated lime and ANSS treatment.

5.7.2. Atterberg Limits Tests

One of the important and principle aims of the present study was to evaluate the changes of liquid limits, plastic limits and plasticity index with addition of hydrated lime and ANSS to the selected soil samples. To achieve this objective, liquid limit and plastic limit tests were conducted on hydrated lime-soil and ANSS-soil mixtures according to consistency test of AASHTO T89 and T90, respectively.

Soil samples were first air dried and pulverized and then sieved with no 40 sieve. Soil passing no 40 sieve was mixed with different proportion of chemical additives at optimum moisture content and kept for curing packed in plastic bags to protect loss of moisture. The proportion of hydrated lime used was 2%, 4%, 6% and 8% and that of ANSS was 2%, 4% and 6%. The atterberg limits tests of hydrated lime-soil and ANSS-soil mixtures were determined after 7, 14 and 28 days of curing to estimate the influence of time on atterberg limit values. The test results of atterberg limits for hydrated lime and ANSS treated soil are presented in Table 5.5 and Table 5.6.

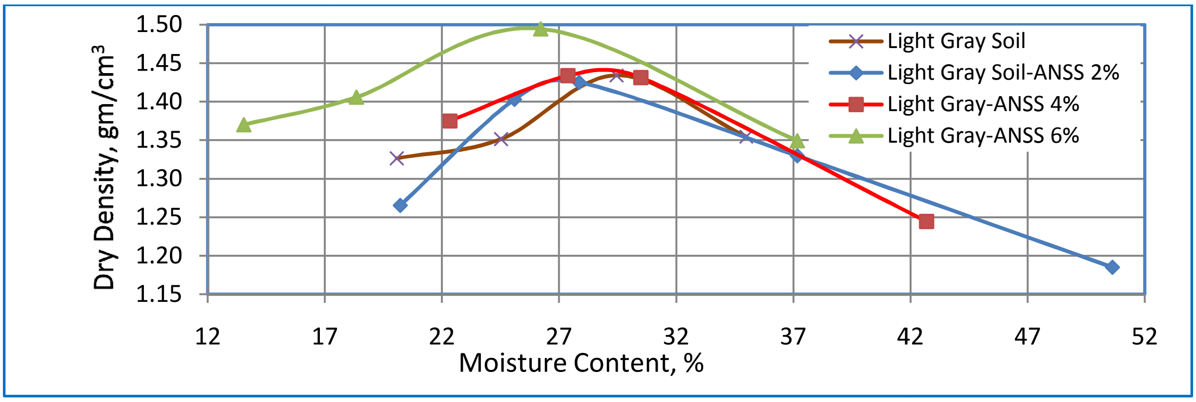


Fig. 5.2 Moisture density relation test result of ANSS treated light gray clay Soil

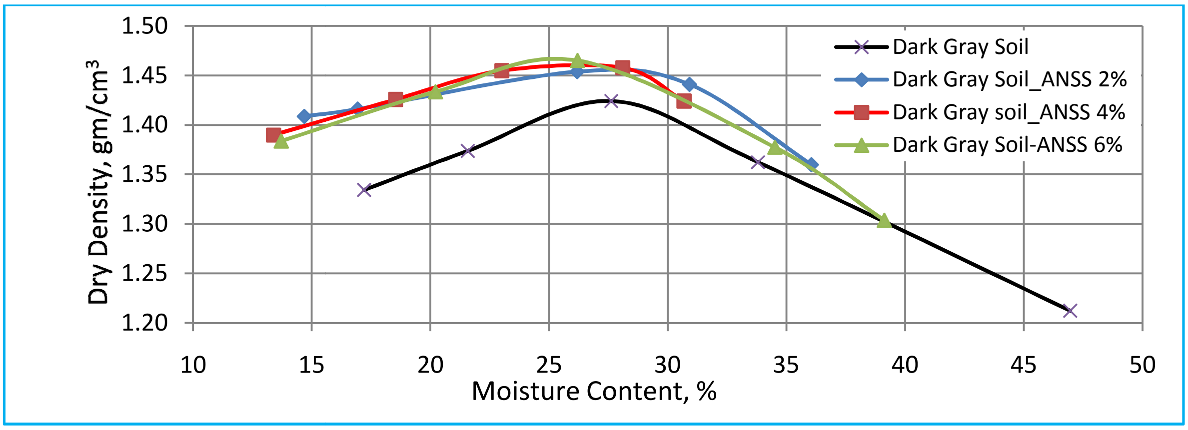


Fig. 5.3 Moisture density relation test result of ANSS treated dark gray clay soil

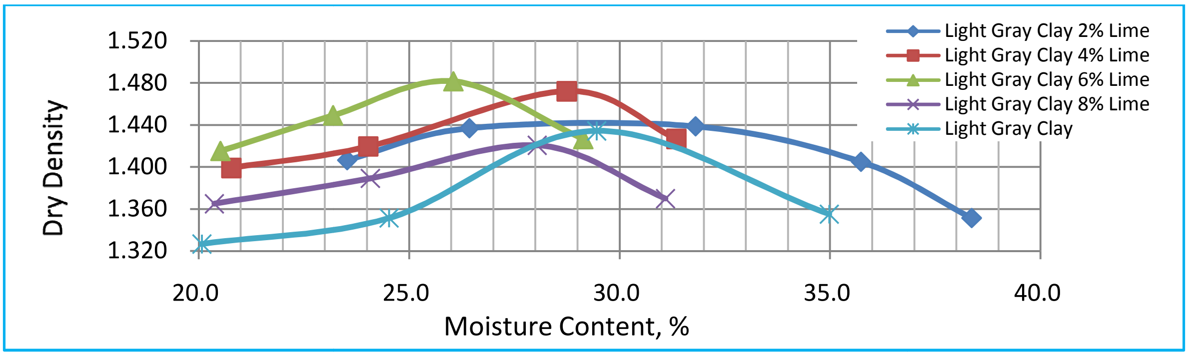


Fig. 5.4 Moisture density relation test result of hydrated lime treated light gray clay soil

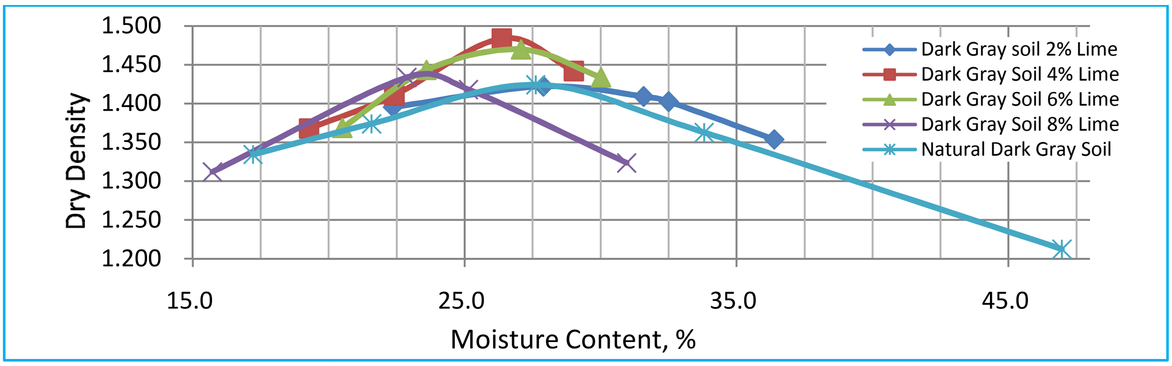


Fig. 5.5 Moisture density relation test result of hydrated lime treated dark gray clay soil

Table 5.5 Atterberg limits test result of hydrated lime treated soil

Soil Type	Curing Period	2%			4%			6%			8%		
		LL	PL	PI	LL	PL	PI	LL	PL	PI	LL	PL	PI
Light Gray Soil	7 days	79	51	28	76	52	24	69	53	16	69	51	18
	14 days	75	49	26	71	53	18	68	59	9	-	-	-
	28 days	-	-	-	-	-	-	69	50	19	-	-	-
Dark Gray Soil	7 days	75	48	27	67	50	17	63	48	15	60	48	12
	14 days	68	52	16	63	44	19	61	47	14	-	-	-
	28 days	-	-	-	-	-	-	62	46	16	-	-	-

From the perusal of Table 5.5 and 5.6, in both hydrated lime-soil and ANSS-soil mixtures, the following observations have been made:

- The liquid limits decrease with increasing hydrated lime and ANSS proportions. Also, liquid limit decreases with increased curing periods.
- The plastic limit increase with increasing hydrated lime and ANSS proportions. The same also happened with increased curing periods.
- The plasticity index decreases with increasing hydrated lime and ANSS proportions. Also it decreases with increasing curing periods.
- Increasing the proportion of the chemicals has more effect than that of increased curing periods on changing the atterberg limits.

Table 5.6 Atterberg limits test result of ANSS treated soil

Soil Type	Curing Period	2%			4%			6%		
		LL	PL	PI	LL	PL	PI	LL	PL	PI
Light Gray Soil	7 days	81	47	34	75	53	22	73	54	19
	14 days	81	50	31	74	54	20	73	55	18
	28 days	-	-	-	-	-	-	72	56	16
Dark Gray Soil	7 days	79	47	32	72	52	20	70	54	16
	14 days	79	48	31	71	53	18	69	54	15
	28 days	-	-	-	-	-	-	68	55	13

5.7.3. Linear Shrinkage

Linear shrinkage tests of the hydrated lime-soil and ANSS-soil mixtures were conducted according to AASHTO T92-97(2000). The sample preparation, proportion of chemical additives used and curing periods were similar to that of atterberg limits test and the test results are presented in Table 5.7.

From table 5.7 in both hydrated lime-soil and ANSS-soil mixtures the following observations have been made:

- The linear shrinkage decreases with increasing hydrated lime and ANSS proportions, also similar effect was observed with prolonged curing periods.

- Increasing the proportion of the chemicals has more effect on changing the linear shrinkage than prolonged curing periods particularly to hydrated lime treated soils.

Table 5.7 Linear shrinkage test result of hydrated lime and ANSS treated soil

Soil Type	Curing Period	Natural Soil	Hydrated Lime Treated Soil				ANSS Treated Soil		
			2%	4%	6%	8%	2%	4%	6%
Light Gray Soil	7 days	22	21	14	11	9	20.7	18.2	13.9
	14 days		23	14	10	-	15	10.7	10.7
	28 days		-	-	13	-	`-	-	10
Dark Gray Soil	7 days	20	19	14	9	7	20.7	18.6	13.9
	14 days		20	14	11	-	13.6	10	9.6
	28 days		-	-	9	-	-	-	8.6

5.7.4. California Bearing Ratio (CBR)

Air dried and pulverized soil passing no 4 sieve was mixed with the chemical additives at optimum moisture content and compacted in CBR molds at maximum dry density. The hydrated lime-soil and ANSS-soil mixtures were kept compacted in CBR molds for 7, 14 and 28 days of curing periods to estimate the influence of time on CBR value. CBR tests were conducted after the curing periods at the worst condition soaked for 96hrs. The CBR test results are shown in Table 5.8.

Table 5.8 CBR test result of hydrated lime and ANSS treated soil

Soil Type	Curing Period	Natural Soil	Hydrated Lime Treated Soil				ANSS Treated Soil		
			2%	4%	6%	8%	2%	4%	6%
Light Gray Soil	7 days	1	3	37	38	82	2	12	18
	14 days		4	39	70	-	3	14	19
	28 days		-	-	38	-	-	-	21
Dark Gray Soil	7 days	1	3	35	58	73	3	21	37
	14 days		4	38	98	-	4	24	40
	28 days		-	-	74	-	-	-	47

From the Table 5.8 in both hydrated lime-soil and ANSS-soil mixtures the following observations have been made:

- The CBR increases with increasing hydrated lime and ANSS proportions and with prolonged curing periods
- Increasing the proportion of the chemicals has more effect on changing the CBR than prolonged curing periods. However, in both soil samples 6% hydrated lime cure for 14 days provide very high CBR value.
- The effect of ANSS on CBR is more on the dark grey clay soil than that of the light grey clay soil where as hydrated lime provide comparable results.

- The effect of hydrated lime on CBR of the sub-grade soil samples is better than that of ANSS
- A decrease in CBR for 28 days of curing period is observed

5.7.5. Percent Swell of CBR

The hydrated lime-soil and ANSS-soil mixtures compacted in CBR molds at optimum moisture content with maximum dry density were gauged for swelling characteristics before and after soaking to evaluate the percent swell. The test helps to evaluate the change in volume of the sub-grade soil after treatment with the chemical additives at different ratios and with varying curing periods when exposed to moisture (Table 5.9).

Table 5.9 Percent swell of CBR test result of hydrated lime and ANSS treated soil

Sample	No of Blows	Natural Soil		Curing Period	Lime Treated								ANSS Treated					
					2%		4%		6%		8%		2%		4%		6%	
		Dry Density g/cc	% Swell		Dry Density g/cc	% Swell	Dry Density g/cc	% Swell	Dry Density g/cc	% Swell	Dry Density g/cc	% Swell	Dry Density g/cc	% Swell	Dry Density g/cc	% Swell	Dry Density g/cc	% Swell
Light Gray Soil	10	1.24	10.53	7 Days	1.216	1.28	1.315	0.08	1.311	0.05	1.247	0.08	1.160	10.18	1.270	1.63	1.160	1.95
	30	1.30	10.39		1.342	1.27	1.381	0.02	1.389	0.03	1.323	0.03	1.310	7.56	1.340	0.83	1.400	1.89
	65	1.44	10.65		1.412	9.90	1.468	0.00	1.461	0.01	1.442	0.02	1.450	5.26	1.440	0.35	1.500	1.69
	10			14Days	1.162	0.08	1.285	0.23	1.300	0.27	-	-	1.240	9.27	1.210	1.61	1.160	1.34
	30				1.368	0.08	1.327	0.21	1.376	0.15	-	-	1.360	7.34	1.360	1.38	1.320	1.42
	65				1.472	0.06	1.444	0.15	1.442	0.12	-	-	1.460	5.52	1.440	0.46	1.500	0.98
	10			28Days	-	-	-	-	1.296	0.19	-	-	-	-	-	-	1.160	1.55
	30				-	-	-	-	1.374	0.17	-	-	-	-	-	-	1.320	0.71
	65				-	-	-	-	1.494	0.14	-	-	-	-	-	-	1.500	0.23
Dark Gray Soil	10	1.25	10.84	7 Days	1.205	0.70	1.304	0.04	1.292	0.05	1.251	0.05	1.160	5.61	1.080	1.58	1.110	1.01
	30	1.33	10.90		1.340	1.02	1.375	0.03	1.378	0.03	1.305	0.04	1.310	4.91	1.310	1.26	1.290	0.45
	65	1.42	10.11		1.454	10.0	1.469	0.01	1.478	0.02	1.435	0.03	1.480	3.40	1.460	1.05	1.470	0.09
	10			14Days	1.028	0.25	1.306	0.82	1.280	0.25	-	-	1.270	8.34	1.240	1.26	1.180	1.32
	30				1.156	0.08	1.383	0.67	1.325	0.16	-	-	1.340	6.37	1.360	1.68	1.320	1.17
	65				1.173	0.08	1.486	0.18	1.432	0.01	-	-	1.470	4.57	1.460	0.38	1.470	0.61
	10			28Days	-	-			1.270	0.36	-	-	-	-	-	-	1.160	0.12
	30				-	-			1.320	0.40	-	-	-	-	-	-	1.230	0.07
	65				-	-			1.430	0.28	-	-	-	-	-	-	1.470	0.05

From Table 5.9 in both hydrated lime-soil and ANSS-soil mixtures the following observations have been made:

- The addition of hydrated lime and ANSS on the sub-grade soils has improved the percent swell considerably.
- The decrease in percent swell of CBR does not show regular pattern with increasing proportion of either hydrated lime or ANSS
- The swell percent is observed to decrease with increasing compaction effort with the same proportion of the chemicals

5.7 Overall Effect of Chemical Stabilization on Sub-grade Soils

The chemical stabilizers, hydrated lime and ANSS, have significantly changed the properties of the sub-grade soil. The changes attained due to different dosages of the chemical additives and the length of the curing periods was observed to vary accordingly. This fact proves that both proportion variation and length of curing periods have impact on the effectiveness of the chemicals to stabilize the sub-grade soil. In most of the cases, however, the effect of proportion of the chemical additives is more significant than that of the length of the curing periods.

The addition of 2% of either hydrated lime or ANSS to the sub-grade soil sample has not brought about significant improvement. However a proportion of at least 4% has changed the engineering property of the sub-grade soil to a greater extent. This has been shown by the improvements of atterberg limits, linear shrinkage, CBR and percent swell of CBR of the soil samples.

In most of the parameters tested the improvement of the sub-grade soil attained by the addition of hydrated lime is better than that of the ANSS. In addition, in almost all of the parameters the improvement of the dark gray soil is higher than that of the light gray soil with addition of either of the chemical additives.

Chapter VI Interpretation and Discussion

6.1. Preamble

Expansive sub-grade soils can be improved by several methods. Among those methods chemical stabilization is one alternative being applied throughout the world. Furthermore, the traditional stabilizers lime and cement in particular are commonly used to improve such expansive sub-grade soils (McKeen, 1976; Chen, 1988; Little and Nair, 2009). In the present study hydrated lime and an industry product ANSS were used to stabilize highly expansive sub-grade soil samples collected from the trial road section in Gerji Area of Addis Ababa.

The sub-grade soil was characterized using soil samples collected every 200m interval by considering the laboratory tests of grain size analysis, mineralogy, Atterberg limits, linear shrinkage, CBR and percent swell of CBR.

Laboratory tests have also been conducted on two representative samples to evaluate the improvement of the sub-grade soil with addition of different proportion of the chemical additives hydrated lime and ANSS. Further, the improvement of the sub-grade soil was also assessed with varying curing periods. The present chapter presents the interpretation of results thus obtained and a detailed discussion on the findings of the present research. In this section alternative feasible treatment methods of poor sub-grade soil are also described in brief.

6.2. Characterization of the Sub-grade Soil

According to the laboratory test results of the natural soil samples obtained during the present study, with proportion of fines passing no 200 sieve ranging from 95% to 98.8%, liquid limits from 95% to 107% and plasticity index from 45% to 55%, the sub-grade soil is classified in to A-7-5 (20) as per the AASHTO and MH in the USCS classification system. As far as the engineering performance of soils of this class is concerned, such soils are expansive soils which have high volume changing properties with variation in moisture content (Chen, 1988; McKeen, 1976).

During the present study the expansivity of the sub-grade soil has been assessed based on the percentage of clay content, plasticity index, liquid limit and activity of clays. Table 6.1 shows the results in comparison with high range values.

Table 6.1: Summary of test results of the natural sub-grade soil in comparison with high range values

Parameter	Results	High range Values	Remarks
Liquid Limit (LL)	95-107	> 60	Chen, 1988
		> 70	Daksanamurthy and Raman, 1973
Plasticity Index (PI)	45-55	> 35	Seed et al, 1962
Clay Content (CC)	47-65	> 28	Holtz and Gibbs, 1956
Activity	0.8-1.2	PI > 30 and CC > 28	Seed et al, 1962
Swelling Potential	23-38	> 25	Based on PI by Seed et al, 1962

Sub-grade soils with liquid limits, plasticity index, swelling potential, clay content greater than 60%, 25%, 35% and 28%, respectively have very high degree of expansiveness (ERA, 2002). Accordingly, as per Table 6.1 all the soil samples show higher values in each parameter and the sub-grade soil in general thus has very high expansive potential.

Literature shows that such highly expansive soil is associated with the presence of the clay mineral montmorillonite (Chen, 1988; Little and Nair, 1976). However, XRD test result of the two representative sub-grade soil samples namely the light gray clay soil and dark gray clay soil contain no montimorillonite minerals instead are composed of the less expansive clay minerals quartz, muscovite, kaolinite and microcline in different proportions. According to the test results obtained, the proportion of the minerals quartz, muscovite, kaolinite and microcline is 70.2%, 3.3%, 9.5% and 17% for the light gray clay soil and 57.7%, 13.9%, 8.2% and 20.2% for the dark gray clay soil, respectively.

The swelling index of minerals is described by Oslon and Mesri (1970, cited in Fell, 2005). According to the authors the swelling index varies for kaolinite, illite, montmorillonite muscovite and sand ranging 0.04-0.08, 0.04-0.64, 0.03-3.60, 0.35-0.42 and 0.01-0.03, respectively. This shows that the soil samples investigated in the present study are composed of minerals that have low swelling potentials as compared to that of soils dominantly composed of montimorillonite. However, the soil samples in contrary show very high swelling potential based on the parameters tested which include plasticity index, linear shrinkage, percent swell and on empirical relations derived from these parameters.

Furthermore, the CBR and percent swell test results as shown in Table 6.2 concludes that the sub-grade soil has a very low load bearing capacity and high swelling potential which makes it unsuitable for sub-grade without any suitable treatment measure.

Table 6.3 shows the characteristics of the sub-grade soil as compared with the requirement of ERA (2002) manual.

Table 6.2 Summary of test results of CBR and percent swell of the natural sub-grade soil

Parameter	Test Result (%)	ERA (2002) Requirement	AACRA (2004) Requirement
CBR	1	> 5%	> 5%
Percent swell of CBR	10-11	< 2%	< 2%

Table 6.3 Laboratory test results summary of sub-grade soil in comparison with ERA (2002) and ACCRA (2004) requirements

Parameter	Number of samples	Laboratory Result		ERA (2001) Requirement	AACRA (2004) Requirement
		% of samples	ranges of values		
PI	9	100	44 to 55	< 30%	<30
LL	9	100	95 to 104	<60	-
CBR	2	100	1	>5%	>5
% swell	2	100	10 to 11	< 2	<2
GI	9	100	>20	-	-

According to ERA (2002) standard manual soil material as sub-grade should full fill a maximum value of 30% and 60% for PI and LL values, respectively and a minimum CBR value of 5%, a swell of 2% is the maximum requirement for most of standard manuals. However, the comparisons above confirm that all the soil samples do not full fill the requirements as a sub-grade and are determined to be unsuitable for sub-grade in road construction. Therefore, the sub-grade soil should be treated with appropriate improving methods before intended to use as road sub-grade. This can be done by different poor sub-grade soil improvement techniques including removal of the poor sub-grade soil and replacement with a suitable material (capping layer), chemical stabilization, compaction, pre-wetting and making the appropriate pavement designs that considers the unsuitability of the sub grade soil.

The following sub topics presents the interpretation of the different techniques that can be applied to overcome the problems of unsuitable sub-grade soil with prior emphasis on the test results of chemical stabilization performed in this particular study.

6.3. Treatment Methods of Poor Sub-grade Soils

Many alternatives are available to reduce the problem arising from poor sub-grade soil. In most cases there is no single method to overcome the problems. A combination of different methods might be applied to effectively minimize the problem.

The most commonly applied treatment methods are replacement of the unsuitable expansive soil with less expansive material, chemical stabilization, compaction control, thick sub base layer and many more.

6.3.1. Removal of Poor Sub-grade Soil and Replace with Suitable Material

The most practical and experience for the treatment of poor sub-grade soil in Ethiopia in general and Addis Ababa in particular is design of capping layer. It involves the removal of the unsuitable expansive low load bearing sub-grade soil and replacement with suitable improved fill material.

Addis Ababa City Roads Authority Manual (AACRA, 2004) has described the method of removing unsuitable sub-grade soil and replacement with fill material imported from economic distance. The manual describes the depth of excavation to be a maximum of 1m for medium and heavy traffic and the fill material should have CBR of greater than 5% and a maximum swell of 2% or less.

The application of this method in Ethiopia is most feasible provided that the thickness of expansive soil to be replaced is within a meter and availability of suitable fill material is within economic distance. In the particular case of Addis Ababa, the geology (Section 3.4) shows that the city and its surrounding area is endowed with road earth material in most cases within economic distances in almost all corners. Therefore, the method is the best alternative particularly for Addis Ababa area where there is sufficient supply of such materials in the surrounding area. However, there are cases where either there is shortage of suitable fill material within economic distance or the fill material source area is protected for other purposes in Addis Ababa and outside Addis Ababa. Furthermore, in places the thickness of poor sub-grade soil to be replaced might be more which demand huge supply of suitable fill material. In these situations the replacement method will not become feasible due to either lack of sufficient fill material or economic reasons which require costly preparation of sub-grade. Therefore, in places where there is fill material of the required quality within economic distance from the project area the replacement method is the best alternative for economic completion and long life of roads. Chemical stabilization is another alternative where the replacement method is proved to be not economical. A detailed interpretation and discussion of the chemical stabilization results is presented later in section 6.4.

6.3.2. Compaction

Compaction by its own improves many engineering properties of poor sub-grade soils. In situ soil used as sub-grade is compacted to improve its density and other properties. Increasing the soil density improves its strength, lowers its permeability and avoids future settlement

(Atkins, 2003). However, to obtained dense mass the gradation is an important factor. Therefore, a well graded soil material provides a suitably denser mass when compacted.

The expansive clay soil under investigation is not suitable enough to be used as sub-grade material by compaction alone. However, where there is suitable blending material available within economic distances the method can help.

At place where the thickness of the expansive soil is high and not economically feasible to replace the full thickness compaction of the cut section helps to provide smooth and stable road bed beneath the capping layer or the stabilized part of the soil. AACRA (2004) manual requires compaction of cut sub-grade in clay soils from 90 to 95% of MDD of AASHTO T180 depending on CBR value.

6.3.3. Design of Pavements According to Sub-grade Quality

Poor sub-grade soils may be made acceptable by using thick base layers because the thicker section will satisfy most of the design requirements. These layers spread pavement loads over a larger sub-grade area. This option is rather require more base material of higher quality. However, the sub-grade soil under study is highly expansive and has low load bearing capacity and thickening the base layer will not be economical therefore this method may not be an appropriate method.

6.4. Chemical Stabilization

Chemical stabilization is another alternative to improve poor sub-grade soil. Chemicals such as lime improves the low load bearing capacity of poor sub-grade soil and lower the plasticity index and percent swell of highly expansive sub-grade soil (Chen, 1988; Little and Nair, 2009, McKeen, 1956).

In the present study the effects and performance of two chemical stabilizers namely hydrated lime and ANSS on highly expansive low load bearing sub-grade soil is evaluated which is based on laboratory test results of Atterberg limits, linear shrinkage, CBR and percent swell of CBR.

6.4.1. Improvements of Stabilized Soil Samples and Performance of the Chemicals

Tables 6.4 to 6.7 shows the summary of PI and CBR test results of hydrated lime-soil and ANSS-soil mixtures, respectively. Furthermore, refer to table 5.9 for swell percent of CBR test results. The test results show improvements attained by sub-grade soil due to addition of the chemical additives and the following observations are made.

Table 6.4 Summary of plasticity index of hydrated lime stabilized sub-grade soil

Parameter	**Curing Period**	**Natural Soil**		**Light Gray Soil**				**Dark Gray Soil**			
		Light Gray Soil	**Dark Gray Soil**	**2%**	**4%**	**6%**	**8%**	**2%**	**4%**	**6%**	**8%**
Plasticity Index	7 days	50	52	28	24	16	18	27	17	15	12
	14 days			26	18	9	-	16	19	14	-
	28 days			-	-	19	-	-	-	16	-

Table 6.5 Summary of CBR of hydrated lime stabilized sub-grade soil

Parameter	**Curing Period**	**Natural Soil**		**Light Gray Soil**				**Dark Gray Soil**			
		Light Gray Soil	**Dark Gray Soil**	**2%**	**4%**	**6%**	**8%**	**2%**	**4%**	**6%**	**8%**
CBR	7 days	1	1	3	37	38	82	3	35	58	73
	14 days			3	39	70	-	3	38	98	-
	28 days			-	-	38	-	-	-	73	-

Table 6.6 Summary of plasticity index of ANSS stabilized sub-grade soil

Parameter	Curing Period	Natural Soil		Light Gray Soil			Dark Gray Soil		
		Light Gray Soil	Dark Gray Soil	2%	4%	6%	2%	4%	6%
Plasticity Index	7 days	50	52	34	22	19	32	20	16
	14 days			31	20	18	31	18	15
	28 days			-	-	16	-	-	13

Table 6.7 Summary of CBR of ANSS stabilized sub-grade soil

Parameter	Curing Period	Natural Soil		Light Gray Soil			Dark Gray Soil		
		Light Gray Soil	Dark Gray Soil	2%	4%	6%	2%	4%	6%
CBR	7 days	1	1	2	12	18	3	21	37
	14 days			3	14	19	3	24	40
	28 days			-	-	21	-	-	47

Changes on Plasticity Index

- The addition of 2%, 4%, 6% and 8% hydrated lime and curing for 7 days has decreased the PI of the light gray soil by 44%, 52%, 68% and 64%, respectively. Furthermore, the addition of 2%, 4% and 6% hydrated lime and extending the curing period to 14 days has decreased the PI by 44%, 64% and 82%, respectively.

- The addition of 2%, 4%, 6% and 8% hydrated lime and curing for 7 days has decreased the PI of the Dark gray soil by 48%, 67%, 71% and 77%, respectively. Furthermore, the addition of 2%, 4% and 6% hydrated lime and extending the curing period to 14 days has decreased the PI by 48%, 64% and 73%, respectively.

- The addition of 2%, 4% and 6% ANSS and curing for 7 days has decreased the PI of the light gray soil by 38%, 56% and 62%, respectively. Furthermore, the addition of 2%, 4% and 6% ANSS and extending the curing period to 14 days has decreased the PI by 40%, 60% and 64%, respectively.

- The addition of 2%, 4% and 6% ANSS and curing for 7 days has decreased the PI of the Dark gray soil by 38%, 62% and 69%, respectively. Furthermore, the addition of 2%, 4% and 6% ANSS and extending the curing period to 14 days has decreased the PI by 42%, 65% and 71%, respectively.

The performance of the chemicals and the improvements of the sub-grade soil samples in plasticity index are better visible in Fig. 6.1.

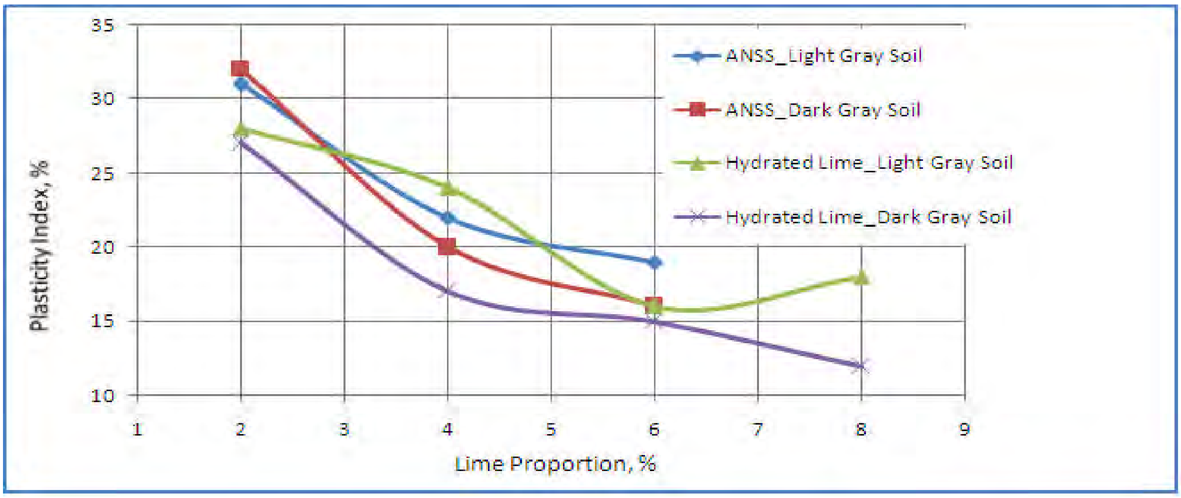


Fig 6.1: Chemical proportion versus PI graph for 7 days curing periods

- The improvement in PI of hydrated lime-soil mixture and ANSS-soil mixture is comparably and more or less appears similar.

- In general terms the improvement in PI of the dark gray soil is more as compared to that of the light gray soil.

<u>Changes in CBR</u>

- The addition of 2%, 4%, 6% and 8% hydrated lime and curing for 7 days has increased the CBR of the light gray soil from 1% of the natural soil to 3%, 49%, 57% and 91%, respectively. Furthermore, the addition of 2%, 4% and 6% hydrated lime and extending the curing period to 14 days has increased the CBR to 3%, 51% and 69%, respectively.

- The addition of 2%, 4%, 6% and 8% hydrated lime and curing for 7 days has increased the CBR of the Dark gray soil from 1% of the natural soil to 3%, 57%, 82% and 104%, respectively. Furthermore, the addition of 2%, 4% and 6% hydrated lime and extending the curing period to 14 days has increased the CBR to 3%, 62% and 103%, respectively.

- The addition of 2%, 4% and 6% ANSS and curing for 7 days has increased the CBR of the light gray soil from 1% of the natural soil to 2%, 12% and 18%, respectively. Furthermore, the addition of 2%, 4% and 6% ANSS and extending the curing period to 14 days has increased the CBR to 2%, 14% and 19%, respectively.

- The addition of 2%, 4% and 6% ANSS and curing for 7 days has increased the CBR of the Dark gray soil from 1% of the natural soil to 4%, 21% and 37%, respectively. Furthermore, the addition of 2%, 4% and 6% ANSS and extending the curing period to 14 days has increased the CBR to 2%, 24% and 40%, respectively.

- The performance of the chemicals and the improvements of the sub-grade soil samples in CBR are better visible in Fig. 6.2.

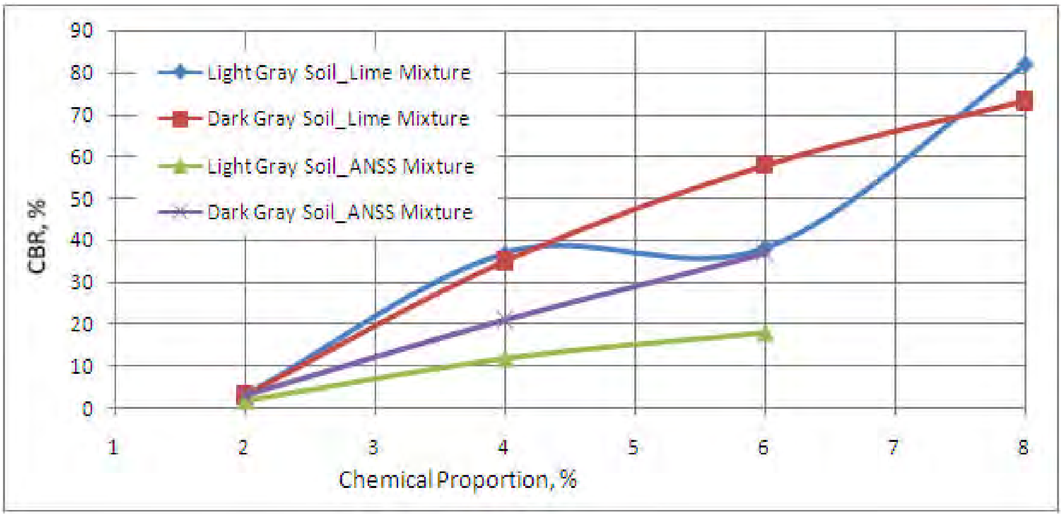


Fig 6.2: Chemical proportion versus CBR graph for 7 days curing periods

- In general the results indicate that the improvement in CBR of hydrated lime-soil mixture is higher than that of ANSS-soil mixture.

- In general terms the improvement in CBR of the dark gray soil is higher than that of the light gray soil

Changes in Swell Percent

- The swell percent decreases much below 2% with the addition of a minimum of 4% chemical additives in both cases.

- With respect to percent swell the improvement of hydrated lime-soil mixture is higher than that of ANSS-soil mixture.

- In general terms the improvement in percent swell of the dark gray soil is higher than that of the light gray soil.

- Major improvement of the sub-grade soil is evidenced by the test results of swell percent where the swell percent is observed to decrease with increased compaction effort.

6.4.2. Suitability of Stabilized Soil Samples as Sub-grade

The suitability of the stabilized soil samples as a sub-grade in road construction is interpreted according to the requirements set by ERA (2002) and AACRA (2004) manuals. ERA (2002) and AACRA (2004) manuals have described the requirements of sub-grade materials. In both the manuals a material to be used as sub-grade must possess PI and swell percent less than 30% and 2%, respectively and CBR must be a minimum of 5%.

In these respects Table 6.5 and 6.6 clearly shows that the addition of 2% of either hydrated lime or ANSS to the soil samples has not satisfied the requirements for the parameters as stated by ERA (2002) as well as AACRA (2004). However, the study conducted proved that the addition of 4%, 6% and 8% hydrated lime or 4% and 6% ANSS to the soil samples has improved the sub-grade soil samples that meet the requirements set by both ERA (2002) and AACRA (2004) standards. In all the cases with the above mentioned proportions it could be possible to lower the PI and percent swell well below 30% and 2%, respectively and raise the CBR value higher than 5%. Therefore, 4% of either hydrated lime or ANSS is sufficiently enough to stabilize the soil samples so as to use as sub-grade material. This fact was initially demonstrated by Eades and Grim PH test which enables to determine the initial lime requirement for stabilization.

6.5. Comparison of Chemical Stabilization with Previous Works

Chemical stabilization of sub-grade soil is still in conceiving stage in Ethiopia and not much practical experiences on the same are available. Some practical experiences in the country that can be referred include sub-grade soil stabilization on trial road sections in Addis Ababa with ANSS and similar industrial product stabilizer agents and more recently a laboratory test conducted on expansive sub-grade soil samples taken from Dejen-Debre Markos Road section. Table 6.7 and 6.8 shows laboratory test results of hydrated lime-soil and ANSS-soil mixtures, previously conducted for comparison with the present study.

Table 6.8: Laboratory test result of hydrated lime-soil mixture cured for 7 days and natural sub-grade soil taken from Dejen-Debre Markos Road section (Source: Gondwana Engineering PLC Lab)

Station	Soil Description	Untreated Natural soil											Hydrated lime treated soil							
		% pass, mm			LL %	PL %	PI %	OMC %	MDD T180 g/cm3	CBR at 95% MDD	swell %	AASHTO Class	Lime %	After CBR			OMC %	MDD T-180 g/cm³	CBR at 95% MDD	Swell %
		2.00	0.425	0.075										LL %	PL %	PI %				
NTP 2 (ETP1)	Dark Silty clay	100	100	98	89	38	51	24.0	1.490	1	9.96	A-7-5 (20)	2%	79	51	28	25.0	1.505	9	0.39
													4%	65	48	17	25.0	1.501	11	0.25
													6%	64	50	14	24.0	1.490	17	0.12
NTP 13 (ETP2)	Dark Silty clay	100	97	94	86	35	51	26.5	1.561	2	8.36	A-7-5 (20)	2%	67	47	20	18.0	1.562	5	0.94
													4%	59	47	12	23.0	1.560	15	0.13
													6%	51	46	5	23.0	1.540	30	0.15
NTP30 (ETP3)	Alluvial dark Silty clay with bunds of reddish Silty clay	100	99	98	100	57	43	29.0	1.385	2	7.85	A-7-5 (20)	2%	71	47	24	30.0	1.448	6	0.15
													4%	57	46	11	33.0	1.395	19	0.13
													6%	53	46	7	32.0	1.369	38	0.11

The test results based on PI, percent swell and CBR shows that even 2% hydrated lime stabilizes the sub-grade soil effectively where as in the case of the present study no remarkable change was observed. This might be due to a difference in mineralogy of the soil samples. However, for proportions of 4% and 6% hydrated lime comparable results are obtained in the present study.

Test conducted at AACRA laboratory on poor highly expansive clay sub-grade soils of CBR 1 to 2% collected from Bethel and Jemo areas and mixed with 4% ANSS provided a CBR of 14% and 18%, respectively.

Table 6.9: Laboratory test result of ANSS-soil mixture and natural sub-grade soil taken from Bethel and Jemo Areas (Source: AACRA Lab)

Station	Soil Description	Untreated natural soil		ANSS Treated soil (4%)			
		OMC %	MDD T180	OMC %	MDD T180	CBR %	Swell %
Bethel Area	Clay Sub-grade Soil	25.1	1.47	30	1.32	14	1.18
Jemo Area	Dark gray clay sub-grade soil			17.5	1.62	18	0.47

6.6. Over all View of Stabilization of Sub-grade Soil

The test results of the natural soil samples in general shows that the sub-grade soil is grouped in to A-7-5 (20) in the AASHTO and MH in the USCS soil classification systems. Soils of this class are known for their high expansiveness which change in volume with varying moisture contents and have very low load bearing capacity.

The test result of the natural soil samples based on liquid limit, plasticity index, linear shrinkage, activity of clays and percent swell shows that the sub-grade is highly expansive. Furthermore, the CBR test result of the soil samples indicates that the sub-grade has very low load bearing capacity. Thus, such sub-grade soil is unsuitable to be used in road construction and proper remedial measure has to be taken before constructing pavements.

Various alternatives to treat such poor sub-grade soils have been assessed. For the case of Addis Ababa area where there is sufficient source of suitable fill material, removal of the unsuitable expansive soil and replacement with fill material is the best alternative. However, in places where there is shortage of suitable fill material within economic distances chemical stabilization is another alternative.

In the present study various proportions of the chemical additives; such as hydrated lime and ANSS has been investigated to stabilize the sub-grade level. According to the results 2% of either hydrated lime or ANSS has not improved the sub-grade soil. However, 4% of either of the chemical additives has provided good results for stabilization of the sub-grade soil.

The PI and percent swell has decreased with addition of the chemical additives with an increased proportion of the chemicals as well as with prolonged curing periods. However, the improvement attained with increasing proportion of the chemical additives is found to be more significant than that of increased curing periods.

During CBR penetration cracking of the samples that has compacted to 65 blows has happened. This is because higher compaction has forced the moisture to expel from the soil sample. On the other hand much of cracking has occurred in samples which were cured for prolonged period of 28days. This might be due to loss of moisture during the longer curing periods.

The improvement of the dark gray clay soil is more in comparison to that of the light gray clay soil in almost all the tests conducted on stabilized mixtures nevertheless of the fact that the soils have similar PI and gradation and grouped in the same soil classification of A-7-5 of AASHTO or MH of USCS classification systems.

Many factors may have contributed to the difference in improvement of the two soil samples one might be the mineralogy. The XRD test result of the soil samples even have the same mineralogy but have different proportion. The difference in the proportion of the minerals present in the soil samples might have contributed to the varying degree of improvements in the properties when chemicals were added to soil samples in different proportions. However, such inference needs more detailed investigation and studies, which is beyond the scope of the present study.

In general the replacement method is the best alternative for the case of Addis Ababa since there is source of suitable fill material within economic distances. Chemical stabilization is another alternative where there is no sufficient fill material within economic distances. However, chemical stabilization, though effective, is comparatively expensive and requires skilled labor, special equipment and availability of desired chemicals in local market. Therefore, for effective preparation of sub-grade and long life of pavements both the methods should be supplemented by appropriate compaction of the road bed with proper drainage arrangements.

Chapter VII Conclusion and Recommendations

7.1. Conclusion

Expansive sub-grade soils pose severe problems to pavements which are constructed over them. Because of the high swelling and shrinkage characteristics and low load bearing capacity when wet, the expansive soils have been a challenge to the road construction sector in Ethiopia in general and Addis Ababa in particular, since these soils occupy major portion in the western, central and southwestern part of the country. Seehra (2008) pointed out that the cyclic wetting and drying processes due to seasonal climatic changes may lead to vertical movements which take place in expansive sub-grade soils and such vertical movements may result into failure of pavements. Such failures are manifested in the form of settlement, heavy depression, cracking and unevenness of road surfacing.

In Ethiopia, as a general practice, the conventional method of removing the expansive soil and replacing it with superior quality of fill material has been practiced to alleviate the problem of expansiveness of sub-grade soils. This method is feasible around Addis Ababa area since there is suitable fill material in all corners of the city. However, many quarries are closed in recent years due to expansion of the city and areas which were considered to be huge sources of earth materials such as; the Entoto ridge are now protected for environmental concerns (AAEPA, 2007). Eventually, this may result into shortage of suitable fill material within economic distances in near future. Thus, the problem of expansive sub-grade soils exists and scarcity of suitable fill material within economic distances in the city forced Addis Ababa City Roads Authority and the Ethiopian Roads Authority to initiate the use of chemicals to stabilize sub-grade and sub base materials. The present study, hence, has the objective of evaluating the performance of a locally manufactured hydrated lime and an imported chemical stabilizer ANSS on highly expansive sub-grade soil samples collected from a trial road section in Gerji Area of Addis Ababa city Administration.

In order to achieve the objectives of the present study literature review of the previous works, field observations and laboratory tests were conducted. For this representative sub- grade soil samples were taken in two stages. In the first stage a total of seven samples were taken at every 200m interval from varying depths. These samples were mainly collected to classify the sub-grade soil. Later, based on the classification two representative samples were collected. These samples were utilized for the purpose of evaluation of the performance of chemicals on the sub-grade soil. This evaluation was made through laboratory test results of Atterberg limits, linear shrinkage, CBR and percent swell of CBR.

Further, mineralogical and chemical composition analysis of the sub-grade soil samples was also conducted. Literature indicates that highly expansive soils are associated with presence of the montmorillonite clay mineral (Chen, 1988). However, according to the XRD mineralogy test results, as conducted during the present study the sub-grade soil is devoid of montmorillonite.

Tests were conducted on both the natural sub-grade soil and treated soil samples to evaluate the improvements achieved by the addition of the chemical agents. The initial lime consumption was determined by PH test whereas for ANSS as such no preliminary test was specified by the supplier and hence previous experience and supplier user guideline was used to determine the trial dosages.

According to the test results, addition of hydrated lime and ANSS has demonstrated significant improvements in the poor sub-grade soil under the present study. The engineering properties of the sub-grade soil has shown improvements with increasing dosages and with prolonged curing periods. In almost all the cases the PI and swelling properties has decreased and the CBR has increased with respective increasing of the chemical dosages. From the study the following findings are deduced;

- The sub-grade soil is highly expansive and has very low load bearing capacity and is classified as A-7-5 in the AASHTO and MH in the USCS systems. The sub-grade is very poor to be used as sub-grade and hence requires avoiding or treating before construction of pavements.

- The addition of 2% of either of the chemical additives; hydrated lime or ANSS, does not assure the improvement of the sub-grade soil to the desired engineering properties.

- The addition of 4% of either of the chemical additives; hydrated lime or ANSS, has sufficiently stabilized the sub-grade soil. With further increment of the curing period the sub-grade soil has further improved.

- In general terms, the improvement of the dark gray soil is more than that of the light gray soil due to the addition of either hydrated lime or ANSS nevertheless both the soil samples are grouped in the same soil class with nearly equal PI, percent swell and CBR. The slight difference in mineralogy of the soil samples may affect the improvements.

- The performance of the locally manufactured hydrated lime in stabilizing the sub-grade soil is higher than that of ANSS.

- Cracks were observed on those highly compacted and cured soil samples for longer periods of 28 days. This could be due to loss of moisture during the longer curing periods. Therefore, moisture, a little above the OMC to account for the loss is required during compaction.

7.2. Recommendations

Based on the present study results following recommendations are forwarded:

- The present study is conducted by taking limited parameters of Atterberg limits, moisture density relation, CBR and percent swell of CBR on stabilized hydrated-soil and ANSS-soil mixtures. It is recommended that additional parameters of swelling potential, unconfined compressive strength and mineralogical tests should also be performed to have more realistic results.

- The chemical additives; hydrated lime and ANSS, has provided promising results in improving the engineering properties of the sub-grade soil. 4% of either of the chemicals may be enough to stabilize the sub-grade soil. However, the results obtained should be verified by field tests.

- In addition to successful stabilization of the sub-grade soil with both types of the chemical additives, the long term durability of the stabilized material is much more important. Therefore, it is recommended to conduct wetting-drying and leachate tests to assess the long term durability of the stabilized material.

- In places like the present situation of Addis Ababa, where there is a supply of suitable earth material within economic distances, priority should be given for the removal of poor sub-grade soil and replacement with suitable fill material for economical reasons. However, in place where there is insufficient supply of the fill material and the environmental concerns are of high priority chemical stabilization as alone or as a combination of other methods is recommended as the best alternative.

- Hydrated lime is observed to perform better than ANSS in stabilizing highly expansive soils even though both have sufficiently stabilized the sub-grade soil samples with equal proportion of 4%. Besides its technical performance hydrated lime is the best alternative over ANSS due to huge availability of limestone deposit in the country, the job opportunity it can create by producing hydrated lime locally and its importance to avoid expending foreign currency for imported products. However, the choice between the two should be based on economic analyses of producing hydrated lime locally and importing ANSS. Furthermore, durability of sub-grade soil stabilized with these additives should be compared before making a choice for selection.

- Mineralogy has an effect on the stabilization of soil with chemical additives. Knowing the mineralogy of soils, hence, helps to understand the response when a chemical agent is mixed. Therefore, it is recommended to study mineralogy of representative soil samples of the different expansive soils of Addis Ababa.

Finally, the results and findings of the present study may be considered as indicative only as these findings are based on limited parameters and on small number of samples. More elaborate sampling and testing would be mandatory before implementation of results from the present study. However, the present study provides a general methodology to conduct similar studies on stabilization of expansive sub-grade soils for pavements design.

References

AASHTO, 1998, Standard Specifications for Transportation materials and Methods of Sampling and testing -American Association of State Highways and Transportation Officials,

Addis Ababa City Administration environmental Protection Authority (AAEPA), 2007, *Mineral Extraction Information,* Addis Ababa, Ethiopia.

AACRA, 2004, Construction Specifications, Addis Ababa, Ethiopia.

AACRA, 2004, Pavement Design Manual, Addis Ababa, Ethiopia.

AACRA, 2004, Soil and Materials Manual, Addis Ababa, Ethiopia.

Aksum Tesfaye, 2001, chemical treatment of “Black Cotton” soil to make it usable as a foundation material, M.Sc. Thesis, Addis Ababa University, Technology Faculty, Addis Ababa, Ethiopia

Akundabweni, L., (1984), *Forage potential of some annual native Trifolium species in the Ethiopian highlands*, PhD Thesis, South Dakota State Univiversity, Brookings (USA). 208 pp.

Alemayehu Mengistu, 2003, Country Pasture/ Forage Resource Profiles, Addis Ababa, Ethiopia

Amer Ali Al-Rawas and Mattheus F.A. Goosen, 2006, *Expansive Soils-Recent advances in characterization and treatment*, Taylor & Francis Group, London, UK

Anyway Solid Environment Solutions, 2003, Guideline to the Construction of Pavement Layers and Stabilized Materials using Anyway Natural Soil Stabilizer (ANSS), www.anywaysolutions.com.

Assegid Getahun, 2007, Geology of Addis Ababa City, Geological Survey of Ethiopia, Ministry of Mines and Energy, Addis Ababa, Ethiopia.

ASTM, 1997, America society for testing material

Atkins, H. N., 2003, Highway Materials, Soils and Concretes, 4th Edition, Prentice Hall, Upper Saddle River, New Jersey.

Beniam Alemue, 2010, Engineering Geoloical Characterization of Granular Sub base Using Lime-a Case Study of Ambo-Gedo Road Project, M.Sc. Thesis, Addis Ababa University, Science Faculty, Addis Ababa, Ethiopia

Bohor B. F. and Randall E. H., 1971, Scanning Electron Microscopy of Clays and Clay Minerals, v. 19; no. 1; p. 49-54; Illinois State Geological Survey, Urbana, III. 61801

Bulman J. N., 1980, Aspects of soil mechanics of particular importance to highway engineering in Africa, 7th Regional Conference for Africa on Soil Mechanics and Foundation Engineering, p649-655, Accra, Ghana.

Chen, F.H., 1988, *Foundations on expansive soils*, Chen and Associates, 96 South Zuni, Denver, CO 80223, U.S.A.

Chittoori B.C.S., 2008, Clay Mineralogy Effects on Long Term Performance of Chemically Treated Expansive Clays, PHD Dissertation, University of Texas at Arlington.

Daniel Gemechu, 1977, Aspects of Climate and Water Budget in Ethiopia, A Technical Monograph Published For Addis Ababa University, Addis Ababa University Press, Ethiopia

Daniel Nebro, 2002, Stabilization of Potentially Expansive Sub-grade Soil using Lime and Con-aid, M.Sc. Thesis, AAU, Technology Faculty, Addis Ababa, Ethiopia.

Daksanamurthy, V. and Raman, V., 1973, A Simple Method of Identifying an Expansive Soil, Soil and Foundations, Japan Society of Soil Mechanics and Foundation Engineering, Vol. 13(1), p 97-104.

ERA, 2002, Pavement design Manual, Volume I and II, Flexible Pavements and Gravel Roads, Addis Ababa, Ethiopia.

Fell R., MacGregor P., Stapledon D. and Bell G., 2005, Geotechnical Engineering of Dams, Tylor and Francis Group plc, London, UK.

Getnet Aschilegn, 2008, Stabilization of Potentially Expansive Soils using an Industry Product RBI Grade 81 chemical, M.Sc. Thesis, AAU, Technology Faculty, Addis Ababa, Ethiopia.

Gourley, C.S. and Schreiner, H.D., 1993, The Extent and Engineering Significance of Expansive Soils, Overseas Development Administration, 94 Victoria Street, London.

Haile Sellasie Girmay and Getaneh Assefa, 1989, Addis Ababa-Nazareth Volcanics: A Miocene-Pleistocene Volcanic Succession in Ethiopian Rift, Ethiopian Journal of Science, Addis Ababa, Ethiopia.

Holland, J.E. and Richards, J., 1982, Road Pavements on Expansive Clays, Vol. 12, No.3. Australian Road Research, Australia.

Holtz, W. G. and Gibbs, H. J., 1956, Engineering Properties of Expansive Clays, Transactions, American Society of Civil Engineers, vol. 121, pp. 641-677.

Kebede Tsehayu & Tadesse H. Mariam, 1990, Engineering Geological Mapping of Addis Ababa, Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.

Keir, D., Ebinger, C., Stuart, G., Daly, E., Ayele, A., 2003, Seismicity of the Northern Main Ethiopian and Southern Red Sea Rifts: EAGLEII, American Geophysical Union, NASA ADS.

Little, D.N., 2006, *Mixture Design and Testing Procedures for Lime Stabilized Soil, Technical Brief*, National Lime Association, 200 N. Glebe Rd., Suite 800, Arlington.

Little, D. N. and Nair, S., 2009, Recommended Practice for Stabilization of Sub-grade Soils and Base Materials, Texas Transportation Institute, Texas A & M University College Station, Texas.

McKeen, R.G, 1976, Design and Construction of Airport Pavements on Expansive Soils, U.S Department of Transportation, Federal Aviation Administration, Systems Research and Development Service, Washington, D.C. 20590

Mengesha Tefera, Tewodros Chernet and Workneh Haro, (1996), Geological Map of Ethiopia (1:2000000), Second Edition and Explanatory notes. Bulletin N0. 3. GSE.

Mesay Gashaw, 2008, Engineering Geological Mapping of Bole Sub-City with Special Reference to Building Foundations on Expansive Soil, M.Sc. Thesis, Addis Ababa University, Science Faculty, Addis Ababa, Ethiopia.

Ministry of Works and Urban Development, 1995, Code of Standards for Seismic Loads, EBCS-8, Addis Ababa, Ethiopia.

Ministry of Works and Urban Development, 2009, *Universal Rural Road Access Program-The Way Forward to Practical Demonstration of Road Construction on Expansive Soil Sub-grade*, Federal Democratic Republic Of Ethiopia, Addis Ababa

Morin, W. J. & Parry, W.T. 1971, Geotechnical Properties of Ethiopian Volcanic Soils, Geotechnique 21, No.3, 223-232

Morin, W. J., 1971, Properties of African Tropical Black Soils, Fifth Regional Conference for Africa on Soil Mechanics and Foundation Engineering, Luanda, Angola.

Muntohar, A.S. and Hashim, R., 2006, Swelling Behavior of Engineered Clay Soil, The second International Conference on Advances in Soft Soil Engineering and Technology, Kuala Lampur, Malaysia.

Murray, H. H., 2007, Applied Clay Mineralogy, Occurrences, Processing and Application of Kaolins, Bentonites, Palygorskite Sepiolite, and Common Clays, Department of Geological Sciences, Indiana University, Bloomington, Indiana, U.S.A.

Naagesh, S. and Gangadhara, S., 2010, *Swelling Properties of Bio-enzyme Treated Expansive soil*, International Journal of Engineering Studies, Volume 2, pp. 155–159, (http://www.ripublication.com/ijes.htm)

EMA, 1981, National Atlas of Ethiopia, Ethiopian Mapping Authority, Addis Ababa, Ethiopia.

Nelson S.A., 2010, Weathering and Clay Minerals, Lecture notes, Tulane University, USA.

Pedarla, A., 2009, Durability Studies on Stabilization Effectiveness of Soils Containing Different Fractions of Montimorillonite, M.Sc. Thesis, University of Texas at Arlington.

Rao Bhavana D.V, 2007, *Steps to Improve Roads on Black Cotton Soils*, NMB Construction Information, India.

Road Design Manual of Kenya, 1987, Ministry of Transport and Communication, Road Department, Nairobi, Kenya.

Rollings, M. P. and Rollings, R. S., 2002, *Tropical Pavement Construction*, US Corps of Engineers Engineering Research and Development Center-CRREL, 72 Lyme Road, Hanover, NH 03755

Seed, H.B., Woodward, R.G. and Lundgren, R., 1962, Prediction of Swelling Potential for compacted clays. Proceedings American Society of Civil Engineers Journal of Soil Mechanics and Foundation Engineering, Volume 88, No.SM3, p53-87

Seehra, S.S., 2008, *Practical Problems of Highway Construction in Black Cotton Soil Areas and In-Place Remedial Measures: A Case Study*, NBM Construction information, New Delhi, India.

Srivastava KL, Mesfin Abebe, Abiye Astatke, Mitiku Haile and Hailu Regassa, Improved management of vertisols for sustainable crop-livestock production, FAO Corporate Document Repository, http://www.fao.org/Wairdocs/ILRI/x5456E/x5456e04.htm, accessed on December 14, 2010.

Tamiru Alemayehu, Tenalem Ayenew, Dagnachew Legese, Yirga Tadese, Solomon Waltenigus and Nuri Mohamed, 2006, Groundwater Vulnerability Mapping of the Addis Ababa Water Supply Aquifers, Addis Ababa, Ethiopia

Tanzanian Pavement and Materials Design manual, 1999, The United Republic of Tanzania Ministry of Works, Tanzania.

Tesfaye Chernet, 1993, Hydrogeology of Ethiopia and Water Resources Development, Ethiopian Institute of Geological Survey, Addis Ababa, Ethiopia.

Thagesen, B. and Robinson, R., 2004, Road Engineering for Development, 2nd Edition, Spon Press, Tylor and Francis Group, London, UK.

Tilahun Mammo, (2005), Site-specific ground motion simulation and seismic response analysis at the proposed bridge sites within the city of Addis Ababa, Ethiopia

Twenfel, W.H, (1950), Principles of Sedimentation, Second Edition, McGraw Hill Book Co., Inc., New York

Van Der Merwe, D. H. 1964, The prediction of heave from the plasticity index and percentage clay fraction of soil. South African Institute of Civil Engineers, vol. 6: pp 103-107.

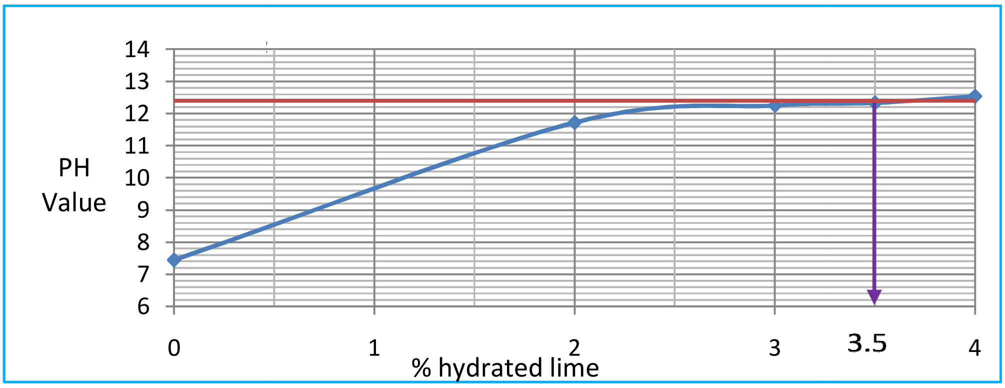
Zanettin, B. and Justin, V.E., 1974, the Volcanics of Western Afar and Ethiopian Rift Margins, Padova, Italy.

Annexure 1: Summary of test results of the natural sub-grade soil

Sample	Sieve Size, mm			Atterberg Limit				LS (%)	Weighted Shrinkage W_s	Expansiveness, ϵex	AASHTO Classification	Proctor Density		3Point CBR (AASHTO T193)				95% MDD	CBR @ 95% MDD
	2	0.425	0.075	LL	PL	PI	W_p					MDD g/cc	OMC %	No. of Blows	Dry Density (g/cc)	CBR %	Swell %		
ST 1	99.5	99.3	98.3	98	49	49	49	22	21.85	64.08	A-7-5 (64)	–	–	– – –	– – –	– – –	– – –	–	–
ST 2	98.9	98.4	95	103	52	52	51	22	21.65	70.88	A-7-5 (65)	–	–	– – –	– – –	– – –	– – –	–	–
ST 3	99.9	99.7	97.5	96	45	51	51	22	21.93	68.99	A-7-5 (64)	–	–	– – –	– – –	– – –	– – –	–	–
ST 4	99.9	99.7	98.8	98	48	50	50	22	21.93	66.60	A-7-5 (65)	–	–	– – –	– – –	– – –	– – –	–	–
ST 5	99.4	99.3	97.5	99	49	50	50	20	19.86	74.21	A-7-5 (64)	–	–	– – –	– – –	– – –	– – –	–	–
ST 6	99.3	98.3	97.5	107	52	55	54	20	19.66	85.58	A-7-5 (71)	–	–	– – –	– – –	– – –	– – –	–	–
ST 7	99.8	99.6	99.3	95	42	53	53	20	19.92	81.50	A-7-5 (67)	–	–	– – –	– – –	– – –	– – –	–	–
Light Grey Soil	100	99.9	98.4	98	48	50	50	22	21.98	66.67	A-7-5 (64)	1.44	31	10 30 65	1.24 1.30 1.44	1 1 1	10.53 10.39 10.65	1.37	1
Dark Grey Soil	100	99.6	99.1	97	45	52	52	20	19.92	79.11	A-7-5 (66)	1.42	28.5	10 30 65	1.25 1.33 1.42	1 1 1	10.84 10.90 10.11	1.35	1

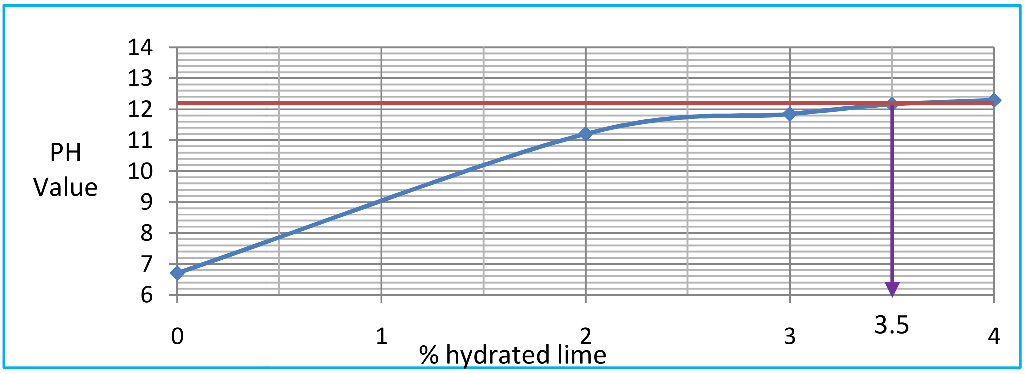
Annexure 2: PH test result of hydrated lime-light gray soil mixture

Hydrated Lime, %	PH Value
0	7.44
2	11.72
3	12.25
3.5	12.53

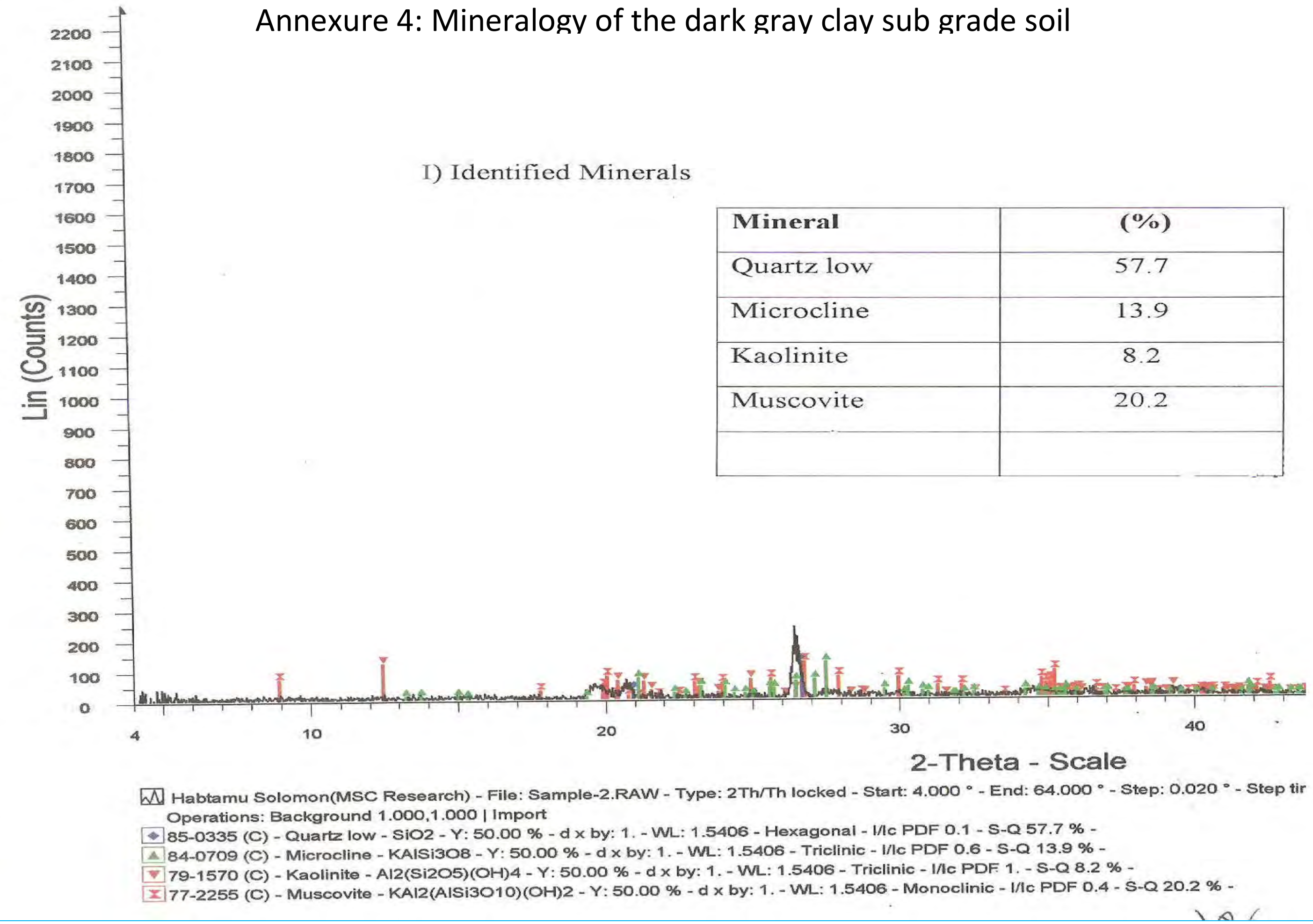


Annexure 3: PH test result of hydrated lime-dark gray soil mixture

Hydrated Lime, %	PH Value
0	6.7
2	11.2
3	11.84
3.5	12.16
4	12.29



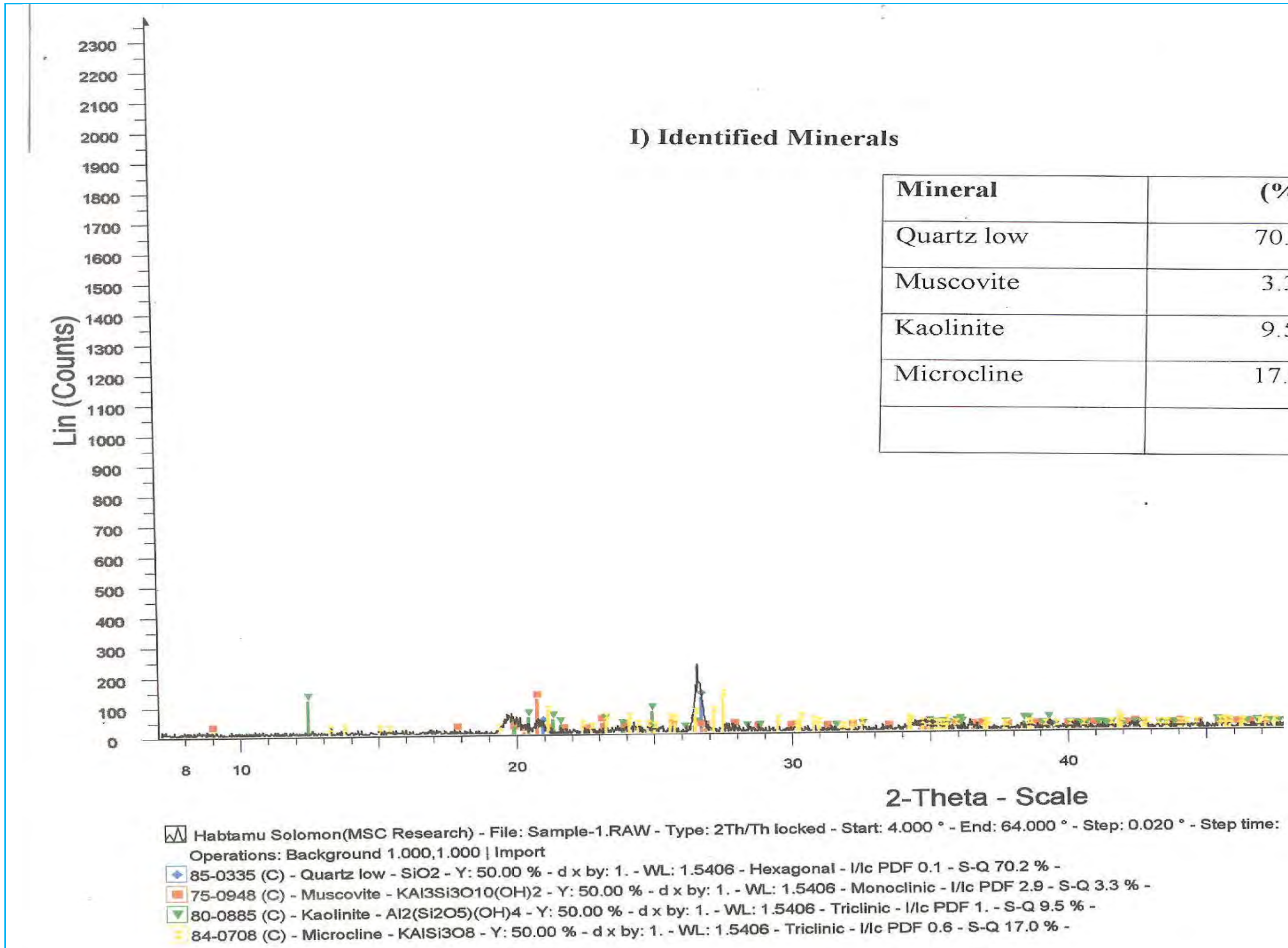
Annexure 4: Mineralogy of the dark gray clay sub grade soil



I) Identified Minerals

Mineral	**(%)**
Quartz low	57.7
Microcline	13.9
Kaolinite	8.2
Muscovite	20.2

Annexure 5: Mineralogy of the light gray clay sub grade soil



I) Identified Minerals

Mineral	(%)
Quartz low	70.2
Muscovite	3.3
Kaolinite	9.5
Microcline	17.0

Annexure 6: Chemical Composition of the Soil Samples and Chemical Agents

Lab No	Field No	SiO2 (%)	Al2O3 (%)	Fe2O3 (%)	CaO (%)	MgO (%)	Na2O (%)	K2O (%)	TiO2 (%)	P2O5 (%)	MnO (%)	SO3 (%)
16284-10	Light Gray Soil	50.87	13.77	10.89	1.57	1.68	0.29	1.39	1.8159	0.045	0.1412	0.04
16285-10	Dark Gray Soil	49.68	13.38	11.56	1.49	1.70	0.28	1.24	2.5266	0.047	0.1536	0.07
16286-10	ANSS	10.51	2.58	1.82	35.47	2.12	0.25	0.82	0.1717	0.118	0.0315	30.47
16287-10	Hydrated Lime	6.21	2.18	3.57	59.47	3.91	0.61	0.79	0.3286	0.208	0.2785	0.58

Lab No	Field No	LOI(%)	V (PPM)	Cr2O3 (PPM)	Sr (PPM)	Ba (PPM)
16284-10	Light Gray Soil	17.05	176	266	110	431
16285-10	Dark Gray Soil	17.45	233	248	116	316
16286-10	ANSS	14.62	42	81	4881	157
16287-10	Hydrated Lime	20.35	95	82	1530	9620

Reference standard material CRM-7003			
	CGL. R.	R.V	RE%
SiO2 (%)	68.12	68.8	0.98
Al2O3 (%)	13	12.3	5.69
Fe2O3 (%)	4.01	4.15	3.37
CaO (%)	0.79	0.74	6.75
MgO (%)	1.1	1.02	7.00
Na2O (%)	0.8	0.74	8.1
K2O (%)	2.41	2.21	9.04
TiO2 (%)	0.66	0.68	2.94
P2O5 (%)	0.15	0.16	6.25

*GSLC Geoscience laboratory center

*RV Referance standard recommended result

*the result indacted above are result of the sample that submitted to the laboratory

Annex 7: Summary of test results of highly expansive sub-grade soil taken from some parts of Ethiopia (Source: Gondwana Engineering PLC Laboratory)

Dejen -Debre Markos Road Project															
Station, km	**Field Material Description**	**Depth (cm)**	**% pass (mm)**			**LL %**	**PL %**	**PI %**	**AASHTO Soil Class**	**OMC %**	**MDD T-180 g/cm^3**	**No of Blows**	**Density g/cm3**	**CBR**	**Swell %**
			2.000	**0.425**	**0.075**										
4 + 000	Dark silty CLAY	60-240	100	100	98	89	38	51	A-7-5 (20)	24.0	1.490	10	1.220	1	11.43
												30	1.387	1	11.04
												65	1.501	2	9.96
13 + 500	Dark silty CLAY	70-135	92	88	86	80	38	42	A-7-5 (20)	17.0	1.510	10	1.266	1	9.13
												30	1.450	1	8.60
												65	1.526	2	7.95
23 + 000	Dark silty CLAY	55-300	100	97	94	86	35	51	A-7-5 (20)	26.5	1.561	10	1.166	1	8.80
												30	1.397	2	8.66
												65	1.497	2	8.38
26 + 500	Dark gray silty CLAY	75-300	94	91	89	86	43	43	A-7-5 (20)	20.0	1.530	10	1.238	1	13.34
												30	1.423	2	13.20
												65	1.522	2	12.37
50 + 500	Dark silty CLAY	0-270	99	94	90	86	42	44	A-7-5 (20)	24.0	1.463	10	1.159	1	8.85
												30	1.370	2	7.33
												65	1.474	2	6.39
56 + 500	Light brown silty CLAY	80-180	97	87	85	76	45	31	A-7-5 (20)	23.5	1.542	10	1.234	2	6.55
												30	1.453	3	5.34
												65	1.527	4	3.79

Annex 7: Summary of test results of highly expansive sub-grade soil taken from some parts of Ethiopia (Source: Gondwana Engineering PLC Laboratory)

Addis Ababa-Tarmaber Road Project

Station, km	Field Material Description	Depth (cm)	% pass (mm) 2.000	0.425	0.075	LL %	PL %	PI %	AASHTO Soil Class	OMC %	MDD T-180 g/cm^3	No of Blows	Density g/cm3	CBR	Swell %
23 + 000	Dark gray silty CLAY	45 - 100	82	80	78	72	29	43	A-7-6 (20)	24	1.535	10	_	1	12.0
												30	_	1.0	12
												65	_	1.0	11.2
31 + 000	Dark silty CLAY	75 - 120	98	96	93	75	31	44	A-7-5 (20)	21	1.548	10	_	1.0	12.0
												30	_	1.0	11.2
												65	_	2.0	10.5
71+000	Dark silty CLAY	70 - 140	100	98	96	71	30	41	A-7-5 (20)	15	1.579	10	_	1.0	12.9
												30	_	1.0	11.2
												65	_	1.0	11.2
76+000	Dark silty CLAY	40 - 90	76	73	71	75	33	42	A-7-5 (19)	25	1.594	10	_	2.0	9.4
												30	_	2	6.9
												65	_	2	5.7
87+200	Dark to dark brown silty CLAY	50 - 130	91	86	84	84	38	46	A-7-5 (20)	23	1.532	10	_	1.0	9.4
												30	_	1	9.4
												65	_	1.000	9.4
112 + 200	Brown to dark brown silty CLAY	55 - 100	84	79	72	50	22	28	A-7-6 (16)	16	1.664	10	_	1.0	13
												30	_	1.0	12
												65	_	2.0	9
132 + 100	Light brown silty CLAY	50 - 100	99	94	80	50	20	30	A-7-6 (18)	16	1.730	10	_	1.0	12
												30	_	2.0	7.2
												65	_	3.0	7

Annexure 8: Summary of test results of hydrated lime treated sub-grade soil

Sample	Lime Ratio %	Curing period (days)	0.425 seive	Atterberg Limit LL	PL	PI	PI_w	LS (%)	Weighted Shirinkage W_s	Expansiveness Nature, Єex	Proctor Density MDD g/cc	OMC %	3Point CBR (AASHTO T193) No. of Blows	Dry Density (g/cc)	CBR %	Swell %	95% MDD	CBR @ 95% MDD
Lime-Light Grey Soil Mixture	2	7	99.9	79	51	28	28	21.00	20.98	17.81	1.448	30	10	1.216	3.00	1.28	1.380	3
													30	1.342	3.00	1.27		
													65	1.412	3.00	9.90		
		14	99.9	75	49	26	26	23.00	22.98	5.23	1.448	30	10	1.162	4.00	0.08	1.380	4
													30	1.368	5.00	0.08		
													65	1.472	4.00	0.06		
	4	7	99.9	76	52	24	24	14.00	13.99	35.50	1.471	29	10	1.315	13.00	0.08	1.397	37
													30	1.381	40.00	0.02		
													65	1.468	49.00	0.00		
		14	99.9	71	53	18	18	14.00	13.99	21.11	1.471	29	10	1.285	18.00	0.23	1.397	39
													30	1.327	23.00	0.21		
													65	1.444	51.00	0.15		
	6	7	99.9	69	53	16	16	11.00	10.99	28.00	1.481	26	10	1.311	23.00	0.05	1.407	38
													30	1.389	27.00	0.03		
													65	1.461	57.00	0.01		
		14	99.9	68	59	9	9	10.00	9.99	15.12	1.481	26	10	1.300	21.00	0.27	1.407	70
													30	1.376	65.00	0.15		
													65	1.442	69.00	0.12		
		28	99.9	69	50	19	19	13.00	12.99	27.41	1.48	26	10	1.296	31.00	0.19	1.407	37
													30	1.374	31.00	0.17		
													65	1.494	53.00	0.14		
	8	7	99.9	69	51	18	18	9.00	8.99	40.59	1.42	28	10	1.247	22.00	0.08	1.35	78
													30	1.323	72.00	0.03		
													65	1.442	91.00	0.02		

Annexure 8: Summary of test results of hydrated lime treated sub-grade soil

Sample	Lime Ratio %	Curing period (days)	0.425 seive	Atterberg Limit				LS (%)	Weighted Shirinkage W_s	Expansiveness Nature, Єex	Proctor Density		3Point CBR (AASHTO T193)				95% MDD	CBR @ 95% MDD
				LL	PL	PI	PI_w				MDD g/cc	OMC %	No. of Blows	Dry Density (g/cc)	CBR %	Swell %		
Lime-Dark Grey Soil Mixture	2	7	99.6	75	48	27	27	19.00	18.92	23.24	1.423	28	10	1.205	3.00	0.70	1.352	3
													30	1.340	5.00	1.02		
													65	1.454	3.00	10.00		
		14	99.6	68	52	16	16	20.00	19.92	6.94	1.423	28	10	1.028	3.00	0.25	1.352	4
													30	1.156	6.00	0.08		
													65	1.173	4.00	0.08		
	4	7	99.6	67	50	17	17	14.00	13.94	18.76	1.485	27	10	1.304	6.00	0.04	1.411	35
													30	1.375	25.00	0.03		
													65	1.469	58.00	0.01		
		14	99.6	63	44	19	19	14.00	13.94	23.54	1.485	27	10	1.306	9.00	0.82	1.411	38
													30	1.383	29.00	0.67		
													65	1.486	62.00	0.18		
	6	7	99.6	63	48	15	15	9.00	8.96	33.40	1.470	27	10	1.292	16.00	0.05	1.397	58
													30	1.378	53.00	0.03		
													65	1.478	82.00	0.02		
		14	99.6	61	47	14	14	11.00	10.96	23.24	1.470	27	10	1.280	13.00	0.25	1.397	98
													30	1.325	84.00	0.16		
													65	1.432	103.00	0.01		
		28	99.6	62	46	16	16	9.00	8.96	35.79	1.47	27	10	1.270	11.00	0.36	1.397	74
													30	1.320	60.00	0.40		
													65	1.430	78.00	0.28		
	8	7	99.6	60	48	12	12	7.00	6.97	33.99	1.44	23	10	1.251	18.00	0.05	1.36	73
													30	1.305	50.00	0.04		
													65	1.435	104.00	0.03		

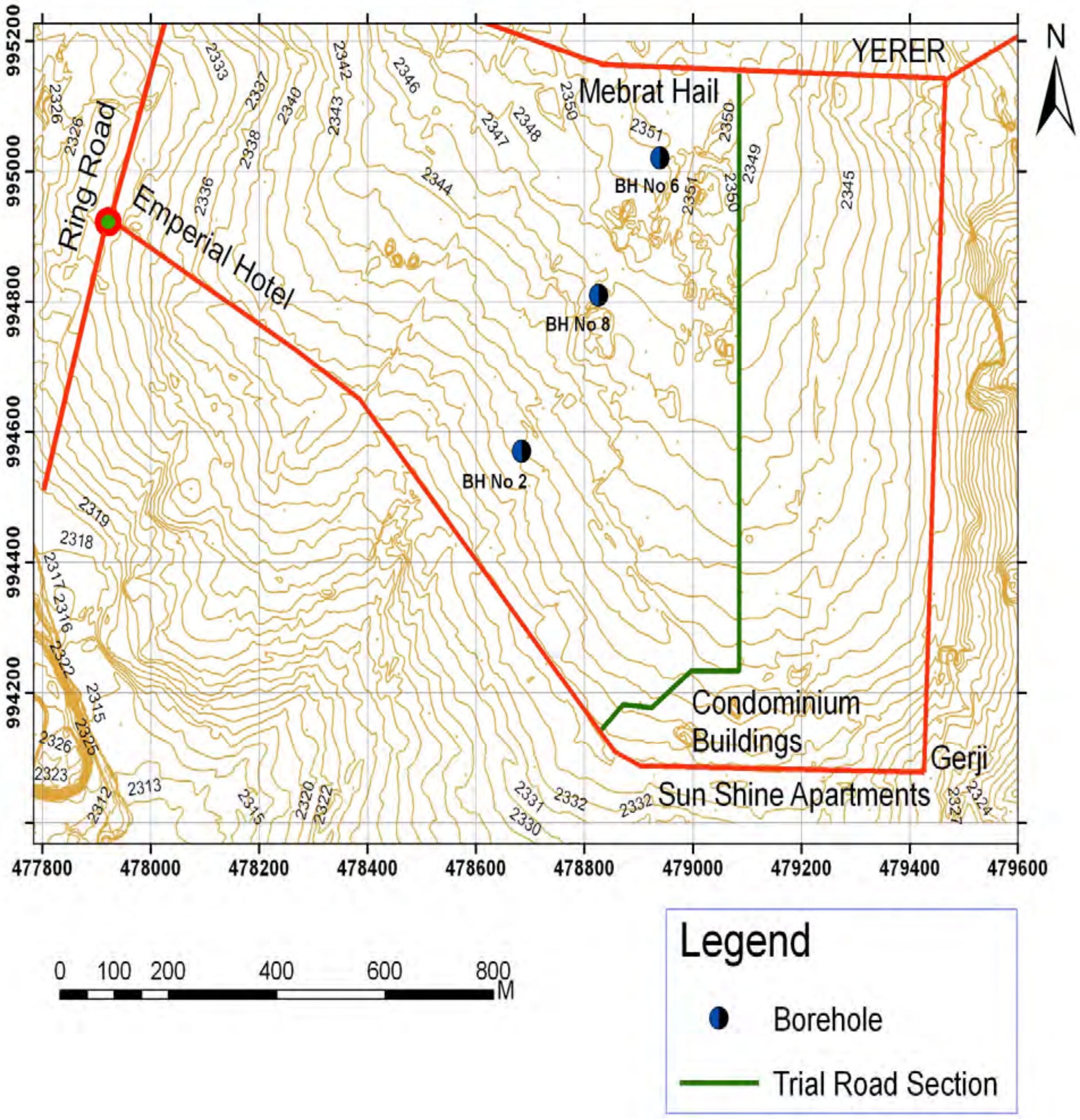
Annex 9: Summary of test results of ANSS treated sub-grade soil

Sample	ANSS Ratio %	Curing Period Days	0.425 seive	Atterberg Limit				LS (%)	Weighted Shrinkage W_s	Expansiveness Nature, €ex	Proctor		3Point CBR (AASHTO T193)				95% MDD	CBR @ 95% MDD
				LL	PL	PI	w_p				MDD g/cc	OMC %	No. of Blows	Dry Density (g/cc)	CBR %	Swell %		
ANSS-Light Grey Soil Mixture	2	7	99.9	81	47	34	34	21.40	21.38	30.64	1.450	28.5	10	1.160	2.00	10.18	1.380	2
													30	1.310	2.00	7.60		
													65	1.450	2.00	5.26		
		14	99.9	81	50	31	31	15.00	14.99	48.38	1.450	28.5	10	1.240	3.00	9.27	1.380	3
													30	1.360	3.00	7.34		
													65	1.460	3.00	5.52		
	4	7	99.9	77	52	25	25	20.70	20.68	11.79	1.440	29	10	1.200	10.00	1.95	1.370	12
													30	1.320	12.00	1.86		
													65	1.440	13.00	1.69		
		14	99.9	75	53	22	22	10.70	10.69	43.56	1.440	29	10	1.210	7.00	1.61	1.370	14
													30	1.360	14.00	1.38		
													65	1.440	15.00	0.46		
	6	7	99.9	73	54	19	19	13.90	13.89	23.90	1.500	29	10	1.210	13.00	1.63	1.430	18
													30	1.340	17.00	0.83		
													65	1.500	18.00	0.35		
		14	99.9	70	55	15	15	13.90	13.89	14.31	1.500	29	10	1.16	13.00	1.34	1.430	19
													30	1.32	16.00	1.42		
													65	1.50	20.00	0.98		
		28	99.9	68	55	13	13	13.90	13.89	9.51	1.5	29	10	1.16	11.00	1.55	1.430	21
													30	1.32	16.00	0.71		
													65	1.50	24.00	0.23		
ANSS-Dark Grey Soil Mixture	2	7	99.6	79	47	32	32	21.40	21.31	25.87	1.450	27	10	1.160	3.00	5.61	1.380	3
													30	1.310	3.00	4.91		
													65	1.480	4.00	3.40		
		14	99.6	79	48	31	31	13.60	13.55	6.94	1.450	27	10	1.270	3.00	8.34	1.380	4
													30	1.340	4.00	6.37		
													65	1.470	5.00	4.57		

Annex 9: Summary of test results of ANSS treated sub-grade soil

Sample	ANSS Ratio %	Curing Period Days	0.425 seive	Atterberg Limit				LS (%)	Weighted Shirinkage W_s	Expansiveness Nature, €ex	Proctor		3Point CBR (AASHTO T193)				95% MDD	CBR @ 95% MDD
				LL	PL	PI	w_p				MDD g/cc	OMC %	No. of Blows	Dry Density (g/cc)	CBR %	Swell %		
ANSS-Dark Grey Soil Mixture	4	7	99.6	74	51	23	23	18.20	18.13	16.78	1.460	26.5	10	1.080	9.00	1.58	1.390	21
													30	1.310	17.00	1.26		
													65	1.460	25.00	1.05		
		14	99.6	70	52	17	17	18.20	18.13	2.44	1.460	26.5	10	1.240	10.00	1.26	1.390	28
													30	1.360	26.00	1.68		
													65	1.460	33.00	0.38		
	6	7	99.6	70	54	16	16	13.90	13.84	16.75	1.470	26	10	1.110	18.00	1.01	1.400	37
													30	1.290	35.00	0.45		
													65	1.470	41.00	0.09		
		14	99.6	67	54	13	13	9.60	9.56	26.28	1.470	26	10	1.180	29.00	1.32	1.400	40
													30	1.320	37.00	1.17		
													65	1.470	42.00	0.61		
		28	99.6	65	47	18	18	8.60	8.57	42.12	1.470	26	10	1.160	29.00	0.12	1.400	47
													30	1.230	40.00	0.07		
													65	1.470	50.00	0.05		

Annexure 10: Borehole location and associated borehole logs



PROJECT: Residential Apartments

LOCATION: Gerji, Addis Ababa

BORING TYPE: Rotary Coring

DATE STARTED: 26/05/95

DATE COMPLETED: 27/06/95

BH No 2

BH ELEVATION: ________

INCLINATION: Vertical

SHEET: 1/1

DEPTH (M)	Casing size (mm)	Drilling Size (mm)	SAMPLE RECORD	SPT /N-VALUE/	DEPTH (M)	PROFILE	TCR (%)	RQD (%)	Field Description of Soil/rock	GWT
					0.60		58			
1					1.05		100			
					1.45		100			
2					1.80		100			
3					3.35		88			
4					4.15		100		Dark to dark gray stiff expansive CLAY	
5		100			5.35		100			NILL
6					6.55		100			
7							100			
8					8.20					
					8.40		100		Yellowish red silty CLAY	
					8.70					
9					9.20		100		Whitish to light gray highly weathered and fractured medium strong IGNIMBRITE	
10					**10.00**		100	0		

BH = Borehole

TCR = Total Core Recovery

RQD = Rock Quality Designation

GWL = Ground Water Level

SPT = Standard Penetration

(Source of data: Addis Ababa Housing Development Office)

LOCATION: Gerji, Addis Ababa

BORING TYPE: Rotary Coring

DATE STARTED: 30/05/95

DATE COMPLETED: 03/06/95

BH No 6

BH ELEVATION: ________

INCLINATION: Vertical

SHEET: 1/1

DEPTH (M)	Casing size (mm)	Drilling Size (mm)	SAMPLE RECORD	S.P.T. /N-VALUE/	DEPTH (M)	PROFILE	TCR (%)	RQD (%)	Field Description of Soil/rock	GWT
		100			0.45		93		Dark to dark gray stiff expansive CLAY	NILL
1					0.85		100			
					1.20		100			
					1.60		100			
2					2.00		100			
3					3.55		81			
4										
5					4.95		100			
6					6.25		100			
					6.75					
7					7.40		96		Yellowish to white gray clay SILT (tuff deposit)	
8					8.35		100			
9					**9.70**		100			
10					**10.05**		100	0	Light gray, highly to moderately weathered and fractured, weak to medium strong IGNIMBRITE	

BH = Borehole

TCR = Total Core Recovery

RQD = Rock Quality Designation

GWL = Ground Water Level

SPT = Standard Penetration

(Source of data: Addis Ababa Housing Development Office)

LOCATION: Gerji, Addis Ababa

BH No 8

BORING TYPE: Rotary Coring

BH ELEVATION: ________

DATE STARTED: 30/05/95

INCLINATION: Vertical

DATE COMPLETED: 03/06/95

SHEET: 1/2

DEPTH (M)	Casing size (mm)	Drilling Size (mm)	SAMPLE RECORD	S.P.T. /N-VALUE/	DEPTH (M)	PROFILE	TCR (%)	RQD (%)	Field Description of Soil/rock	GWT
					0.00		93			
1							100			
					1.30		100			
							100			
2							100			
3							81			
					3.50					
4	116	116					100		Dark to dark gray stiff expansive CLAY	
5					5.00					
6							100			
					6.25					
7					7.00					NILL
8							100		Dark gray to yellowish red silty CLAY	
					8.50					
					8.85		100			
9					9.00					
					9.50		100			
10					**10.00**		100	0	Light gray, moderately to highly weathered, and fractured medium strong IGNIMBRITE	
11		100			10.70		100	0		
					11.60		100	0	Whitish purple to red silty CLAY (tuff deposit)	
12					11.70					
13							100		Light gray to red sandy silty with ignimbrite fragments	

LOCATION: Gerji, Addis Ababa

BH No 8

BORING TYPE: Rotary Coring

BH ELEVATION: ________

DATE STARTED: 30/05/95

INCLINATION: Vertical

DATE COMPLETED: 03/06/95

SHEET: 2/2

DEPTH (M)	Casing size (mm)	Drilling Size (mm)	SAMPLE RECORD	S.P.T. /N-VALUE/	DEPTH (M)	PROFILE	TCR (%)	RQD (%)	Field Description of Soil/rock	GWT
14										
15					15.00		100		Light gray to red sandy silty with ignimbrite fragments	
16					16.20					
17		100					100			NILL
18					17.50					
					18.20				Red stiff CLAY	
19							100		White to gray silty CLAY (decomposed ignimbrite)	
20					**20.00**					

BH = Borehole
TCR = Total Core Recovery
RQD = Rock Quality Designation
GWL = Ground Water Level
SPT = Standard Penetration
(Source of data: Addis Ababa Housing Development Office)