ADDIS ABABA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

ADDIS ABABA INSTITUTE OF TECHNOLOGY
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING

STABILIZATION OF EXPANSIVE CLAY SOILS USING POTASSIUM CHLORIDE

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A Thesis Submitted to School of Graduate Studies in Partial Fulfillment of the Requirements For the Degree of Masters of Science in Civil Engineering

(Geotechnical Engineering)

Addis Ababa University
Inistitute of Technology

School of Civil and Enviromental Engineering

Stabilization of Expansive Clay soils Using Potassium Chloride

Addis Ababa

November, 2015.

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DECLARATION

I here by declare that this thesis is my original work under the supervision of Dr. Henok Fikre, in school of Civil and Environmetal engineering, Addis Ababa University during the year 2015 as part of Master of science program in Geotechnical engineering.

I further declare that this work has not been submitted to any other University or institution for the award of any degree or diploma and all sources of materials used for thesis have duly acknowledged.

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November, 2015.

Acknowledgements

I am happy to acknowledge my advisor, Dr.Ing Henok Fikre, for his guidance, constat encouragement, friendly approach through out this thesis work. As an advisor, he provided me the imputs and guidance for this study. His support and patience throughout this research is sincerely appreciated.

I am also grateful to Ethiopian Roads Authority (ERA) for giving me this chance of study in geotechnial engineering which is area of my interest, Besides to its contribution to the country in supporting man power capacity building.

And finally I would like to extend my special thanks to my families, friends, teachers, laboratory technicians and others who, directly or indirectly, stood on the side of me in support of best out come of my work, eventhough I could not mention their best doing with such a few words.

(Alemayehu Lemi)

Table of Contents

Chapter IV: Materials and Methods

Chapter V: Laboratory Test Results And Discussions

Chapter – VI Conclusion and Recommendation

List of Figures

List of Tables

AACRA	Addis Ababa City Roads Authority
AASHTO	American Association of Highway and Transportation Officials
ASTM	American Society for Testing and Materials
CEC	Cation Exchange Capacity
CBR	California Bearing Ratio
CH	Highly Compressible Clayey
$Ca(OH)_2$	Calcium Hydroxide
ERA	Ethiopian Roads Authority
FSI	Free Swell Index
KCl	Potassium Chloride
LL	Liquid Limit
MC	Moisture Content
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
OPC	Ordinary Portland cement
PI	Plastic Index
PL	Plastic Limit
UCS	Unconfined Compressive Strength

Abstract

Expansive soils, such as black cotton soils, are basically susceptible to detrimental volumetric changes, with change in moisture. The cyclic wetting and drying process causes vertical movements in expansive soils and movements lead to failure of structures. These soils also have very low load bearing capacity when wet. This behavior of soil is attributed to the presence of mineral montimirrilonite, which has an expanding lattice. Understanding the behavior of expansive soil and adopting the appropriate control measures have been great tasks for the geotechnical engineers. Extensive research has been going on to find the solutions associated to problems of expansive soils. There have been many methods available to control expanssiveness of these soils. The removal of expansive soils and replacement with suitable material has been widely practised all over the world where there is suitable material within economic distances. Chemical stabilization is another alternative being used world wide even if the method is at conceiving stage in Ethiopia. Treating expansive soils with electrolytes is one of the chemical stabilization techiques to improve the behavior of expansive soils.

In the peresent study, the performance of Potassium chloride was evaluated based on laboratory test results on expansive soil collected from Addis Ababa around Kality area. The soil was initially characterized and classified based on indicative tests and found to be A-7-5 according to AASHTO and CH according to USCS systems. Soils with this category have very low load bearing capacity and are highly expansive soils. Then the effects of Potassium chloride on the the engineering properties of the soil were evaluated and it was generally investigated that Potassium chloride decreases the swelling properties and increases load bearing capacity of the expansive soils to the minimum required level. So it can be used as a soil stabilizer chemical when it is sufficiently abundant and ecconomically feasible.

Chapter I. Introduction

1.1. General Background

Expansive soil is the term generlly refered to any soil or rock that has potential for shriking or swelling under changing moisture condition. The primary problem that arises with regard to expansive soil is that the deformations are signifiantly greater than elastic deformations and they can not be predicted by classical elastic or platic theories (John D.Nelson and Debora J.Miller, 1992). Movement is usually in uneven pattern and of such a magnitude that it causes extensive damage to the structures and pavements resting on it.

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

World expansive soils occur both in temprate and tropical climates. Problems associated with these soils have been reported in Africa, Australia, Europe, India, Israel, South America, the United states as well as some regions in Canada. In the United states alone, expansive soils have been estimated to produce at least two billion dollars of damage anually. In many areas of tropics especially Africa and India, tropical expansive soils often known as black cotton soils are the major problematic soils. These soils show very strong swelling and shrinkage characteristics under changing moisture conditions (Chen, 1998).

The conditions under which expansive soils formed are:-

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

Soil stabilization refers to the procedure in which a special soil cementing material or other chemical materials are added to a natural soil to improve one or more of its properties. Soil stabilizing additives are used to improve the properties of less-desirable soils. When used, these stabilizing agents can improve soil moisture content, increase soil particle cohesion and serve as cementing and water proofing agents. A difficult problem in civil engineering works exists when the soil is found to be clayey soil. Soils having high clay content have the tendency to swell when their moisture content is allowed to increase (FU HUA CHEN, 1975). Many researchers have been done on the subject of soil stabilization using various additives; the most common methods of soil stabilization of clay soils in pavement work are cement and lime stabilization. The high strengths obtained from cement and lime stabilization may not always be required, however, and there is justification for seeking alternative additives which may be used to alter the soil properties.

This thesis focuses on the stabilization technique that is in practice in India, Iraq, Algeria and other parts of the world for improving the expansive soil for reducing its swelling potential. Modification of bearing capacity of soil by chemical admixture is a common method for stabilizing the swell-shrink tendency of expansive soils. Potassium chloride is one among these Chemicals that can be used in place of lime which is commonly used as stabilizer. The readily dissolvability in water and supply of adequate cations for ready cation exchange is its advantage over other chemicals. Therefore, potassium chloride can be used as stabilizing material where it can be cheap and easily available. In our country, Ethiopia, potassium chloride is currently in progress to be produced at large scale as the report of ministry of mineral and energy indicated (Shifarew Ayale, 2010). This study evaluated the potential of KCl as stabilizer chemical and it was found Potassium chloride changed the properties of A-7-5 according to AASHTO and CH according to USCS untreated soil sample from high swell potential to low swell potential soil, decrease plasticity index by 88.5%, increase the maximum dry density of the soil by 28%, decrease the optimum water content by 30%, increase the soaked CBR value of the soil by 800%, decrease swelling pressure by 98% and increase the unconfined compressive strength of 7 days of curing by 172%. Most of the engineering properties of the soil were fails in to the required range for the addition of 10% KCl. Hence it can be an alternative chemical that can be used, as stabilizer widely in our country where it is better to apply as compared to other methods of stabilization which were being used.

1.2. Problem Statement

Expansive soil is also a major contributor to the burden that natural hazards place on the economy (John D.Nelson and Debora J.Miller, 1992). Despite the fact that, billions of dollars in yearly damage losses have been attributed to these problematic soils, the state of practice in design and construction is severely limited by continued lack of understanding of expansive soil behavior and soil-structure interaction.

During the last few decades, damages due to swelling action have been observed clearly in arid and semi-arid regions in the form of cracking and breakup of pavements, road ways, building foundations, slab on grade members, channel and reservoir linings, irrigation systems, water lines and sewer lines (Cokca 2001.)

Over past decades, residential,commercial and infrastructural developments have been icreased in most of our country. The construction of these projects have been undertaken on expansive soils due to lack of knowledge of problematic nature of these soils and recently due to lack of suitable land for infrastrutures and other developments. In addtion to this the project consumes a lot of of money as a result of removal and replacement.

Inorder to prevent these problems it is essential to stabilize existing soils before commencing the construction activities.

1.3. Objectives of the Study

1.3.1. General Objective

The main objective of this research is to evaluate the performance of potassium chloride on stabilizing expansive clay soils for the purpose of safe pavement and building construction.

1.3.2. Specific Objectives

The specific objectives of the present research work are;

- To determine the physical and engineering properties of soil under study to confirm wether the soil is expansive or not.
- To evaluate changes in the physical and engineering properties of soils after treating by potassium chloride.

1.4. Methodology of the Study

The research was conducted using literature review on expansive soils, field observations, collection of samples for laboratory testing and analysis of the laboratory test results. Certain laboratory tests were conducted on soil samples before mixing with the selected stabilizing chemical agent to check whether the collected sample was expansive or not. A construction site where soil samples for laboratory testing were collected was selected at the Southern part of Addis Ababa around Kality. After the samples were confirmed to be expansive soil, full characterization and classification of the soil was made by conducting necessary laboratory tests.

Commercial grade potassium chloride was purchased and used to test the effect of KCl on the engineering properties of expansive soil in the laboratory.

Literature review was undertaken inorder to provide a framework and understanding regarding expansive soils and problems associated with such soils. Emphasis was given to review previuos works on treatment of expansive soils particularly to chemical stabilization techniques. Literature sources include maps, reports, books, journals and oline materials available on internet.

Experiences of other countries with similar physical characteristics to Ethiopia have been referred to build up a picture on the procedures and methods adopted in dealing with expansive soils and chemical stabilization.

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

- Grain size analysis(sieve and hydrometer)
- Specific gravity
- Atterberg limits
- Free swell test
- California Bearing Ratio (CBR)
- Unconfined compressive strength (UCS)
- Proctor test
  - Optimum Moisture Content (OMC)
  - Maximum Dry Density (MDD)
- Swell Consolidation test

The engineering properties of the soil samples after stabilization were tested at different percentages of chemical stabilizer .

The proportion of potassium chloride was taken as 0%, 2.5%,5%,10%,15% and 20%

Laboratory tests that were conducted on treated potassium chloride-soil mixtures.

- Atterberg limits
- Free swell test
- California Bearing Ratio (CBR)

- Unconfined compressive strength (UCS)
- Proctor test
    - Optimum Moisture Content (OMC)
    - Maximum Dry Density (MDD)
- Percent swell of CBR
- Swell consolidation test

The test results are evaluated providing prime consideration to the effects of the chemical on engineering properties of the soil. The results of the tests from the natural untreated and treated specimens have been compared. Finally improvements in the engineering properties of the sample have been analyzed and interpreted. This data together with data obtained from literature and other secondary sources have been compillied, and based on the results obtained, appropriate conclusions and recommendations have been made.

1.5. Significance of the Research

The road network provides the principal mode of freight and passenger transport. 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 road sector plays a vital role in growing the economy of the country. The limitation of the road network in Ethiopia often causes remoteness and isolation of communities. Remoteness leads to lack of services and severly 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 construction projects creates siginificant damaging impacts on the local environment and its inhabitants. Therefore, construction techniques implemented to solve the socio-economic problems need to be found not only time and cost effective but also environmentally friendly.

The research work improves the knowledge of expansive soils in the country and will be indicative of the better method of improvement of such soils. For sub-grade and foundation preparation, particularly in the construction sector, chemical stabilization minimizes cost of construction by reducing depletion of natural resources by improving properties of insitu soils to acceptable level.

The research will serve as a reference guide for practicing Civil Engineers and Researchers that practice in the area of study. This is useful in the sense that, it will cut down initial costs of new projects which are to commence and add our knowledge on the behaviors of expansive soils. As Ethiopia is in progress to be one of the largest scale potassium chloride producing county, this study also enables many construction companies to stabilize expansive soils using this chemical which will be cheaper and abundant ever.

1.6. Problems of the Study

The researcher suspects that there may be laboratory test results errors because of some technical problem with laboratory equipment's, light problem, lack of distilled water in the laboratory of Addis Ababa Institute of technology.

1.7. Organization of the thesis

The present research is conducted using literature review on expansive soils and improvement methods, sampling of soil, laboratory testing and analysis on the soil from Addis Ababa around Kality area. So as to present the results of the research in a more systematic manner, it is divided in to six chapters and the scheme of presentation is as follows.

Chapter 1 comprises the introduction part, which include the background of the study, problem statement, objectives of the study, methodology, significance of the research, problems of the study and organization of the thesis.

Chapter 2 presents the literature review. It includes genesis of expansive soils, Mineralogy of expansive soils, identification and Classification of expansive soils, distribution of expansive soils, mechanisim of swelling and potash abundance and exploration in the context of Ethiopia.

Chapter 3 presents a review on soil stabilization and high-lights history and concept of soil stabilization, methods of soil stabilization that have been widely practiced over all the world

Chapter 4 presents materials and methods which consist of general idea, materials used in the thesis work such as soil, potassium chloride and water. In addition the methodology followed to handle the whole thesis work is discussed. Natural soil is also fully characterized and identified in this chapter.

Chapter 5 presents laboratory test results and discussions. The chapter discuses the core findings of the entire work by addressing the effects of potassium chloride on the geotechnical properties of expansive soils one by one.

Chapter 6 presents conclussions and recommendations. This chapter summarizes the whole findings and recommend some ideas that the researcher think to be useful for the future research.

Chapter II. Literature Review

2.1. Expansive Soils

2.1.1. Genesis of expansive soils

Expansive soils are mainly formed from two parent materials. The first group comprises the basic igneous rocks, such as basalts of deccan plateau in India, the dolerite sills and dykes in centeral region of south africa and gabbros and norites west of pretoria North. In these soils the feldspar and proxene minerals of the parent rocks have decomposed to form montmorillonite and other secondary minerals. The second parent materials comprises the sedimentary rocks that contain montmorillonite as constituent which breaks down physically to form expansive soils. In north America, bed rock shale found in the pierre formation and the more recent laramie and Denver formation are examples of this type of rock. In Israel there are marls and lime stones. In south Africa the shale of Ecca series.

The montmorillonite was probably formed from two separate origions. The products of weathering and errosion of rocks in the highlands were carried by streams to the costal plains. The fine grained soils eventually became shale accumulating in the ocean basin. Mean while volcanic erruptions, sending up clouds of ash, fell on the plains and seas. Finally, these ashes were altered to montmorillonite(Chen,1975).

2.1.2. Mineralogy of Expansive Soils

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

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

Kaolinite is a typical two-layer mineral having a tetrahedral and an octahedral sheet joined to form a 1-1 layer structure held by a relatively strong hydrogen bond. Kaolinite does not absorb water and hence does not expand when it comes in contact with water (Murray, 2007; Nelson, 2010). However, Gourley et al (1971) in their study indicated the swelling property of kaolinite. Nelson (2010) described that kaolinite is formed by weathering or hydrothermal alteration of rocks rich in feldspar in low PH condition to favor the leaching out of ions like sodium, potassium, calcium, magnesium and iron. The montmorillonite group clays on the other hand have a 2-1 layer structure formed by an octahedron sandwiched between two tetrahedrons. This group of clays can have significant amounts of magnesium and iron substituting into the octahedral layers. The most important aspect of the montimorillonite group is the ability for water molecules to be absorbed between the layers, causing the volume of the minerals to increase when they come in contact with water (Nelson, 2010).

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

2.1.3. Identification and classification of Expansive Soils

2.1.3.1. Identification of expansive soils

Expansive soils that exihibit high swelling potential can be recognized by both field observation and laboratory tests(Chen,1988,Nelson,1992).

In the field observation soils exihibiting black or grey color, wide or deep shrinkage cracks, high dry strength and low wet strength, shiny appereance on cut surfaces, cracks near structures are commonly expansive soils.

In the laboratory,there are three methods that are used to identify expansive soils:-

Minerological identification

It is generally believed that swelling potential of any clay can be evaluated by identification of constituent minerals of that clay.

The techniques that can be used are:- X-ray diffiraction, differential thermal analysis, dye adsorption, chemical analysis, and electron microscope resolution.

In-direct methods

These methods include the index property, potential volume change and activity methods which are valuable tools in evaluating sweeling property.

Direct methods

These methods offer the most useful data by direct measurement and tests are simple to perform and do not require complicated equipments. Direct measurement of expansive soil can be made by the use of conventional one – dimentional consolidometer.

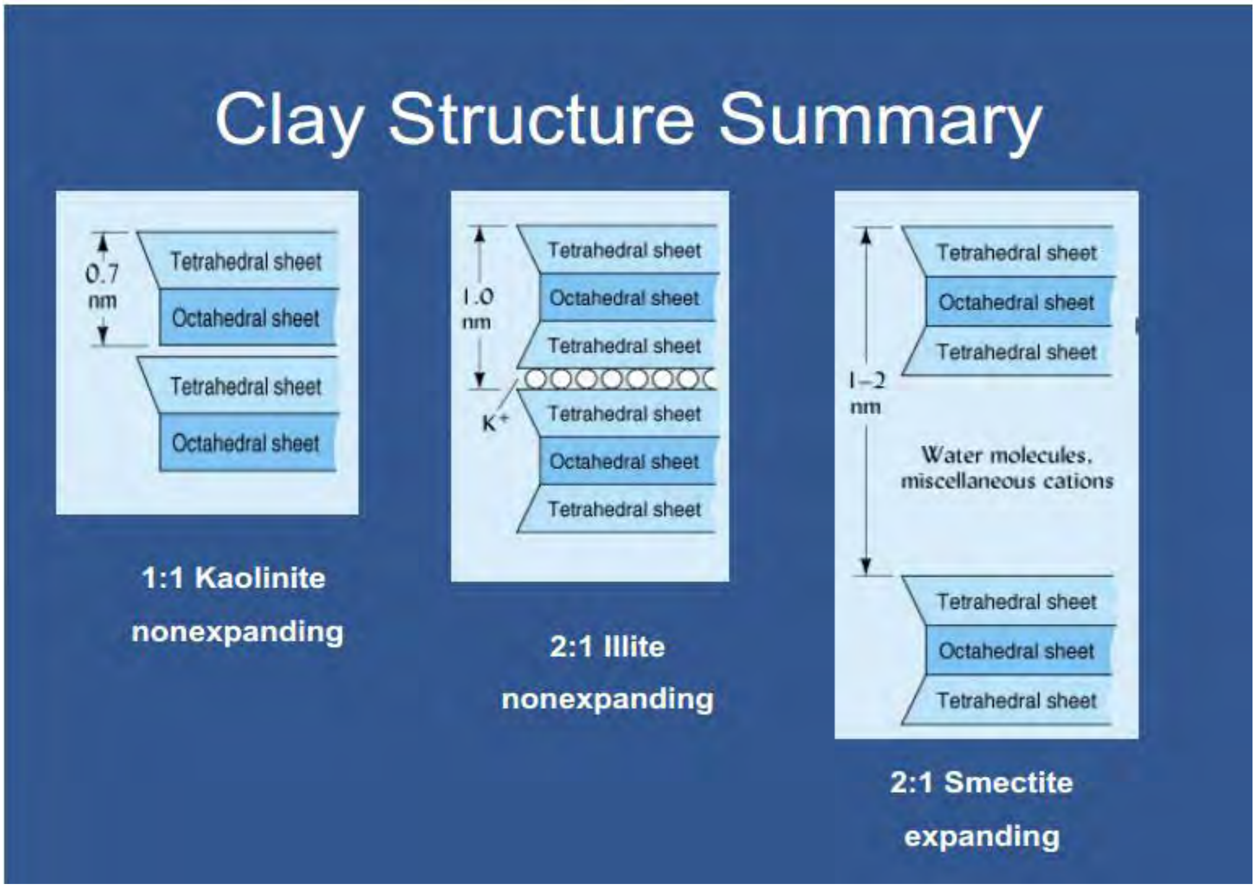

Fig 2.1 Structures of Basic Clay Minerals (Alemayehu Teffera and Mesfin Leikun, 1999).

2.1.3.2 Classification of expansive soils

Parameters determined from expansive soil identification tests have been combined in a number of different classification schemes. The classification system used for expansive soils are based on indirect and direct prediction of swell potential as well as combinations to arrive at a final decision.

Classification Using General Methods

Soils are classified in the general schemes: United Soil classification systems (USCS) and the American Association of State High Way and Transportation Officials (AASHTO) method according to index properties. Soils rated CM or CH by the USCS, and A-6 or A-7 by AASHTO, can be considered potentially expansive (Nelson, 1992).

Cation Exchange Capacity (CEC)

The CEC is the quantity of exchangeable cations required to balance the negative charge on the surface of clay particles. CEC is expressed in milli-equivalents per 100 grams of dry clay.

CEC is related to clay mineralogy. High CEC values indicate a high surface activity. In general, swell potential increases as CEC increases. Typical values of CEC for three basic clay minerals are given in Table 2-1.

Table 2-1 Typical CEC values of basic clay minerals after Mitchell, 1976and (Nelson, 1992).

Clay Mineral	CEC (meq/100 gm.)
Kaolinite	3-15
Illite	10-40
Montmorillonite	80-150

Classification using soil index properties

Prediction of swelling potential using Atterberg limits are the most popular approach. Many of the procedure also include the clay content.

Method of Chen

Prediction (1988) presented a single index method for identifying expansive soils using only plasticity index (Table 2-2).

Table 2-2 Expansive soil classification based on plasticity index (Chen, 1988).

Swelling Potential	Plasticity Index (%)
Low	0-15
Medium	15-35
High	35-55
Very High	55 and above

Method of Seed et al

After an extensive study on swelling characteristics of remolded, artificially prepared and compacted clays, Seed et al (Chen, 1988) have developed a based on activity and percent clay sizes (Fig 2-1).

The expansion was measured as the percentage of swell on soaking from 100% maximum density and optimum moisture content in a standard AASHTO compaction test under a surcharge of 1psi (6.9KPa).

The activity is defined as: $A_c = PI/(C - 10)$ (2.1)

Where,

A_c = Seed's activity number

C is the percentage of clay size finer than 0.002 and

PI is the plasticity index.

Table 2.3 Relation between activity and potential of expansion(Arora,2003)

ACTIVITY	POTENTIAL OF EXPANSION
Ac < 0.75	Low (inactive)
0.75 < Ac < 1.25	Medium (normal)
Ac > 1.25	High (active)

Classification Using Swell potential.

Free swell index is also one of the most commonly used simple tests to estimate the swelling potential of expansive clay. The procedure involves in taking an oven dried soil samples passing through 425µm sieve, 10cc soil placed in to 100ml graduated cylinder and distilled water was filled. Finally, change of volume of soil was recorded after 24Hrs. Then the volume change is divided by initial volume and expressed as percentage to get free swell index. Then the free swell index value is used to give fair approximation wether the soil is expansive or not. According to most of the references, soils with free swell index value less than 50% are not expansive, free swell index value 50% -100% are marginal and free swell index value greater than 100% are expansive soils.

2.1.4 Distribution of expansive soils

Expansive soils are wide spread in African continent, occurring in South Africa, Ethiopia, Kenya, Mozambique, Morocco, Ghana, Nigeria etc. In other parts of the world cases expansive soil have been widely reported in USA, Australia, Canada , India, Israel, Turkey, Argentina, Venezuela etc.(Alemayehu Teffera and Mesfin Leikun,1999).

2.1.5 Mechanics of Swelling

If environment of an expansive soil has not been changed, swelling does not take place. Environmetal change can consist of pressure release due to excavation, desiccation caused by temperature increase, and volume increase due to moisture introduction. By far the most important element is the effect of water on expansive soils.

There must be a potential gradient,which can cause water migration,and a continous passage through which water transfer can take place. With the introduction of water, volumetric expansion takes place. If pressure is applied to prevent expansion, the pressure required to maintain the initial volume is the swelling pressure.

Thickness and location of potentially expansive layers in a profile considerably influence potential movement. Greatest movement will occur in profiles that have expansive clays extending from the surface to depths below the active zone. Less movement will occur if expansive soil is overlain by non expansive material or have got shallow depths. Water contents in the upper few meters of the expansive soil profile are affected by enviromental factors and generally called zone of seasonal variation or the active zone (Fig 2.2).

2.2 Potassium Chloride

2.2.1 Potash

The word "potash" is derived from the Dutch word "potash", and originally referred to as wood ash. Potassium carbonate, a pre chemical of pre-modern times was extracted from it. However, today potash refers to potassium compounds and potassium bearing materials. The most common is potassium chloride. The most important chemical compounds are potassium chloride (KCl), potassium sulfate (K_2SO_4), and potassium carbonate (K_2CO_3). In nature these compounds are found in several forms amongst which the most important minerals are Sylvite (potassium chloride) and Carnallite (hydrated potassium chloride) (Shiferew Ayale, 2010).

2.2.2. Abundance of Potash

Potassium occurs abundantly in nature and it is the seventh most common element in the earth's crust. Some clay minerals which are associated with heavy soils are rich sources of potassium. Potassium chloride is soluble in water and subsequently is easily extracted and readily amenable to chemical operations, reduced by metals such as magnesium, aluminum and their compounds and they have different density.

2.2.3. Exploration History of Potash in Ethiopia

During World War II, Italian and other foreign Companies undertook exploration activities in different parts of the Danakil depression of northern Ethiopia and exploited some mineral resources such as potash and Sulphur. The evaporates the central parts of the Danakil depression cover an area of 1150 km^2, the major part of which is known as the salt plain and centered on Dallol at approximately $14^0$15'N and $40^0$2o'E (Shiferew Ayele, 2010).

Fig. 2.3 Location map of Dallol Potash Deposit

The presence of evaporate minerals and particularly of the Danakil depression has been known since the early years of the century and a number of attempts at small scale production were made prior to the second World War. But Ralph M. parsons Company made series attempts of large – scale potash production between 1958 and 1967. The chronological exploration history of potash deposits in the Dallol area according to Ministry of Mines and Energy is given below.

Table 2.4. The Chronological Exploration History of Potash in the Dallol Area (Shifarew Ayele, 2010.)

Concession Period	Work Undertaken	Name of Company
1911	Deposits of sulfur and potash of Dallol recognized as potentially economic	Tullio Pastori.
1916 - 1929	Exploited the surface sulfur and potash sporadically until August 1929	Compagnia Mineraria Coloniale
1929 – 1949	Dallol abandoned.	
1949 – 1954	Mining sulfur, potash, and magnesium. Small amounts of potash were mined for domestic use.	Dallol Company Limited
1954 – 1958	Negotiated take-over of the Dallol Company's concession and concession extension rights with the Ethiopian Government	Parsons Company
1958 – 1959	Parsons established its Dallol Camp, began geologic investigations of Dallol Mountain and initiated a drilling program south and southwest of Dallol in the area of surface potash.	
1959 – 1960	Parsons continued drilling in the area of surface potash and began a program of exploratory, drilling south and west of Dallol. Feasibility studies were initiated on open pit mining the "Crescent" Ore Body. Gravity and magnetic geophysical surveys in the Dallol area were conducted	
1961	As a result of the exploration drilling, sylvite ore body was discovered west of Dallol. This ore body was named the Musley Ore Body. The potash bearing formation was called the Houston Formation. A new program of Drilling was initiated to determine the extent of this ore body.	Parsons
1962	Continued drilling in the Musley area and tested the potash horizon for the presence of brines. Attempted to sink a 5' diameter shaft for test purposes in the Musley ore body.	
1963	Continued drilling at Musley.	
1964	Parsons turned operations at Dallol-Musley over to International Minerals Corporation prior to partnership after attempting to sink an 8' diameter pilot shaft and drilling several test holes:	
1965	Parsons attempted to sink another pilot shaft but abandoned it because of the inability to seal off water in the clastic and in the evaporites. A fourth shaft sinking operation was initiated. This shaft, called the "Jenkins Shaft", was completed in December 1965. During the period January through May an Exploration program for minerals other than sulfur and evaporites was completed	Parsons
1966	Underground exploration in the pilot mine was begun with intent to check the dryness of the Houston Formation, barren zones in the ore and the effects of faulting in the orebody along with mining methods and ore benefaction tests.	Parsons

Concession Period	Work Undertaken	Name of Company
1967	In March 1967, as a fault zone was being approached underground, surface water in the fault broke through into the mine flooding it. Attempts were made to dewater the mine but all failed. Detailed investigations into the hydrology and its structural correlations were initiated in the Musley area.	Parsons
1968 -1970	In April 1968, Parsons relinquished its concession rights and ceased its operations in Dallol (plate 1). In June, the Ministry of Mines took over all Dallol operation. In the wave of Parsons Co. Surrendering their concession in April 1968, Salzdetfurth A.G. and Ethiopian Potash Company got concessions to explore for new deposits in the Danakil Depression. The former company carried out some exploratory work including drilling in the southern part of Dallol during the work the company drilled eight shallow holes of which only one encouraging potash. In the early 1970, the company ceased their concession because the findings of these shallow potash layers in the concession area were not realized. The concession of the Ethiopia Potash Company covered the northern part of the depression up to the Red Sea, but the company concentrated its effort in a small area in he vicinity of Colluli.. Apart from reconnaissance survey, the company doesn't seem to have made any significant progress.	Salzdetfurth A.G. & Ethiopian Potash Company
1972	Carried out comprehensive appraisal of the previous works of potash in Dallol area. The Company suggested a better method of operation to exploit the Musely ore body and provided the full capital required for the project	United Development Inc. (UDI)
1981	UDI market study was updated.	Walsh
1984	Estimated that the proven and probable reserves of the Musely ore body amount to 15 and 16 million tons of KCl, respectively	Ethio-Libyan Mining Company (ELMICO)

The potash deposits occur within the evaporite on Mountain Dallol, a sequence evenly bedded layers sequence which is essentially confined to the limits of about 20-30 cm thick inter bedded below present sea level of the Danakil depression.

The evaporites in the Danakil depression consist of salt formation that includes gypsum halite and potash. Exploration works carried out by various companies until now have revealed the presence of two Ore bodies at Dallol. These are Crescent and Musley Ore bodies.

Crescent Ore Body

This ore body situated about 1km south-west of mount Dallol. It is irregular in shape, relatively flat lying and about 1000m long and 100m wide. The deposit surrounds the bubbling spring of magnesium chloride referred to as “Black Mountain”, which lies on the surface and occurs in depth of 300 feet, mainly in the form of Carnallite and some sylvite. The maximum thickness is given at 200 feet. The Ore reserves in the crescent Ore body have been estimated at 10-12 million tones, product of which based on a cut-off value of 25% KCl over a minimum thickness of 5 feet, 3million tones of KCl recoverable ore. This ore body is said to be most suited for open cut mining (United Development Inc., 1972).

Musley Ore Body

This ore body is located at about 4.5km west of Mountain Dallol close to the large alluvial formations at the mouth of the Musley canyon. It extends over a length of about 4km and about 1.5km wide with a trend of 25^{o} N. Musley the largest potash deposit was extensively explored during the 1960’s, within the thick sequence of halite. There is a potash rich interval consisting of sylvite (upper – most) carnalities and basal kainite. This interval was explored at Musley by drilling at 300m spacing by shaft sinking (90 meters) and by some 800 meters of underground workings to evaluate mining ability. Drilling indicated the presence of a potash bearing horizon at 500m depth similar to that explored by the underground work and shallow drilling. Drilling and underground workings developed an Ore reserve estimate for Musley of 66 million metric tons proven and 32 million metric tons probable (Ministry of Mines and Energy, 1994).

Chapter III. Review on Soil Stabilization

3.1. History and concept of soil stabilization

Soil stabilization is the process of modification of one or more engineering properties of problematic(expansive) soils to achieve the desired specification for certain construction purpose. It is required when the soil available for construction is not suitable for the intended purpose. In its broadest senses stabilization includes compaction, preconsolidation, drainage and many such processes. However the term stabilization is generally restricted to the process which alter the soil material it self for improvement of its properties (K.R Arora,2003).

The necessity of improving the engineering properties of soil has been considered as old as construction has existed. Many of accient Chinese, Romans and Icas buildings and road ways which existed till today utilized diffirent techniques of soil stabilization. The use lime as building material dates back 5,000 years when lime and clay where mixed and compacted to form bricks used in the construction of the pyramids. About 2,000 years ago the Romans used lime to improve the quality of their roads

The modern Era of soil stabilization began in the United states during 1960's and 1970's when storages of aggregates and petroleum resources forced engineers to consider alternatives of road construction instead of soil replacement (Caterpillar,2006). The use of cement stabilization is over 65 years old with methods and materials proven and well stabilished (Tensar,1998). Non – traditional stabilization products have been in development since the 1960's with many research papers and projects written on the subject. Despite the multitude of information available the acceptance of these soil stabilization products are to be proven through time (Alex E. and David Jones, 2010).

3.2 Methods of Soil stabilization

Thre are various methods of soil stabilization and their effects on the engineering properties of the soils.

3.2.1 Mechanical Soil Stabilization

Mechanical stabilization is the process of improving the properties of the soil by changing its gradation. Two or more natural soils are mixed to obtain a composite material which is superior to any of its components. To achieve the desired grading, some times the soils with coarse particles are added to a soils with fine particles or fine soils are removed, mechanical stabilization is also known as granular stabilization.

For the purpose of mechanical stabilization, the soils subdivided in to two categories.

1. **Aggregates** :- these are soils which have a granular bearing skeleton and have particles of size larger than 75μ.
2. **Binders: -** these are soils which have particles smaller than 75μ. They donnot possess a bearing skeleton.

The aggregates consist of strong ,well graded, angular particles of sand and gravel which provide internal friction and incompressibility to a soil. The binders provide cohesion and imperviuos to a soil. These are composed silt and clay. The quantity of binder should be sufficient to provide plasticity to the soil , but it should not cause swelling.

Proper blending of aggregates and binders is done inorder to achieve reqiured gradation of mixed soil . The blended soil should posses both internal friction and cohesion.

The material should be workable during placement. When propely placed and compacted, the blended materials becomes mechanically stable, the load carrying capacity is increased, the resistance agnaist temprature and moisture changes also improved.

The mechanical stability of the mixed soil depends on mineral strength of the aggregate, mineral composition, gradation, plasticity characteristics and compaction. Mechanical stabilization is the simplest method, it improves the sub grades of low bearing capacity. It is extensively used in the construction of bases, sub-bases and surfacing of roads.

3.2.2 Chemical Stabilization

3.2.2.1 Lime Stabilization

Lime stabilization has been used succesfully on many projects to minimize swelling and improve soil plasticity and workability. Many state high way departments have researhed lime stabilization and frequently use this treatment method.

Lime tabilization is done by adding lime to a soil. It is useful for stabilization of clayey soils. When lime reacts with soil , there is exchange of cations in the adsorbed water layer and decrease the plasticity of the soil occurs. The resulting material is more friable than original clay. and is therefore, more suitable as sub-grade.

Lime is produced by burning of lime stone in kilns. The quality of lime obtained depends upon the parent material and production process. Basically there are five types of lime:- High calcium quick lime (CaO), Hydrated or high calcium lime [$Ca(OH)_2$], Dolomotic lime ($CaO + MgO$), Normal or Hydrated dolomitic lime [($Ca(OH)_2 + MgO$], Pressure hydrated dolomitic lime [($Ca(OH)_2 + MgO_2$] (K.R Arora,2003).

The quick lime is more effective as stabilizer than hydrated lime; but the latter is more safe and convenient to handle. Generally, the hydrated lime is used. It is also known as slaked lime, the higher the content of lime, the less is the affinity for water and the less is the heat generated during mixing.

The amount of lime required for stabilization varies between 2 to 10% of the soil. However if the lime is used only to modify some of the physic – chemical characteristics of the soil, the amount of lime is about 1 to 3%.

The following amount may be used as a rough guide (K.R Arora,2003).

i) 2 to 5% for clay gravel having less than 50% silt – clay fraction.

ii) 5 to 10% for soil with more than 50% silt – clay fraction.

iii) For soils having particle size particle size intermediate between one and two above, the quantity of lime required is between 3 to 7%.

iv) About 10% for heavy clays used as bases and sub- bases lime stabilization is not effective for sandy soils. However, these soils can be stabilized in combination with clays, fly ash or other pozzolanic materials which serve as hydraulically reactive ingredients.

Chemical and physical changes in lime stabilization

When lime reacts with wet soil, it alters the nature of the adsorbed layer by base exchange. Calcium ions replace the sodium or hydrogen ions. The double layer is usually depressed due to an increase in the concentrtion. However, sometimes the double layer may expand due to high PH value of lime.

When lime reacts chemically with silica and alumina in soils, a natural soil composed of calcium alumino silicate complexes is formed, which causes a cementing action. The reaction depends upon the effective concentration of the reactants and temprature.

In lime stabilization, the liqiud limit of the soil generally decreases, but the plastic limit increases. Thus the plastisity index of the soil decreases, the soil becomes more friable and workable. The strength of the lime stabilized soil is generally improved. It is partly due to decrease in plastic properties of a soil and partly due to formation of cementing material. Increase in th unconfined compressive strength is some times as high as 60 times. The modulas of elasticity of the soil is also icreases substaintially .

Addition of lime causes high concentration of lime ions in the double layer. It causes the decrease in the tendency of attraction of water. Consequently,the resistance of the soil to water adsortion, capillary rise and volume changes on wetting and drying is substaintially increased. The lime stabilized bases or sub- bases from a water resistant barrier which stops penetration of rain water. There is an increasing in optimum water content and reduction in maximum dry density. In swampy areas where water content is above the optimum , application of lime to soil helps in drying the soil. Cyclic freezing and thawing can cause a temporary loss of strength, but because of subsequent healing action , there is no loss of strength in along run.

3.2.2.2 Cement Stabilization

Cement stabilization is done by mixing pulverized soil and portland cement with other and compacting the mix to attain a strong material. The material obtained by mixing soil and cement is known as soil – cement.

The soil – cement becomes hard and durable construction material as cement hydrates and develops strength.

Mitchell and Freitag (1959) have divided the soil – cement in to three categories.

1. **Normal soil -cement:-** consists of 5 to 14% of cement by volume. The quantity of cement mixed with soil is sufficient to satisfiy hydration requirements of the cement and to make the mixture workable. The normal soil – cement is quite weather resistant and strong. It is commonly used for stabilizing sandy and other low plasticity soils.

2. **Plastic soil - cement:-** this type of soil – cement also contains cement 5 to 14% by volume, but it has more quantity of water to have wet consistency similar to that of plastering mortar at the time of placement. The plastic soil-cement can be placed on steep or irregular slopes where it is difficult to use normal road making equipment. It has also been successfully used for water proofing lining of canals and reserviors. The plastic soil cement can be used for protection of steep slopes agnaist erossive action of water.

3. **Cement - modified soil:-** This is a type of soil-cement that contains less than 5% of cement by volume. It is semi hardened product of soil and cement. It is quite inferior to the other two types. As the quantity of cement used is small, it is not able to bind all soil particles in to coherent mass. However, it interacts with the silt and clay fractions and reduces their affinity for water. It reduces the swelling characteristics of the soil. The use of cement modified soils is limited.

Factors affecting cement stabilization are:-

i) Type of soil: granular soil with sufficient fines are ideally suited for cement stabilization. Such soils can be easily pulverized and mixed.

Granular soils with defficient fines, such as beach sands can also be stabilized but these soils require more cement. Silty and clayey soils can be produce satisfactory soil – cement but those with high clay content are difficult to pulverize. Moreover, the quantity of cement increases with an increase in clay content. Organic matter if present in collodial form, interfres with hydration of cement and causes a reduction in the strength of soil – cement.

ii) **Quantity of cement: a well** – graded soil requires about 5% cement. Whereas a poorly graded uniform sand may require about 9% cement. Non plastic soil silts require about 10% cement. Whereas plastic clays may need about 13% cement. The actual quantity of cement required for a particular soil is ascertained by laboratory testes. For base- courses , samples are subjected to durability tests for determination of the quantity of the cement required. Some times , the quantity of cement is determined according to a minimum UCS. Generally a minimum strength of about 1500 kN/m^2 for clayey soils and about 5500 kN/m^2 for sandy soils is specified.

iii) **Quantity of water:** The quantity of water used must be sufficient for hydration of cement and silt-clay cement and making the workable. Generally, the amount of water accertained from compaction consideration is adequate for hydration as well.

iv) **Mixing,compaction and curing :** the mixture of the soil, cement and water should be thoroughly mixed as the success of cement stabilization depends on thorough mixing. If not properly mixed, it may result in a non- homogenous weak product. However, the mixing should not be continued after the cement has started hydrating as it would result in a loss of strength**.**

v) **Admixture :** to increase the effectiveness of cement as stabilizer, admixtures are some times added to soil cement. Admixtures may permit a reduction in the amount of cement required. These may also help stabilization of soils which are not responsive to cement alone. Lime and calcium chloride have been used as adimixture for clays and soils containing harmful organic matter to make them more responsive for cement. Fly ash acts as a pozzolana an is effective for stabilization of dune sand.

3.2.2.3 Salt Stabilization

The following chemical have been succesfully used.

1. Calcium Chloride. When calcium chloride is added to soil, it causes Colloidal reaction and alters the characteristics of soil water. As calcium chloride is deliquescent and hygroscopic, it reduces the loss of moisture from the soil. It also reduces the chances of frost heave as freezing point water is lowered. Calcium chloride is very effective as dust palliative. As the soils treated with calcium chloride do not easily pick –up water, the method is effective for stabilization of silts and clayey soils which lose strength with an increase in water content.

Calcium chloride causes a slight increase in the maximum dry density. However the optimum water content is slightly lower than that of untreated soil. It causes a small decrease in the strength of the soil. However, if the compacted soil is put to water imbibition, water pick-up is reduced and the strength of the treated soil is greater than that of the untreated soil.

It may be noted that the most of the benefits of stabilization require the presence chemical in the pore fluid. As soon as the chemical is leached out, the benefits are lost. The performance of treated soils depends to a large extent on the ground water movement (K.R Arora,2003).

2. Sodium Chloride. The action of sodium chloride is similar to that of calcium chloride in many respects. However, the tendency for attraction of moisture is somewhat lesser than that of calcium chloride. When sodium chloride is added to the soil, crystallization occurs in the pores of the soil and it forms a dense hard material with the stabilized surface. The pores in the soil get filled up with and retard further evaporation of water. Sodium chloride also checks the tendency for the formation of shrinkage cracks (K.R Arora,2003).

3. Potassium Chloride. According to the International journal of Advance in engineering and technology, University College of Engineering, JNTUK, Kakinada, India, June 2012, the performance of chemically stabilized expansive soil was evaluated using some salts. Among these salts potassium chloride is one and the addition of 1% KCl by dry weight of soil, decreases liquid limit by 57%, PI by 26%, Defferential free swell by 40%. The addition of 1% KCl increases CBR by 80% and UCS by 133%. Earth science research published by Canadian center of science and education, June 29, 2012, stated the influence of mineral salts (KCl and $MgCl_2$) on swelling properties of expansive soil. The result showed that the stabilization by the addition of KCl modified the properties of the soil and results are quite satisfactory in significantly reducing the swelling properties of the soil.

Chapter IV. Materials and Methods

4.1. General

The stability and durability of pavements and buildings are largely dependent on the characteristics of the soil underneath. In most cases soils form sub-grade of roads and foundation of buildings usually found in flat low lying areas are expansive and the thickness of the soil mass is considerable. The soil mass might vary from non expansive to highly expansive and when the expansive soils are encountered it poses problems unless and otherwise proper improvement measures are taken.

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

In the present study laboratory tests were conducted on natural untreated representative samples to characterize the soil. To assist the laboratory testing and subsequent identification of soil, field investigation was under taken before pitting and sampling. The field investigation included identification of soil based on observation of colour and soil texture on the site where the sample was collected. The laboratory tests conducted include:- grain size analysis, free swell, specific gravity, Atterberg limits, swell consolidation, moisture density relation, unconfined compressive strength, CBR. These tests were deemed enough to characterize the soil for the present research work.

This section comprises of description of index and engineering characteristics of samples which were used to characterize the soils.

4.2. Materials

4.2.1. Expansive Soil

The Expansive soil sample used for this research work is collected from Addis Ababa,Akaki Kality Sub City around Galan condominium from road construction project. The soil is black in colour. Both disturbed and undisturbed soil samples were collected at a depth of about 1.5m to 2.0m. Full properties the soil is addresed in the methodology section.

4.2.2. Potassium chloride

Commerial grade potassium chloride was purchased from Neway Chemicals PLC. The chemical content of this chemical, which is sealed, was indicated on its container. The purity of this chemical is about 99.5% whereas the rest 0.5% is other impurities which are summarized in the following table.

Table 4.1 Chemical Specification of Potassium Chloride (Manufacturer Manual).

Purirty of Potassium Chloride	
1. Minimum Assay	99.5%
2. PH (2% solution)	5.5 – 8.5
Maximum Limits Of Impurities	
1. Bromide (Br)	0.01%
2. Iodie (I)	0.002%
3. Sulphate (SO_4)	0.003%
4. Phosphate (PO_4)	0.005%
5. Total Nitrogen (N)	0.001%
6. Heavy Metals (as Pb)	0.0005%
7. Iron (Fe)	0.0002%
8. Calcium (Ca)	0.001%
9. Barium (Ba)	0.001%
10. Magnesium (Mg)	0.0005%
11. Sodium (Na)	0.02%
12. Loss on Drying	0.2%

4.2.3. Water

According to the standard test, it is recommended to use distilled water to conduct certain laboratory tests like Atterberg limits and specific gravity. But due to lack of distilled water in the laboratory of Addis ababa inistitute of technology AAU, tap water is used to conduct all laboratory tests discused below.

4.3. Methods

4.3.1. Soil Investigation and Description

Field investigations of the soil included field description of the soil and collection of representative soil samples for laboratory tests.

Sampling of the soil was conducted at Addis Ababa around kality area on Akaki-Lebu road construction site.

The terrain of the land feature is flat and extensively covered by expansive soil. The sample was taken at a depth of about 1.5m - 2m.

4.3.2 Laboratory Testing and Analysis of Samples

Tests for soil classification which included grain size distribution, free swell, specific gravity, and Atterberg limits. These are indicative tests that are usually used for identifying wether the soil is expansive or not.

The conducted tests however included hydrometer analysis, Atterberg limits, wet sieve analysis, specific gravity, swell consolidation, moisture density relation, free swell, unconfined compressive strength, CBR and percent swell of CBR to fully characterize and attain the objective of the research.

4.4. Soil Classification

The most widely used soil classification systems for engineering purposes are American Association of State High Way and Transportation Officials (AASHTO) and Unified soil classification system (USCS). The AASHTO system of soil classification comprises seven groups of inorganic soils from A-1 to A-7 with 12 subgroups in all. The system is based on particle-size distribution, liquid limt and plasticity index.

On the other hand the Unified Soil classification system is based on the recognition of the type and predominance of the constituents considering grain – size, gradation, plasticity and compressibilty. It divides soil in to three major divisions: coarse grained soils, fine grained soils and highly organic soils. Field identification is accomplished by visual examination for the coarse-grained soils and a few simple hand tests for the fine-grained soils. In the laboratory, the grain-size curve and the Atterberg limits tets are used.

4.4.1. Grain Size Analysis test

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

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

Table 4.2 Grain size analysis laboratory test result of natural soil

Sieve designation	4.75	2.36	2.0	1.18	0.6	0.425	0.3	0.15
% passing sieve	99.69	98.71	98.58	97.94	97.47	97.37	97.33	96.81
Sieve designation	0.075	0.071	0.037	0.019	0.01	0.005	0.003	0.001
% passing sieve	92.09	92.08	86.66	83.72	80.79	74.93	69.06	61.11

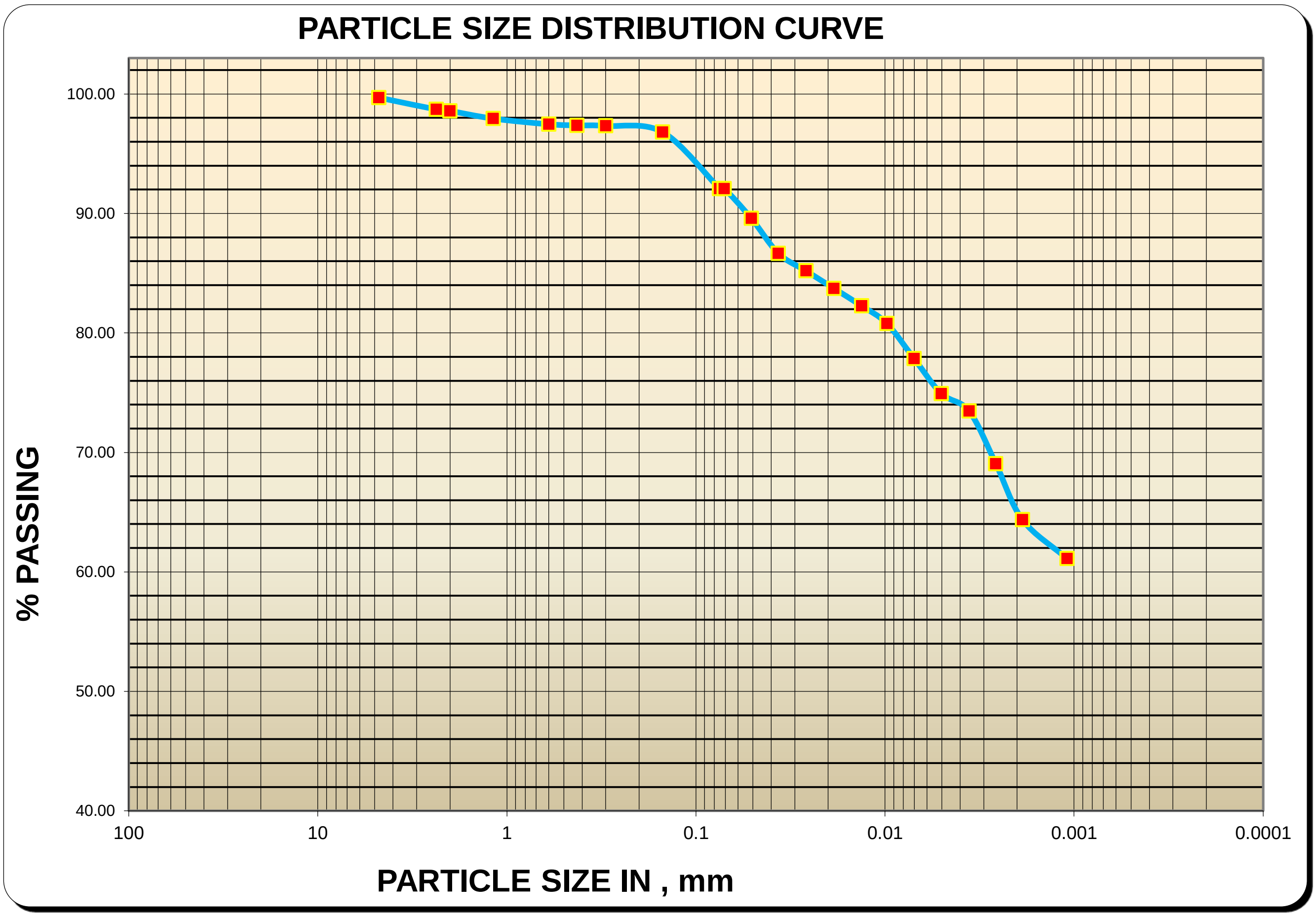

Fig 4.1: Grain Size Distribution Curves for natural Soil Sample Tested

4.4.2. Atterberg Limit tests

The nature and response of soil upon change to moisture content is determined by Atterberg limit tests. This parameter is basic in the AASHTO and USCS soil classification systems.

The Atterberg limit depends on the type of predominant clay mineral available in the soil mass. If the predominant clay is montmorillonite the liquid limit can reach or even exceed 100%.

It is also expected that the Atterberg limit is less for illite dominated soil and even lesser for kaolinite dominated soils. In general, soils that exhibit plastic behavior over wide ranges of moisture content and that have high liquid limits have greater potential for swelling and shrinking (Nelson, 2010).

The test results analysis in general shows that the soil can be classified as A-7-5, according to AASHTO and CH according to USCS soil classification system.

Table 4.3. Atterberg limits and GI for the natural soil sample tested for soil classification

Sample No.	**Atterberg limit**		
	LL(%)	**PL(%)**	**PI(%)**
1	**104**	**52**	**52**

4.4.3 Free Swell Test

The test includes the determination of the free swell for the natural soil and soil mixture. This test has not yet been standardized by AASHTO and ASTM. The method was suggested by Holtz and Gibbs, (1956) to measure the expansive potential of cohesive soils. The free swell test gives a fair approximation of the degree of expansiveness of the soil sample. The procedure consists of pouring very slowly of 10 cubic centimeters of that part of the dry soil passing No. 40 sieve in to a 100 cubic centimeters graduated measuring cylinder and letting the content stand for 24 hours until all the soil completely settles on the bottom of graduating cylinder. Then the final volume is noted for calculation. The Free swell of original soil is given in table 4.3.

Table 4.4 Free Swell Index of untreated soil

Initial Volume (cc)	Final Volume		Average Final Volume (cc)	Free Swell Index (%)
	Sample No.1 (cc)	Sample No.2 (cc)		
10.0	25.5	26.0	25.8	158

4.4.4 Specific Gravity test

Specific gravity which is the measure of heaviness of the soil particles is determined by the method of pychnometer method using a soil sample passing No. 10 sieve and oven dried at 105 degree centigrade.

The test includes the determination of the specific gravity for the natural soil. The test was conducted in accordance with AASHTO T100-93 testing procedure. The specific gravity of as-received soil is found to be 2.76 which indicates the soil Inorganic clay.

4.5. Unconfined Compressive Strength (UCS)

The unconfined compressive strength test is applicable only in cohesive soils. The test is carried out in cylindrical specimen with dimensions of 50mm diameter and 70mm in length. In this test the soil goes to failure by axial load only with no confining stresses. The UCS values are determined in accordance to AASHTO T-208.

The unconfined compressive strength tests were conducted for both natural and treated samples. 7 days cured test was conducted on treated samples. The test result on the untreated soil sample revealed that the Unconfined compressive strength of the soil is 146 kPa.

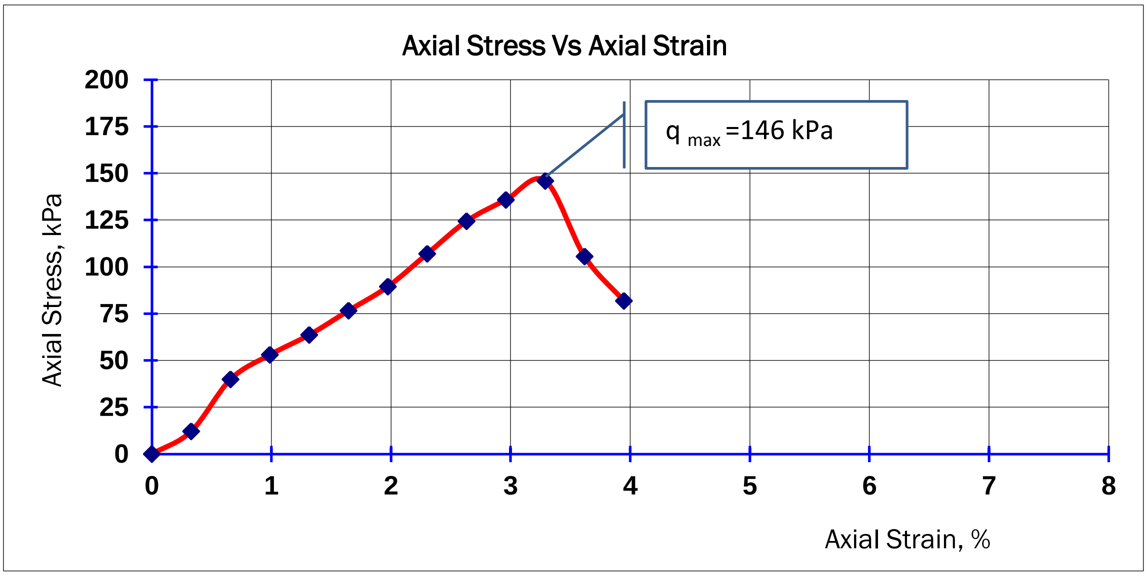

Fig 4.2: Unconfined Compressive strength of natural soil.

4.6 CBR Swell Test

Readings of swelling value were taken before and after soaking of CBR for two samples and the swell percent calculated is presented as:-

The result showed that the percent swell of CBR was 10% and it is comparable to values obtained from laboratory tests of expansive soils found in different parts of Ethiopia. The value is above the specified maximum value of 2%, hence this soil need to be treated before use.

4.7. Moisture Density Relations of the Soil

Standard Proctor compaction tests were conducted on the soil to determine the relationship between the moisture content and dry density for specific compaction effort according to AASHTO T99-94.

The optimum moisture content 43.68% and the maximum dry density is 1.16gm/cm^3 .

4.8. California Bearing Ratio (CBR)

Strength of the soil has also been determined. A one point CBR test was conducted according to AASHTO T193 and the CBR values at 95% MDD was determined. The test result showed that the soil has very low CBR value of 1% which does not satisfy the minimum requirements as sub-grade material.

4.9. Overall Characterization of the soil

The grain size analysis of the soil samples showed that, it is mostly clay because about 92% of the soil pass sieve no 200. The soil has been found to be highly expansive with plasticity index of 52% and thus, these soils can be classified as A-7-5 according to AASHTO classification system and CH according to USCS.

All the indirect methods and empirical relations as well as the percent swell test showed that the soil is highly expansive. Such high expansivity of fine grained soils are expected to be dominated by montimrillonite clay minerals, though mineralogical test can not be carried out.

The soil has very low load bearing capacity of 1% and very high swelling potential beyond the permissible limits. Such soils are potentially problematic and results in serious damages to pavements constructed on them, unless treated appropriately. Therefore, appropriate treatment methods should be conducted before any structure is constructed over such poor soils.
The next chapter presents treatment of this expansive soil with potassium chloride using laboratory investigation.

Chapter V.   Results and Discussions

5.1. Introduction

In this chapter Laboratory test results are briefly discussed and the effect of potassium chloride is evaluated for each laboratory tests. Revision on the physical properties of in-situ soil has also been summarized in this chapter , to make the comparison between treated and untreated soil samples easier.

5.2. Discussion on Test results of Untreated soil

According to the laboratory test results of the natural soil sample obtained during the present study, the proportion of fines passing no 200 sieve 92% , liquid limit 104% and plasticity index 52%, the soil is classified in to A-7-5 as per the AASHTO and CH as per the USCS classification system. As far as the engineering performance of soils of this class is concerned, such soils are expansive soils which have high volume changing properties with variation in moisture content (Chen, 1988; McKeen, 1976). The liquid limit and plasticity index values are very much greater than the Ethiopian Roads Authorities requirements, i.e, liqiud limit less than 60% and plasticity index less than 30%. According to ERA's design manual of 2002, soils with swelling potential and clay content greater than 35% and 28% respectively have high degree of expansiveness.

Accordingly, sample show higher values in each parameter and the soil in general thus has very high expansive potential. The free swell index of 158% also revealed that the soil is very expansive soil, since its free swell index is greater than 100%.

Furthermore, the CBR and percent swell of 1% and 10% respectively indicate that the soil has a very low load bearing capacity and high swelling potential when compared to ERA's specifications of CBR > 5% and percent swell of less than 2% which makes it unsuitable for construction without any suitable treatment measure.

However, the comparisons above between ERA design manual and laboratory results of the soil shows that, the soil sample do not full fill the requirments as a sub-grade and are determined to be unsuitable for sub-grade in road construction. Therefore, the sub-grade soil should be treated with appropriate improving methods before use as road sub grade. This can be done by different soil improvement techniques including removal of the soil and replacement with suitable material (capping layer), chemical stabilization, compaction, pre-wetting and making the appropriate pavement designs that considers the unsuitability of the soil.

5.3. Effects of Potassium Chloride on Egineering properties of soil

Chemical stabilization is an alternative to improvement method for poor soils. Chemicals such as lime improve the low load bearing capacity of poor soils and lower the plasticity index and percent swell of highly expansive soil (Chen, 1988, Little and Nair, 2009, Mc Keen, 1956). In the present study the effect and performance of Potassium chloride, one of the chemical stabilizers, on highly expansive and low load bearing soil is evaluated which is mainly based on laboratory test results of free swell, Atterberg limits, standard compaction, CBR and percent swell of CBR , swell consolidation and unconfined Compressive strength.

5.3.1. Effect of potassium chloride on free swell of soil

The free swell tests were conducted on natural soil and treated soil samples by pouring 10g of soil sample passing No 40 sieve in to graduated cylinder filled with water. Then the free swell of both treated and untreated soil samples were determined as the ratio of change in volume to the initial volume, expressed as percentage.

Free swell tests were conducted by mixing potassium chloride at different proportion of 0, 2.5, 5, 10, 15 and 20 percentages by dry weight of soil sample. The effect of KCl on the free swell index of the soil sample is graphically summarized in Fig 5.1.

Table 5.1 Effect of Different percentage of KCl on Free swell index of natural soil

%KCL	0.0	2.5	5.0	10	15	20
%FSI	158	103	79	60	43	28
% Decrease of FSI	0	35	50	62	73	82

Percent decrease in the free swell index = $[(FSI_f - FSI_o)/ FSI_o]*100$ (5.1)

FSI_f = value of FSI of the soil for respective percentage of KCl.

FSI_o= value of FSI of untreated soil (zero percent KCl).

The results show that a significant reduction in the swell potential of the soil sample was observed by adding different proportion of potassium chloride. The free swell index value decreased from 158% to 28% which was significant change. This result was achieved at 20% KCl proportion to the soil sample, which shows about 80% decrease in the free swell index. The result obtained guaranteed, the soil stabilized using potassium chloride show low degree of expansion as compared to untreated soil, as a result, the soil to have a free swell within the allowable requirements.

Generally, increase in percentage of potassium chloride decrease potential swell of the soil. This might be due to chemical reaction and Cation exchange between the soil and potassium chloride.

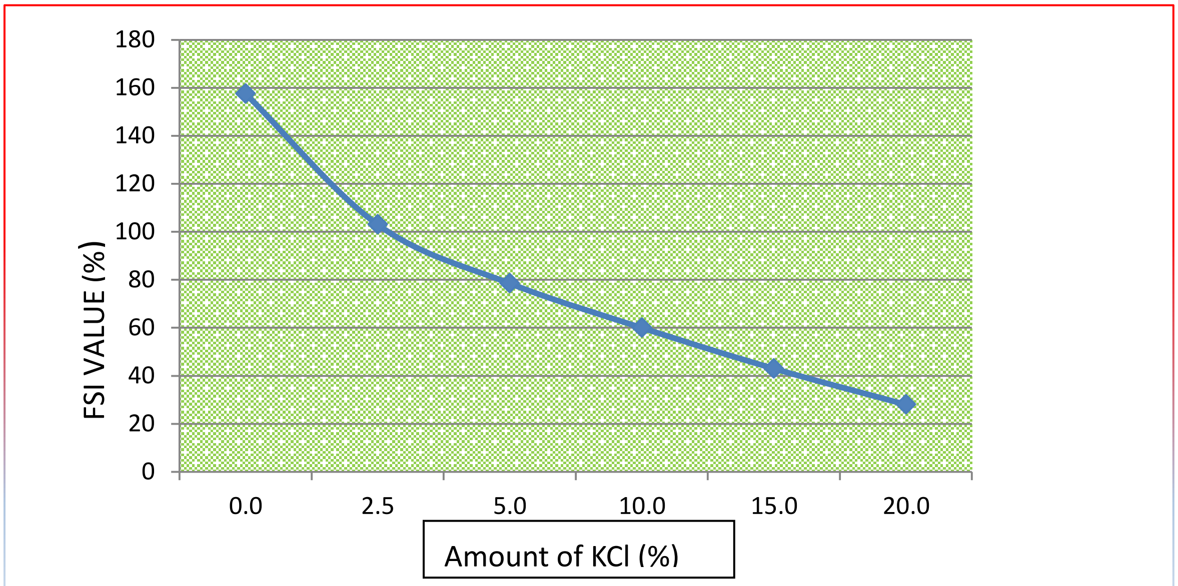

Fig 5.1 Effect of potassium chloride on free swell index of the soil

5.3.2. Effect of potassium chloride on Atterberg limits of soil

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

Soil samples were first air dried and pulverized and then sieved with no 40 sieve. Soil passing no 40 sieve was mixed with different proportion of chemical at optimum water content and sealed with plastic for 24 hours inorder to give sufficient time for chemical reaction before test.

The proportion of KCl used was 0%, 2.5%, 5%, 10%, 15% and 20%. Then Atterberg limits of these soil samples were determined after 24 hours.

From Table 5.2 KCl-soil mixtures, the following observations have been made.

Table 5.2 Effect of percentage of KCl on Atterberg limits of natural soil.

KCl (%)	0	2.5	5	10	15	20
Liquid limit (%)	104	90	75	62	59	57
Plastic limit (%)	52	50	49	49	51	50
PI value (%)	52	40	26	13	8	7
% decrease of PI	0	23.1	50.0	75.0	84.6	86.5

Percent decrease in plasticity index = $[(PI_f - PI_o)/ PI_o]*100$ (5.2)

PI_f = value of PI of the soil for respective percentage of KCl.

PI_o = value of PI of untreated soil (zero percent KCl).

- The liquid limits signficantly decrease with increasing Potassium chloride proportions because KCl disperses the soil particles apart and the cohesion of soil highly decreases. Consequently, the soil exhibit sandy nature.
- The plastic limit almost kept constant with increasing potassium chloride proportions.

The values of plastic limits showed inconsistency, even to mention the very insignificant Changes observed. The chemical have not shown significant change on the plastic limit of the soil because the dispersing effect of the chemical doesn't affect the plastic nature of the soil but its luiquid limit only.

- The plasticity index also signifacntly decreases with increasing potassium chloride proportion. This is because of the decrease in the liquid limit, as plasticity index is the difference between liquid limit and plastic limit.

According to the results observed from the laboratory test, one can judge that the behavior of soil sample was changed from very high plasticity soil to low plasticity soil. Soils of plasticity index greater than 35% are classified as highly plastic and 0-15% low plastic soil as reviewed in section 2.1.3.2.

The optimum percentage of potassium chloride that completely changed the soil from high to low plastic soil was observed at 10%, for which the PI value was 13%. The maximum decrease in PI value was seen at 20%KCl and the PI value is decreased from 52% to 7% which is about 88.5% of initial plasticity index.

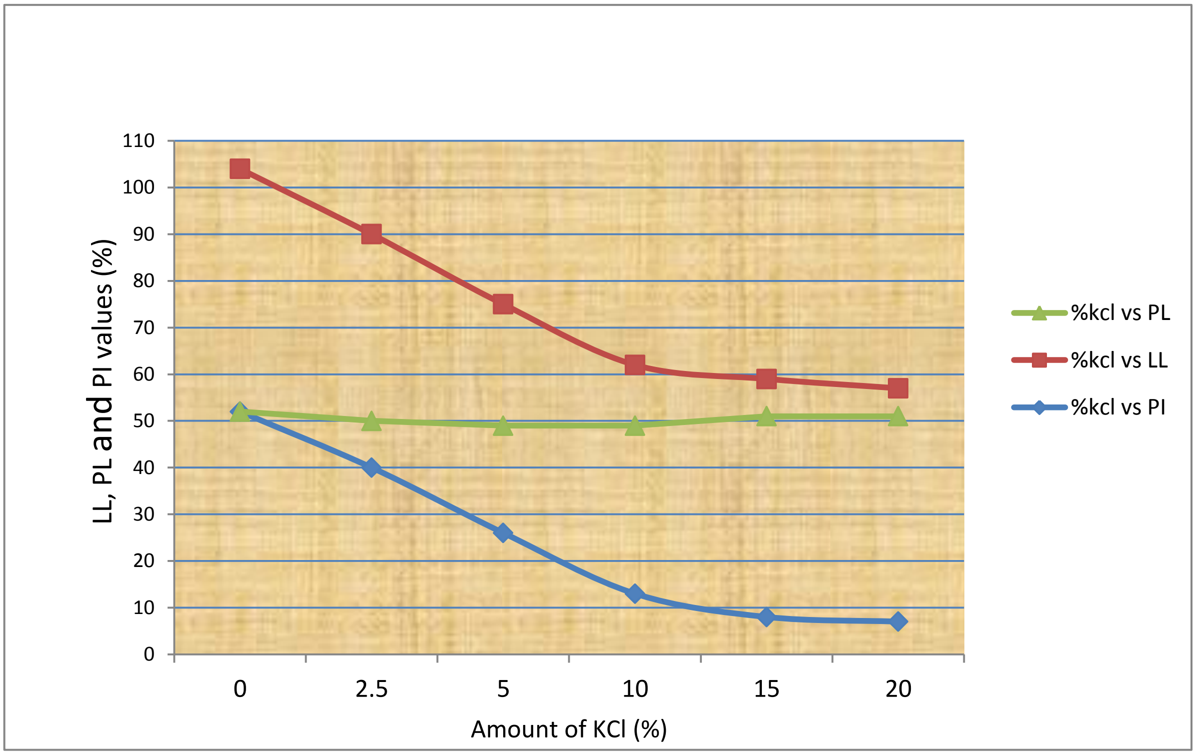

Fig 5.2 Effect of potassium chloride on Atterberg limits

The treatment of the soil with potassium chloride, have brought very appreciable result in decreasing the plasticity of the soil. According to ERA 2002 specification, the maximum values of PI and LL were 30% and 60% respectively to use the soil as a sub grade material. Therefore both ERA specification requirements are attained simultaneously at 10%KCl. Hence the chemical is successful in stabilizing expansive soils with regard to Atterberg limits.

Generally, increasing the percentage of potassium chloride, decrease the plasticity index of the soil. The reason for high decrease in plasticity index was expected to be a flocculation and agglomeration reaction during the cation exchange.

5.3.3. Effect of potassium chloride on Moisture Density Relations of the Soil

Air dried and pulverized soil passing No 4 sieve was used to determine moisture-density relation of the soil mixed with varying proportions of the chemical additives. The soil was mixed with varying ratios of poatassium chloride.

Further, standard proctor test was carried out according to AASHTO T99-94. Moisture content versus dry density graph was produced and optimum moisture content (OMC) and maximum dry density (MDD) were determined from the graph. The test results are shown in Table 5.3.

Table 5.3 Moisture Density Relation test results of Potassium chloride Treated soil

Moisture content and Dry Density							% KCL
MC (%)	24.18	28.91	38.10	43.68	53.35		0.0%
DD(gm./cc)	1.12	1.13	1.15	1.16	1.07		
MC (%)	26.13	39.26	48.73	51.83			2.5%
DD(gm./cc)	1.20	1.28	1.17	1.10			
MC (%)	*22.92*	*26.33*	*30.20*	*39.57*	*49.10*	*57.18*	5.0%
DD(gm./cc)	*1.20*	*1.25*	*1.31*	*1.25*	*1.12*	*1.03*	
MC (%)	27.91	36.83	43.64	51.05			10.0%
DD(gm./cc)	1.18	1.33	1.21	1.10			
MC (%)	*23.33*	*27.83*	*31.23*	*46.45*	*54.64*	*57.65*	15.0%
DD(gm./cc)	*1.26*	*1.32*	*1.38*	*1.16*	*1.06*	*1.03*	
MC (%)	*23.04*	*27.73*	*31.43*	*40.68*	51.35		20.0%
DD(gm./cc)	*1.28*	*1.37*	*1.48*	*1.21*	1.08		

Expansive soil treated with potassium chloride yielded the typical bell shaped compaction curves. The highest dry density for the untreated soil was observed to be 1.16 g/cm^3.

Even though the compaction curve is normal, the curve shifted to the left and upward in the case of treating the soil with potassium chloride, which also means addition of potassium chloride decrease optimum moisture content and increase maximum dry density.

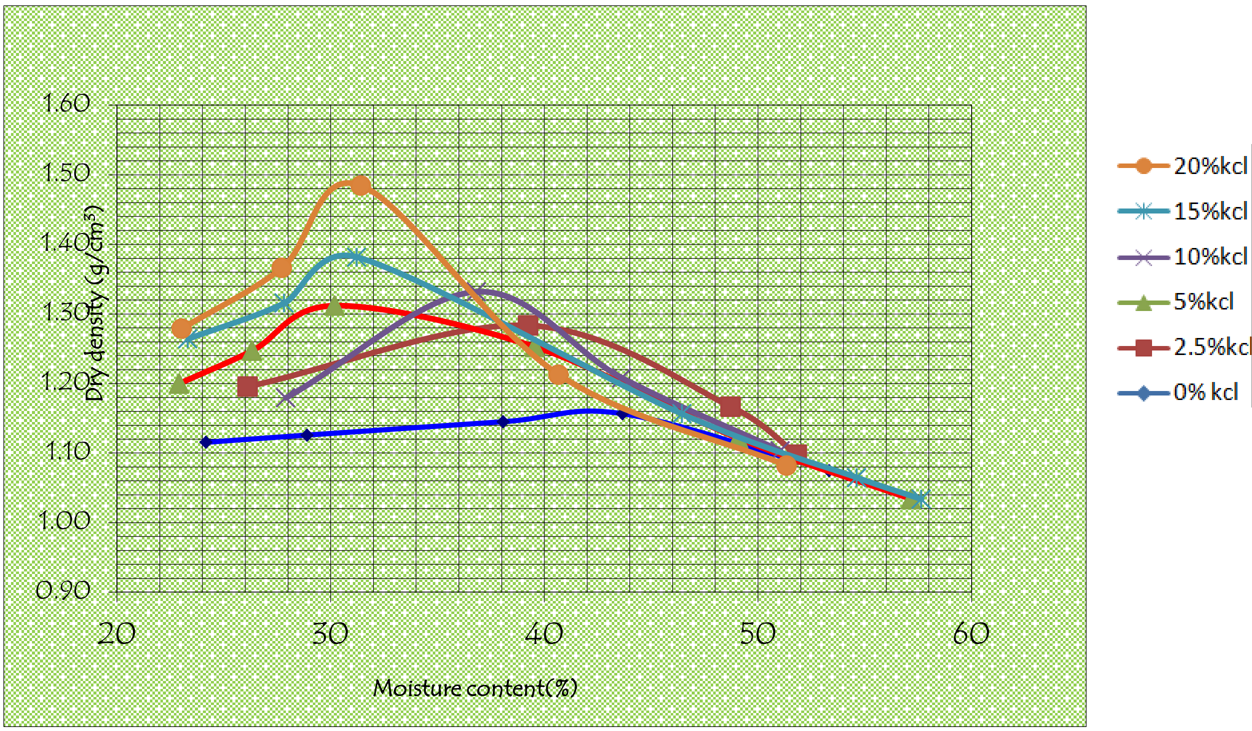

Fig 5.3 Moisture density relation test results of potassium chloride treated soil

The addition of potassium chloride increase the maximum dry density of the natural soil from 1.16 g/cm^3 to 1.48 g/cm^3 for 20% potassium chloride, for 24hrs cured soil sample. This result implied that there is a maximum increase in maximum dry density of a natural soil by 28%. However, increase in potassium chloride percentage decrease optimum water content of the natural soil from 43.68% to 30% for the addition of 5% potassium chloride. This result assures that there was 31% decrease in the OMC of the soil sample.

Generally, increasing the percentage of potassium chloride led increase in the maximum dry density and decrease optimum water content. But at 10% potassium chloride OMC of the soil unexpectedly increase which might be due to data registration problem or some technical problem during laboratory testing. The higher dry density achieved is believed to be, due to the reason that potassium chloride disperses the soil particles apart during the chemical reaction. Therefore, the dispersed soil particles are compressed easily and result in the maximum dry density. This is due to the extra negative charge made available by the deploymerization of chemical.

Table 5.4 MDD and OMC of treated soil at different percentage Of KCl .

S.no	KCl (%)	MDD(gm./cm^3)	OMC (%)	Remark
1	0	1.16	43.6	
2	2.5	1.28	39.2	
3	5	1.31	30.2	
4	10	1.33	36.8	
5	15	1.38	31.2	
6	20	1.48	31.4	

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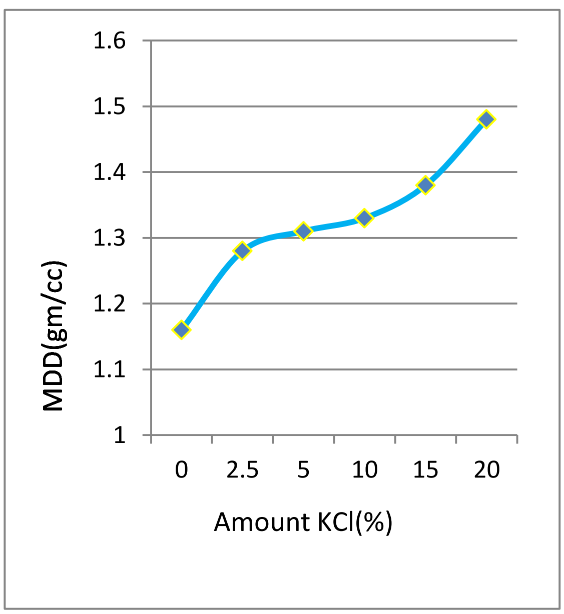

Fig 5.4 MDD vs. %KCl

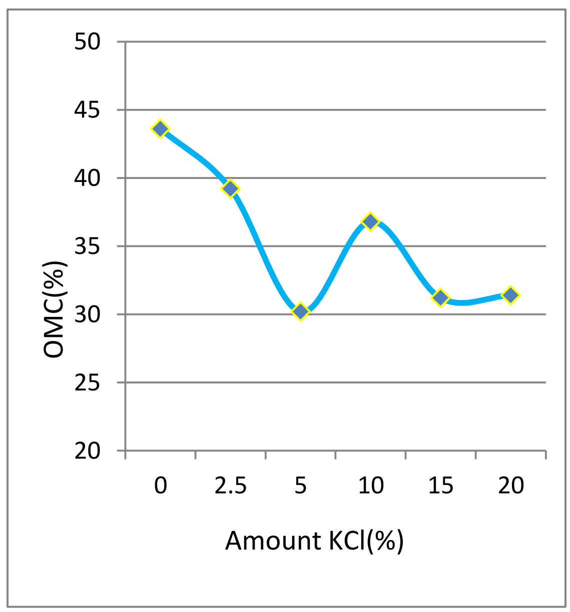

Fig 5.5 OMC vs. %KCl

5.3.4. Effect of potassium chloride on CBR value of the Soil

5.3.4.1. Effect of potassium chloride on soaked CBR of the soil

Air dried and pulverized soil passing no 4 sieve was mixed with potassium chloride at optimum moisture content and compacted in a CBR mold at maximum dry density. The potassium chloride-soil mixtures were kept compacted in CBR molds for 24hours for the sake of chemical reaction completion. Then CBR tests were conducted after the sample was soaked for 96 hrs. The CBR test results are shown in the Table 5.5.

Table 5.5 CBR test results of potassium chloride treated soil

KCl (%)	**0**	**5**	**10**	**15**	**20**
CBR value (%)	1	5	7	8	**9**
%increase in CBR	**0**	**400**	**600**	**700**	**800**

Percent increase in CBR value = $[(CBR_f - CBR_o)/ CBR_o]*100$ (5.3)

CBR_f = value of CBR of the soil for respective percentage of KCl.
CBR_o = value of CBR of untreated soil (zero percent KCl).

The effect of potassium chloride as shown in the Table 5.5 shows that the addition of 20% potassium chloride resulted in the CBR value of 9 which is the maximum value. As it can be seen from the table, as the percentage of potassium chloride increases the CBR value also increases but the increase in the CBR value is not as considerable result as the swelling properties of the soil discussed so far.

The CBR value of potassium chloride-soil mix was increased by 400, 600, 700, and 800 percents for 5%, 10%, 15% and 20% increase in potassium chloride amount respectively. This shows that the load bearing capacity of the soil increase considerably.

However according to Ethiopian Roads Authority pavement design manual specification potassium chloride treated soil satisfied a minimum CBR value not less than 5%. Hence one can conclude that an optimum increase of 5% potassium chloride can peak out expansive soils from problematic sub grade material to fair sub grade material.

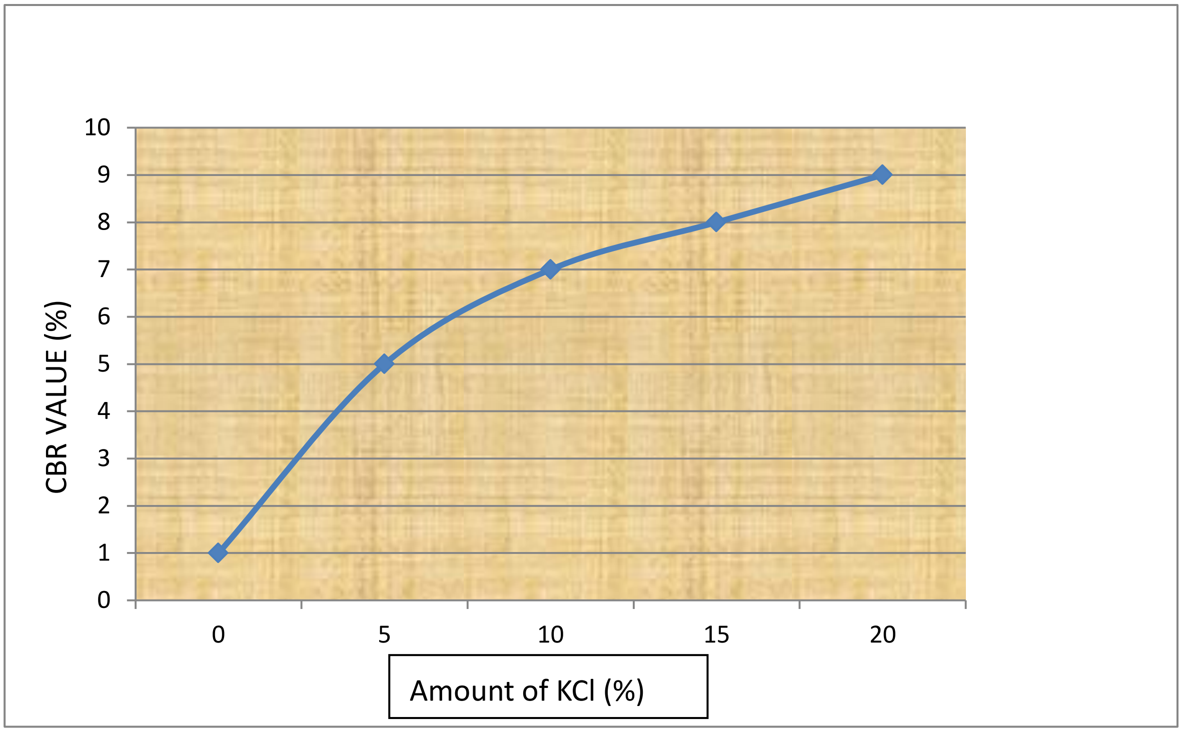

Fig 5.6 Effet of potassium chloride   Soaked CBR value of natural soil.

Generally the improvement in the load bearing capacity of the soil is expected to be due for the reason that the soil structure attain dispersed property which led the soil to attain better maximum dry density. As a result treated soil would have attained better load bearing capacity as compared to the natural soil.

5.3.4.2. Effect of potassium chloride on Unsoaked CBR of the soil

Air dried and pulverized soil passing no 4 sieve was mixed with potassium chloride at optimum moisture content and compacted in CBR molds at maximum dry density. The potassium chloride-soil mixtures were kept compacted in CBR molds for 24hours for the sake of chemical reaction completion. Then CBR tests were conducted directly without soaking the sample.The CBR test results are shown in the Table 5.6

Table 5.6 Effect of Potassium chloride on the Unsoaked CBR of natural soil.

Unsoaked CBR					
KCl (%)	0	5	10	15	20
CBR (%)	14	18	16	9	8
% Increase of CBR	0	29	14	-35	-42

Percent increase in CBR value = $[(CBR_f - CBR_o)/ CBR_o]*100$ (5.4)

Table 5.6 shows that the addition of 5% potassium chloride resulted in the unsoaked CBR value of 18 which is the maximum value. As it can be seen from the table, as the percentage of potassium chloride increases the CBR value also increases for 5% and 10%, then decreases for the remaining percentages of 15% and 20% .

The Unsoaked CBR value of potassium chloride-soil mix was increased by 29% and 14% for 5% and 10% addition of KCl respectively. However, it decreases with 35% and 42% for an addition of 15% and 20% potassium chloride. This is due to the expectation that, soil needs more water to complete chemical reaction for the reason that, potassium chloride retains water than soil. In addition potassium chloride disperses soil particles apart for the higher proportion of KCl and hence soil loose its strength due to deficiency of water for chemical reaction and dispersed particles.

Generally, it is better to use the optimum value of 5% potassium chloride which deliver as the maximum unsoaked CBR value. Comparatively the unsoaked CBR value was greater than soaked CBR value, but bearing capacity modification for the unsoaked case was unsuccesful except for 5% KCl. Therefore it is not recommended to use Potassium chloride as chemical stabilizer where the ground water table is found at deeper depth.

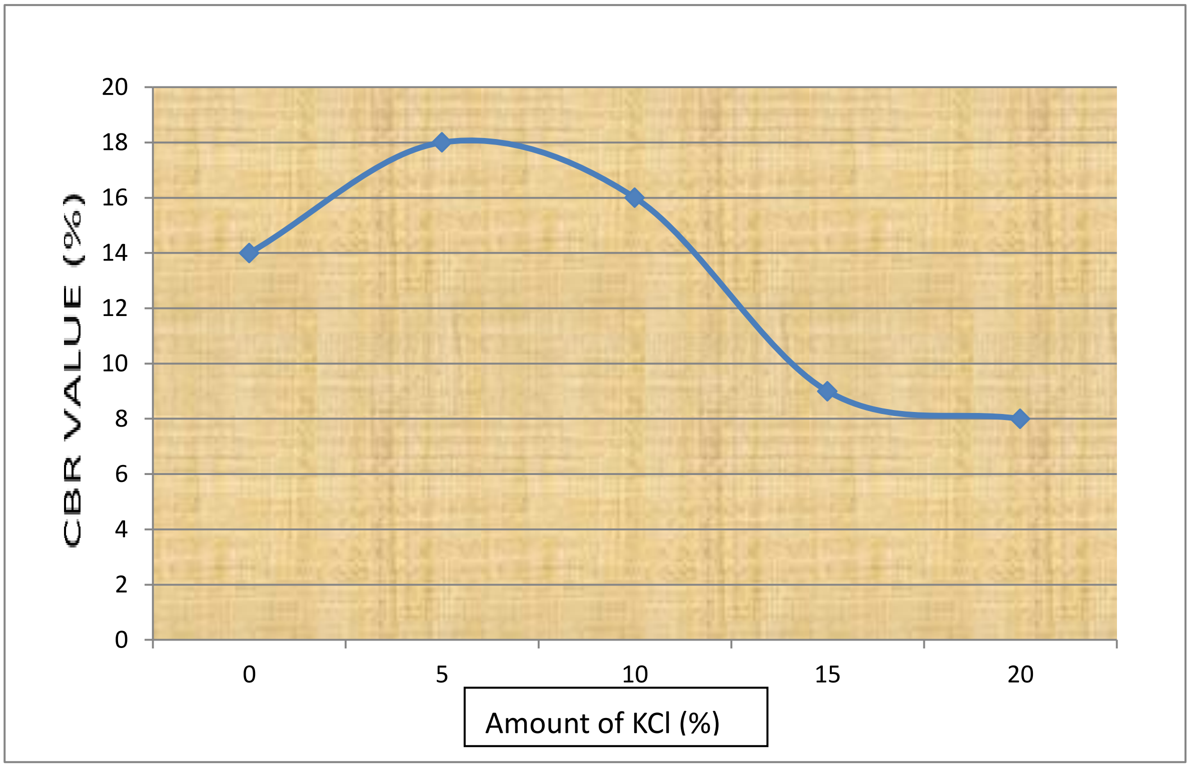

Fig 5.7 Effet of potassium chloride on unsoaked CBR value of natural soil

5.3.4.3. Effect of potassium chloride on CBR- Swell of the soil

The CBR swell of the soil is measured by placing the tripod with the dial indicator on the top of soaked CBR mold. The compacted soil samples of the CBR mold are soaked for 96 hours in a water bath to get the CBR swell of the soil. The initial dial reading of the soil of the dial indicator on the soaked CBR of mold is taken just after soaking the sample. At the end of ninety six hours the final dial reading of the dial indicator is taken hence the swell percentage of the initial sample length is 116.43mm. Then CBR swell is calculated by dividing change in CBR swell recorded by initial height of the sample and multiplying by hundred.

Table 5.7 Effect of KCl on CBR-Swell of Natural soil

Soaked CBR-SWELL					
% KCl	0	5	10	15	20
%CBR-SWELL	10	3	2	1.46	0.96
% Decrease of CBR swell	0	70	80	85	90

Percent decrease in CBR swell = $[(CBRS_f - CBRS_o)/ CBRS_o]*100$ (5.5)

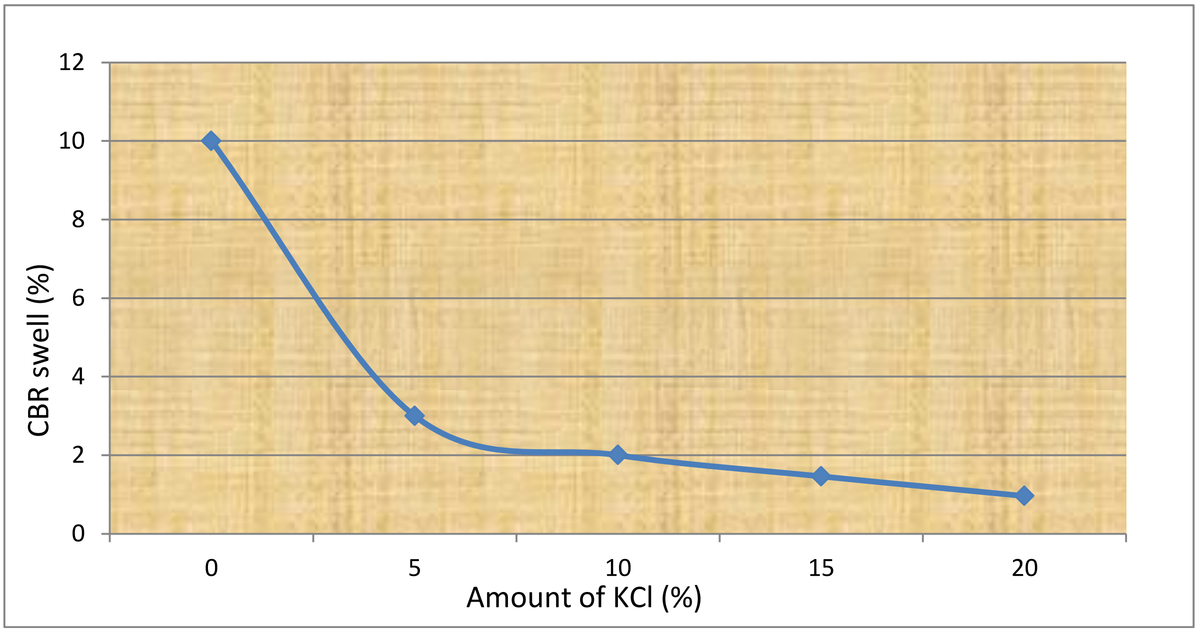

Fig 5.8 Effet of potassium chloride on CBR swell value of natural soil

The effect of potassium chloride on the CBR-Swell for the soil-potassium mixtures are shown in Figure 5.7. When treating the expansive soil at 20% potassium chloride content, sample gives CBR-Swell of 0.96 from a value of 10% for a natural soil. The CBR-swell of expansive soil decreased with all higher proportion of potassium chloride contents. This shows that the swelling potential of the sample decreased with potassium chloride stabilization. This is due to the cation exchange and flocculation and agglomeration of the soil particles.

5.3.5. Effect of potassium chloride on Swelling Pressure of the Soils

Swelling pressure is defined as the pressure which prevents the specimen from swelling or that pressure which is required to return the specimen back to its original state (void ratio, height) after swelling (ASTM, 1996). Basically, the methods of measuring swelling pressure can be either strain controlled or stress controlled. Strain controlled method is based on the principle of controlling the strain that is developed as water is added. In such a test, modification to the conventional Odometer is required to allow the control of strain during testing and measurement of the resulting loads.

Stress controlled tests use the conventional odometer. The samples are placed in the consolidation ring trimmed to the height of the ring. After loading with the standard load of 1psi (6.9kPa), water is added to the sample. When swelling of the sample is ceased, the vertical stress is increased in increments until the sample is compressed back to its original height. The stress required to compress the sample to its original height is the zero volume change swelling pressure or simply swelling pressure. Swelling pressure is an integral soil property, hence whether determining it through strain or stress controlled, the result is expected to be the same (Chen, 1988).

The effect of potassium chloride on the swelling pressure for the soil-potassium mixtures are shown in Figure 5.8. When treating the expansive soil at 15% potassium chloride content, sample gave swelling pressure of 28kPa from a value of 310kPa for a natural soil.

The swelling pressure of expansive soil decreased with all higher proportion of potassium chloride contents. This shows that the swelling potential of the sample decreased with increase in potassium chloride.

The swelling pressure of untreated soil decreased from 310kPa to 60kPa, 40kPa, 28kPa and 24kPa for the addition of 5%, 10%, 15% and 20% potassium chloride respectively. This result implied that potassium chloride is effective on stabilizing expansive soils with respect to swelling pressure.

Table 5.8 Effect of KCl on swelling pressure of natural soil.

SWELLING PRESSURE					
KCl (%)	0	5	10	15	20
SWELLING PRESSURE(kPa)	310	60	40	28	24
% Decrease of S.P	0	80	87	90	92

Percent decrease in swelling pressure = $[(SP_f - SP_o)/ SP_o]*100$ (5.6)

SP_f = value of SP of the soil for respective percentage of KCl.

SP_o = value of SP of untreated soil (zero percent KCl).

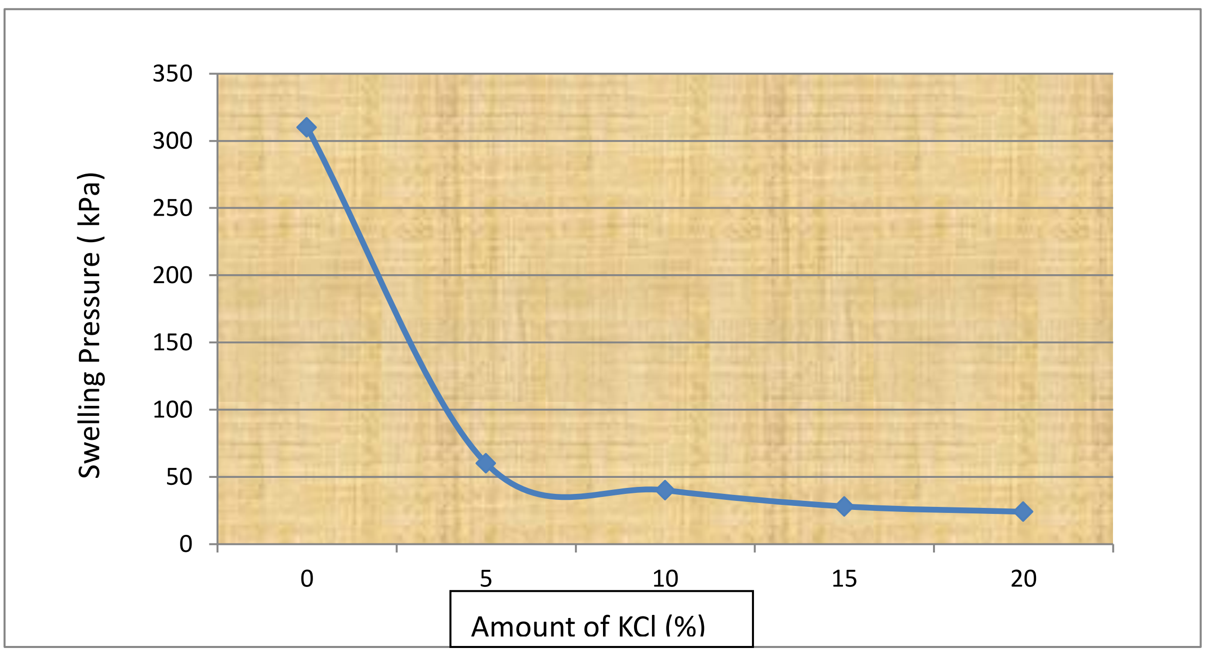

Fig 5.9 Effect of KCl on swelling pressure of natural soil

5.3.5 Effect of potassium chloride on Unconfined Compressive Strength of the Soils

The unconfined compressive strength of the remoulded samples prepared at MDD and optimum moisture content with addition of 0%, 5%, 10%, 15% and 20% of potassium chloride to the expansive soil are presented in table 5.8. The prepared samples are tested after 1 day and 7 days. The sample was cured in the test tube after compaction for one and seven days by sealing the tube with plastic inorder to avoid moisture content reduction. Then the sample has extruded from the sampler and have been made for the test.

Table 5.9 Effect of KCl on UCS values of natural soil

UCS VALUES						
% KCl	Curing day	0	5	10	15	20
UCS (kPa)	One day	146	101	95		
% Decrease of UCS	One day	0	30.8	34.9		
UCS (kPa)	Seven days	146	317	374	384	397
% Increase of UCS	Seven days	0	117.1	156.2	163.0	171.9

Percent decrease/increase in UCS = $[(UCS_f - UCS_o)/ UCS_o]*100$ (5.6)

UCS_f = value of UCS of the soil for respective percentage of KCl.

UCS_o = value of UCS of untreated soil (zero percent KCl).

As shown in the table, the unconfined compressive strength is increasing with time. This might be due to chemical reaction. It is observed that the unconfined compressive strength of the stabilized expansive soil is decreasing for one day curing. This seems due to the dispersing effect of the chemical, which leads high reduction in the cohesion. Therefore, at higher percentage of potassium chloride the UCS value of the soil gets lower and lower. But the unconfined compressive strength of the soil icreasing for 7 days of curing with percentage of potassium chloride added to the soil.

The justification forwarded for this are chemical reaction between soil and chemical and soil cohesion regain due to pericipitation of potassium chloride. The UCS of treated soil is decreased by 30.8% and 34.9% for 5% and 10% for one day curing respectively and the sample couldnt be extrude from the test tube properly for the 15% and 20%. The UCS of treated soil increases with the percentage of potassium chloride for seven days of curing and maximum increase is observed at 20% addition of potassium chloride which is 172%.

Chapter VI. Conclusion and Recommendations

6.1. Conclusion

The plasticity and swelling properties of the soil has shown significant improvement by treating the soil with potassium chloride. However the strength characteristics of the soil has shown less improvement as compared to swelling and plasticity properties of the soil, eventhough they fullfill minimum required range.

Generally Potassium chloride can be an alternative expansive soil stabilizing chemical where sufficiently abundant and when economically feasible as compared to other methods of soil stabilization as overall performance of the soil has improved by treating the expansive soil with potassium chloride.

6.2. Recommendations

Based on the present study results the following recommendations are forwarded:

- The environmental impacts of the chemical application have not been taken into account in the study. Further studies of this aspect may be important.

- The chemical potassium chloride has provided promising results in improving the engineering properties of the soil by laboratory tests. However, the results obtained should also be verified by coresponding field tests.

- In addition to successful stabilization of the soil with potassium chloride, the long term durability of the stabilized material is much more important. Therefore, it is recommended to conduct wetting-drying and leachate tests to asses the long term durability of the stabilized material.

- In places where there is a supply of suitable earth material within economic distances, cost comparison should be given priority to select the better problem solving alternative. However, in places where there is insufficient supply of the fill material and the environmetal concerns are of high priority, potassium chloride stabilization can be selected.

- This thesis was conducted by using imported potassium chloride purchased from local suppliers. Therefore it is important to conduct expansive soil stabilization using locally produced potassium chloride.

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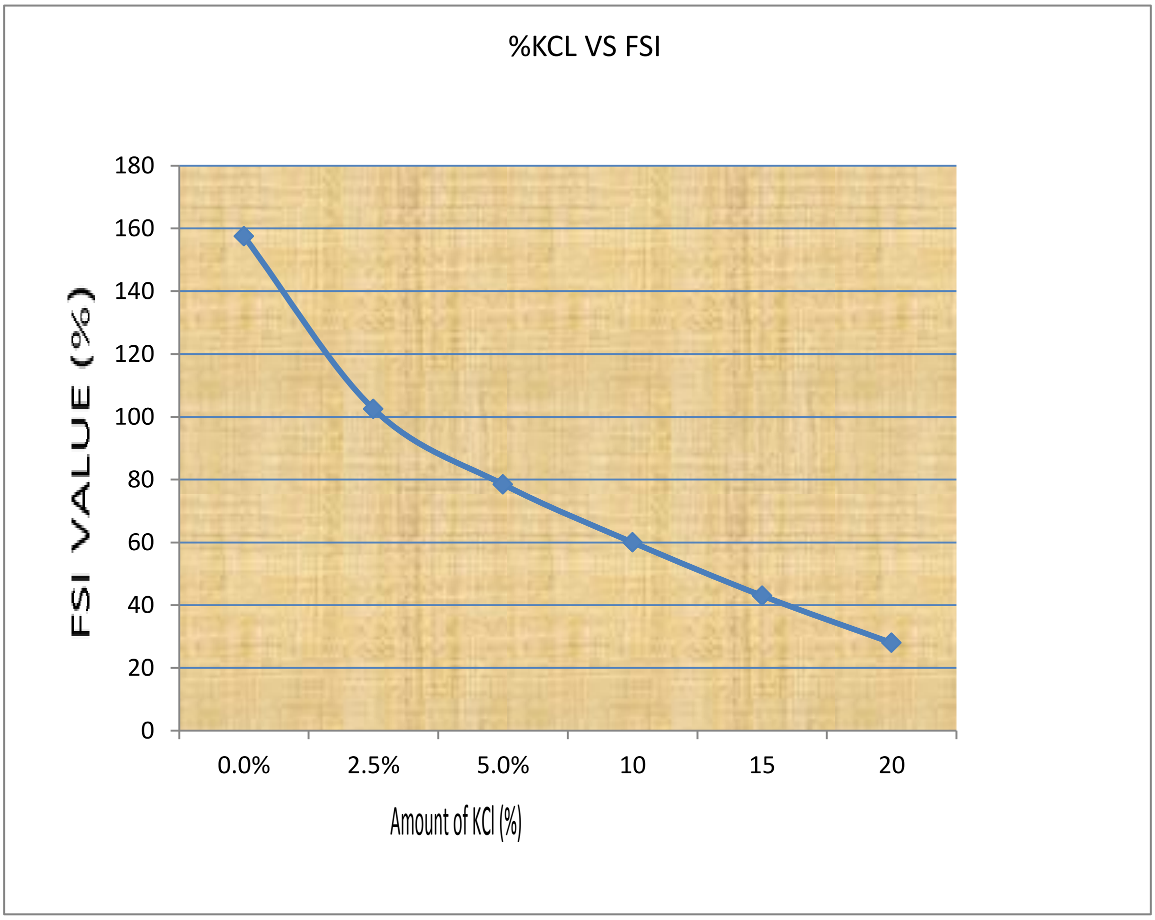
Appendix

Appendix 1: Chemical specification of Potassium chloride used for stabilization

Appendix 2: Summary of different proportion of KCl on Free Swell Index.

%KCL	0.0%	2.5%	5.0%	10	15	20
FSI (%)	158	103	79	60	43	28
% Decrease of FSI	0	35	50	62	73	82

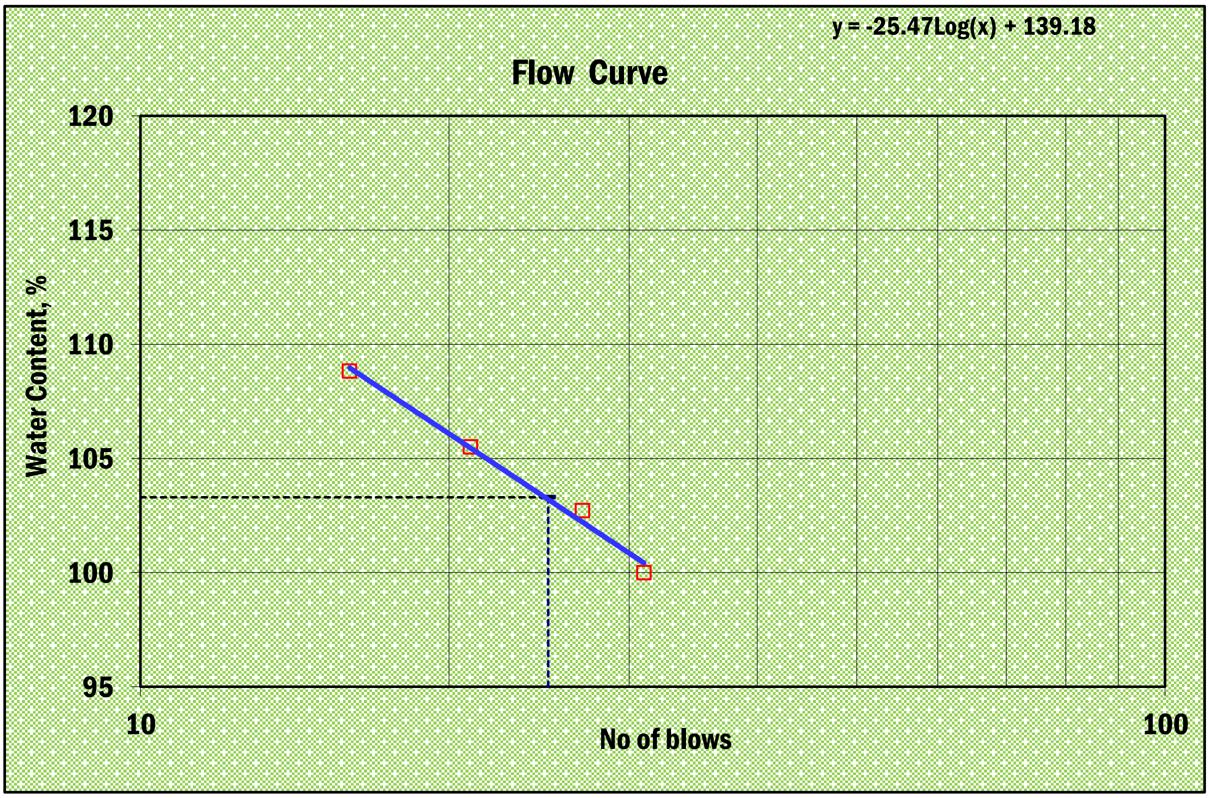


Appendix 3: Summary of different proportion of KCl on Atterberg Limits.

1. **0% Potassium chloride**

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	MF	M3	A304	AL1	D35	B4T
Mass of container, g	15.50	15.90	15.80	20.80	15.60	15.50
Mass of container + Wet soil, g	30.40	31.21	30.00	36.88	22.10	21.40
Mass of container + Dry soil, g	22.85	23.35	22.90	28.50	19.90	19.40
Mass of water, g	7.55	7.86	7.10	8.38	2.20	2.00
Mass of dry soil, g	7.35	7.45	7.10	7.70	4.30	3.90
Water content, %	102.72	105.50	100.00	108.83	51.16	51.28
No of blows	27	21	31	16	------	------

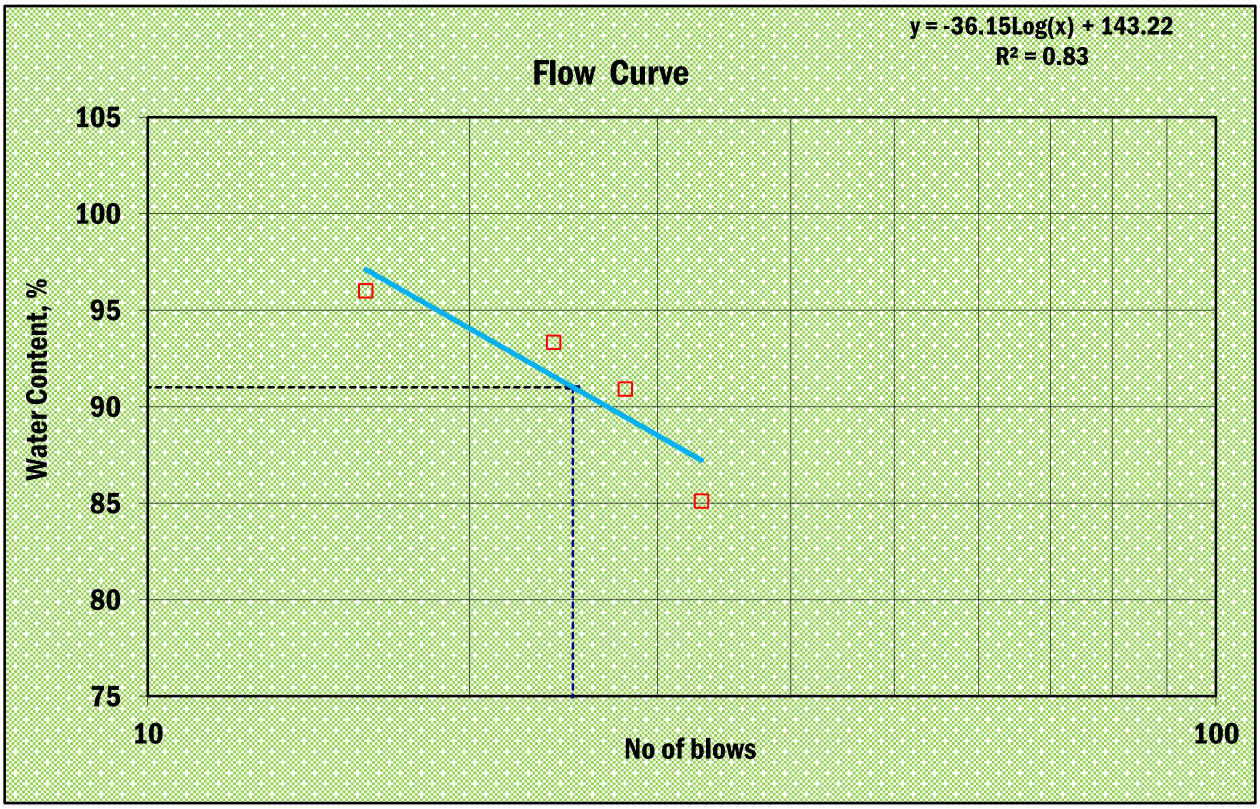
Liquid Limit, % = 104 Plastic Limit, % = 51 PI, %= 52



2. 2.5% Potassium chloride

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	G3	PR	C7	A24	D31	M3
Mass of container, g	15.80	15.30	20.60	15.70	15.60	15.50
Mass of container + Wet soil, g	33.20	30.00	37.40	30.20	22.00	21.40
Mass of container + Dry soil, g	25.30	22.90	29.50	23.30	19.90	19.40
Mass of water, g	7.90	7.10	7.90	6.90	2.10	2.00
Mass of dry soil, g	9.50	7.60	8.90	7.60	4.30	3.90
Water content, %	83.16	93.42	88.76	90.79	48.84	51.28
No of blows	33	16	28	24	------	------

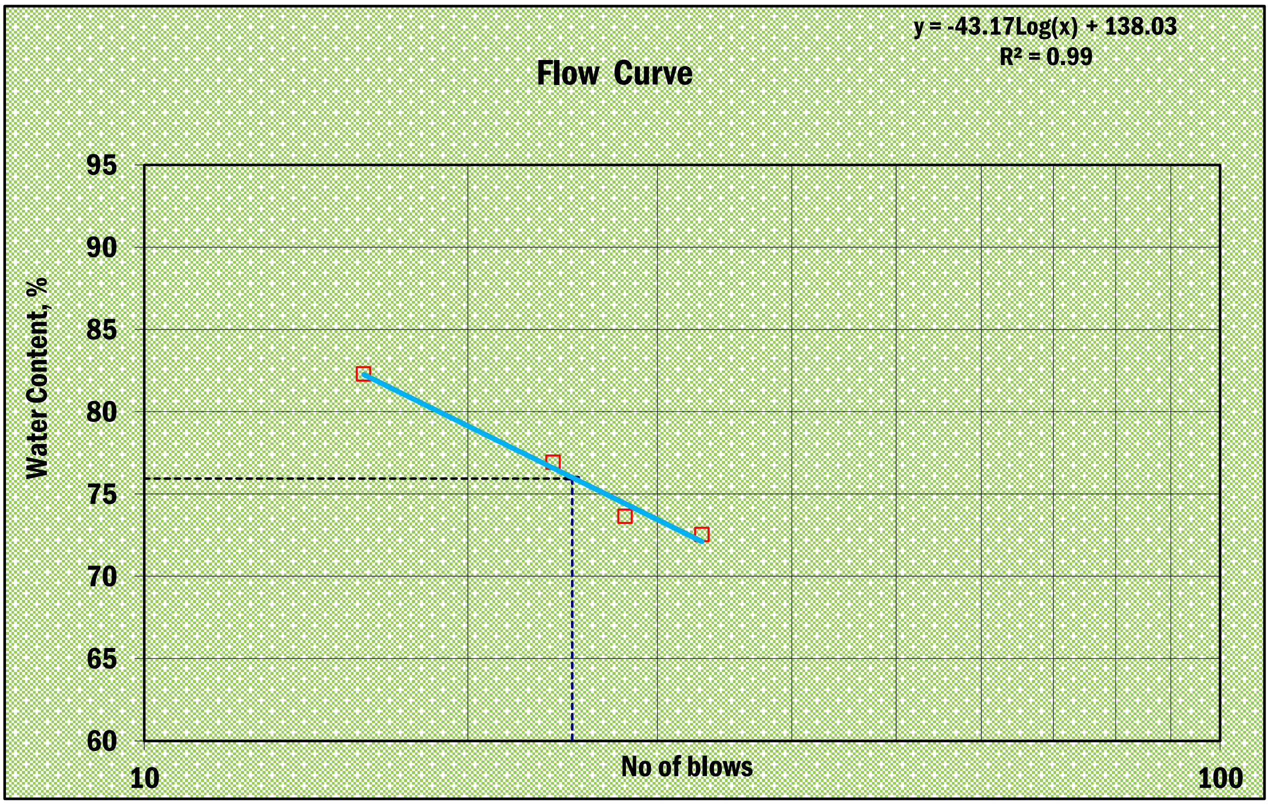
Liquid Limit, % = 91 Plastic Limit, % = 50 PI, %= 41



3. 5% Potassium chloride

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	HSO3	CRS	58	19	G3	D31
Mass of container, g	15.10	15.80	15.50	15.50	15.80	15.60
Mass of container + Wet soil, g	32.60	36.50	31.30	31.20	28.70	20.40
Mass of container + Dry soil, g	24.70	27.50	24.60	24.60	24.50	18.80
Mass of water, g	7.90	9.00	6.70	6.60	4.20	1.60
Mass of dry soil, g	9.60	11.70	9.10	9.10	8.70	3.20
Water content, %	82.29	76.92	73.63	72.53	48.28	50.00
No of blows	16	24	28	33	------	------

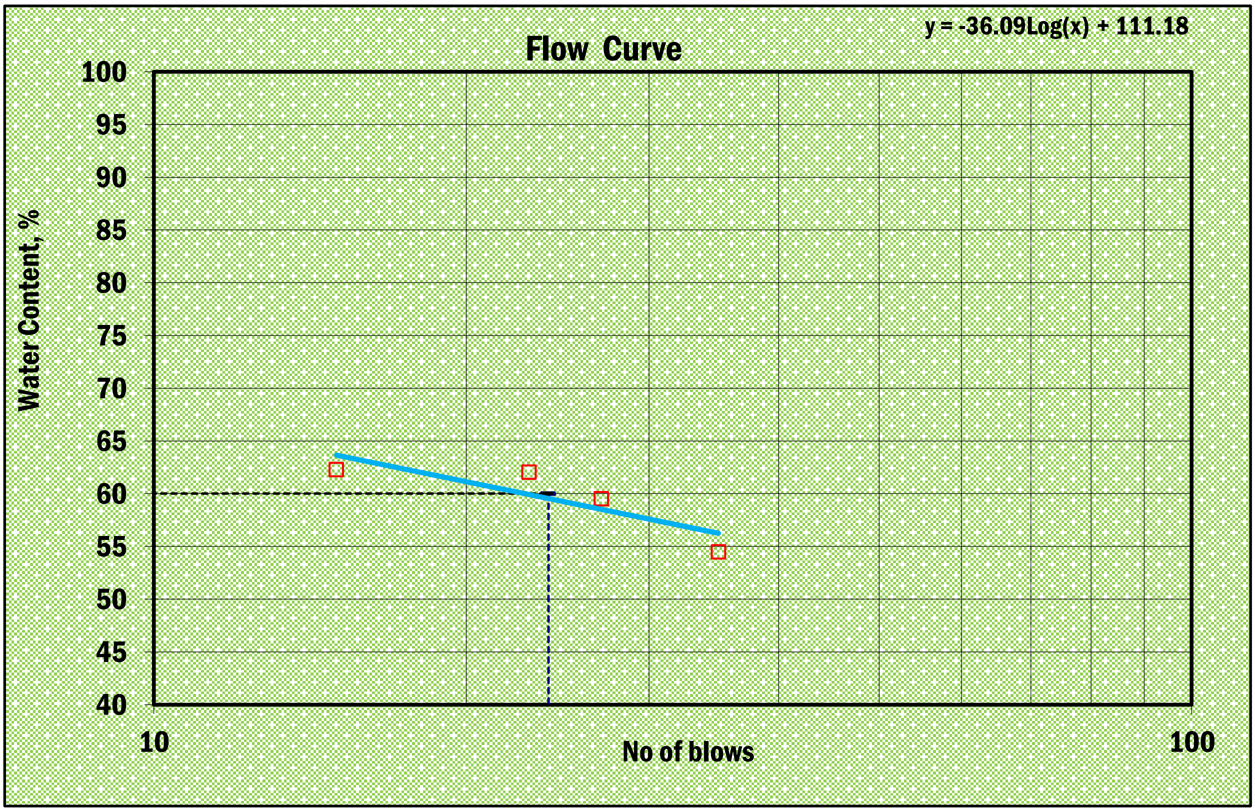
Liquid Limit, % = 76 Plastic Limit, % = 49 PI, %= 27



4. 10% Potassium chloride

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	AB	M10	BB	S4	Y3	D25
Mass of container, g	13.90	10.80	15.80	15.50	17.20	15.90
Mass of container + Wet soil, g	31.20	30.90	33.30	34.00	25.70	23.70
Mass of container + Dry soil, g	25.00	23.30	26.50	26.80	22.70	21.30
Mass of water, g	6.20	7.60	6.80	7.20	3.00	2.40
Mass of dry soil, g	11.10	12.50	10.70	11.30	5.50	5.40
Water content, %	55.86	60.80	63.55	63.72	54.55	44.44
No of blows	35	27	23	15	------	------

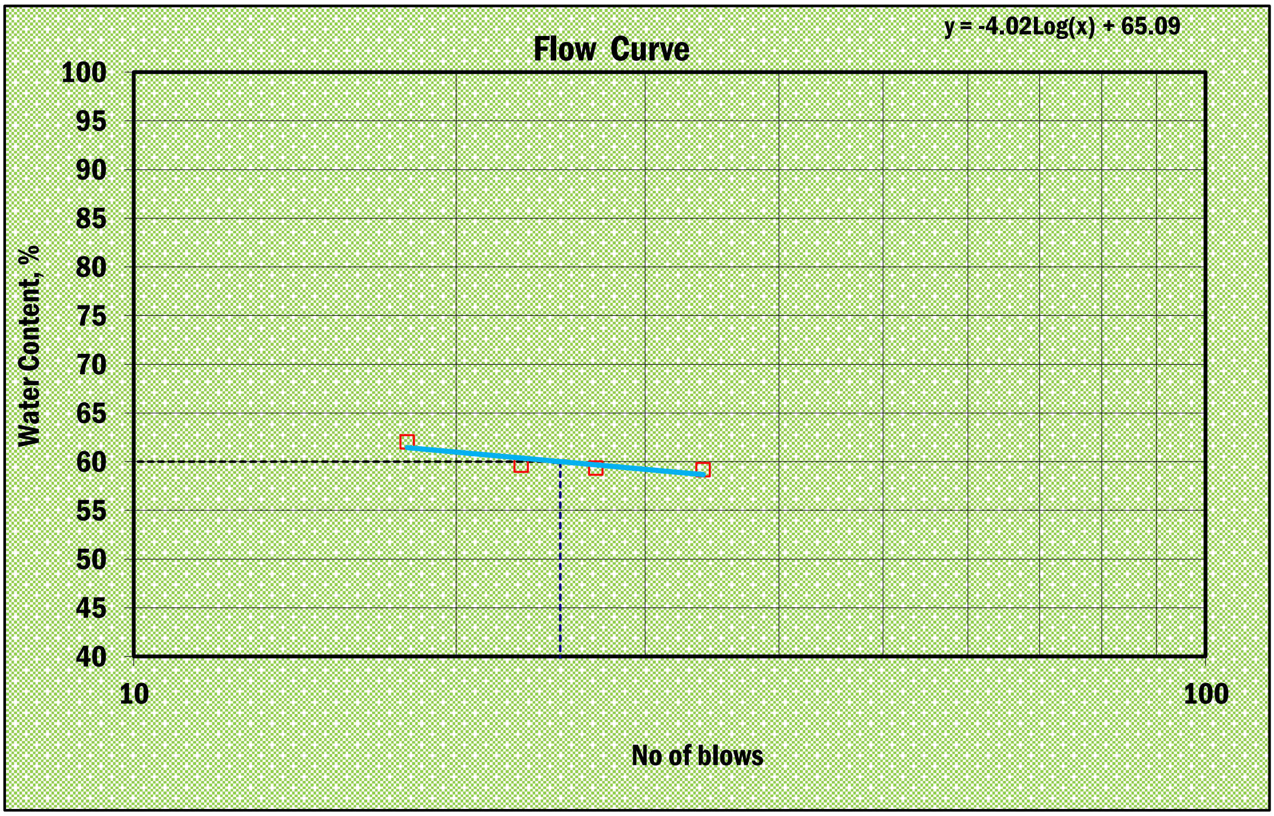
Liquid Limit, % = 60 Plastic Limit, % = 49 PI, %= 11



5. 15% Potassium chloride

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	40	28	72	F3	32	AB
Mass of container, g	15.60	15.50	15.80	15.80	15.50	15.50
Mass of container + Wet soil, g	30.10	32.10	31.40	33.30	25.00	27.40
Mass of container + Dry soil, g	24.70	25.90	25.60	26.60	21.70	23.50
Mass of water, g	5.40	6.20	5.80	6.70	3.30	3.90
Mass of dry soil, g	9.10	10.40	9.80	10.80	6.20	8.00
Water content, %	59.34	59.62	59.18	62.04	53.23	48.75
No of blows	27	23	34	18	------	------

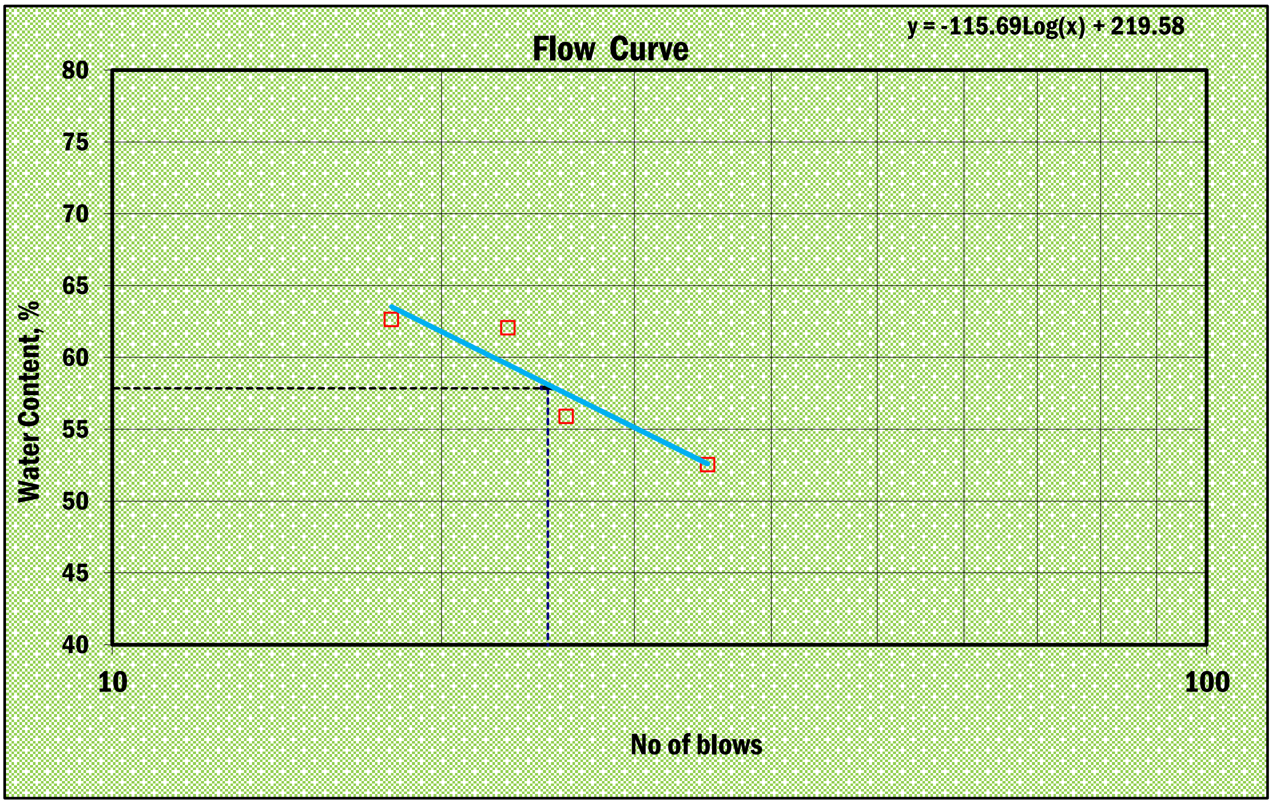
Liquid Limit, % = 60 Plastic Limit, % = 51 PI, %= 9



6. 20% Potassium chloride

	Liquid Limit				Plastic Limit	
Trial No	1	2	3	4	1	2
Container No	AM	G8	B11	P3L3	A50	PL1
Mass of container, g	15.30	15.90	15.60	15.90	15.60	10.50
Mass of container + Wet soil, g	30.40	32.00	33.10	31.80	24.50	23.20
Mass of container + Dry soil, g	25.20	25.80	26.40	26.10	21.40	19.00
Mass of water, g	5.20	6.20	6.70	5.70	3.10	4.20
Mass of dry soil, g	9.90	9.90	10.80	10.20	5.80	8.50
Water content, %	52.53	62.63	62.04	55.88	53.45	49.41
No of blows	35	18	23	26	------	------

Liquid Limit, % = 58 Plastic Limit, % = 51 PI, %= 7

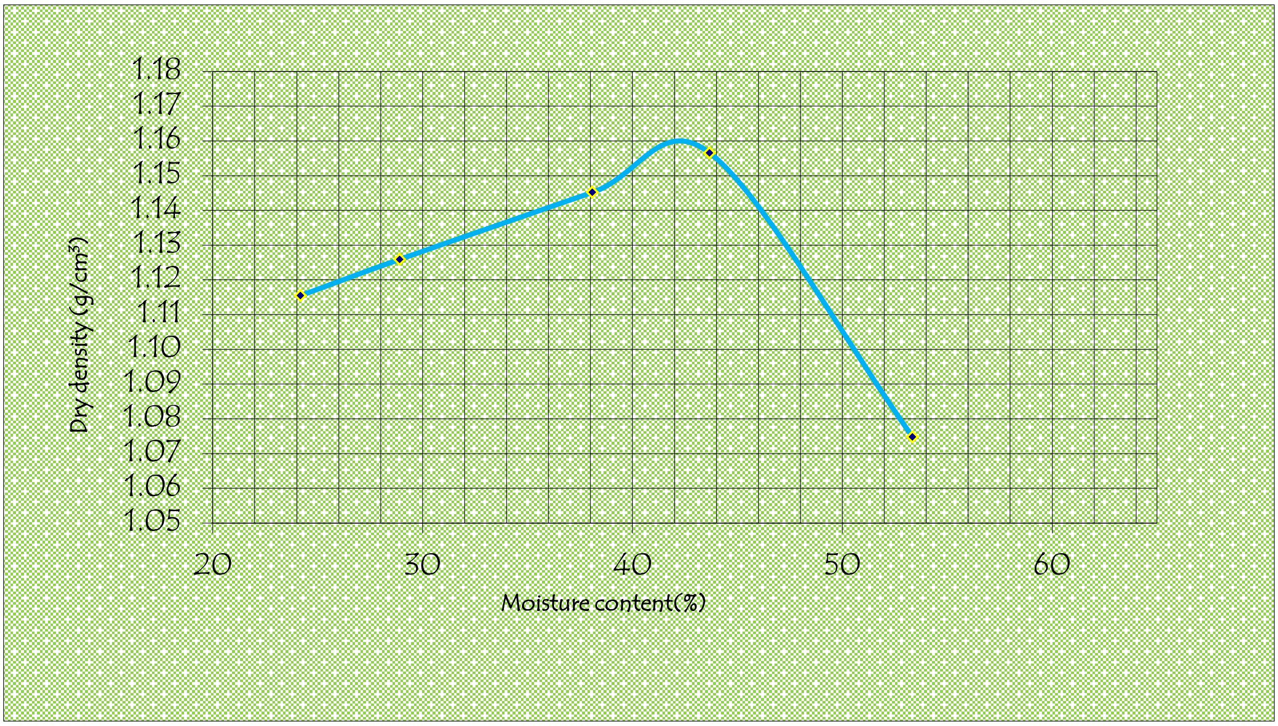


Appendix 4: Summary of different proportion of KCl on Moisture – Density relation.

1. **0% Potassium chloride**

Determination No.	1	2	3	4	5
Mass of Mold, g	5592.4	5592.4	5592.4	5592.4	5592.4
Mass of mold+ Compacted Soil, g	6900	6962.6	7085.3	7162.7	7148.3
Mass of Compacted soil, g	1307.6	1370.2	1492.9	1570.3	1555.9
Volume of Mold,cm3	944	944	944	945	944
Bulk density, g/cm3	1.39	1.45	1.58	1.66	1.65
Water Contenet, %	24.18	28.91	38.10	43.68	53.35
Dry density, g/cm3	1.12	1.13	1.15	1.16	1.07

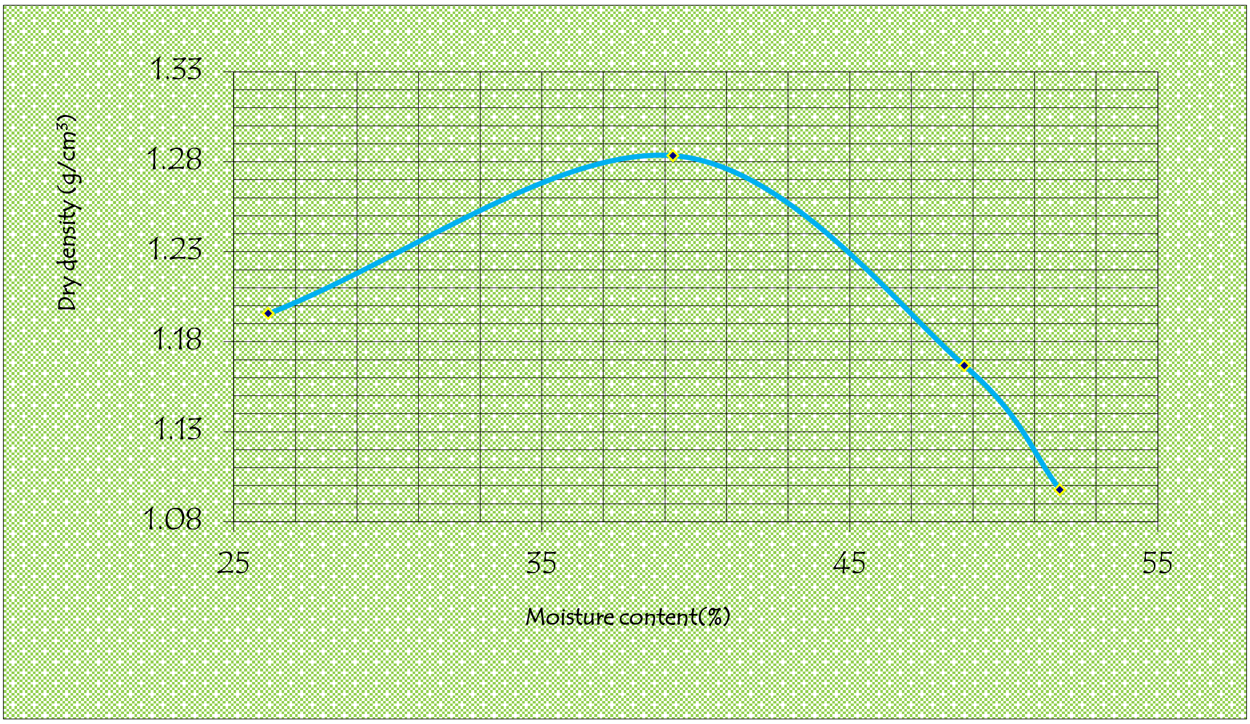
MDD = 1.16 OMC 44



2. 2.5% Potassium chloride

Determination No.	1	2	3	4
Mass of Mold, g	3138.7	3138.7	3138.7	3138.7
Mass of mold+ Compacted Soil, g	4562.2	4825.9	4776.7	4712
Mass of Compacted soil, g	1423.5	1687.2	1638	1573.3
Volume of Mold,cm3	944	944	944	944
Bulk density, g/cm3	1.51	1.79	1.74	1.67
Water Content, %	26.13	39.26	48.73	51.83
Dry density, g/cm3	1.20	1.28	1.17	1.10

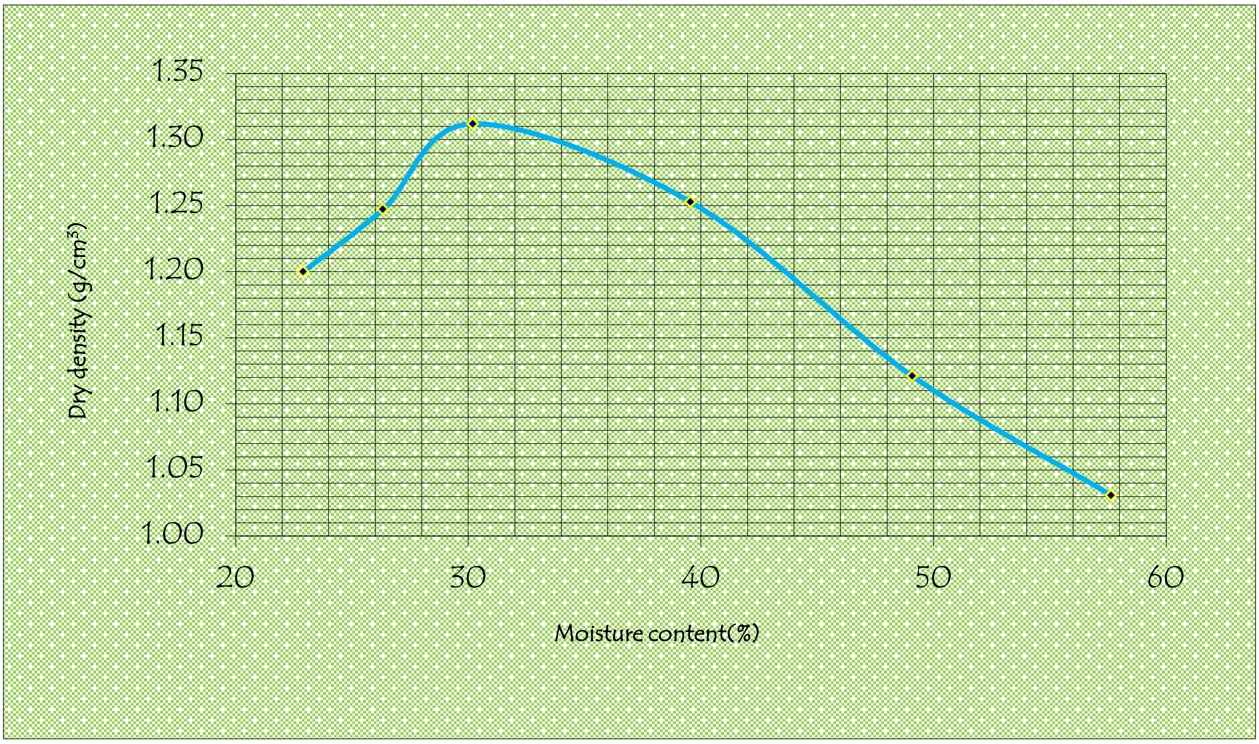
MDD = 1.28 OMC (%) = 39.0



3. 5% Potassium chloride

Determination No.	1	2	3	4	5	6
Mass of Mold, g	3138.7	3138.7	3138.7	3138.7	3138.7	3138.7
Mass of mold+ Compacted Soil, g	4594.7	4626.1	4751.2	4789.09	4718.1	4672.7
Mass of Compacted soil, g	1456	1487.4	1612.5	1650.39	1579.4	1534
Volume of Mold,cm3	944	944	944	944	945	944
Bulk density, g/cm3	1.54	1.58	1.71	1.75	1.67	1.63
Water Content, %	22.92	26.33	30.20	39.57	49.10	57.65
Dry density, g/cm3	1.20	1.25	1.312	1.25	1.12	1.03

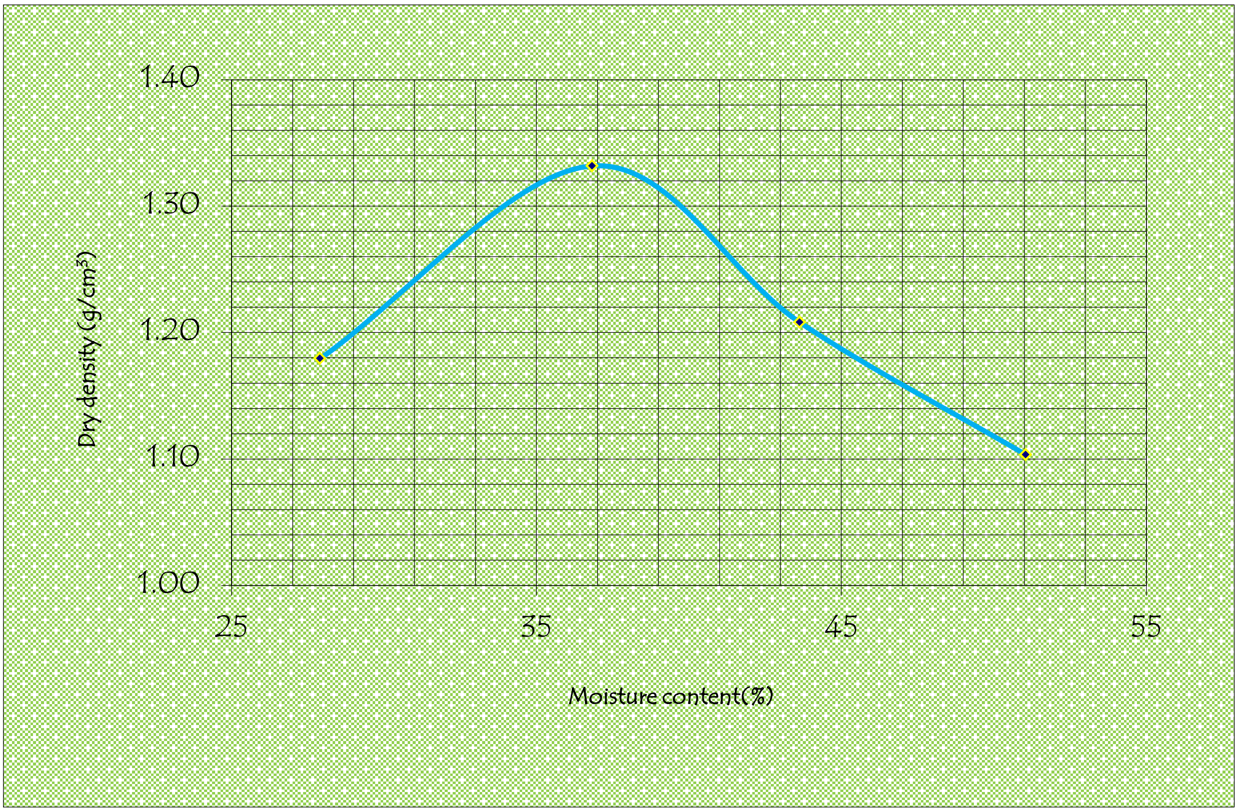
MDD = 1.31 OMC (%) 30.0



4. 10% Potassium chloride

Determination No.	1	2	3	4
Mass of Mold, g	3138.7	3138.7	3138.7	3138.7
Mass of mold+ Compacted Soil, g	4562.7	4858.9	4776.7	4712
Mass of Compacted soil, g	1424	1720.2	1638	1573.3
Volume of Mold,cm3	944	944	944	944
Bulk density, g/cm3	1.51	1.82	1.74	1.67
Water Content, %	27.91	36.83	43.64	51.05
Dry density, g/cm3	1.18	1.33	1.21	1.10

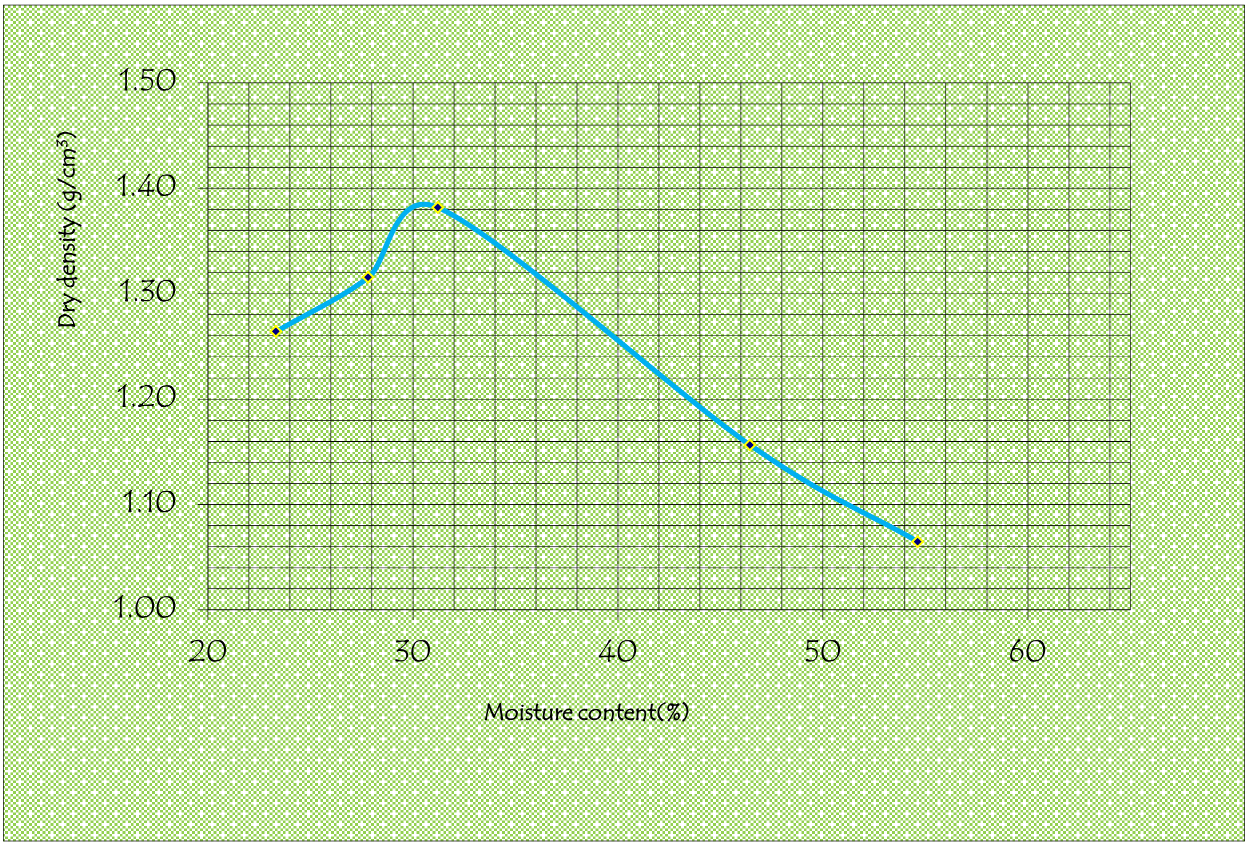
MDD = 1.31 OMC, (%) = 37.0



5. 15% Potassium chloride

Determination No.	1	2	3	4	5
Mass of Mold, g	3143.7	3143.7	3143.7	3143.7	3143.7
Mass of mold+ Compacted Soil, g	4615.5	4731.2	4855.4	4744.1	4697.9
Mass of Compacted soil, g	1471.8	1587.5	1711.7	1600.4	1554.2
Volume of Mold,cm3	944	944	944	945	944
Bulk density, g/cm3	1.56	1.68	1.81	1.69	1.65
Water Content, %	23.33	27.83	31.23	46.45	54.64
Dry density, g/cm3	1.26	1.32	1.38	1.16	1.06

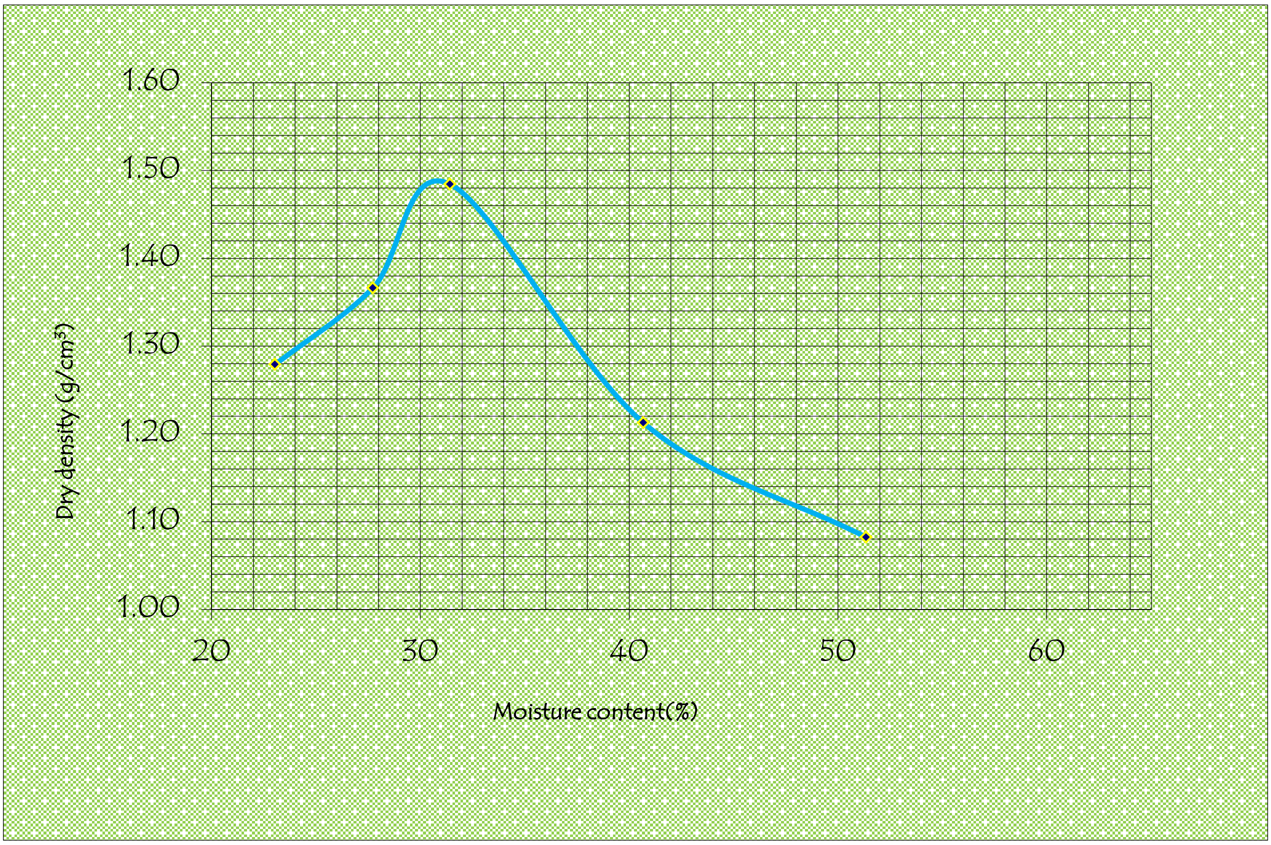
MDD = 1.16 OMC (%) = 44



6. 20% Potassium chloride

Determination No.	1	2	3	4	5
Mass of Mold, g	3143.7	3143.7	3143.7	3143.7	3143.7
Mass of mold+ Compacted Soil, g	4629.2	4791.2	4985.4	4754.1	4689.9
Mass of Compacted soil, g	1485.5	1647.5	1841.7	1610.4	1546.2
Volume of Mold,cm3	944	944	944	944	944
Bulk density, g/cm3	1.57	1.75	1.95	1.71	1.64
Water Content, %	23.04	27.73	31.43	40.68	51.35
Dry density, g/cm3	1.28	1.37	1.48	1.21	1.08

MDD 1.47 OMC, (%) = 31

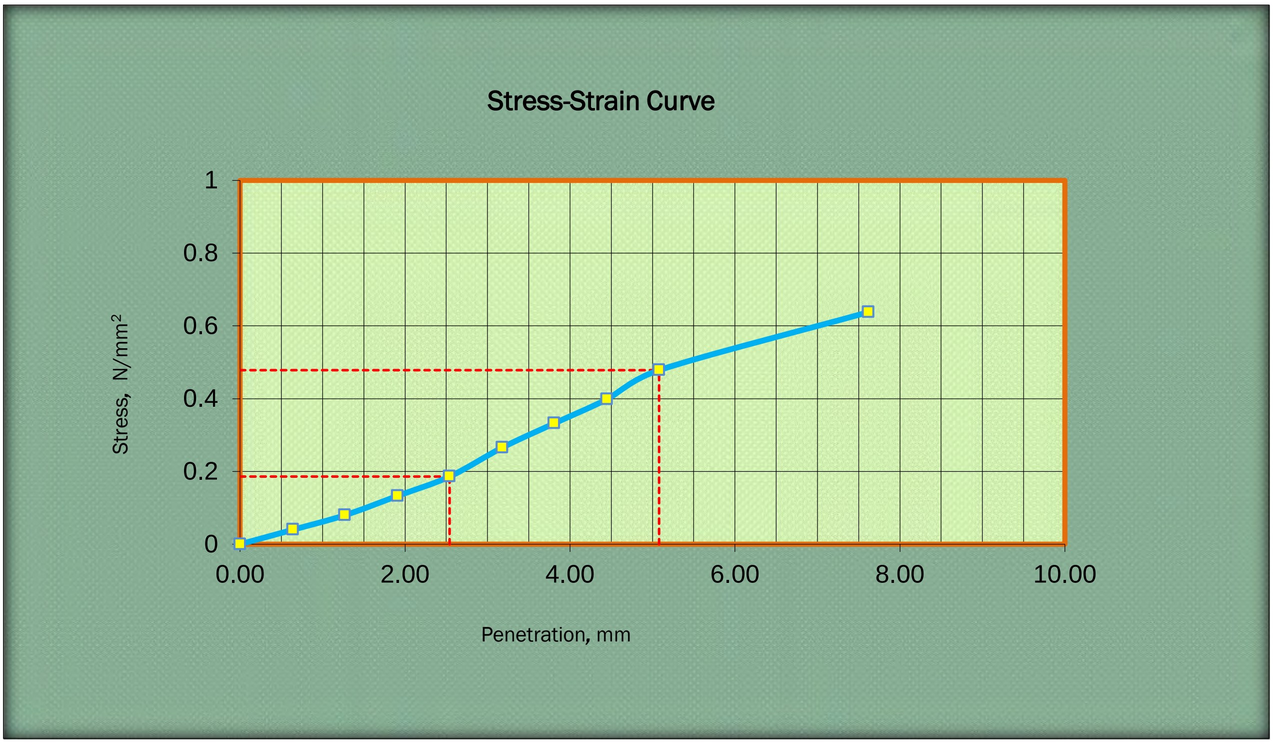


Appendix 5: Summary of different proportion of KCl on Soaked CBR relation

1. 5% Potassium chloride

Blow/ Layer	56/5		
Swell, %		Optimum Most. Content	30
CBR Value, %	**4.6**	Max. Dry Density Moisture Content	1.31

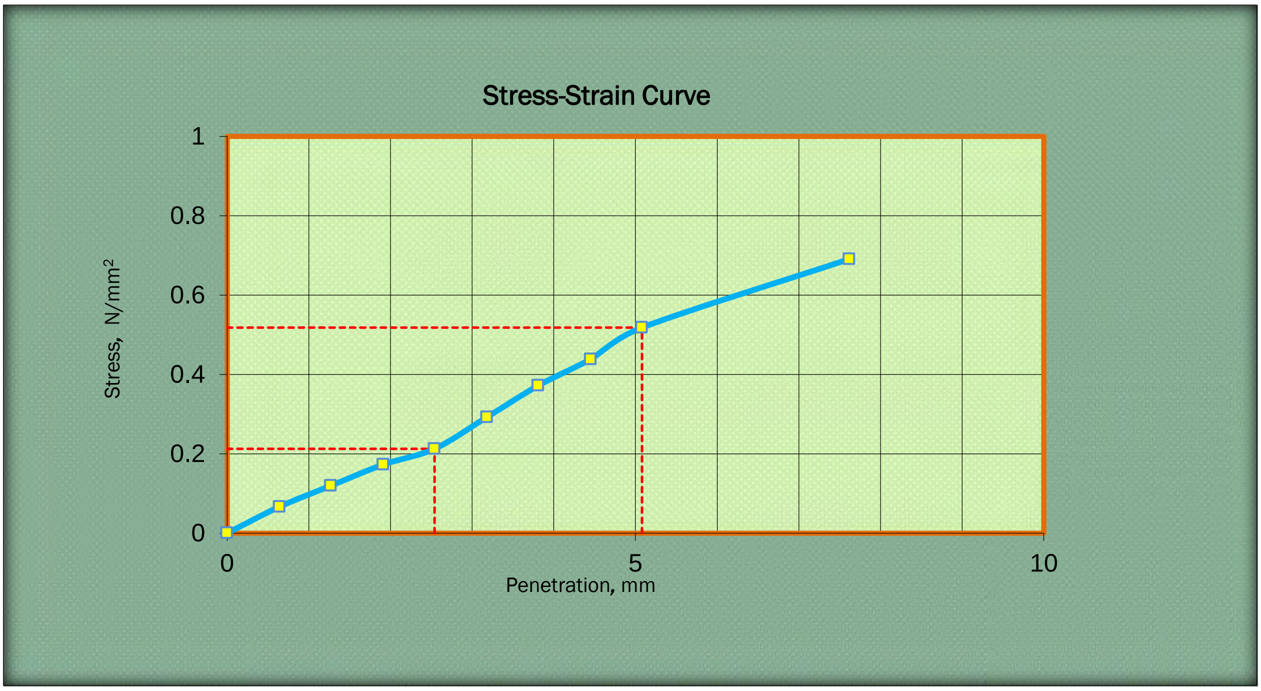
Penet. (mm)	Ring Reading (Div.)	Load (N)	Stress (N/mm^2)	Standard stress (N/mm^2)	CBR (%)
0.00	0.0	0	0.00		
0.64	3.0	77	0.04		
1.27	6.0	154	0.08		
1.91	10.0	257	0.13		
2.54	14.0	360	0.19	6.9	2.70
3.18	20.0	514	0.27		
3.81	25.0	643	0.33		
4.45	30.0	771	0.40		
5.08	36.0	925	0.48	10.3	4.64
7.62	48.0	1234	0.64		



2. 10% Potassium chloride

Blow/ Layer	56/5		
		Optimum Most.	
Swell, %		Content	37
CBR Value, %	**7.32**	Max. Dry Density Moisture Content	1.31

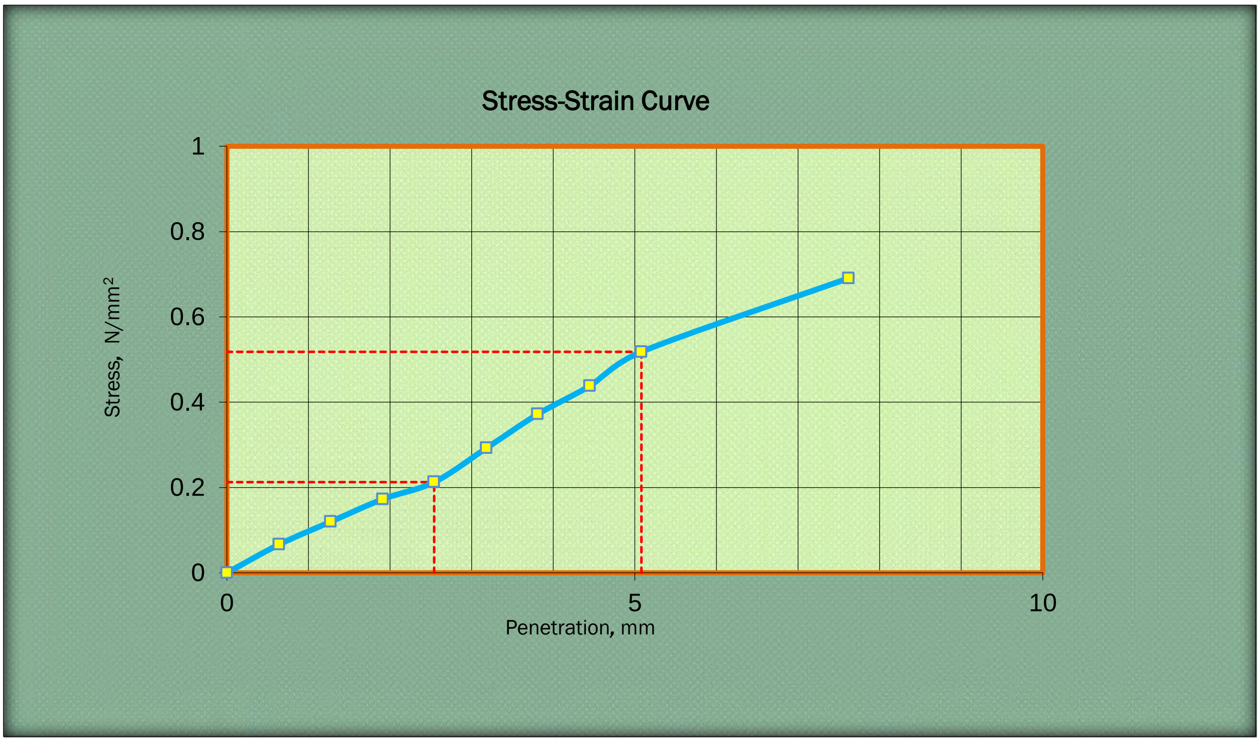
Penet. (mm)	Ring Reading (Div.)	Load (N)	Stress (N/mm^2)	Standard stress (N/mm^2)	CBR (%)
0.00	0.0	0	0.00		
0.64	5.0	129	0.07		
1.27	14.0	360	0.19		
1.91	27.0	694	0.36		
2.54	38.0	977	0.50	6.9	7.32
3.18	44.0	1131	0.58		
3.81	48.0	1234	0.64		
4.45	51.0	1311	0.68		
5.08	53.0	1362	0.70	10.3	6.84
7.62	61.0	1568	0.81		



3. 15% Potassium chloride

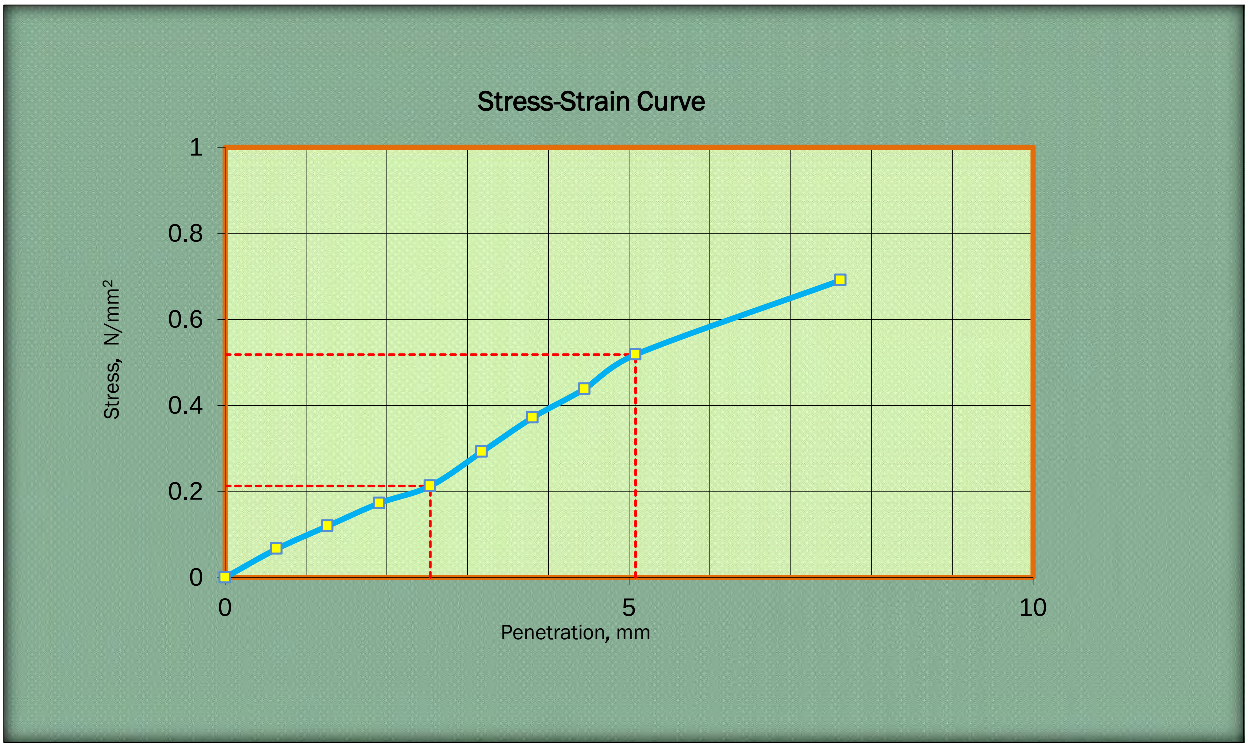
Blow/ Layer	56/5		
Swell, %		Optimum Most. Content	37
CBR Value, %	**7.32**	Max. Dry Density Moisture Content	1.31

Penet. (mm)	Ring Reading (Div.)	Load (N)	Stress (N/mm^2)	Standard stress (N/mm^2)	CBR (%)
0.00	0.0	0	0.00		
0.64	5.0	129	0.07		
1.27	14.0	360	0.19		
1.91	27.0	694	0.36		
2.54	38.0	977	0.50	6.9	7.32
3.18	44.0	1131	0.58		
3.81	48.0	1234	0.64		
4.45	51.0	1311	0.68		
5.08	53.0	1362	0.70	10.3	6.84
7.62	61.0	1568	0.81		



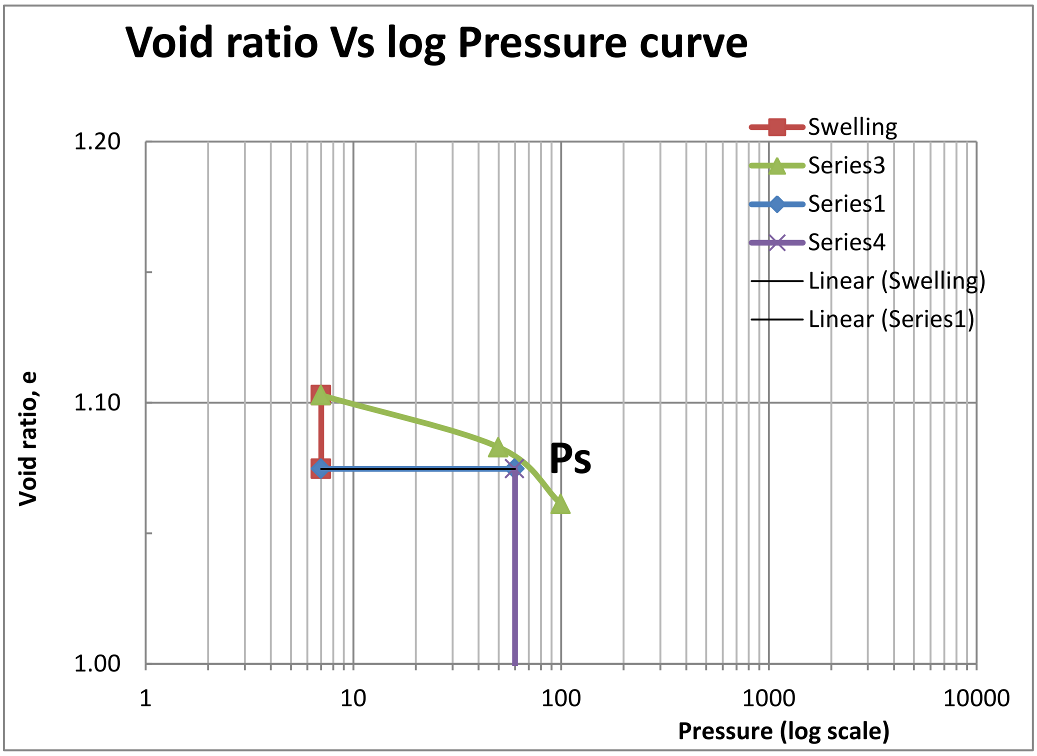
4. 20% Potassium chloride

Blow/ Layer		56/5			
Swell, %			Optimum Most. Content		37
CBR Value, %		**9.43**	Max. Dry Density Moisture Content		1.31
Penet. (mm)	Ring Reading (Div.)	Load (N)	Stress (N/mm^2)	Standard stress (N/mm^2)	CBR (%)
0.00	0.0	0	0.00		
0.64	10.0	257	0.13		
1.27	23.0	591	0.31		
1.91	36.0	925	0.48		
2.54	49.0	1260	0.65	6.9	9.43
3.18	55.0	1414	0.73		
3.81	59.0	1517	0.78		
4.45	62.0	1594	0.82		
5.08	65.0	1671	0.86	10.3	8.38
7.62	73.0	1877	0.97		

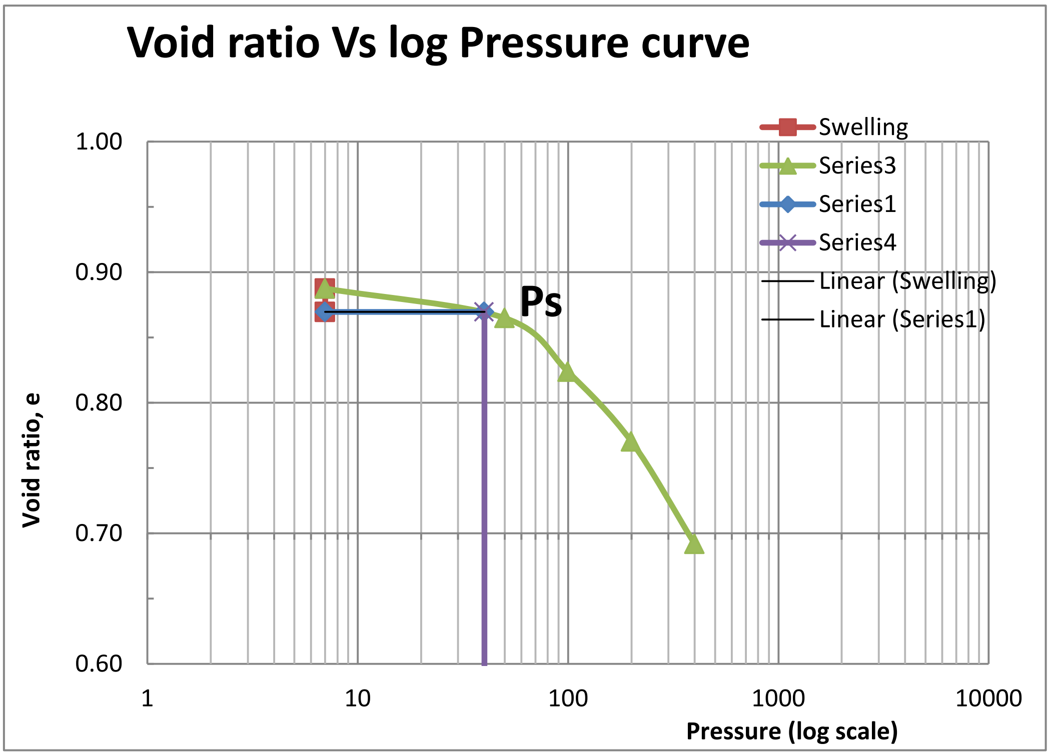


Appendix 6: Summary of different proportion of KCl on Swelling Pressure curve

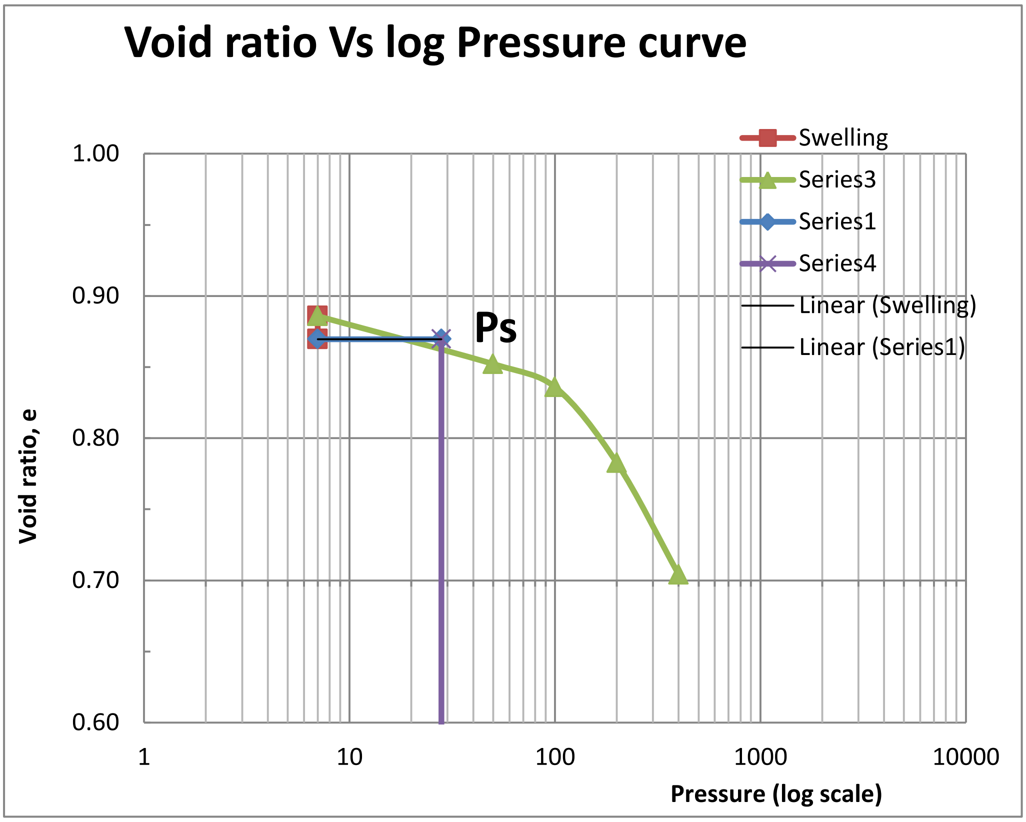
1. **5% Potassium chloride**



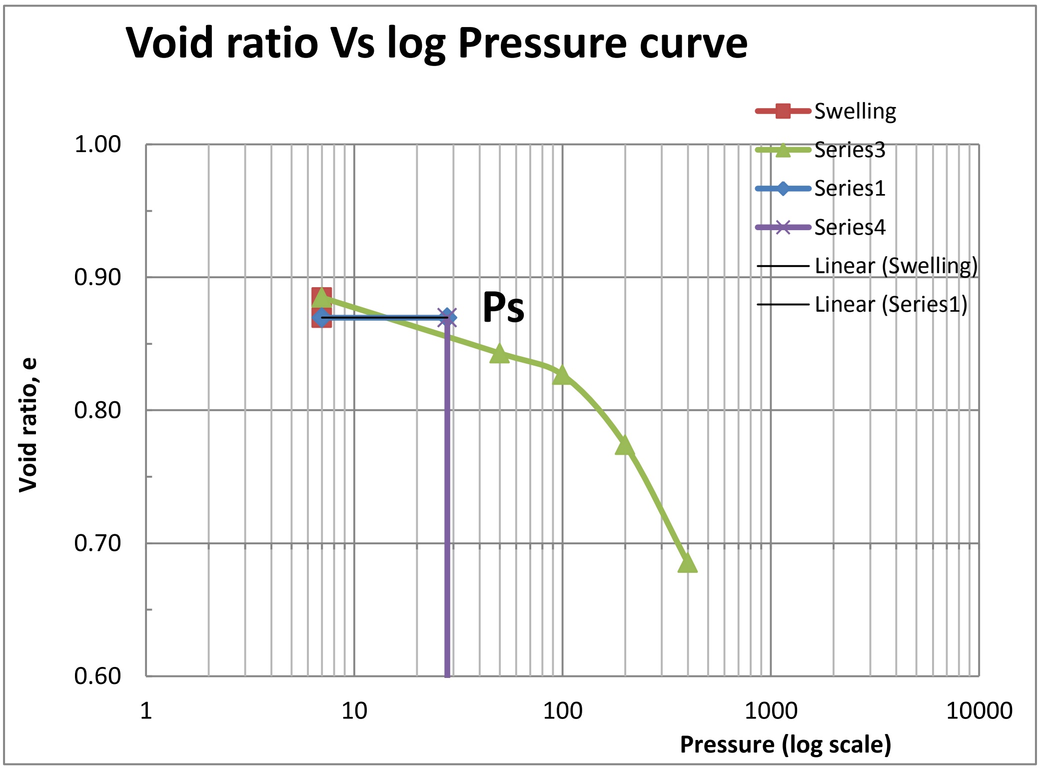
2. **10% Potassium chloride**



3. **15% Potassium chloride**

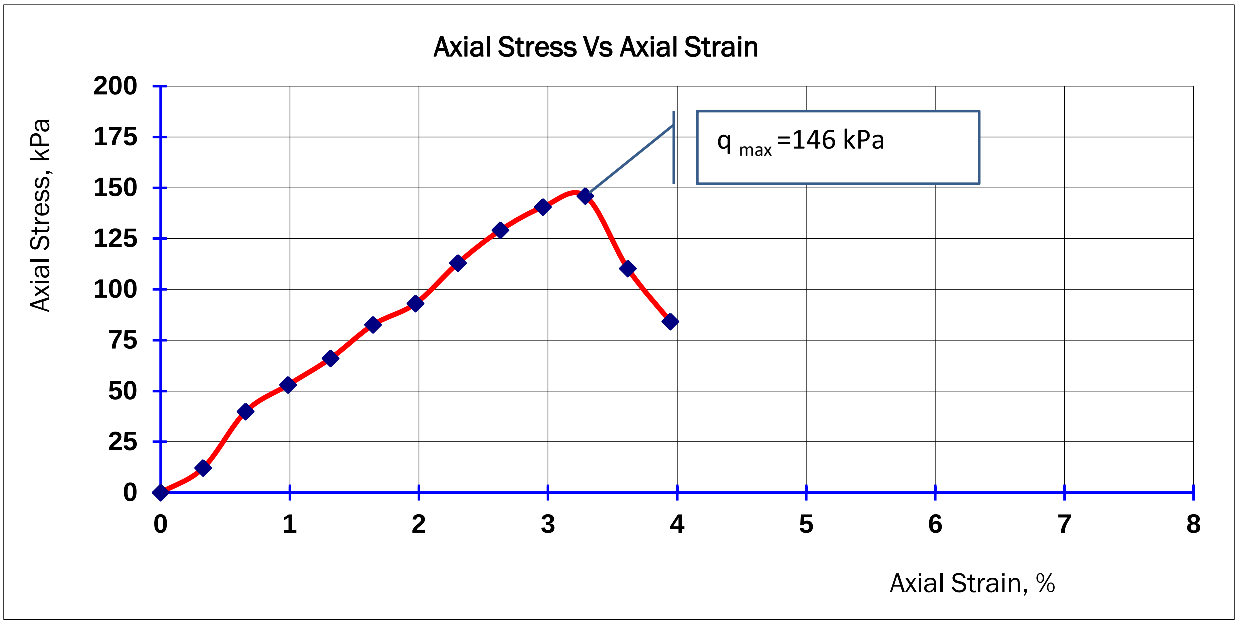


4. **20% Potassium chloride**

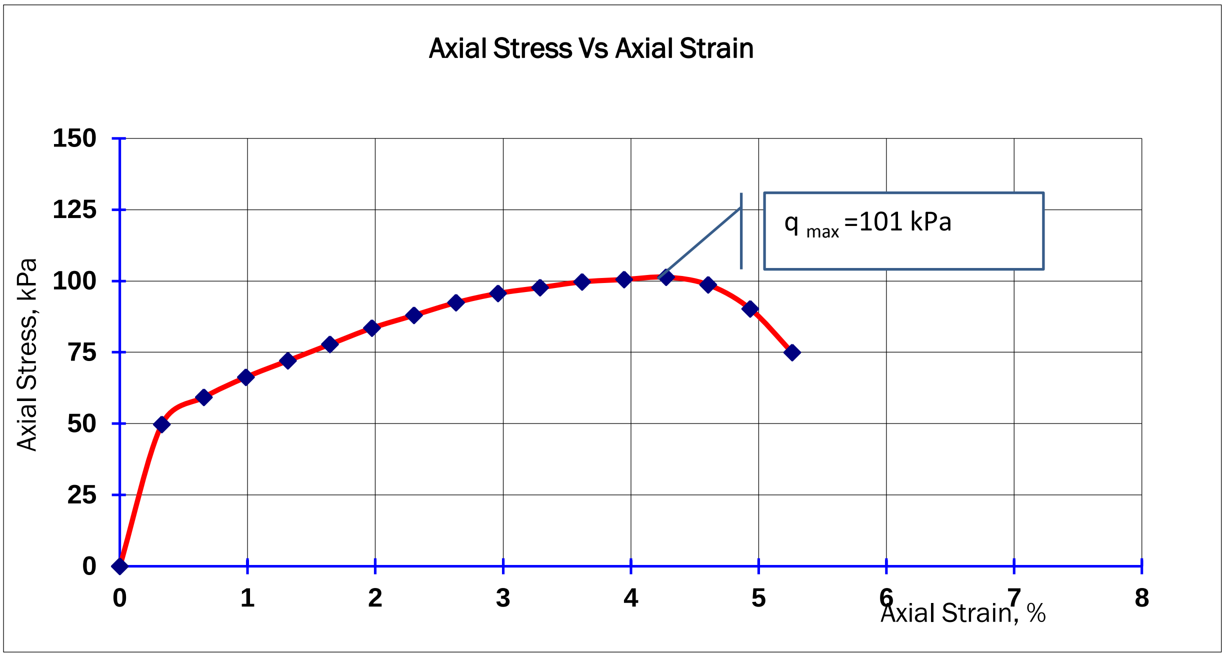


Appendix 7: Summary of different proportion of KCl on 1 Day cured UCS curves

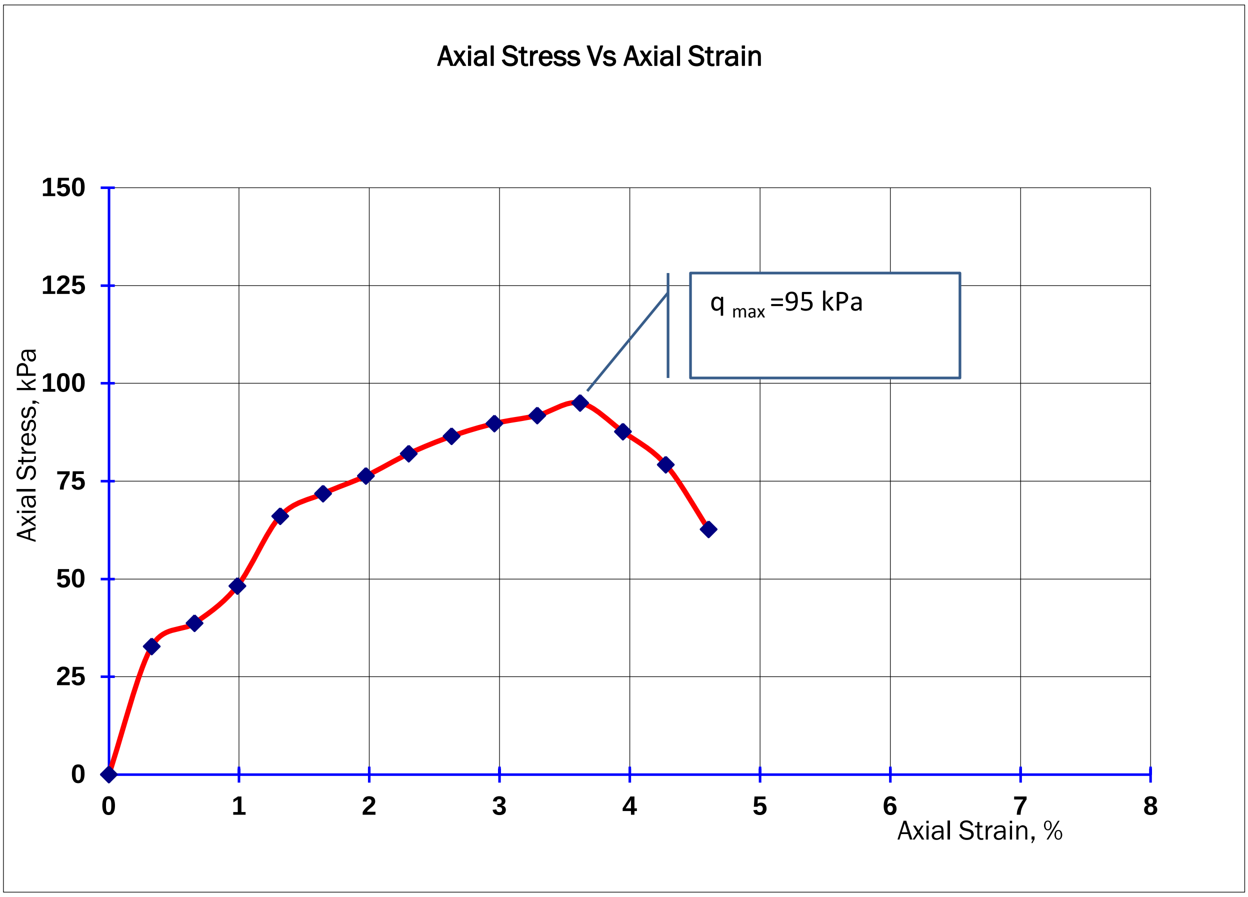
1. 0% Potassium chloride



2. 5% Potassium chloride

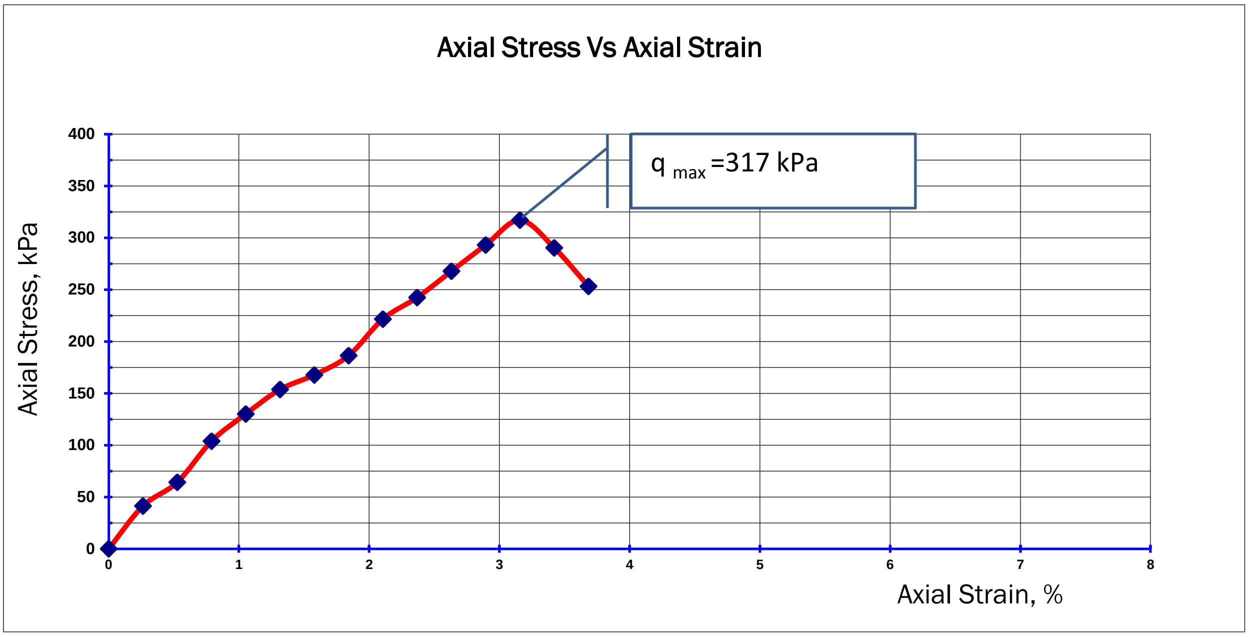


3. 10% Potassium chloride

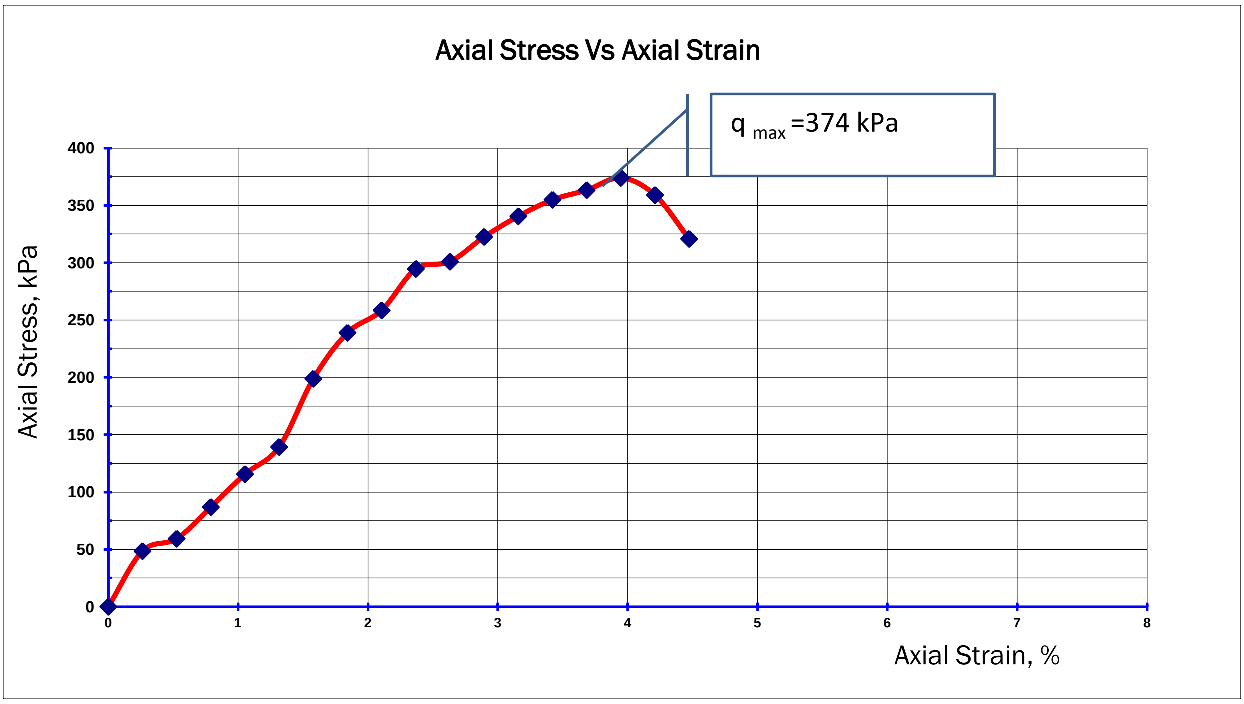


Appendix 8: Summary of different proportion of KCl on 7 Days cured UCS curves

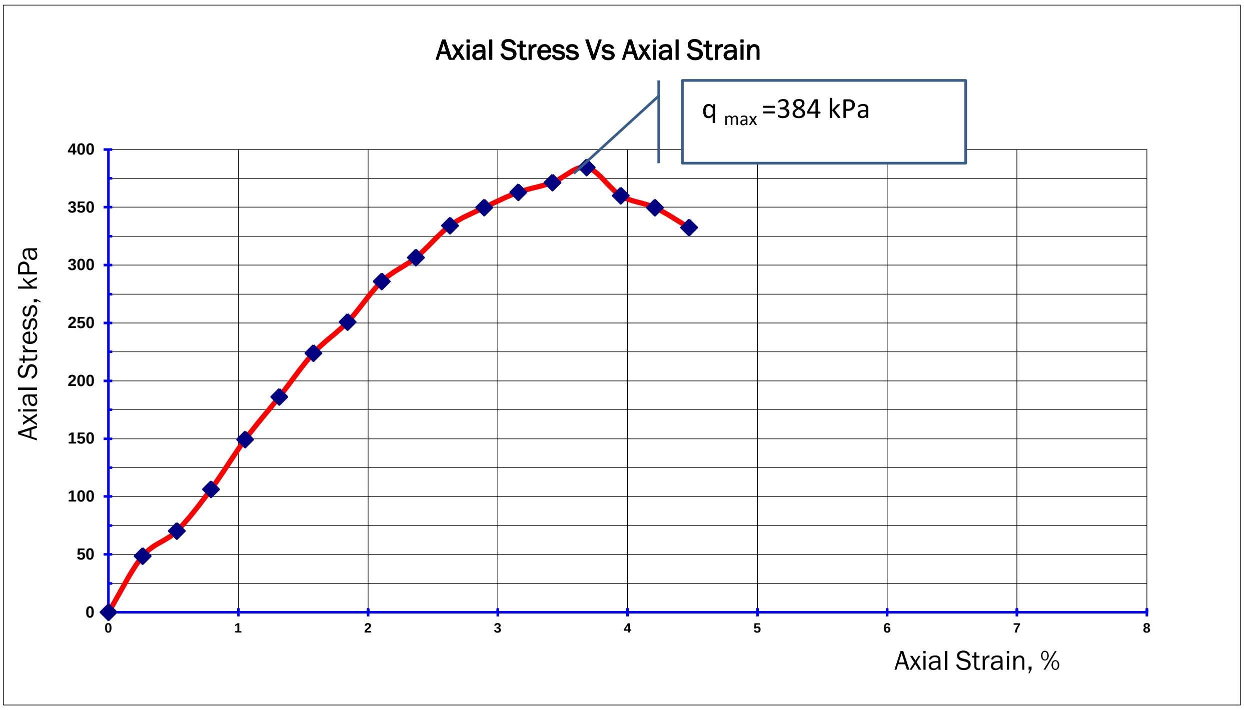
5. 5% Potassium chloride



6. 10% Potassium chloride



3. **15% Potassium chloride**



4. **20% Potassium chloride**