EVALUATION OF SODIUM SILICATE AND ITS COMBINATION WITH CEMENT/LIME FOR SOIL STABILIZATION

BY

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CONSTRUCTION TECHNOLOGY AND MAGEMENT

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DECLARATION

I hereby declare that the thesis entitled EVALUATION OF SODIUM SILICATE AND ITS COMBINATION WITH CEMENT/LIME FOR SOIL STABILIZATION has been carried out by me under the supervision of Prof. Abebe Dinku, Department of Addis Ababa University during the year 2011 as part of Master of Science Program in Construction Technology and Management. I further declare that this work has not been submitted to any other University or institution for the award of any degree or diploma.

Place: Addis Ababa

Date: October 2011

Ehitabezahu Nigussie

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ABSTRACT

This research work is aimed to evaluate the suitability of slightly alkaline liquid sodium silicate for stabilization of montmorillonitic clay and clayey sand with gravel in Ethiopia. The study is also aimed to investigate the effect of applying sodium silicate in combination with hydrated lime or ordinary Portland cement on the engineering properties of treated soils. The laboratory work involved grain size analysis and index property determination to classify soil samples. Atterberg limit test, Proctor test and California Bearing Ratio tests were used to evaluate properties of treated soils. Montmorillonitic clay was treated using 2%, 4% and 6% lime, 1%, 2.5% and 6% liquid sodium silicate and the respective combinations of the additives by dry weight of the soil. Clayey sand with gravel was treated with 3%, 5% and 7% cement, 1%, 2.5% and 6% liquid sodium silicate and the respective combinations of the additives by dry weight of the soil. Samples were compacted after typical soaking duration of 30 to 45 minutes to account for strength loss due to compaction delay. Samples were typically cured for 3 and 7 days before testing and additional 28 days of curing were considered for Atterberg limit test. Sodium silicate reduced plasticity indexes of samples at least by 11.96% compared to untreated soils. Curing enhanced the reduction in plasticity of soils treated with sodium silicate. It was observed that lime reduced the plasticity index of treated soils; however, carbonation reversed improvements. Atterberg limit samples treated with cement resulted in non-plastic soil. Treating expansive soil with sodium silicate or combination of lime and sodium silicate gave odd curves from which a maximum dry density or optimum moisture content could not be determined. Blending clayey sand with sodium silicate or its respective combination with cement proportionally decreased the dry density of the soil. Sodium silicate or its respective combination with lime gave decreased strength values and increased swelling properties compared to the respective lime treatments. Mixing clayey sand with cement gave significant strength values. Applying 1% sodium silicate in concert with cement gave shear strength values larger than the respective cement treatments. When the quantity of sodium silicate was increased to 2.5% and beyond it hindered strength development. Curing enhanced strength development and reduced swelling properties for all treated soils. Findings imply that good quality materials, dense compaction, proper curing and sufficient stabilizers should be applied for cementitious stabilization. The necessary precautions also need to be taken whenever cementitious stabilizers are applied in combination with sodium silicate so that the soil could be involved in the hydration process. Sodium silicate is not a suitable stabilizer for expansive soils, but it relatively gives encouraging results on course grained materials. Good drainage system is highly recommended for sodium silicate stabilization.

Key words: California Bearing Ratio, Dry Density, Plasticity Index, Soil Stabilization

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SYMBOLS AND ABBREVIATIONS

AACRA	Addis Ababa City Roads Authority
AASHTO	American Association of Highway and Transportation Officials
ASTM	American Society for Testing and Materials
C	Cement
CBR	California Bearing Ratio
CS	Clayey Sand
C-S-H	Calcium Hydrogen Silicate
ERA	Ethiopian Roads Authority
L	Lime
LL	Liquid Limit
MC	Moisture Content
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPC	Ordinary Portland cement
PI	Plastic Index
PL	Plastic Limit
SADC	Southern Africa Transport and Communications Commission
SS	Sodium Silicate
UCS	Unconfined Compressive Strength

1. INTRODUCTION

1.1 General Background

Soils are naturally occurring materials that are used for road construction and other civil engineering works. Soils are used for the construction of all layers of pavements except the surface which is made of concrete or asphalt. Soils are, therefore, a critical element influencing the success of a construction project (Departments of US Army, 1994).

However, not all naturally occurring materials are suitable for construction. Problematic soils such as expansive clay cause major problems in the design, construction and maintenance of pavements. It is estimated that about 40% of the country of Ethiopia is covered with expansive clay pausing economical and construction challenges to the sector (Molenaar, 2005). Over the past 13 years, it is reported that 40% of the total road sector development expenditure in Ethiopia was allocated to rehabilitation and upgrading of trunk roads with additional 11% utilized for maintenance works alone (ERA, 2011).

This urges the need for wider application of cost effective and environmentally friendly technologies, such as chemical stabilization, to be customized and adopted to the current road construction trend in the country. Chemical stabilization is a process by which substandard and/or problematic soils are treated with chemicals to attain improved strength and stability properties (Caterpillar, 2006).

Sodium silicate is one of the safest industrial chemicals with diverse applications including soil stabilization (Peter M., 2003). This research aims to evaluate the performance of this chemical as a soil stabilizer in Ethiopia by using a locally produced liquid product. The study also aims to investigate if there is synergetic effect to combining sodium silicate with traditional soil stabilizers, lime and cement, on the engineering properties of stabilized soils.

1.2 Rationale of the Research

In the context of Ethiopia's geography, pattern of settlement and economic activity, transport plays a vital role in facilitating economic development. In particular, road transport provides the means for the movement of people, utilization of land and natural resources, improved agricultural production and marketing, access to social services and opportunities for sustainable growth. Therefore, the road transport system supports social and economic growth and plays a key role as a catalyst to meet poverty reduction targets in Ethiopia.

However, majority of design, construction and maintenance approaches used in the road sector in the country are based on practices and procedures developed in other countries, under conditions that are often dissimilar to those in Ethiopia. Direct application of these international practices can lead to higher than necessary construction and maintenance costs and a sub-optimal road performance (ERA, 2011). Therefore, contextual studies are mandatory.

In Ethiopia, applying chemical additives for pavement stabilization is not a wide spread practice. However, both traditional and non-traditional stabilizers have been introduced and applied to road construction. Studies have been made by postgraduate students of Addis Ababa University to evaluate suitability of these chemicals particularly for expansive subgrade stabilization. However, no research has been made to evaluate locally produced liquid chemicals such as sodium silicate for soil stabilization in Ethiopia. Therefore, this study is an attempt to investigate the properties of liquid sodium silicate as a soil stabilizer and evaluate the effect of its application in concert with traditional stabilizers, hydrated lime and ordinary Portland cement for soil stabilization.

1.3 Objectives

The objective of this thesis work is to study the suitability of sodium silicate for expansive soil stabilization, unsuitable for pavement subgardes, by increasing their bearing capacity and decreasing the swelling pressure and heave. In addition to this, it aims to investigate suitability of the chemical to decrease pavement thickness by increasing the bearing capacity of substandard subbase materials. Cement and lime are well known subbase and subgrade stabilizers. This study aims to assess the potential improvement in strength and decrease in plasticity of soils by combining these stabilizers with sodium silicate. The study has the specific objective of investigating the response of soils though the application of the chemical additives at various curing durations.

1.4 Scope of the Study

This study has been supported by secondary resources and a series of laboratory experiments. However, the findings of the research are limited to two soil samples considered in the research which are expansive clay and clayey sand with gravel. The results are also specific to the type of chemical additives used and test procedures that have been adopted in the experimental work. Therefore, findings should be considered indicative rather than definitive for filed applications.

1.5 Methodology

The present study started by setting a clear framework of the research by reviewing secondary resources form the literature, research bulletins, previous studies and the internet. Samples of soil that represent expansive subgrade and sub-standard subbase soil were collected from Bole Senior Secondary and Preparatory School and Bole-Gergi road section, both found in Addis Ababa. Primary data was collected for the study by conducting a series of laboratory tests.

Sample preparation of the experimental work involved air and/or sun-drying, pulverization (for expansive clay) and sieving of soil to the required particle size. Classification of soil was determined by running index property and grain size analysis tests. Improvement in the index properties of the soil were assessed using Atterberg limit test. Shear strength development of the soil was studied using California Bearing Ratio (CBR) test and swelling potential was assessed by CBR swell results.

The following particulars were considered with respect to the additives and the mixing ratios used. Expansive clay was treated with lime, sodium silicate and combination of the two additives. Clayey sand was treated with cement, sodium silicate and combination of the two additives. A variation in curing duration was taken as another variable.

Expansive clay was treated at the following mixing ratios;

- 0%, 2%, 4% and 6% of hydrated lime by dry weight of the soil
- 0%, 1%, 2.5% and 6% of sodium silicate by dry weight of the soil
- Combination of the respective mixing ratios mentioned above (e.g.2% lime and 1% sodium silicate, 2% lime and 2.5 sodium silicate etc.) for the combined application
- Curing durations were varied at 0, 3, 7 and 28 days for Atterberg samples while CBR samples (made using results of standard compaction) were cured for 0, 3 and 7 days.

Similarly for clayey sand with gravel the following mixing ratios were considered;

- 0%, 3%, 5% and 7% of ordinary Portland cement by dry weight of the soil
- 0%, 1%, 2.5% and 6% of sodium silicate by dry weight of the soil
- The respective mixing ratios mentioned above were applied in concert and
- Treated Atterberg samples cured for 0, 3, 7 and 28 days and CBR samples (made using results of modified compaction) were cured for 0, 3 and 7 days.

1.6 Organization of the Thesis

The presentation of this thesis work is organized in six chapters. The first chapter gives a brief description of the thesis background, objectives, scope and methodology employed. The second chapter explains the importance of stabilization and its significance in the Ethiopian context. The third chapter discusses the conceptual back ground of the additives used for the research and important parameters that can affect stabilization process. Important details from previous studies are also included in this chapter. The fourth chapter briefly describes the characterization of materials used for the study, experimental design and standardized testing procedures followed. The fifth chapter reports the test results obtained; analysis of results and discussion of results with respect to the theoretical background and with respect to findings of previous studies is also made. Finally, conclusions and recommendations drawn from the study are presented in chapter six.

2. THE NEED OF SOIL STABILIZATION

2.1 Historical Background

The necessity of improving the engineering properties of soil has been considered as old as construction has existed. Many of the ancient Chinese, Romans and Incas buildings and road ways which exist till today utilized different techniques of soil stabilization (Caterpillar, 2006). The use of lime as a building material dates back 5,000 years when lime and clay were mixed and compacted to form bricks used in the construction of the pyramids of Shensi in Tibet. About 2,000 years ago the Romans used lime to improve the quality of their roads. The Romans also made mixtures of lime and volcanic ash called "pozzolana" in which the principles of today's cement can be seen. John Smeaton built the Eddystone lighthouse in 1756 using a mixture of blue lime and pozzolanic clay without being aware that he had discovered the basic principle of cement manufacture. This enabled Joseph Aspdin to patent the process, which he called "Portland cement" in 1824 (Gautrans, 2004).

The modern era of soil stabilization began in the United States during 1960’s and 1970’s when shortages of aggregates and petroleum resources forced engineers to consider alternatives of road construction instead of soil replacement (Caterpillar, 2006). Since 1930 tests have been carried out in the United States with lime stabilization but success was achieved only ten years thereafter (Gautrans, 2004). The use of cement stabilization is over 65 years old with methods and materials proven and well established (Tensar, 1998). Non-traditional stabilization products have been in development since the 1960’s with many research papers and projects written on the subject. However, despite the multitude of information available the acceptance of these stabilization products is to be proven through time (Alex E. and David Jones, 2010).

2.2 Significance of Stabilization in the Ethiopian Context

The road network provides the principal mode of freight and passenger transport in Ethiopia. Efficient transport plays a huge role in promoting development by lowering transport costs, cutting travel time and improving the quality of transport services. Therefore, the performance of the road sector plays a vital role in growing the economy of the country.

However, only 30% of Ethiopia's area is served by a modern road transport system with road density of 44.4 km per 1000 square kilometers which is lower than the average road density of 54 km per 1000 square kilometer for Sub-Saharan African countries. This limitation of the road net work in Ethiopia often causes remoteness and isolation of communities. Remoteness leads to lack of services and severely constrains citizens' ability to contribute to the economy and development of the country (ERA, 2011).

On the other hand, the extraction of substantial amounts of non-renewable natural resources for road construction creates significant damaging impacts on the local environment and its inhabitants (SADC, 2003). Therefore, construction techniques implemented to solve these socioeconomic problems need to be not only time and cost effective but also environmentally friendly.

Chemical stabilization minimizes cost of pavement construction by reducing thickness of pavement layers and reduces depletion of natural resources by improving properties of in situ soil to acceptable levels. A stabilizer is more often required to improve the properties of weak and very weak soils (Alex E. and Jones D., 2010). Such kind of weak soils can be referred to as problematic soils.

Addis Ababa City Roads Authority (AACRA) manual (2004) defines *problem soils as soils which are not suitable for road construction.* The manual further classifies problematic soils in to low strength, *expansive*, dispersive and organic soils. Expansive soils are commonly occurring problematic soils that have a significant coverage in Ethiopia as shown in figure 2.2 below.

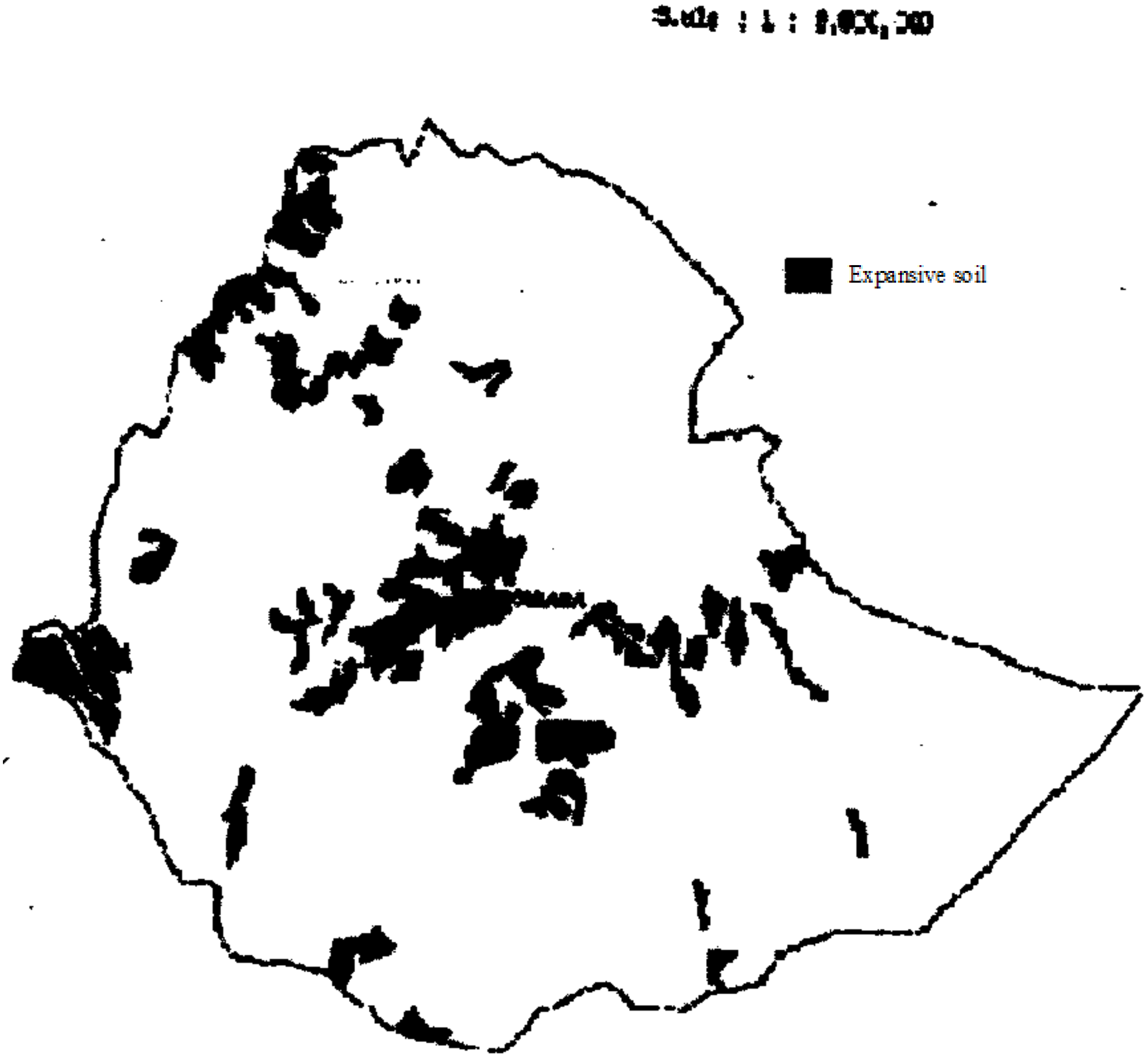


Figure 2.2 Distribution of Expansive Soil in Ethiopia

Expansive soil is characterized by its high swelling behavior, consecutive volume change and lose of strength in CBR when saturated. In the dry state, expansive soil becomes fissured and affected by soil falls, which gives way to develop into gullies. The development of cracks allows water to enter deep in to the subgrade material causing considerable expansion due to change of volume *and causes deformation of pavement* *surfaces.* Difficulty in road and airport runway performance in Addis Ababa caused by expansive soil can be a good example. Based on investigations conducted around Bole area, thickness of black cotton soil in Addis Ababa varies from 0.3 to 10m.

In Ethiopia, pavement soil stabilization is mainly limited to mechanical stabilization particularly blending soils of two or more gradations. It is a recommended practice to replace sub-standard or problematic soils in Ethiopia instead of treating them with traditional stabilizers for economical reasons (AACRA, 2004). The use of imported material that has to be borrowed at a specific site and transported over significant distances to the construction site is also expensive not only due to production and transportation costs, but also heavy haul of large quantities that damages the existing infrastructure resulting in increased maintenance costs. *Therefore, upgrading qualities of in situ substandard soils in to acceptable construction materials needs to be investigated* (Molenaar, 2005).

Chemical stabilization in pavement construction has been widely used in many parts of the world. For example, in South Africa, stabilization has been extensively used that one or more of the pavement layers in every sealed road in Gauteng (one of the provinces) is stabilized (Gautrans, 2004). In Ethiopia, the primary use of cement and lime stabilization has so far been with gravelly soils to produce road bases (ERA, 2002). Non-traditional stabilizers that have been introduced to the country include RBI Grade 81, CON-AID, SS44/LS40, Pure Crete and Zym-Tec Enzyme (Aschle G. 2008, Ashuro T. 2010).

3. CONCEPTUAL REVIEW

3.1 What is Soil Stabilization?

When unsuitable materials are encountered measures like avoiding the route, redesigning the pavement with thicker sections or replacing the poor soil with good quality materials are viable but increasingly expensive options. With improved technological advances and concern for depletion of non-renewable resources, improving the properties of soil using chemical additives is gaining increased popularity (Caterpillar, 2006).

Soil stabilization is a process whereby increased strength and stability of the soil is attained mainly by mechanical or chemical means. *The most common improvements achieved through stabilization include better soil gradation, reduction of plasticity index or swelling potential, increase in durability and strength.* In wet weather, stabilization may also be used to provide a working platform for construction operations. These types of soil quality improvement are referred to as soil modification. Soil stabilization decreases damage caused by settlement, washing and collapsing (Departments of US Army, 1994).

3.2 Methods of Soil Stabilization

3.2.1 Mechanical Stabilization

Mechanical stabilization can be defined as a process of improving the stability and shear strength characteristics of the soil without altering the chemical properties of the soil (Molenaar, 2005). *It is common to use both mechanical and chemical means to achieve specified stabilization.* The main methods of mechanical stabilization can be categorized in to compaction, mixing or blending of two or more gradations, applying geo-reinforcement and mechanical remediation (Caterpillar, 2006).

3.2.2 Chemical Stabilization

Chemical stabilization is a method of improving the engineering properties of a material by adding chemical substances. Chemical stabilization is used for a wide range of purposes including: improving the bearing capacity and strength of pavement layers, dry temporary bypasses during rainy periods, delay certain chemical reactions that are detrimental to road soils or aggregates, dry out soil where the moisture content is too high for successful compaction, make soil less permeable where necessary, *reduce the plasticity of soils used in road construction and thereby reducing the effect of moisture variations*, *changing clay to a more granular and workable material and reducing swelling and shrinkage properties* (Gautrans, 2004).

Dallas N. and Nair S. (2009) classify chemical stabilizers in to three groups:

- **Traditional stabilizers:** such as Hydrated lime, Portland cement and Fly ash;
- **Non-traditional stabilizers:** comprised of sulfonated oils, ammonium chloride, enzymes, polymers, potassium compounds and
- **By-product stabilizers:** which include cement kiln dust, lime kiln dust etc.

Over and above these, there are inorganic and hydraulic products that are often clustered into non-traditional soil stabilizers. Perhaps a better term for them would be `hydraulic soil stabilizers` (Alex E. and Jones D., 2010).

This research evaluates the suitability of sodium silicate and its combination with traditional stabilizers (cement and lime) for soil stabilization. Accordingly, the respective soil additives and their mechanisms of stabilization are briefly discussed in section 3.3, 3.4 and 3.5 of this thesis. Further information on non-traditional stabilizers and their mechanism of stabilization can be found in (Ashuro T., 2010).

3.3 Lime Stabilization

The use of lime to dry, modify and stabilize soil is a well established construction technique (National lime association, 2006). The treatment of pavement subgrades with lime can significantly improve the engineering properties of a wide range of soils; typically medium, moderately fine and fine-grained soils.

The two primary types of lime used in construction today are quick lime (calcium oxide) and hydrated lime (calcium hydroxide). Heating lime stone at elevated temperatures produces quicklime and the addition of water to quicklime produces hydrated lime. Equation 3.3(a) and (b) show the reaction from which quick lime and hydrated lime are produced (Justin P. and Robert L. 2004).

$$CaCO_3 + \text{Heat} \rightarrow CaO + CO_2 \qquad \text{Equation [3.3(a)]}$$

$$CaO + H_2O \rightarrow Ca(OH)_2 + \text{Heat} \qquad \text{Equation [3.3(b)]}$$

Hydrated lime in the form of lime is used in the majority of lime stabilization work. Quick lime represents approximately 10 percent of the lime used in the lime stabilization process. Other forms of lime sometimes used in lime stabilization work are dehydrated dolomitic lime, monohydrated dolomitic lime, and dolomitic quick lime (Tensar, 1998).

According to AASHTO (2008) lime has a number of effects summarized as follows;

- **Soil drying:** is a rapid decrease in soil moisture content due to the chemical reaction between water and quicklime and the addition of dry material in to a moist soil.
- **Modification:** is improvement that occurs in the short term, during or shortly after mixing (within hours). Modification reduces the plasticity of the soil and improves short-term strength to the desired level.

- **Stabilization:** is a longer term reaction that is derived from the hydration of calcium-silicates and/or calcium aluminates in Portland cement or due to pozzolanic reactivity between free lime and soil or added pozzolans. A soil that is lime stabilized also experiences the effects of soil drying and modification (ERA, 2002).

3.3.1 Mechanisms of Lime Stabilization

Lime-soil reactions can broadly be grouped in to initial and longer-term (AASHTO, 2008). The initial reactions involve cation exchange by replacing the exchangeable Na^+ or K^+ ion in the clay by the Ca^{2+} ion of the lime. By this replacement of ions, the double water layer around the clay particle will decrease in thickness resulting in a significant change of the plasticity characteristics of the soil (Molenaar, 2005). According to Handy (1994) the rapid change in plasticity is also due to a strong reaction between the OH^- from the lime and the H^+ from clay mineral structure to form water. This process increases negativity of clay particles and free Ca^{++} ions satisfy this increased negative charge, as a result strengthening the electrostatic forces of flocculation (Tensar, 1998).

Longer-term reactions involve interactions between free lime $Ca(OH)_2$ and soil particles. These interactions are referred to as pozzolanic as they involve pozzolans, the alumina and silica made available from the soil by the high pH lime-water solution. These pozzolanic reaction products are similar to cementitious products formed when Portland cement hydrates. Maintaining a high enough pH condition, typically a pH of 12.4, is required to solubilize soil pozzolans that participate in these reactions. When these pozzolans react with free lime and water, a cementing effect among particles as well as an alteration of surface mineralogy occurs. These pozzolanic reactions contribute to an increase in strength which can be considerable depending on the mineralogy of the soil. Soil mineralogy is briefly discussed in section 3.6.1 of this thesis.

Pozzolanic reaction is a slow process compared to flocculation/ agglomeration reaction in soil. Therefore, mellowing periods, normally about one day up to four days are prescribed to maximize the effect of short term reactions in reducing plasticity and increasing workability (Justin P. and Robert L. 2004, AASHTO, 2008). Christopher M. and Thomas L. define mellowing time as *a rest time between mixing soil with water and additives and compacting the mixture to form specimens.*

The gain in strength associated with the formation of pozzolanic reactions is accelerated by heat, an advantage when using lime stabilization in hot climates. Strength also increases with time. *During the first one or two days after construction this increase is rapid. Thereafter, the rate slows down although strength gain continues provided the layer is well cured* (ERA, 2002).

3.3.2 Mix Design and Strength Characteristics

When using lime as a stabilizer, the goal of the mixture design is to find the optimum lime content to adequately stabilize the soil to meet desired strength requirements (Christopher M. and Thomas L., 2005). The optimal amount of lime can be determined by measuring the pH of the soil–lime mixture. As soon as free lime occurs, the pH will take its maximum value and will not increase further (Tensar, 1998).

Strength requirements can vary depending on the intended use of the subgrade and the overall cost associated with construction. In some instances it may be desirable to achieve the strongest subgrade possible in order to minimize pavement thickness or increase service life of pavement. In other instances, it may be desirable to reach a lower strength level that reduces the life cycle costs for the pavement. In still other instances, the goal may be only to improve the workability of the soils such that they are compactable. Therefore, a wide range of lime contents can be used to produce various desired results.

After estimating the optimum lime content, strength testing is used to verify the actual optimum lime content. *Lime contents between 2 to 10 percent are typically capable of producing significant strength gains.* While there is no universal definition of significant strength gain, most design procedures implement a requirement for unconfined compressive strength (UCS) increase of 50psi (345kPa) to be a viable option (Christopher M. and Thomas L., 2005).

3.4 Cement Stabilization

Portland cement is comprised of calcium-silicates and calcium-aluminates that hydrate to form cementitious products (AASHTO, 2008). Portland cement stabilization, commonly referred to as soil cement, is a mixture of Portland cement, water and soil compacted to a high density. Soil cement is sometimes referred to as a *cement treated* subgrade or cement stabilized subbase. When cured, the soil cement mixture becomes a hard, rigid base material. A flexible or rigid pavement surface is placed on top of the soil cement to complete the pavement structure.

Cement stabilization differs from other forms of chemical stabilization in such a way that structural strength is primarily obtained from the cementing action rather than from internal friction, cohesion, chemical ion exchange and/or waterproofing of the materials. Almost all types of soils can be used for cement stabilization except highly organic soils and heavy clay soils.

The four fundamental control factors for the design and construction of soil cement are moisture content, curing procedure and duration, compaction and cement content. Cement stabilization is generally considered to be too expensive for workability improvements alone (Tensar, 1998).

3.4.1 Mechanisms of Cement Stabilization

Hydration reaction is the primary mode of strength gain in soil cement. Free lime, $Ca(OH)_2$, produced during the hydration process can comprise up to about 25 percent of the cement and water mix on a weight basis. This free lime can produce pozzolanic reaction between the lime and soil, which can continue as long as the pH is high enough to solubilize the soil minerals (AASHTO, 2008).

The hydration product obtained from cement stabilization occurs through the same type of pozzolanic reactions as lime stabilization. It is the origin of silica required for pozzolanic reaction that differs. With cement stabilization, the cement already contains the silica, unlike lime stabilization where silica needs to be broken down from clay. Therefore, unlike lime stabilization, cement stabilization is fairly independent of soil properties (Christopher M. and Thomas L., 2005).

Tensar (1998) classifies mechanisms of cement stabilization in to four major groups

- **Hydration of cement (highest importance):** continuous skeleton of hard, strong material forms and encloses a matrix of unaltered soil. Strengthening of treated material and filling some of the voids occurs. Permeability and shrink/ swell tendencies are reduced and resistance to changes in moisture content is increased.
- **Cation Exchange (high importance):** Cation exchange alters electric charge, reducing plasticity and resulting in flocculation and aggregation of soil particles.
- **Carbonation (minor):** Lime generated during hydration of cement reacts with carbon dioxide in air to from cementing agents.
- **Pozzolanic Reactions (minor):** Free lime liberated during hydration reacts with silica or alumina from clay particles in the presence of moisture to form cementing agents.

Cement hydration is rapid and causes immediate strength gain in stabilized layers. Therefore, a mellowing period is not typically allowed between mixing and compaction. The general practice is to compact soil cement before or shortly after initial set, preferably within 2 hours of mixing (AASHTO, 2008).

However, published test procedures are not consistent on the mellowing time they indicate. Christopher M.and Thomas L. (2005) made a study on varying the effects of mellowing time on cementitious and polymer stabilizers on expansive sugrades. They found that strength started to decrease after 30 minutes of mellowing. *This decrease in strength is also comparable to the decrease in strength caused by two hours of delay.* Therefore, they specified a maximum allowable time of 30 minutes between mixing and compaction. *Based on this finding, treated samples used for this research were typically soaked for 30-45minutes before compaction to account for the loss of strength due to compaction delay.*

3.4.2 Mix Design and Strength Characteristics

The goal of mixture design using cement stabilization is to find the lowest cement content that will produce the desired strength. The cement content determines whether the characteristics of the mixtures are dominated by the properties of original soil or hydration products. The strength of soil cement increases linearly with the quantity of cement added to the soil (Christopher M.and Thomas L., 2005, ERA, 2002).

Cement stabilization is ideally suited for well graded aggregates with sufficient amount of fines to effectively fill void space and float the coarse aggregate particles. General guidelines for stabilization are that the plasticity index should be less than 30 for sandy materials. For fine-grained soils, soils with more than 50 percent by weight passing No. 200, the general consistency guidelines are that the plasticity index (PI) should be less than 20 and the liquid limit (LL) should be less than 40 in order to ensure proper mixing.

A more specific guideline based on the fines content is given in the equation [3.4.2] below defining the upper limit Plasticity Index (PI).

$$PI \leq \frac{20 + 50 - (\%\ \text{smaller than } 0.075\text{mm})}{4} \qquad \text{Equation [3.4.2]}$$

Cement content requirements vary depending on the soil type and desired properties of the soil cement. For most soil cement applications, Type I or Type II Portland cement conforming to ASTM C150 is used. Generally, as the clay content of the soil increases, the quantity of cement required increases. AASHTO soil classification system is used for pavement soil classification in Ethiopia. AASHTO's cement requirement for different types of soils is summarized in Table 3.4.2.

Table 3.4.2 Cement requirement for AASHTO soil Groups

AASHTO Soil Group	Usual Range in Cement Requirement in percent by		Typical Cement Content Percent by Weight
	Volume	Weight	
A-1-a	5-7	3-5	5
A-1-b	7-9	5-8	6
A-2	7-10	5-9	7
A-3	8-12	7-11	9
A-4	8-12	7-12	10
A-5	8-12	8-13	10
A-6	10-14	9-15	12
A-7	10-14	10-16	13

Water is necessary in soil cement to help obtain maximum compaction and cement hydration. Moisture contents of soil cement usually range from 10 to 13 percent by weight of oven dry soil cement. Water should be potable or relatively clean, free from harmful amount of alkalis, acids or organic matter (Dallas N. and Nair S., 2009, Tensar, 1998).

3.5 Sodium Silicate

Sodium silicate is one of various water soluble chemicals obtained in the form of crystals, glasses, powder or aqueous solutions which is produced by chemical fusion of silica sand and soda ash. Silicates are inorganic, polymeric, alkaline silica-based materials. All silicates are made of three basic components: silica (SiO_2) for which sand is the raw material, alkali (Na_2O or K_2O) for which soda ash or potash is the raw material and water (Peter M., 2003).

Sodium Silicate has diverse application as a raw material in the production of adhesives and cements, pulp and paper production, detergent and soap etc. Sodium silicate has a wide application for water treatment. Sodium silicate has also applications in sealing concrete products. Figure 3.5 shows production process of sodium silicate.

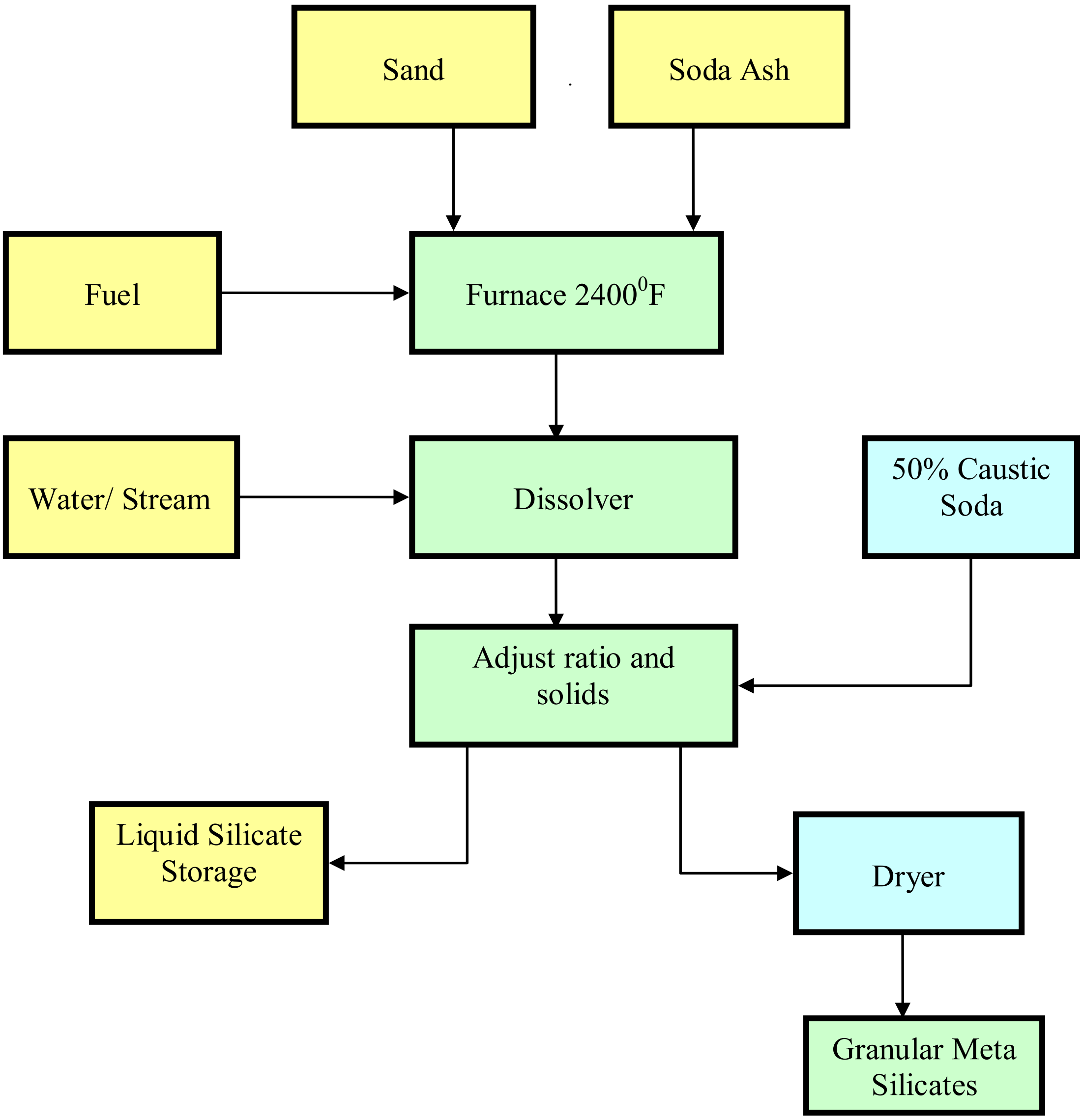


Figure 3.5 Production of sodium silicate

3.5.1 Sodium Silicate as Soil Stabilizer

The gel-forming property of sodium silicate is used as advantage in soil stabilization. *Sodium silicate solutions, along with reacting chemicals, have been used for the consolidation of porous soil structures for many years*. Soils are solidified and stabilized to increase their load-bearing capacity, to arrest settlement and lateral movement of foundations, and to control the flow of water in earthwork engineering projects such as dams, mines, tunnels, and excavations (OxyChem hand book). Soluble silicates are derived from, and ultimately return to nature, as silica (SiO_2) and soluble sodium compounds.

Since these are among the Earth's most common chemical components they offer minimum potential for harmful environmental effects (Turner C). Most of the documented research on polymers has been conducted in the agricultural industry where the products have been used to bind soils to prevent erosion by wind and water. (Gautrans, 2004)

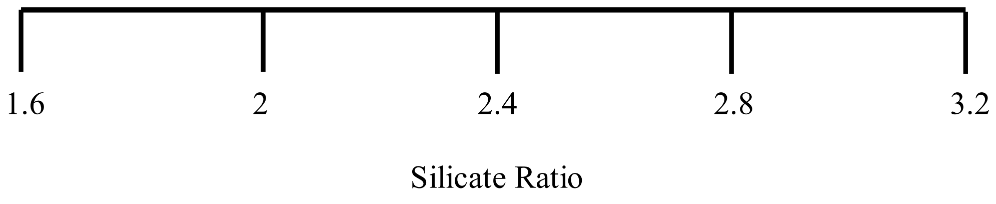
3.5.2 Important Properties of Sodium Silicate

Sodium silicate has three basic important properties which are weight ratio, pH and viscosity.

- **Weight ratio** it is defined by the ratio of SiO_2/Na_2O. Weight ratio is the most important physical property of silicate. It determines the reactivity of silicate and the physical properties such as viscosity. *As the ratio of silicate increases, the alkalinity of the solution decreases while the desired strength increases.* Properties of sodium silicate as a function of ratio are summarized in table 3.5.2 here under.

Table 3.5.2 Properties of silicates as a function ratio

High	Alkalinity	Low
High	Buffering	Low
High	Solubility	Low
High	Bound Moisture	Low
High	Drying Time	Low
Low	Desired Strength	High



- **Viscosity** is a function of weight ratio, solids and temperature. The viscosity of the silicate binder must be low enough so that good mixing and wetting of particles can be achieved. *The viscosity of silicates increases as the content of* Na_2O *by weight increases.* Silicate viscosity can be reduced by diluting with water or by heating.
- **pH of silicates** *is also a function of ratio; as the weight ratio increases, the pH decreases. All silicate products are in the pH range from 11 to 13* (Peter M., 2003).

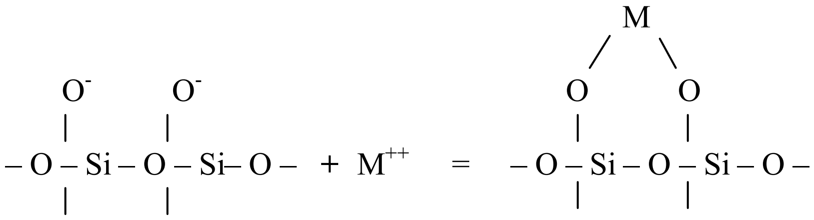
3.5.3 Mechanisms of Sodium Silicate Stabilization

Depending on how they are modified, silicates may be involved in four basic types of chemical reactions. Hydration/dehydration, surface charge modification, metal ion reaction and precipitation/gelation.

- **Hydration/ Dehydration:** Glassy nature of silicates imparts *strong and rigid physical* properties to a dried film coating. Bonds formed by dehydration can be dissolved in water unless silicate is post treated to temperature of more than 250^0C.
- **Surface charge modification:** Dissolved silica donates its ionic charge of 2 to other materials and cause them to repel one another causes *dispersion and flocculation effect of silicates and it only occurs with liquid silicates*
- **Metal Ion Reaction:** Soluble silica reacts with multivalent metal ions such as Calcium, Magnesium, Cadmium, Iron, Lead etc. and precipitates these metals out of solution and renders them in to insoluble and non-reactive product that displays long term stability.
- **Precipitation/Gelation reaction:** Occurs when the pH of a silicate solution drops below 10.7, such as due to addition of acid. It is another method of insolubilizing silicates other than heating dried silicates above 250^0C. Bonds formed are weaker but less likely to be destroyed by water.

The primary mechanism polymers stabilize soil is by physical bonding. That is when the water in the emulsions evaporates leaving a soil polymer matrix. Improvement in strength therefore, depends on physical property and ability of the polymer to coat soil particles adequately. *Thus, stabilization with polymer emulsions is suitable for granular materials but is less effective in fine grained soils because of reduced mixing efficiency resulting from their high specific surface area.*

Experiments also demonstrated a synergistic effect when polymers are applied in concert with small percentages of Type I portland cement. When diluted in water, soluble silicates depolymerize to form negatively charged oxygen sites.



$$-O-\underset{|}{\overset{\overset{\displaystyle O^-}{|}}{Si}}-O-\underset{|}{\overset{\overset{\displaystyle O^-}{|}}{Si}}-O- \; + \; M^{++} \; = \; -O-\overbrace{\underset{|}{\overset{\overset{\displaystyle O}{|}}{Si}}-O-\underset{|}{\overset{\overset{\displaystyle O}{|}}{Si}}}^{M}-O-$$

These sites are available to react with divalent metal cations as shown above. When *Portland cement and silicates are applied in concert, the cement hydration provides early strength where as the residual polymer provides improved ductility*. The ratio of cement and soluble silicate must be properly proportioned so that enough silicate is available for reaction, *but an excess is avoided that might react with all of the calcium in the system and inhibit set and strength development reactions* (Jeb S., 2007, PQ Corporation).

3.5.4 Mix Design and Strength Characteristics

Polymers typically used in soil stabilization produce excellent tensile and flexural strength, producing physical bonds with excellent strength (Jeb S., 2007). Silicates can be used to agglomerate many different materials such as metal fines, minerals, coke, absorbent materials, animal feed, carbon dust, *clay,* fertilizers, fly ash, glass chips, metal additives etc. The amount of silicate binder needed depends on particle surface area, percent moisture, method of curing, chemical composition and method of agglomeration. *Generally 1% to 4% silicate is required to bind the particles.*

For reactive materials such as clay, the silicate can be added directly to the material or be diluted with water before addition depending on absorptive properties of the material. *Bonds formed by dehydration are stronger but they can be dissolved in water unless post-treated to a temperature of 250*^{0}*C. When silicates are used in conjunction with a setting agent, the bond is formed by metal silicate reaction* or gelation depending on the type of setting agent used (PQ Corporation). Experiments also showed there is significant improvement in strength associated with curing polymers for 7 or 28 days compared to untreated samples under wet conditions (Jeb S., 2007).

3.6 Important Soil Properties

In this section, mineralogy and compaction characteristics of clay soils have been chosen to be discussed due to their relevance on the analysis of the results obtained in the experimental study. Detailed information on soil classification and soil cement can be found in (Tadege A., 2007).

3.6.1 Soil Mineralogy

The bulk of serious soil problems in road engineering are associated with fine grained materials. If fine grained materials have a high liquid limit (LL) and a high plasticity index (PI), they will show excessive swelling and shrinkage as well as a low bearing capacity when wet. This property is caused by clay minerals from which fine grained materials are made of.

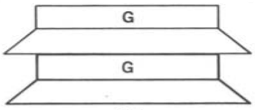
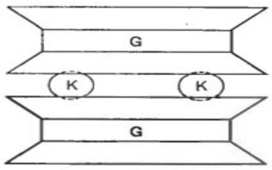
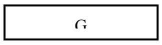
Clays are silicates built of two basic building blocks, silicate tetrahedron and aluminum or magnesium octahedron. Clay particles are less than 2 microns (0.002mm) in diameter. Clay minerals are formed by sandwiching tetrahedral and octahedral layers and sheets together. Tetrahedron sheet can be considered as a layer of silicon ions between a layer of oxygen and a layer of hydroxyl ions.

The centers of these tetrahedrons generally contain a silicon ion (Si^{4+}) but occasionally this is replaced by an aluminum ion (Al^{3+}) which, although it has not the same electrical value, has almost the same size as the silicate ion. This phenomenon is called isomorphous substitution. Isomorphous substitution is the most important cause of net electrical charge that a soil particle carries. Isomorphous substitution takes place in the following order;

$$Li^+ < Na^+ < H^+ < K^+ < NH^+ << Mg^{2+} < Ca^{2+} << Al^{3+}$$

There are three common groups of clay minerals of interest to soil and road engineers, kaolinite, illite and montmorillonite. The symbolic representation of the minerals is presented in table 3.6.1 and each group is briefly discussed here-under.

Table 3.6.1 Clay minerals

No.	Clay Mineral	Symbol	Remark
1	Kaolinite		 Silica sheet
2	Illite		 Gibbiste sheet (Octahedral sheet - Al^{3+} are the main cations)
3	Montomorillionite		The same as illite except balancing cation is not necessarily K^+ but can be any cation.

Kaolinite: The thickness of one kaolinite sheet is 7.2 Å. The chemical bonds inside of a sheet of kaolinite are covalent bonds and are very strong. The kaolinite sheets are locked together by weaker hydrogen bonds between the oxygens of the silica sheet and the hydroxyls of the alumina sheet. Hence, the particles have well developed cleavage parallel to the sheets. The hydrogen bonds are strong enough to provide considerable reinforcement between the sheets and as a result, the kaolinite flakes grow fairly large in nature (often 100 or more sheets in thickness). In addition, water cannot enter between sheets to expand or shrink the particles. Thus, the mineral is relatively stable.

Illite: The thickness of one illite sheet is 10 Å. The bonds within each sheet are very strong covalent bonds. The octahedral layer may contain Al, Mg, Fe or other cations. In the tetrahedral layer 1 in 7 Si^{4+} ions are replaced by an Al^{3+} ion giving the sheet a large deficit of positive charge. Some deficiency also results from insufficient charges in the octahedral layer. Hence, the illite sheet must not only adsorb cations to balance broken bonds at the edges of the sheet, but must also adsorb cations to balance charge deficiencies inside each sheet. To balance the positive charge deficit in the tetrahedrons potassium ions, K^+ ions enter between two tetrahedral layers. The exterior tetrahedral layers of the illite sheets are almost in contact with each other since the adsorbed potassium ion fits very nicely; cations inside the particle are unable to exchange. Because of the relatively strong bond, water will not easily penetrate and swell and shrinkage is not so much of a problem.

Montmorillonite: Structurally montmorillonite, *commonly known as expansive soil*, is similar to illite. The difference is much of the charge deficiency in montmorillonite comes from the octahedral layer. This charge deficit must be balanced in the same way as it is done with illite. However, the distance between the charge deficit and the cation is larger with the montmorillonite than with the illite. The bond between montmorillonite sheets is much less than that of illite; cations are also less firmly held. This in turns means that the charge balancing cation is not necessarily K^+ like in illite but can be any cation. The adsorbed cations are unable to lock the sheets firmly together and as a result, particles separate into a single sheet when montmorillonite is dispersed in water. *As a result, excessive heave or shrinkage due to moisture fluctuation makes them problematic soils. This lack of reinforcement between the sheets makes it impossible for large particles to form and thus montmorillonite particles are also very small.*

3.6.2 Electrical Charge on Soil Particle and Interaction with Water

A soil particle in nature attracts ions to neutralize its net charge. Experiments have shown that the net charge of clay particles is negative. Repulsive forces are highly dependent on the characteristics of the system. Attractive force (van der Waals' force) is independent of the characteristics of the fluid between particles. *Any change in the characteristics of the soil water system that reduces the thickness of the double layers reduces this repulsive force for the same inter-particle spacing.*

A tendency towards flocculation or dispersion may be caused by an alteration in the system characteristics which alters the double layer thickness. *Flocculation is caused by a decrease in double layer thickness* as a result of factors such as temperature increase or decrease of pH. *In general a flocculated structure has a higher strength and a lower compressibility than a dispersed structure.* Figure 3.6.2 compares flocculation and dispersion.

Figure 3.6.2 Flocculation (left), Dispersion (right)

3.6.3 Compaction Characteristics

Compaction is important to give pavement soil the required strength to carry the loads that will be applied. Differences in soil structure as a result of compaction can have a pronounced effect on its engineering properties, dry density and the water content. Compaction tests in the laboratory are therefore performed to establish the optimum values. Proctor test is the most commonly used laboratory test for compaction.

The main purpose of compaction effort is to increase soil density by deforming soil lumps and expelling air between them. Loose moist soil consists of *lumps of particles that are held together by effective stress caused by capillarity*. The compaction process attempts to deform these lumps and make them a single unit. Adding water aids compaction process as water serves as a lubricant for soil particles to slide over each other, increasing the density of soil. But when the quantity of water is beyond the optimum level, it drives soil particles apart, decreasing dry density. This is the process that is believed to result in peak moisture – density relationships.

However, the process that results in the familiar peaked compaction curve is quite complex. It involves capillary pressures, pore air pressure, permeability, surface phenomena, osmotic pressures and the concepts of effective stress, shear strength and compressibility (Molenaar, 2005, Tadege A., 2007). Experiments (including this thesis work) have shown that compaction curves can deviate from the usual bell shape.

Lee and Suedkamp (1972) studied compaction curve for 35 soil samples using ASTM D 698 and their findings are summarized in figure 3.6.3 below (Braja M., 2006).

Name of curve	Description	Liquid limit	Remark
Type A	Single peak	30<LL<70	
Type B	One and half peak	LL<30	
Type C	Double peak	LL<30	
Type D*	No definite peak (Odd shaped)	LL≥70	*Such soils are uncommon; might exhibit compaction curves of C or D

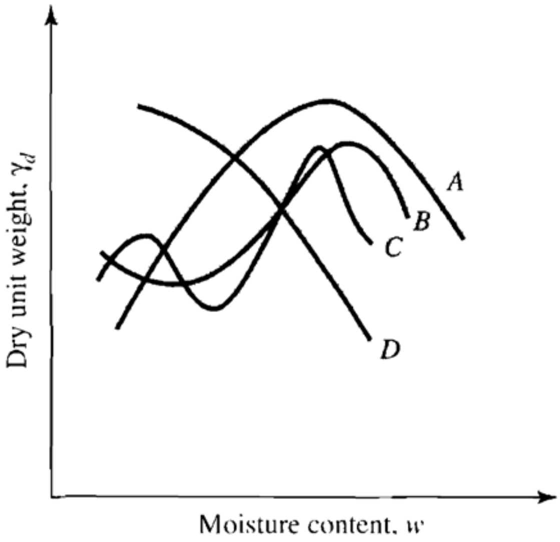


Figure 3.6.3 Types of compaction curves

3.6.4 Relations between Laboratory and Field Compaction

It is quite obvious that the compaction in the laboratory by means of the Proctor method differs substantially from the way compaction is achieved in the field. The relation between lab and field compaction can only be obtained on the basis of experience and by means of test sections.

3.6.5 Swelling

Flocculated structures on the other hand swell more than dispersed structures. Specimens that are compacted at the dry side of the optimum moisture content show more swell. Some of the water that enters a compacted specimen during swelling is required simply to fill the pores and bring the soil to a saturated condition, as distinct from water adsorbed by the soil during the swelling process (Molenaar, 2005).

3.7 Carbonation

Carbonation is the process by which lime and cementitious products added to a material or developed during the hydration reactions of cementitious stabilization of a material react with carbon dioxide in the atmosphere or soil air. Carbonation could be an explanation where failures of roads due to surface disintegration have occurred in lime-stabilized bases. Stabilized material can lose, on average, about 40 per cent of its unconfined compressive strength due to carbonation, regardless of it having been stabilized with lime and/or cement. The most common effects of carbonation are:

- Loss of strength, especially in the top part of the stabilized layers
- *Return of plasticity index to that of the original material*
- Flaking and blistering of the primed base courses
- Formation of a loose layer of material between the base and surfacing
- Movement and cracking of the surfacing on the base course (loose surfacing)

Disintegration of the stabilized layer during carbonation is caused by the volume increase (10 percent) as $Ca(OH)_2$ changes to $CaCO_3$ and to a lesser extent, the volume decrease (2 percent) as the cementitious products revert to silica and calcium carbonate. If the stresses generated by these volume changes exceed the tensile strength of the stabilized material, micro-cracking will occur resulting in loss of strength and deterioration. For this reason, the tensile strength is so important. *Adding sufficient stabilizer helps to develop a tensile strength sufficient enough to resist micro-cracking.*

However, not all carbonated materials are prone to failure. *The level of deterioration due to carbonation is highly dependent on the quality of materials used. W*eak or marginal quality materials, especially with residual basic crystalline and calcrete materials are susceptible to carbonation and moisture ingression. Tests to confirm carbonation include: phenolphthalein test, dilute hydrochloric acid test and determination of pH.

The best way of reducing carbonation from the top is effective curing, compacting layers to the highest density as practically possible and application of both prime and surfacing as soon as possible. It is stressed that possibility of carbonation should in no way prevent the use of lime and cement as stabilizing agents, the importance of proper curing and sufficient addition of stabilizer should be emphasized (Gautrans, 2004, TRH13, 1986).

3.8 Significance of Curing

The hydration reactions of cementitious stabilization require a constant source of moisture. These reactions commence when the stabilizer is applied and continue slowly for a long period provided moisture is present. *The first seven days after construction, however, are the most critical, during which effective curing is essential.* This is not the case where only lime is used.

Curing is essential to limit or compensate for drying out from inhibiting the hydration process. Curing is therefore a key element in the quality of the finished layer. The following are different curing methods in pavement construction;

- **Regular application of water:** stabilized layer is kept moist by regular spraying with water. Top layer dries out between applications and becomes weak. It has more disadvantageous over benefits and it should be avoided.
- **Covering with impermeable sheeting:** an impermeable sheet or cover can be placed over the finished layer immediately after compaction. This is suitable for all pavement layers. The disadvantage of using this method is it is expensive and it is difficult to apply in strong winds.
- **Covering with consequent layer:** is spreading the material for the subsequent layer over the stabilized layer and keeping it moist. This is an effective curing technique and it is suitable for longer curing periods such as lime or slag stabilization. It requires careful application.
- **Application of a curing membrane:** application of *a good bituminous membrane* is the most effective curing method. However, it is costly to use for layers other

than the base. Application can cause heating of layer which accelerates hydration process and lead to thermal stress and cracking. High temperature also reduces the ultimate strength of the upper layer.

3.9 Construction of Stabilized Layers

3.9.1 Preparation of the Surface for Stabilization

To apply stabilizers to the soil, loose layer should be shaped and the levels checked. Excess soil must be removed and hollows filled in. If the soil is very dry, it is advisable to water it well the previous afternoon so that it can soak overnight. However, spraying of excessive water should be avoided as it interferes with effective mixing and compaction.

3.9.2 Methods of Spreading Stabilizers

Stabilizers can be delivered on site in bulk or packed in bags/pockets. Before spreading of stabilizers takes place, the required mass of stabilizer per square meter and the length of road that can be covered should be calculated. Sample calculations obtained from Gautrans Manual 2004 are attached in annex IV.

- **Bulk spreading:** the use of stabilizers in bulk results in uniform distribution. Larger quantities can also be handled with less labour. When labour-intensive construction is a project requirement, however, stabilizer in bags should be used.
- **Spreading by hand from pockets:** pockets of stabilizer are laid out in three or four rows, evenly spaced over the width of the road. The distance between the rows must be such that their spacing is approximately the same as the spacing between pockets along the road. Pockets are opened and spread with shovels; a grader blade is used to spread the stabilizer on even surfaces.

3.9.3 Mixing of Stabilizer and Water

Conventional construction process involves the following: when spreading is complete, the stabilizer is partly worked in to the layer using the ripper teeth of the grader. Then water is applied evenly over the width of the layer using pressure sprays. The required water should be applied gradually after each application has been mixed in rather than a single operation. It is important to determine that complete mixing has been achieved by opening the layer at a minimum of six points over the length and width of the job-lot for a visual inspection. The best compaction moisture content (MC) should be determined from trial sections, as it depends on material properties and the type and efficiency of available equipments. Equipments used on site for stabilization are listed in table 3.9.3 below:

Table 3.9.3 Equipments used for pavement soil stabilization

No.	Equipment	Function of Equipment
1	Bulk tanker with sraybar	It is used to spread the stabilizer, but it should not be used in excessively windy situations
2	Road Grader	It is used to spread heaps of imported soil; to blade and cut the layer to the final level.
3	Water Bowser	It is used to haul and spread water evenly over the road width. Also used for curing where water spray curing is utilized.
4	Compaction Equipment	Includes tamping, grid, pneumatic tyred and vibratory rollers. Used to compact stabilized surface.
5	Recyler	Particularly useful for recycling existing roads during rehabilitation, with the addition of cement (lime is seldom used in recycling).

3.9.4 Compaction

Except for lime modification; *treated layers should be compacted as quickly as possible to maximize the benefits of stabilization.* Most soils contain some water which will react with the stabilizer. Therefore, the time allowed starts when the stabilizer first comes in to contact with the soil. If cementation occurs during compaction, which is a possibility particularly under hot working conditions, problems with density and strength will be noted. Corrective measures need to be identified including;

- Processing shorter lengths
- Utilization of extra equipment or
- Using a different stabilizer

The speed of the compaction is important. Rollers moving either too fast or too slow will not compact to the required density. Thus, proof rolling should be carried out to identify a suitable range of rolling speeds.

3.9.5 Construction Safety

Lime, cement and sodium silicate are strongly alkaline and can be dangerous if not handled carefully. Workers should be trained and necessary safety precautions need to be taken including physical damages due to handling of packed bags, typically 40 to 50kg (Gautrans, 2004).

3.10 Minimum Requirements for Pavement Stabilization in Ethiopia

AACRA pavement design manual (2004) states subgrade materials with CBR values < 3% and swelling potential > 2% need to be replaced or treated with stabilizing agents. The manual also recommends subgrade material which has been stabilized should not be assigned a CBR of more than 15% for design purposes. ERA manual (2002) requirements are given in table 3.9 below.

Table 3.10 Minimum requirements for pavement stabilization in Ethiopia

Code	Description	Unconfined compressive strength (Mpa) (Cement Stabilized)	Minimum CBR value (%) (Lime Stabilized)
CB1	Stabilized base course	3.0-6.0	100
CB2	Stabilized base course	1.5-3.0	80
CS	Stabilized sub-base	0.75-1.5	40

3.11 Previous Studies

The subject of stabilization is relatively well researched in Ethiopia and different parts of the world. Studies on soil stabilization have been made by post graduate students of Addis Ababa University including Tesfaye A. (2003), Tadesse S. (2003), Nebro D. (2002), Tadege A. (2007), Agru Y. (2008), Ashuro T. (2010). Most of these studies focused on evaluating the suitability of chemical additives introduced in the country for expansive subgrade stabilization. However, no study has been made on evaluating sodium silicate.

3.11.1 Cementitious Stabilization

In relation to cementitious stabilization it is worth mentioning the following details:

Tesfaye A. (2001) studied improvement of expansive soil by addition of lime and cement on “Black Cotton Soil” from different parts of Addis Ababa. Index properties, compaction characteristics and swelling pressure of soil-cement and soil-lime were determined using Atterberg limit test, moisture-density relations, free swell and swelling pressure tests. The conclusions and findings drown from the study are;

- Expansive soil becomes moderately active to inactive based on the amount of lime and cement added.
- Swelling pressure of expansive soil decreases with increasing lime, cement and molding water content.
- 4-6% of lime and 9-12% of cement yielded significant improvement on plasticity and swelling properties of expansive soils.

Nebro D. (2002) evaluated lime and liquid stabilizer called Con-Aid for stabilization of potentially expansive subgrade soil on samples collected form Addis-Jimma road which had indicated different pavement damages exacerbated by the presence of expansive soils. The experimental study involved Atterberg limit test, moisture-density relation, UCS, CBR and CBR swell. The findings and conclusions of the study can be summarized as follows:

- Addition of lime reduced maximum dry density and increased the optimum moisture content.
- 4% of lime by dry weight of the soil was optimum lime content to stabilize the soil even though increased quantity of lime led to increased strength.
- Addition of lime reduces the swelling potential but no significant improvement in the engineering properties of the soil was attained by addition of Con-Aid.

Argu Y. (2008) has made a study on light gray and red clay soils of Addis Ababa using SA44/LS-40, lime and combination of the two additives at different application rates. The experimental study was made by Atterberg limit test, soaked CBR and CBR swell, swelling pressure and free swell tests. The conclusions and findings of the study are;

- Applications of lime alone results in modest improvement in the CBR value of the soil, while applications of the chemical with lime results in remarkable improvement in the CBR value of the soil.

- The application of SA-44/Ls-40 alone results promising reduction in the swelling pressure in light gray clay; however, it is ineffective in improving the soaked CBR value.
- 0.3lit/m^3 of SA-44/LS-40 and 2% lime is an optimum proportion in increasing soaked CBR and reducing swell potential of light gray soil and 0.08lit/m^3 of SA-44/LS-40 and 4% lime is an optimum mix for red clay soil.

Christopher M. (2005) investigated the suitability of traditional and non-traditional stabilizers on three highly plastic Virginia soils that have caused problems or resulted in poor performance service. Samples were collected from Northern Virginia, Staunton and Lynchburg. The applied soil stabilizers were: quicklime, hydrated lime, palletized lime, cement, lignosulfonate, synthetic polymer, magnesium chloride. The research used unconfined compressive strength test to compare effects of stabilization. The conclusions and findings drawn from the study are;

- *Traditional lime and cement stabilizers were far more effective than liquid stabilizers in increasing strength.*
- *Liquid stabilizers were ineffective on soils with high moisture content.*
- Proprietary cementitious stabilizer was more effective in increasing strength than lime but was not as effective as a cement stabilizer.
- Quick and hydrated lime increased workability of soils although they did not produce strengths comparable to cement.
- Strength of soils stabilized with cement and proprietary cementitious stabilizer can be estimated based on the water-amendment ratio of the mixture and
- The strength of soils stabilized with lime can be estimated based on combination of plasticity index and water-amendment ratio of the mixture.

3.11.2 Sodium Silicate Stabilization

With respect to studies made on soil stabilizing properties and evaluations of sodium silicate it is worth discussing the following details and findings;

Satee J. did a study on the effect of aging on the stress-strain behavior of the soil laterite soil obtained from campus of Skudai around University Technology of Malaysia. Atterberg limit, specific gravity, maximum dry density and optimum moisture content were determined. The sample was then classified as sility gravel with high plasticity. Samples were mixed with 0.6M, 0.7M and 0.8M of sodium silicate. UCS samples compacted at maximum dry density and optimum moisture content cured for 0day, 1day, 14days and 28 days were used to evaluate the effects. The research concluded that;

- The maximum improvement in strength was obtained when 0.6Mof sodium silicate was used to stabilize the soil for all ranges of curing durations considered.
- A relative relationship between the concentration of sodium silicate and the soil strength could not be achieved as the difference in concentrations applied for the test was very small.
- The soil strength was improved proportional to the curing day, where each concentration of reaches maximum strength for 28 days of curing.

Alen F. et al (2003) investigated the mechanisms by which clay soils are modified by liquid chemical agents using non-traditional stabilizers. They used reference clays (kaolinite, illite and montmorillonite) and five mixed native Texas clay soils with high sulfate content. To increase the likelihood of observing the stabilizer mechanisms, additives were applied at 10% and 50% by dry weight of the soil which was much more than suggested by manufacturers (0.002 to 0.1% by dry weight of the soil). Atterberg limit test, Proctor test, undrained shear strength, undrained triaxial compression and one dimensional swell tests were used to evaluate results. The findings and recommendations of this research include;

- *Sodium silicate is the principal component of the polymer stabilizer they used and the mechanism of stabilization is formation of adhesive aggregated material without altering clay layers chemically.*
- *No significant, consistent improvement in engineering properties were observed at the suggested application rates and 10X the rates suggested by manufacturers.*
- The application rates, and not the degree of dilution in water is the key parameter for expressing how much product should be applied to the soil.
- Unconfined compression tests are not recommended to evaluate shear strength of stabilized, resilient modules tests should preferably be used instead.
- Project specific rates should be determined before applying chemical products to the soil.

Abdel N. et al (2010) investigated the effect of mixing lime and sodium silicate on the shear strength, CBR and other soil properties. The study aimed to reduce the cost of bitumen by using surface layer stabilizers. Highly plastic light brown silt clay from south of Kark/Jordan was obtained for the study. Direct shear, free swell, Atterberg limit and CBR tests were used. The main findings of the research can be summarized as;

- 4% lime and 2.5% sodium silicate has improved the maximum dry density.
- Shear strength increases as lime concentration increases up to 4%.
- The shear strength increases as sodium silicate concentration increases.
- The CBR has improved when the soil treated by lime and sodium silicate at the mix of 6% lime and 2.5 molar sodium silicate.
- The free swell has reduced tremendously at the mix of 6% lime and 2.5 molar sodium silicate.

3.12 Summary of Previous Studies

From the previous research works the following main findings can be summarized;

1. As the amount of cementitious stabilizer increases, swelling pressure of expansive soil decreases.
2. Lime reduces maximum dry density and increases the optimum moisture content of expansive soils.
3. Adding 4% lime by dry weight of the soil is an optimum quantity in terms of improving plasticity and swelling properties.
4. Mixing traditional stabilizers (especially lime) with non-traditional additives can be a viable option of soil stabilization.
5. Traditional stabilizers, lime and cement, are far more effective than liquid stabilizers in increasing strength.
6. Quick and hydrated lime increased workability of soils though they did not produce strengths comparable to cement.
7. Sodium silicate stabilizes by forming *adhesive aggregated material without altering clay layers chemically and smaller application rates do not bring improvements in the properties of the soil.*
8. Mixing sodium silicate with lime increased dry density and yielded good results in reducing plasticity and swell characteristics of sility clay soil obtained from Jordan.
9. Curing improves the strength of cementitious and sodium silicate stabilization.

4. EXPERIMENTAL METHODOLOGY

In this section description and classification of materials used for the research, testing procedures and results are presented. Soil tests were done in the Geotechnical Engineering and Highway Engineering Laboratories of Addis Ababa University. Chemical evaluation of liquid sodium silicate was done at the Chemical Engineering Laboratories of Addis Ababa University and Chora Gas and Chemical Product Factory Laboratories. Relevant data of material characterization obtained from secondary resources is acknowledged.

4.1 Sample Collection

For this study two soil samples that represent expansive subgrade and subbase soil that does not fulfill ERA's grading requirement 2002 were obtained from in situ soil of Addis Ababa's Bole Senior Secondary and Preparatory School and borrowed material from Gergi-Bole Road section respectively. Figure 4.1 shows an overview of the samples.

Figure 4.1 Soil Samples [Sample 1 (Left), Samples 2 (Right)]

4.2 Standard Testing Procedures

ASTM and AASHTO standards are used for testing soils in the laboratory. Specific standards considered in the study are summarized in table 4.2.

Table 4.2 Standard Testing Procedures

No	Name of Test	Test description	ASTM	AASHTO
1	Grain Size analysis	Standard Test Method for Particle-Size Analysis of Soils	D422-63	
2	Atterberg limit test	Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils	D 4318-98	
3	Soil Classification	Standard practice for classification of soils for engineering purposes (Unified Soil Classification System)	D2487-98	
4	pH test	Standard Test Method for Using pH to Estimate the Soil-Lime Proportion Requirement for Soil Stabilization	D6276-99a	
5	Standard compaction	Standard Test Method for Laboratory Compaction Characteristics of Soil Using Standard Effort	D 698-91	
6	Modified compaction	Standard Test Method for Laboratory Compaction Characteristics of Soil Using Modified Effort	D 1557-91	
7	CBR test	Standard Test Method for the California Bearing Ratio		T 193-93

4.3 Material Characterization

4.3.1 Soil

Soil samples were prepared for test by drying, pulverizing (for expansive clay) and sieving to the required size. Grain size analysis of samples was determined according to ASTM D 422. Index properties of soils were determined using Atterberg limit test according to ASTM D 4318. Organic content of fine grained soil was checked using liquid limit values of oven dried sample according to ASTM D 2488. Soil classification was made according to ASTM D 2487 and AASHTO soil classification standards. Results are presented in figure 4.3.1 and table 4.3.1.

Figure 4.3.1 Grain Size Distribution Curve

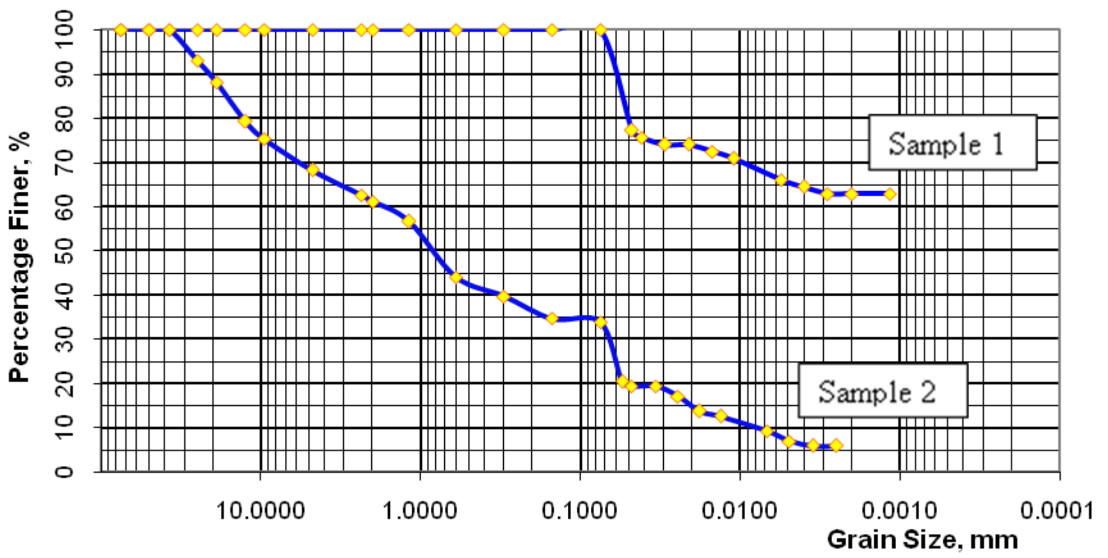


Table 4.3.1 Soil classification

Index and swelling properties (%)					Soil classification	
Sample	LL	PL	PI	Free Swell	ASTM D 2487 (Unified Soil Classification System)	AASHTO standards
1	130*	38	92	115	Inorganic Fat clay	A-7-6 (41)
2	38	22	16	30	Clayey Sand with gravel	A-2-6

*LL obtained for oven dried sample is 117%

For further understanding, mineralogy of gray expansive soil obtained from Bole area (Bole-Gergi in situ soil) studied by Habtamu (2011) is attached in annex I.

4.3.2 Lime

Hydrated lime used for the study was obtained from Senkele lime factory. Chemical composition of Senkele hydrated lime was studied by Solomon H. (2011), results are presented in table 4.3.2.

Table 4.3.2 Chemical composition of Senkele Hydrated Lime

Constituent	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	SO_3
Hydrated lime*	6.21	2.18	3.57	59.47	3.91	0.61	0.79	0.3286	0.208	0.2785	0.58

*Loss on ignition is 17.04%

4.3.3 Cement

Mugher ordinary Portland cement (OPC) was used for this study. The oxide composition of the cement is presented below (Awol A., 2011).

Table 4.3.3 Oxide composition of Mugher OPC

Oxide Composition of Mugher OPC	
Constituent	Total Percentage
CaO	66.31
SiO_2	20.03
Al_2O_3	5.94
Fe_2O_3	3.73
SO_3	1.14
MgO	1.07
Insoluble residue	0.12
Loss on ignition	0.08

4.3.4 Sodium Silicate

Liquid sodium silicate used for this study was obtained from Alied Chemicals Plc. Specific gravity and pH values were measured at room temperature at the Chemical Engineering Laboratories of Addis Ababa University and the total alkalinity of sodium oxide was determined at Chora Gas and Chemical Product Factory using hydrochloric acid titration according to OxyChem manuals (2004). According to Alied Chemicals Plc. the given liquid sodium silicate has weight ratio of 2.2 and viscosity of 42 boome. Results are summarized in table 4.3.4 below.

Table 4.3.4 Properties of liquid sodium silicate used for the study

Properties	Result
Color	Light olive green
Specific gravity	1.44
pH	12.2
Viscosity	42 boome
Total Alkalinity as sodium oxide	10.4 %
Weight ratio	2.2

4.4 Experimental Design

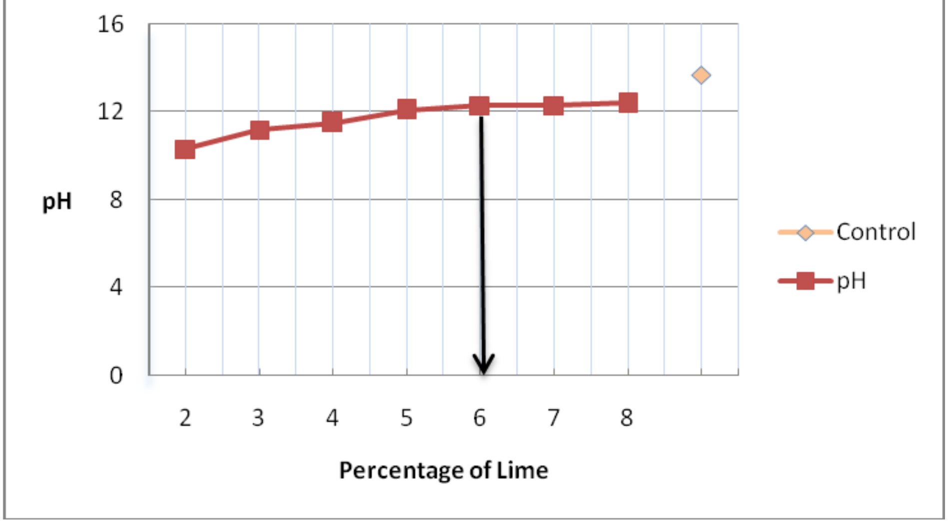
Soil sample 1, classified as fat clay, is highly expansive gray clay commonly known as “black cotton” soil. In this thesis it is referred to as “expansive clay”. As discussed in the literature review, such montmorillonitic soils are best stabilized using lime. In this experiment this soil was treated with lime, sodium silicate and combination of lime and sodium silicate at various curing durations.

Soil sample 2, classified as clayey sand with gravel (SC) is a course grained material that contains more fines than specified for subbase materials. Hence, it does not fulfill grading requirements. In this thesis this sample is referred to as “clayey sand”. To evaluate how additives affect plasticity and improve strength parameters of this soil, it was treated with cement, sodium silicate and combination of cement and sodium silicate at various curing durations.

4.4.1 Mixing Ratios and Sample Designation

The optimum amount of lime added to expansive clay was estimated using pH test according to ASTM D 6276. As shown in figure 4.4.1 the optimum amount of lime was determined to be 6% by dry weight of the soil. The proportion of lime combined with expansive clay was taken as 6%, 4% and 2% by dry weight of the soil.

Figure 4.4.1 pH Test



The minimum amount of cement added to the second sample was determined according to AASHTO cement requirement for soil groups given in table 3.4.2 of the literature review. Since the soil is classified as A-2-6, the minimum quantity of cement that is required to stabilize the soil is 7% by dry weight of the soil. Similarly the quantity of cement added to clayey sand sample was taken at 7%, 5% and 3% by dry weight of the soil.

Sodium silicate was mixed with the soil at 1%, 2.5% and 6% by dry weight of the soil according to 1 to 4% mixing ratio by dry weight of the soil given in section 3.5.4 of the literature review. The minimum mixing ratio was limited to 1% based on the findings of Alen F. et al (2003) that smaller ratios do not bring improvement in the engineering properties of the soil.

Mixing ratios and sample designations used for this study are summarized in Table 4.4.1.

Table 4.4.1 Mix ratios and designation of samples

No.	Sample 1 (Expansive clay)			Sample 2 (Clayey Sand)		
	Percentage of lime	Percentage of sodium silicate	Sample Designation	Percentage of cement	Percentage of sodium silicate	Sample Designation
1	-	-	0%	-	-	0%
2	2	-	L2	3	-	C3
3	4	-	L4	5	-	C5
4	6	-	L6	7	-	C7
5	-	1	SS1	-	1	SS1
6	-	2.5	SS2.5	-	2.5	SS2.5
7	-	6	SS6	-	6	SS6
8	2	1	L2SS1	3	1	C3SS1
9	2	2.5	L2SS2.5	3	2.5	C3SS2.5
10	2	6	L2SS6	3	6	C3SS6
11	4	1	L4SS1	5	1	C5SS1
12	4	2.5	L4SS2.5	5	2.5	C5SS2.5
13	4	6	L4SS6	5	6	C5SS6
14	6	1	L6SS1	7	1	C7SS1
15	6	2.5	L6SS2.5	7	2.5	C7SS2.5
16	6	6	L6SS6	7	6	C7SS6

4.4.2 Mixing Procedures

Soil and additives were mixed in such a way that the additive is first added to the prepared sample and dry mixed with the soil. When cement or lime was applied in concert with sodium silicate, soil sample was first dry mixed with the respective cementitious stabilizer and sodium silicate was added there after followed by a thorough mixing. Finally, wet mixing was done by sprinkling water uniformly and thorough blending the whole soil matrix. Care was taken not to apply sodium silicate directly on cement as it is observed to form hydration products that made further mixing difficult and non-uniform.

4.4.3 Atterberg Limits

Atterberg limit test is used to determine the plastic and liquid limits of a fine grained soil. The liquid limit (LL) is the water content at which soil in a standard cup cut by a groove of standard dimensions will flow together for a distance of 13 mm when subjected to 25 shocks dropped from 10mm at a rate of two shocks per second. The plastic limit (PL) is the water content, at which a soil can no longer be deformed by rolling into 3.2 mm diameter threads without crumbling (Reddy K).

Atterberg limits were determined according to ASTM D 4318 on particles passing No. 40 sieve. Curing durations were varied at 3, 7 and 28 days; it was observed that it became increasingly difficult to run the tests as the curing days were reduced.

4.4.4 Moisture-Density Relations

Moisture-density relationships were determined using Proctor test. For expansive clay sample, standard compaction test was conducted according to ASTM D 629. Modified compaction test was used for clayey sand sample according to AASHTO T 197. To account for the loss of strength due to compaction delay, mellowing time of 30 to 45 minutes was considered (see section 3.4.1 of the literature review).

To study the effect of mellowing time on dry density of expansive clay treated with sodium silicate, compaction tests were made after 30 min, 6hours and 24 hours of soaking keeping the rest of the parameters constant. Soil was mixed with 1%, 2.5% and 6% of sodium silicate by dry weight of the soil using moisture content obtained at the third trial of the respective compaction test results.

An attempt has also been made to study the effect of mode of mixing on maximum dry density of expansive clay treated with sodium silicate. Mixing ratio of 2.5% was randomly chosen and compacted using moisture content obtained at the third trial of the standard compaction test result. Keeping the rest of the parameters constant, the first set of samples were compacted after dry mixing the chemical with the soil and adding the required quantity of water after wards. The rest of the samples were compacted after diluting the chemical with the same quantity of water and applying it to the soil.

4.4.5 California Bearing Ratio (CBR) Test

The CBR test measures the shearing resistance of a soil under controlled moisture and density conditions. CBR value is the ratio of load required to effect a certain depth of penetration in to a soil specimen compacted at a given moisture content and dry density to the load required to obtain the same depth of penetration on a standard sample of crushed stone (Ashchile G., 2008). CBR can be used for modified materials up to values of about 150 (Department of Transport, 1986).

However, CBR is not suitable for testing cementitious stabilization. This is because CBR is determined after soil specimens have been soaked in water for four days. That means if soil is stabilized using sufficient amount of stabilizer and hardening occurs, the soaking acts as an efficient means of curing providing hydration and preventing carbonation resulting in higher strength than can be achieved in the field. For lower percentages of stabilizer (modification), the soaking could have a weakening effect, although this is not always the case in the pavement (Gautrans, 2004). For this thesis work, the use of CBR for testing strength parameters of soil-cement was chosen for the following reasons;

- Strength assessment in this thesis work consistent of evaluating sodium silicate as a pavement soil stabilizer in addition to cementitious additives. ERA manual (2002) section 7.4.2 recommends the use of the CBR test alternative to UCS test for cement stabilization. *However, there is no formal standard specification (eg.ASTM or AASHTO) to make evaluations for non-traditional stabilizers* (Alex E. and Jones D., 2010). Therefore, the CBR test is used as a consistent comparison mechanism.
- CBR measures shear strength at worst field conditions (after 4 days of soaking) which can help simulate pavement failures on problematic soils aggravated by drainage problems. Sodium silicate which does not precipitate or is involved in cementitious reactions has a tendency to dissolve in water. Therefore, CBR test is used in this thesis as an assessment of durability to certain extent answering how strength of sodium silicate treated soil is affected by presence of extra moisture.

However, to account for the over or under estimation of strength of soil-cement due to the soaking process, standard procedures of 7 days soaking after 7 days of curing recommended by ERA (2002), section 7.4.2 cement stabilization, was modified to 4 days of soaking after the respective curing durations. Reducing soaking days is also meant to avoid the effect of significant cement hydration from masking the effects of the sodium silicate.

The CBR test for clayey sand sample was done on soil passing 19mm according to AASHTO T 193. Curing durations of 3 and 7 days of were considered after compaction. However, compaction curves of expansive clay treated with sodium silicate or its combination with lime gave an odd curve; which means definite optimum moisture content or maximum dry density could not be picked. Therefore, to make a general evaluation on the effect of applying sodium silicate on strength development, CBR samples were prepared using soil passing No. 4 sieve and treated samples were compacted using moisture content obtained at the third trial of the compaction results. The swelling potential of clayey sand sample was negligible; therefore, CBR swell was compared for expansive clay.

No surcharge loads have been applied to compacted samples during curing durations assuming no traffic flow is allowed during construction. When the allocated curing period is finished, the sample is soaked in a water tab for 96 hours. CBR penetrations were made with a surcharge load of approximately 4.5 kg for expansive clay according to ASTM recommendations and a surcharge load of at least 7 kg for clayey sand sample.

4.4.6 Sample Curing

Atterberg limit test samples were prepared using soil passing No. 40 sieve and thoroughly mixed with the respective additive; they were then cured for 3, 7 and 28 days after treatment. Curing durations were varied at 0, 3 and 7 days for treated CBR samples. “Covering with impermeable sheeting” was the curing technique used by applying impervious plastic to soak or cover samples.

4.4.7 UCS and Swelling Pressure Tests

UCS is the most common test for evaluating cemented materials (Department of Transport, 1986). Improvement (reduction) in swelling pressure is also one of the basic parameters to evaluate additives for expansive soil stabilization. However, both tests require compacting samples at the optimum moisture content and maximum dry density which could not be determined due to the odd curves obtained for expansive clay sample in the presence of sodium silicate. Therefore, these tests were left out making a general assessment using CBR and CBR swell as explained earlier.

5. RESULTS AND DISCUSSION

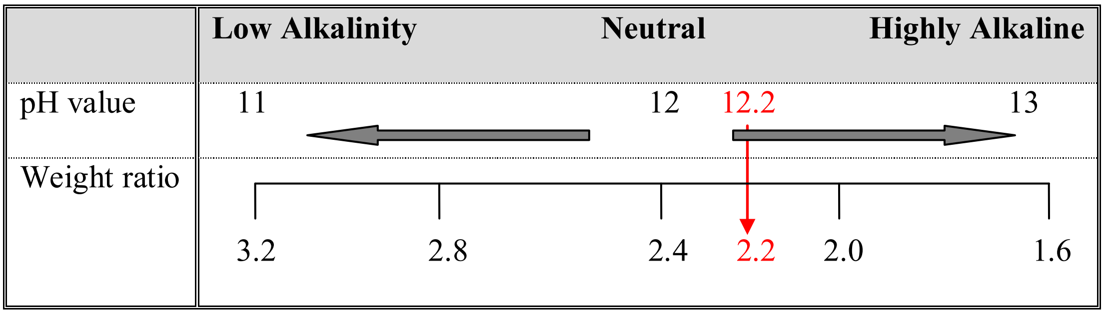
In this section test results are presented and their analysis is briefly discussed.

5.1 Test Results

5.1.1 Properties of Sodium Silicate

The weight ratio of sodium silicate ranges from 1.6 to 3.2 which is inversely related to pH value as it has been discussed in section 3.5.2 of the literature review. The pH range of sodium silicate which should be between 11 and 13 also imply "low" or "high" alkalinity of a silicate solution is a relative term.

Table 5.1.1 pH and weight ratio of sodium silicate used



	Low Alkalinity Neutral Highly Alkaline
pH value	11 12 12.2 13
Weight ratio	3.2 2.8 2.4 2.2 2.0 1.6

The weight ratio of the liquid sodium silicate used in this study is 2.2 and the pH is measured to be 12.2 which comply with the theoretical range. Table 5.1.1 shows this relation with respect to the results obtained. This value also shows the sodium silicate used for the study slightly deviates from the neutral range and it can be considered slightly alkaline. According to table 3.5.2, medium to slightly lower dried strength and medium to slightly higher solubility and drying time are expected.

5.1.2 Atterberg Limits

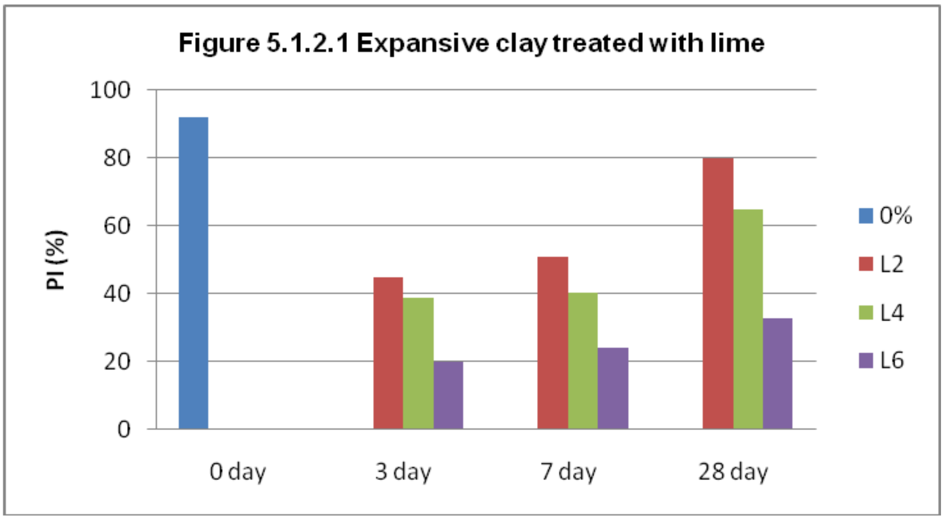
Atterberg limits have been conducted for curing durations of 0, 3, 7 and 28 days for clayey sand and expansive clay samples. Clayey sand treated with sodium silicate and/or cement became non-plastic at all curing durations considered. Cured samples are observed to turn in to solid masses as the quantity of cement and sodium silicate increased. Figure 5.1.2 depicts this finding.

Figure 5.1.2 Non-plastic clayey sand sample

Therefore, Atterberg limit test results discussed below are the data obtained from treating expansive clay with lime and/or sodium silicate.

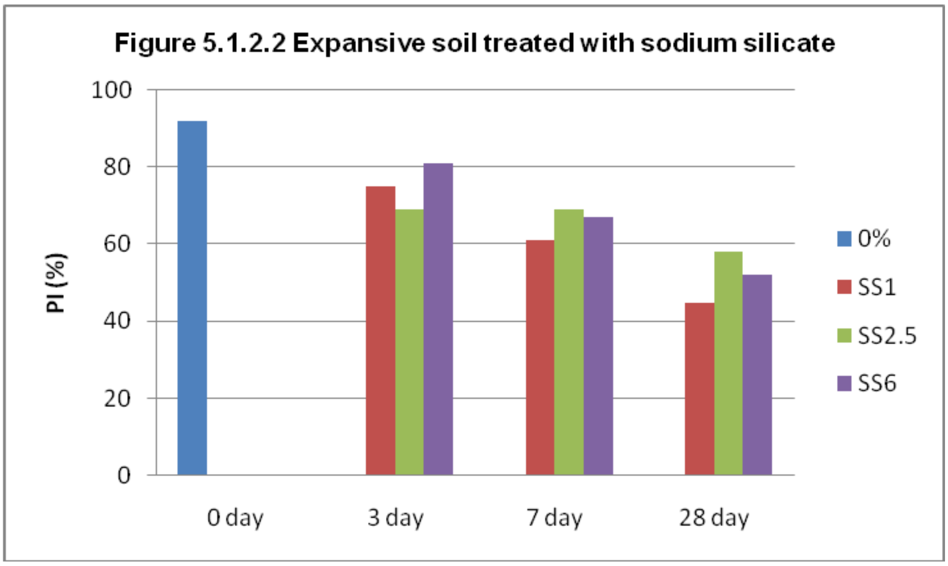
5.1.2.1 Expansive Clay Treated with Lime

Black cotton soil showed the highest reduction in PI when it is treated with 6% lime cured for 3days which is 78.26% reduction compared to untreated soil. The minimum reduction in plasticity is obtained for soil treated with 2% lime and cured for 28 days with 13.04% reduction in plasticity index compared to untreated soil. As it is shown in figure 5.1.2.1, the reduction in plasticity is directly proportional to the quantity and inversely related to the curing duration for soil samples treated with lime. However, the reduction in plasticity decreased after 3 days of curing.



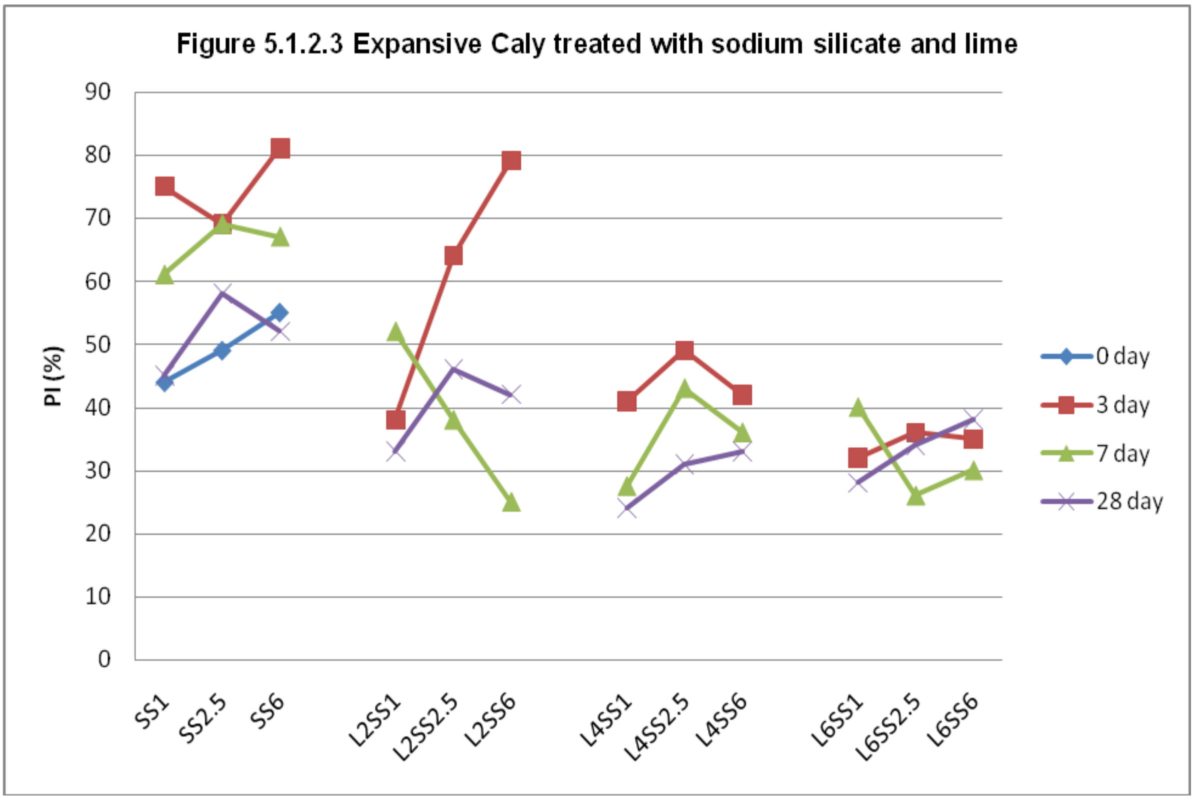
5.1.2.2 Expansive Clay Treated with Sodium Silicate

The maximum reduction of plasticity index for expansive clay treated with sodium silicate is 51.09% which was obtained for 1% of sodium silicate cured for 28 days. The minimum reduction in plasticity is obtained for expansive clay treated with 6% sodium silicate cured for 3 days which is 11.96%. The data is not consistent in showing how the quantity of sodium silicate relates to the reduction in PI. However, as shown in figure 5.1.2.2 there is a general tendency of decrease in plasticity associated with increased curing duration.



5.1.2.3 Expansive Clay Treated with Lime and Sodium Silicate

Expansive soil sample treated with sodium silicate shows a minimum reduction of 11.95% for soil treated with 2% lime and 6% sodium silicate cured for 3 days and a maximum reduction of 52.17% for soil treated with 4% lime and 1% sodium silicate cured for 28 days compared to untreated soil. These values are comparable to improvements gained by applying sodium silicate alone. The result, however, is inconsistent in showing how the curing duration or quantity of sodium silicate and it combination with lime relates to the reduction in plasticity. Figure 5.1.2.3 depicts this phenomenon.



5.1.3 Moisture-Density Relations

5.1.3.1 Effect of Additives on Expansive Clay

Native soil and expansive soil treated with lime yielded the typical bell shaped compaction curves with the highest density being 1.27g/cm^3 for 0% additive. However, expansive clay treated with sodium silicate or its respective combination with lime yielded odd curves.

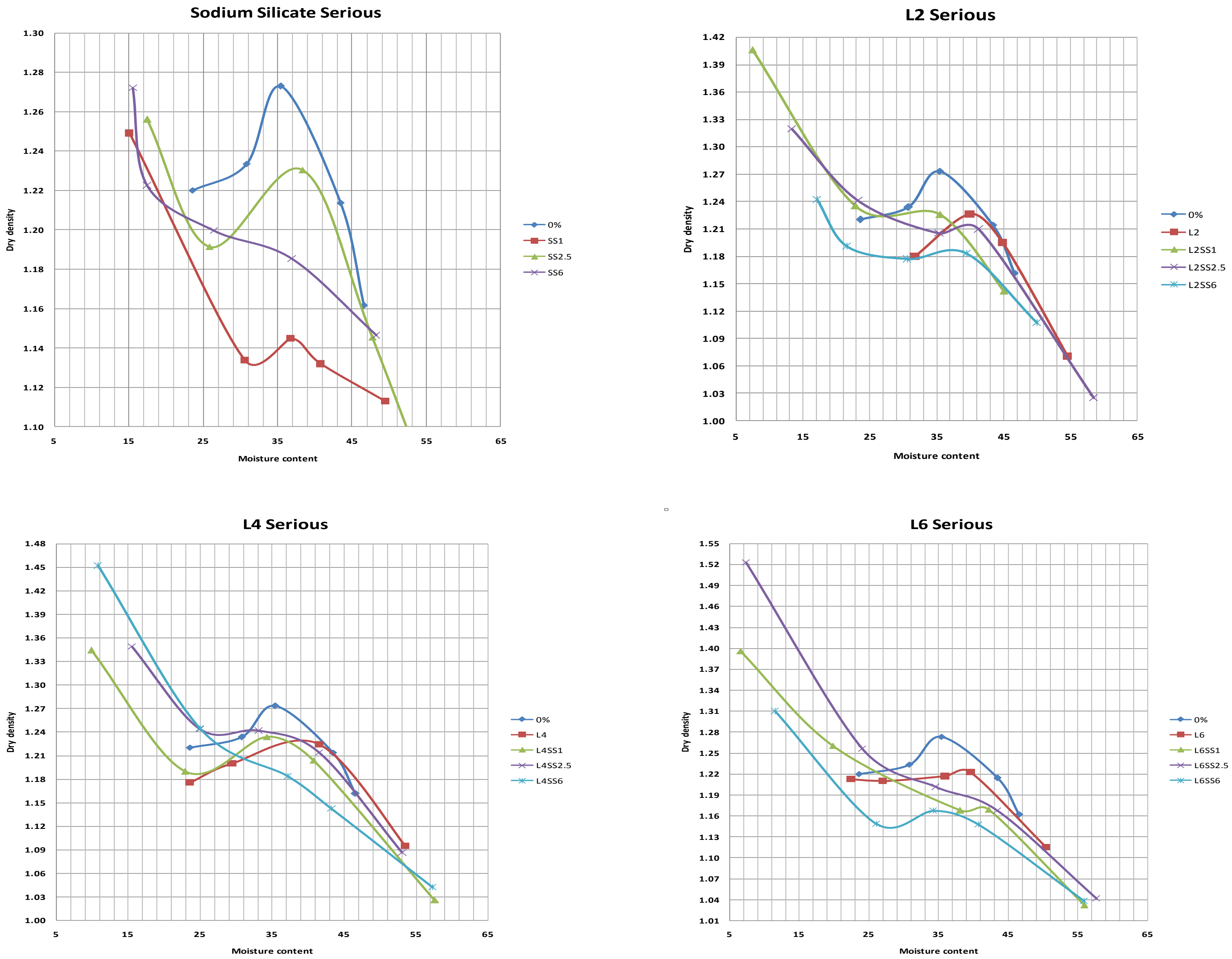


Figure 5.1.3.1(a) Compaction Curves of expansive claytreated with sodium silicate and its combination with lime

Figure 5.1.3.1 (a) shows type D curve and type C compaction curves obtained with the highest density being at the direst side, which is uncommon. Since the compaction curves obtained are odd, a definite optimum moisture content and maximum dry density could not be determined.

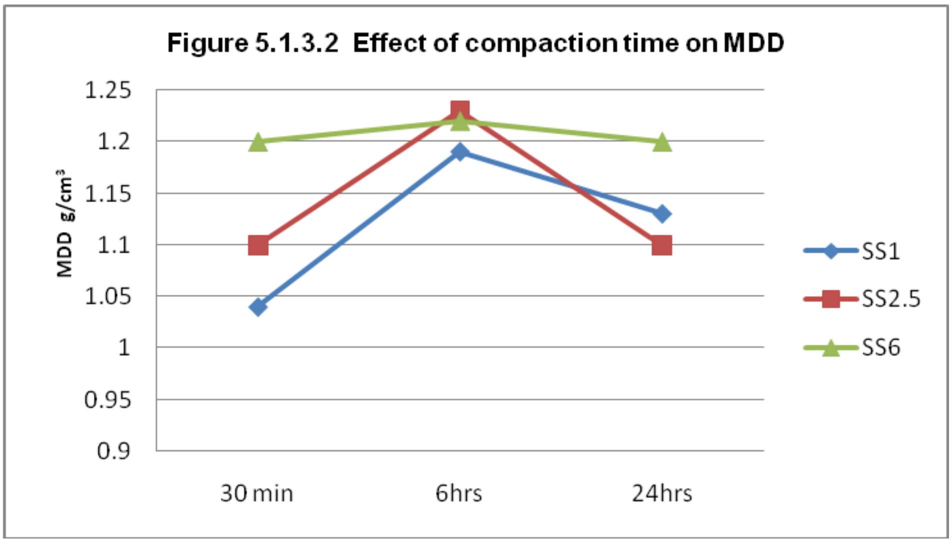
On the other hand, treating soil with lime alone gave the typical bell shaped curves. These curves sifted to the right with respect to untreated soil sample, which also means addition of lime decreased the maximum dry density and increased the optimum moisture content. This result is in harmony with the findings of Nebro D. (2002).

Standard compaction tests made for trial purposes using larger quantities of sodium silicate also showed agglomerating effect of sodium silicate. Figure 5.1.3.1(b) shows this effect of sodium silicate solution on expansive clay sample after 30 minutes of soaking.

Figure 5.1.3.1(b) Agglomeration effect of sodium silicate

5.1.3.2 Effect of Time Variation

For standard compaction tests conducted to study the effect of time variation on maximum dry density of expansive clay soil treated with sodium silicate, results show there can be a relationship between soaking time and maximum dry density. As shown in figure 5.1.3.2 for all quantities of sodium silicate considered, the highest maximum dry density was obtained for compaction tests made after 6hours of soaking.



5.1.3.3 Effect of Mixing Mode

For tests done by varying the mode of mixing, results summarized in table 5.1.3.3 shows mode of mixing did not bring change on the maximum dry density of the expansive clay treated with sodium silicate. This finding is in harmony with the conceptual background given in section 3.5.4 of the literature review. However, it should be noted these results apply for through and uniform mixing.

Table 5.1.3.3 Effect of mixing mode on maximum dry density

Mode of mixing		Trial 1	Trial 2	Trial 3
		Dry density, g/cm^3		
1	Wet mixing	1.20	1.16	1.17
2	Dry mixing	1.21	1.15	1.19

5.1.3.4 Effect of Additives on Clayey Sand

Clayey sand soil treated with sodium silicate showed the typical bell shaped compaction curves for all the quantities of sodium silicate and/or its combination with cement. Figure 5.1.3.4 (a) summarizes the OMC-MDD relationships obtained.

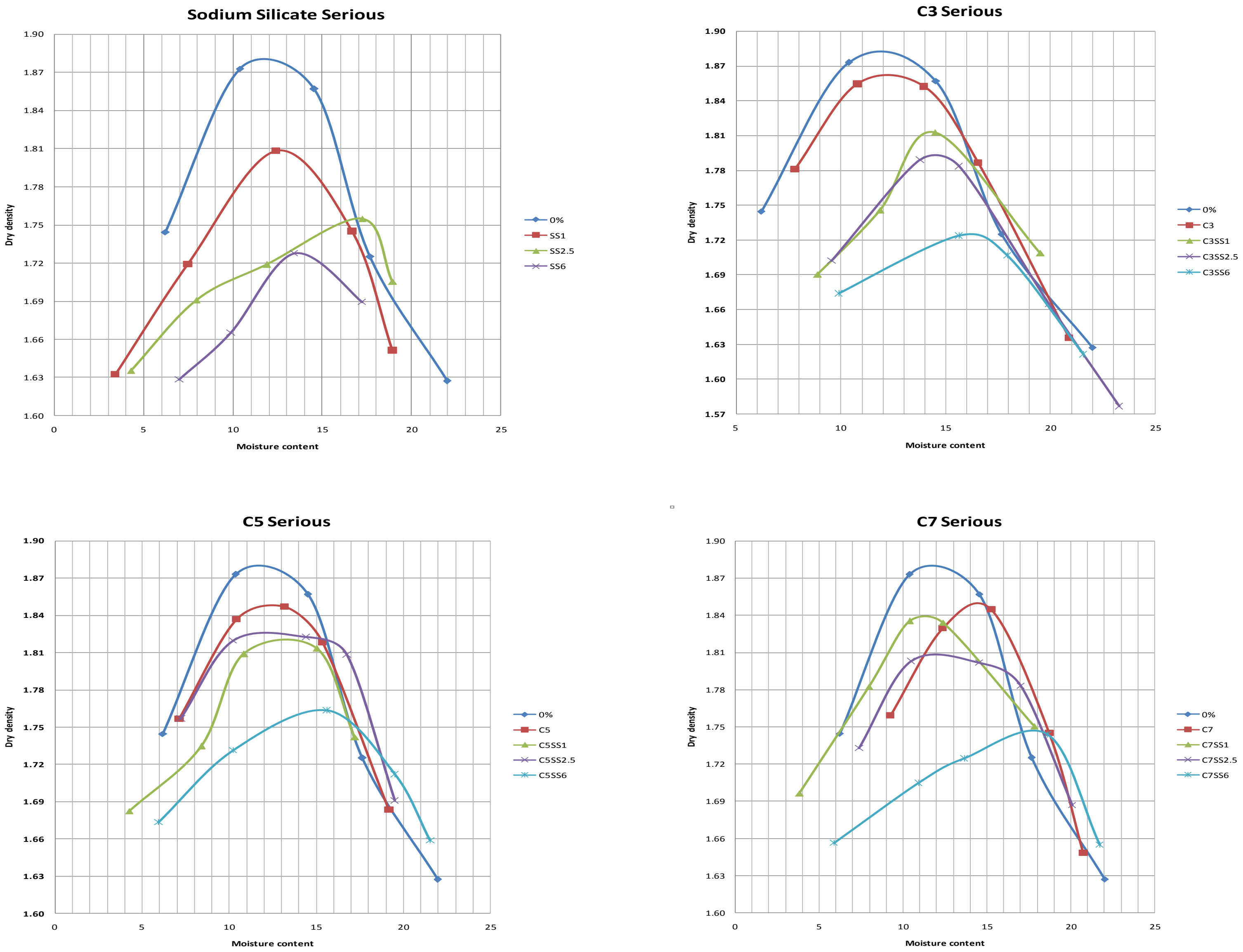
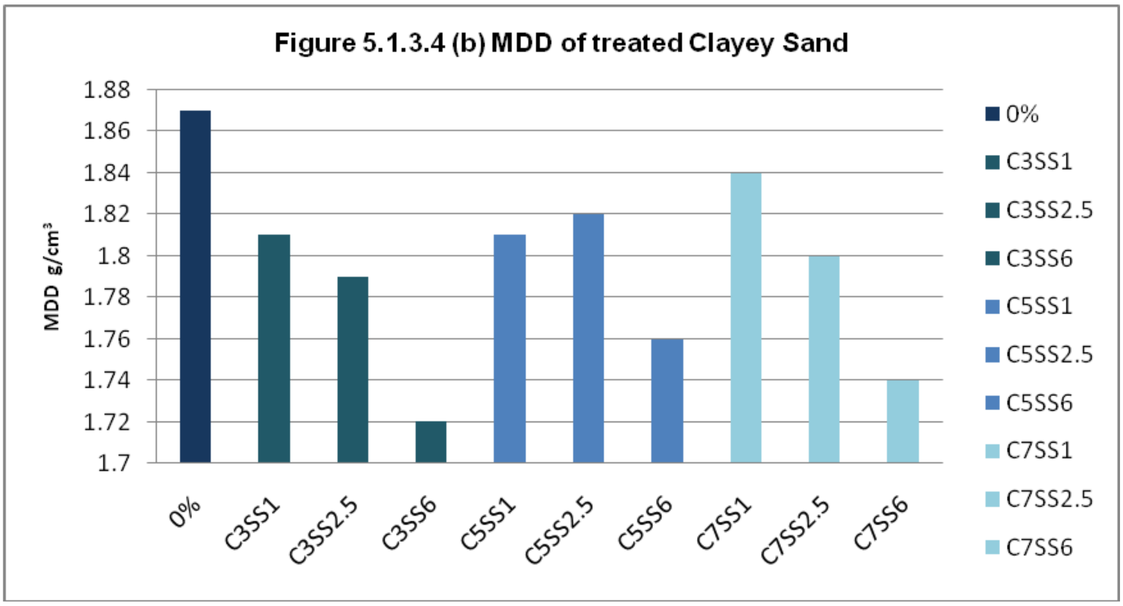


Figure 5.1.3.4 (a) Compaction Curves of clayey sand soil treated with sodium silicate and its combination cement

The dry density of clayey sand treated with the respective quantities of cement does not show significant change in the maximum dry density compared to each other; however, the optimum moisture content of C5 increased by 5.37% with respect to C3 and OMC of C7 increased by 8.9% with respect to C5.

For clayey sand soil treated with the combination of cement and sodium silicate, a decrease in the maximum dry density of the soil was observed with increasing the quantity of sodium silicate except for C5SS2.5. As it shown in figure 5.1.3.4 (b) the decrease in MDD is the largest for C3SS6 with 8.02% decrease in MDD compared to untreated sample. C5SS6 and C7SS6 show 5.88% and 6.95% decrease in MDD compared to untreated sample respectively.



5.1.4 CBR Values

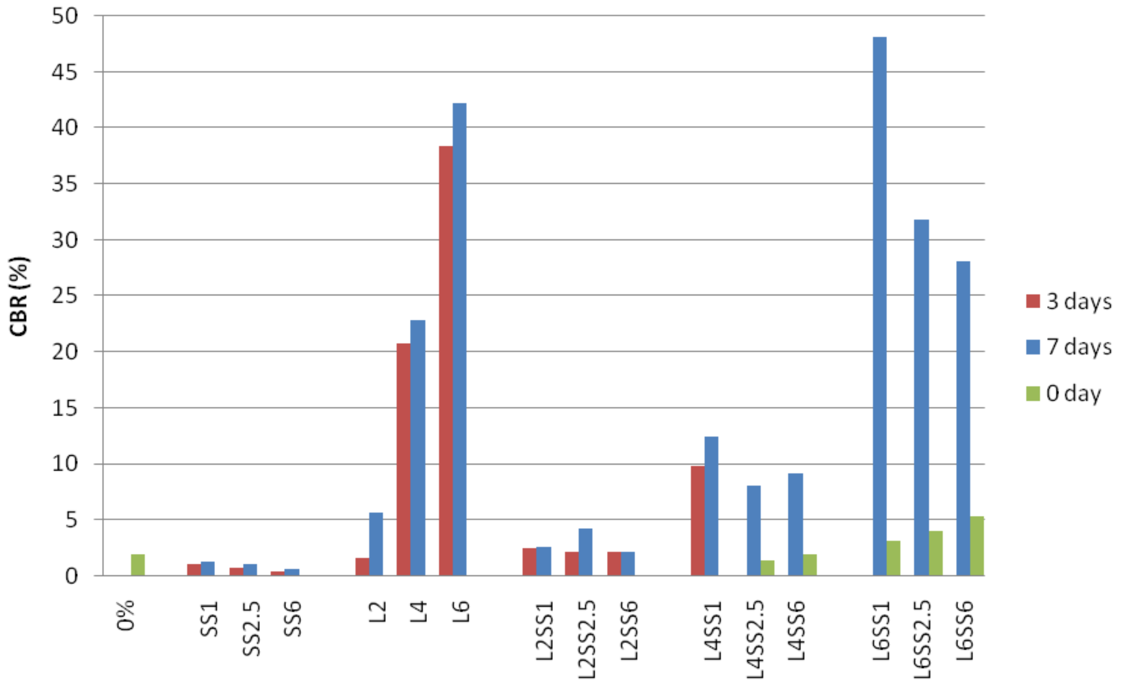
5.1.4.1 CBR Values of Expansive Clay

Soil treated with sodium silicate using the third moisture content of the compaction test results does not show any improvement in strength compared to untreated soil sample. Results presented in figure 5.1.4.1 also show that the CBR of treated soil decreases as the quantity of sodium silicate increases. Results also show that curing enhances the strength development of expansive soil treated with sodium silicate. For example, for 1%, 2.5% and 6% sodium silicate added to expansive clay, there is 14.63%, 33.33% and 22.86% increase in strength of 7 days curing compared to 3 days curing. However, the data is inconsistent in showing how mixing lime and sodium silicate relates to strength development.

Soil treated with 2% lime cured for 7 days fulfilled the strength requirements of a subgrade, but since the quantity of lime is low, this result may not necessarily imply long term stabilizing effects. With CBR of 22.85%, soil treated with 4% lime can effectively be used as a subgrade soil. Expansive clay treated with 6% lime yielded CBR of 42.19% which is more than the minimum strength requirement for subbase except it does not fulfill the grading requirement.

Big differences in CBR values between cured and uncured sample for 6% of lime and its respective combination of sodium silicate magnifies the importance of curing for lime stabilized soils.

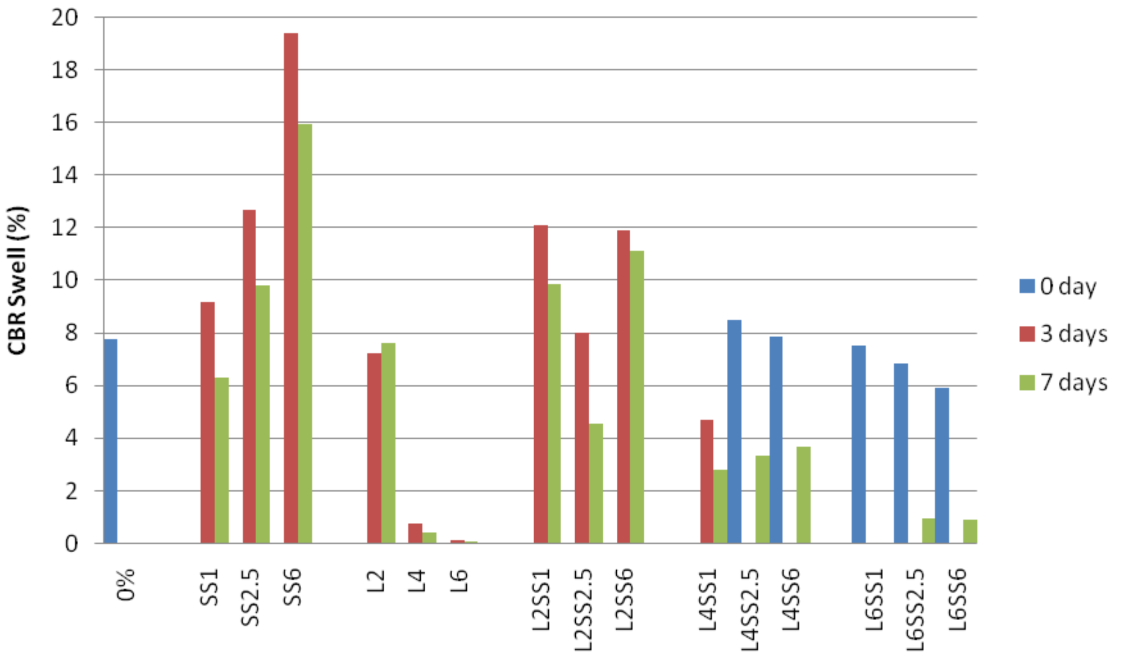
Figure 5.1.4.1 CBR results of expansive clay



5.1.4.2 CBR Swell of Expansive Clay

Expansive soil treated with 6% sodium silicate showed the largest CBR swell which is 59.67% larger than untreated sample. Results shown in figure 5.1.4.2 below also show curing has the effect of reducing swelling potential of sodium silicate treated soil. CBR swell of 1% sodium silicate showed the largest improvement in swelling potential with 7 day cured sample having 31.44% less CBR swell compared to samples cured for 3 days. Curing samples treated with 2.5% and 6% of sodium silicate and cured for 7 days showed 22.66% and 11.77% reduction in CBR swell compared to samples cured for 3 days.

Figure 5.1.4.2 CBR swell for expansive clay



CBR swell showed significant reduction with the addtion of lime. CBR swell of expansive clay treated with 6% lime yeilds almost nil swelling. This finiding is also in haromony with results obtained by Nebro D. (2002). Results also show swelling potential of expansive clay treated with sodium silicate and/or lime is inversly related to the curing duration. For instance, L6SS1 which shows 0% swelling for 7 days of curing showed 7.54% increment in swelling values when the curing duration is reduced to 0 days.

5.1.4.3 CBR Values of Clayey Sand

Results show there is significant improvement in strength of soil as a result of cement addition. Clayey sand treated with 3% cement yielded CBR values of more than 215%. This value increases with the percentage of cement added to the soil. Some of the results obtained from three point CBR test could not be completed for dial readings beyond about 1000 due to limitations in the capacity of the CBR machine used. For such cases, further readings were stopped and those values are highlighted in the table 5.1.4.3 (a).

For seven days of curing, results also show that there is a slight increase in CBR values associated with applying 1% of sodium silicate to the given quantity of cement compared to the respective cement treatments alone. However, CBR values decreased when the quantity of sodium silicate added to soil cement is increased to 2.5% or 6%.

For clayey sand treated with sodium silicate alone, there is at least 19% increase in CBR values for soils treated with 1% of sodium silicate with respect to untreated soil. However, CBR values significantly dropped when the quantity of sodium silicate added to the soil is increased to 2.5%. For soil treated with 6% sodium silicate, however, the CBR values increased at least by 14% compared to untreated soil. These results largely deviate for what is obtained 2.5% of sodium silicate by dry weight of the soil. Therefore, further investigations are recommended.

Table 5.1.4.3 (a) CBR results of clayey sand sample for 7 days of curing

7days of Curing		10 blow	30 blow	65 blow	CBR
0%	CBR for 2.54 penetration	12.83	62.94	72.78	42.88
	CBR for 5.08 penetration	11.78	52.88	67.37	
0% (1)	CBR for 2.54 penetration	4.92	26.72	30.24	24.50
	CBR for 5.08 penetration	4.24	25.44	26.62	
C3	CBR for 2.54 penetration	20.39	123.41	319.26	216.50
	CBR for 5.08 penetration	24.73	91.86	230.83	
C3SS1	CBR for 2.54 penetration	21.10	228.19	348.09	
	CBR for 5.08 penetration	30.62	195.03	242.85	
C3SS2.5	CBR for 2.54 penetration	65.05	158.93	232.76	210.50
	CBR for 5.08 penetration	56.77	137.56	211.99	
C3SS6	CBR for 2.54 penetration	21.10	33.40	37.62	38.38
	CBR for 5.08 penetration	16.49	23.79	35.80	
C5	CBR for 2.54 penetration	116.38	237.34	355.12	357.50
	CBR for 5.08 penetration	95.87	244.02	237.90	
C5SS1	CBR for 2.54 penetration	181.08	362.86	365.67	
	CBR for 5.08 penetration	146.04	243.08	244.97	
C5SS2.5	CBR for 2.54 penetration	67.86	220.81	363.91	
	CBR for 5.08 penetration	53.70	177.36	243.79	
C5SS6	CBR for 2.54 penetration	24.61	89.31	51.69	121.00
	CBR for 5.08 penetration	17.90	75.37	38.16	
C7	CBR for 2.54 penetration	128.69	362.16	367.43	
	CBR for 5.08 penetration	122.48	242.61	246.14	
C7SS1	CBR for 2.54 penetration	33.40	103.72	368.49	
	CBR for 5.08 penetration	42.40	147.45	246.85	
C7SS2.5	CBR for 2.54 penetration	32.35	318.91	148.03	
	CBR for 5.08 penetration	32.98	243.79	166.29	
C7SS6	CBR for 2.54 penetration	176.51	100.21	199.36	317.00
	CBR for 5.08 penetration	174.54	136.38	221.41	
SS 1 (1)	CBR for 2.54 penetration	12.31	58.02	62.94	53.17
	CBR for 5.08 penetration	10.84	51.35	53.00	
SS 1 (2)	CBR for 2.54 penetration	20.04	55.55	49.58	60.50
	CBR for 5.08 penetration	16.25	44.05	38.86	
SS2.5	CBR for 2.54 penetration	23.56	37.62	91.42	
	CBR for 5.08 penetration	19.08	32.27	78.91	
SS 2.5 (1)	CBR for 2.54 penetration	15.12	16.88	17.93	17.03
	CBR for 5.08 penetration	14.13	15.07	16.96	
SS 2.5 (2)	CBR for 2.54 penetration	14.42	8.09	16.17	15.50
	CBR for 5.08 penetration	14.84	8.48	16.25	
SS6	CBR for 2.54 penetration	13.01	73.84	76.65	69.75
	CBR for 5.08 penetration	12.72	71.13	74.20	
SS6 (1)	CBR for 2.54 penetration	24.26	42.90	54.15	47.90
	CBR for 5.08 penetration	19.79	38.16	49.46	

For clayey sand soil cured for 3 days, additon of cement alone ashowed the greatest CBR value. For 3 days of curing, strength development due to the additon of sodium silicate to soil cement could not be observed. However, similar to 7 days of curing, there is a decrease in CBR values associated with increasing the amount of sodium silicate added to soil-cement. Results are summerized in Table 5.1.4.3 (b).

5.1.4.3 (b) CBR results of clayey sand sample for 3 days of curing

3days		10 blow	30 blow	65 blow	CBR
C3	CBR for 2.54 penetration	70.67	205.69	362.86	
	CBR for 5.08 penetration	57.71	164.88	243.08	
C3SS1	CBR for 2.54 penetration	195.49	59.77	191.63	
	CBR for 5.08 penetration	166.06	51.82	180.90	
C3SS2.5	CBR for 2.54 penetration	24.96	99.86	75.24	91.75
	CBR for 5.08 penetration	20.02	81.50	81.73	
C3SS6	CBR for 2.54 penetration	57.31	32.70	40.43	11.00
	CBR for 5.08 penetration	53.47	34.15	36.98	
SS1	CBR for 2.54 penetration	15.82	32.35	67.16	51.13
	CBR for 5.08 penetration	11.54	30.62	60.30	

5.2 Statistical Analysis

Statistical analysis was made on results using analysis of variance (ANOVA), mainly two factors without replication. Hypothesis (H_{1i}) and null hypothesis (H_{0i}) were defined as;

H_{11}: Quantity of additives affects the dependent variable significantly.

H_{01}: Quantity of additives does not affect the dependent variable significantly.

H_{12}: Curing affects the dependent variable significantly.

H_{02}: Curing does not affect the dependent variable significantly (Jerrold H, 1999).

For compaction tests, time variation and mixing mode were used to formulate the second null hypothesis. The analysis was limited to expansive soil as Atterberg limit data is non-existent and CBR values are inconclusive for clayey sand. Outcomes are summarized in table in table 5.2 (a), (b) and (c) below and spread sheets are attached in annex III.

Table 5.2 (a) Outcome of statistical analysis for Atterberg limit test

Series Tested	Control Sample	Dependent Variable	Conclusion	
			Null Hypothesis 1 (H_{01})	Null Hypothesis 2 (H_{02})
L	0%	PI	Reject null hypothesis	Fail to reject null hypothesis
L2+SS	L2	PI	Fail to reject null hypothesis	Fail to reject null hypothesis
L4+SS	L4	PI	Fail to reject null hypothesis	Fail to reject null hypothesis
L6+SS	L6	PI	Fail to reject null hypothesis	Fail to reject null hypothesis
SS	0%	PI	Reject null hypothesis	Reject null hypothesis
SS1+L	SS1	PI	Reject null hypothesis	Fail to reject null hypothesis
SS2.5+L	SS2.5	PI	Fail to reject null hypothesis	Reject null hypothesis
SS6+L	SS6	PI	Fail to reject null hypothesis	Fail to reject null hypothesis

The analysis shows increasing the quantity of lime or sodium silicate alters PI values of native soil significantly. Curing duration affects PI of native soil treated with sodium silicate. For 1% of sodium silicate and lime series, increasing the quantity of lime affects PI values significantly. Results also show curing has a pronounced effect on the PI of soil treated with combination of 2.5% sodium silicate and the respective quantities of lime.

Table 5.2 (b) Outcome of statistical analysis for Proctor tests

Series Tested	Control Sample	Dependent Variable	Conclusion	
			Null Hypothesis 1 (H_{01})	Null Hypothesis 2 (H_{02})
SS	30 min Compaction	MDD	Reject null hypothesis	Fail to reject null hypothesis
SS2.5	Dry Mix	MDD	-	Fail to reject null hypothesis

Analysis of two way and one way ANOVA for standard compaction test results show variation of compaction time or mixing mode does not have a significant effect on the dry density of expansive soils treated with sodium silicate. However, quantity of sodium silicate is hugely reflected on dry density of treated soils.

Table 5.2 (c) Outcome of statistical analysis for CBR tests

Series Tested	Control Sample	Dependent Variable	Conclusion	
			Null Hypothesis 1 (H_{01})	Null Hypothesis 2 (H_{02})
L	0%	CBR	Reject null hypothesis	Fail to reject null hypothesis
SS	0%	CBR	Reject null hypothesis	Fail to reject null hypothesis
L2+SS	L2	CBR	Fail to reject null hypothesis	Fail to reject null hypothesis
L	0%	CBR Swell	Reject null hypothesis	Fail to reject null hypothesis
SS	0%	CBR Swell	Reject null hypothesis	Fail to reject null hypothesis
L2+SS	L2	CBR Swell	Reject null hypothesis	Fail to reject null hypothesis

The analysis shows both CBR and CBR swell values of expansive clay treated with lime or sodium silicate are significantly affected by the quantity of the respective additives put to the soil. For combination of 2% lime and sodium silicate series, the quantity of sodium silicate is reflected on the CBR swell values. Similar comparisons for LL4 and LL6 series could not be made due to inconsistent continuity of data over the curing durations.

5.3 Discussion of Results

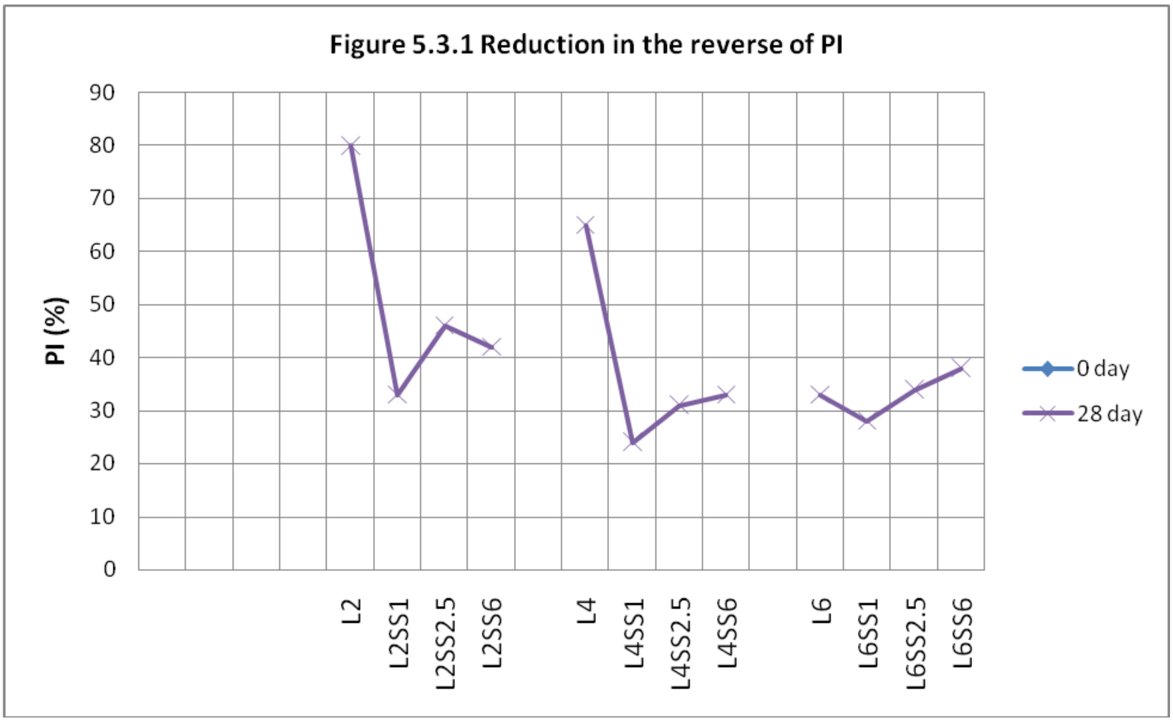
5.3.1 Atterberg Limits

Increased reduction in plasticity associated with increased amount of lime is expected as more calcium is available for cation exchange to take place. The increase in plasticity observed for lime treated expansive clay at increased curing durations can be mainly attributed to the reverse in PI due to carbonation reaction aggravated by premature wetting during soaking of samples.

Gutrans stabilization manual (2004) states *the plasticity of stabilized materials should not increase after it has been effectively treated with lime during the life of a road.* The manual also explains in cases where the plasticity has returned, it can be attributed to one or more of the following factors;

- Poor mixing of the stabilizer with the material
- Insufficient stabilizer added to the material
- Destruction of the stabilizer before it reacted with all the clay particles in the material, e.g. premature wetting/drying
- Stabilizer or soil types that form clods, the stabilizer reacted only with the outer surface of clay lumps. Disintegration of these lumps after carbonation has affected the layer results in return of the PI.

The reverse of PI is magnified as the quantity of lime is reduced which shows stabilizing effects of lime decrease as the amount is reduced. Results summarized in figure 5.2.1 also show adding 1% sodium silicate in combination with lime yielded encouraging results in reducing the reverse of carbonation process. But further investigations are necessary to explain this finding and implement results.



General decrease in plasticity of expansive clay treated with sodium silicate might be the result of stronger film formed by the chemical due to further dehydration reactions. Reduction in plasticity when lime and sodium silicate are applied together can be results of metal ion reactions between depolymerized silicate in addition to lime-clay ion-exchange reactions. Inconsistent results due to the *combination of sodium silicate and lime to montmorillonitic clay* can be caused by the differences in stabilizing mechanisms of the two additives. Lime causes flocculation (clumps the clay minerals together in to an "aggregate") while sodium silicate just does the opposite by making montmorillonite particles repel one another.

5.3.2 Moisture-Density Relations

The highest dry density achieved at the direst side of the compaction curve for expansive clay treated with sodium silicate shows the surface charge modification effect of liquid sodium silicate. As stated in section 3.6.2 of the literature review, dispersed particles are compressed easily resulting in increased dry density. This is due to the extra negative charge made available by the depolymerization of the chemical. However, *altering clay layers chemically is not expected* according to the studies of Alen F. et al (2003). The highest dry density obtained at the driest side also shows the surface charge modification effect of the chemical that might have reduced the capillarity tension (capillarity tension is prominent at the dry side that makes clay particles clump together).

On the other hand the decrease in dry density associated with the addition of compaction water shows the surface charge modification effect of the chemical decreases with the addition of water (or dilution of the silicate). Therefore, for montmorillonitic clay, it can be expected that stabilization mechanism of sodium silicate by agglomerating soil particles proposed by Alen F. et al (2003) and (Jeb S., 2007) is put to its best use at the driest side of compaction. That is, with addition of more water, silicate dissolves losing its sticking power in addition to decreased surface modification effects explained above.

The “pick” points that are sometimes obtained in the odd curves can be attributed to the normal bell shaped nature of clay overlapping with the deflocculation phenomenon. Experiments on varying the mode of mixing show we can use which ever mixing mode that is suitable for field application and get the same results given that a through and uniform blending is made.

In general, increase in optimum moisture content and decrease in maximum density associated with the addition of cement or lime to soil can be attributed to the increase in the quantity of fines consuming increased amount of water and increased resistance of treated soil to compaction due to flocculation resulting in decreased density (Gautrans, 2004, Molenaar, 2005).

5.3.3 CBR and CBR Swell

The CBR values of expansive clay treated with sodium silicate showed significant increase in swell values opposed to the improvements in swelling properties reported by Abdel N. et al (2010) on silty clay sample. This can be attributed to the difference in the type of clay used for this experiment and the later. *Findings of this study imply that sodium silicate is not a suitable additive to stabilize montmorillonitic clays.*

Expansive clay treated with sodium silicate showed more swelling compared to untreated sample. This swelling value also increased with increasing the quantity of sodium silicate. Expansive clay treated with combination with lime and sodium silicate also showed more swelling than expansive clay treated with lime alone.

As it is discussed in the 3.6.1 of the literature review, montmorillonitic clays swell due to dispersion of mineral sheets caused by weak bonds set apart by water. Surface charge modification property of liquid sodium silicate aggravates dispersion of particles and therefore swelling property of montmorillonitic clays. This is demonstrated by the increased swell values that are observed with the increase in the amount of sodium silicate added to the soil.

That is;

Increased amount of sodium silicate → Increased surface modification Effect →

Increased dispersion of montmorillonitic minerals → Increased swell and heave

For clayey sand sample treated with the combination of cement and sodium silicate, encouraging results obtained for 1% of sodium silicate can be attributed to availability of alkaline pH and additional silicates for cementitious reactions. Decreased CBR values obtained as the amount of sodium silicate added to the soil cement is increased to 2.5% and 6% can be attributed to excess silicates made available due to the addition of sodium silicate that reacted with all the calcium in the system and inhibit set and strength development reactions (PQ manual).

Strength development in CBR values of soil cement treated with sodium silicate is not reflected for the three days of curing that can be due to the slow release of calcium hydroxide in Portland cement during the cement hydration process. As a result, enough calcium may not have been generated for C-S-H gel formation compared to 7 days of curing (Gautrans, 2004).

5.3.4 Effects of Curing

In general, curing yielded increased strength and reduced swelling values for all the additives considered including sodium silicate. Strength values increased as the curing durations are lengthened. However, specific techniques of curing used might have implications on the results.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The following are the main conclusions drawn from this study;

1. The addition of sodium silicate changes clayey sand sample of PI 16 % in to non-plastic and resulted in a minimum of 11.96 % reduction in PI of expansive soil PI 92 % which led to the belief that sodium silicate decreases plasticity of soils.
2. Carbonation has detrimental reversing effects on plasticity index of soils attained by stabilization.
3. Sodium silicate is not a suitable additive for montmorillonitic clay (expansive soil) stabilization.
4. Mixing sodium silicate with lime is not a viable option for montmorillonitic clay (expansive soil) stabilization.
5. Applying 1% sodium silicate by dry weight of the soil in concert with ordinary Portland cement has positive implications on strength development of soil-cement.
6. Sodium silicate has inhibiting effect on strength development of soil-cement when its quantity is increased to and beyond 2.5% by dry weight of the soil.
7. Proper curing is mandatory for strength development of cementitious stabilizers. Curing also enhances strength of soils treated with sodium silicate.
8. Varying the mode of mixing does not bring a change in dry density of expansive clay treated with sodium silicate; however, sodium silicate should not be directly applied to cementitious stabilizers as it forms hydration products before the soil can be engaged in the reaction.

6.2 Recommendations

Based on the findings of the research the following are the main recommendations;

1. When pavement layers are treated with cementitious stabilizers in Ethiopia, good quality materials should be used and attention needs to be given to construction procedures such as compacting pavement layers densely and curing properly.
2. For cementitious stabilization, attention needs to be given to applying sufficient quantity of stabilizer to the soil to minimize potential pavement cracking and deterioration due to carbonation.
3. When lime is used for soil stabilization, covering with subsequent layers is a recommended curing technique. However, careful application needs to be given due attention.
4. Sodium silicate should not be used as a pavement soil stabilizer for expansive subgrade stabilization.
5. Good drainage system and limited moisture ingression needs to be adopted when using sodium silicate as a soil stabilizer.
6. Awareness needs be raised about construction practices of chemical stabilization in Ethiopia and testing procedures need to be standardized.
7. The following topics are recommended for future studies
    - Effects of sodium silicate in reducing carbonation of lime treated soils
    - Evaluation of sodium silicate for stabilization of lateritic soils in Ethiopia
    - Application of sodium silicate for concrete durability in Ethiopia
    - Stress-strain properties of soil cement

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