EXPANSIVE SOIL STABILIZATION OF SUBGRADE WITH LIME FOR RAVI - CHENAB CORRIDOR

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DEDICATION

This thesis is dedicated to my beloved **Mother** who has been an inspiration throughout my life, my **loving Sister; Tuba Salman** who always interested and concerned about my studies and my respected **advisor Brig Dr Sarfraz Ahmed**, who's guidance made me able to finish my research work.

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(*Engr. Muhammad Ali Naveed)*

ABSTRACT

This study focuses on review of modern techniques/ technologies for improving trafficability of combat roads/ tracks with special emphasis on Ravi Chenab corridor in Central Comd AOR. The research work is primarily a lab-cum-field study for soil improvement using pozzolanic additives especially lime. In-situ soil conditions are evaluated through detailed investigation and identifying zones with similar soil profiles. Suitable percentages of soil stabilizer will be determined through array of tests to ascertain optimum blends for different types of soils present in the study area.

Wide range of soil modification techniques; including but not limited to geo-synthetics, geo-grids and pozzolanic additives (lime, fly ash, bagasse ash etc) are reported in literature for soil improvement/ stabilization with varying degree of success. However, various research studies have found lime outperforms all other modifiers for clayey soils, thus making it a preferred choice for our study to treat A-7-5, Clay, being the most problematic soil found in the study area.

Soil treated with lime exhibits a significant **increase of 50.60% in coarse fraction** and decrease in Atterberg's limit **(Liquid limit decreased by 41.92 %** and **plasticity index reduced by 79.96 %**) of soil by lime stabilization. **OMC increased by 13.15 % and MDD decreased by 8.63%** with modified proctor test. Classification of soil changed from AASHTO A-7-5 soil to A-4 soil and its behavior from **clayey to silty soil**, thus improving its trafficability class. Significant strength improvement **(soaked un-confined compressive strength increased by 3.48 times and unsoaked increased by 6.75 times** of soil in soaked and unsoaked condition with lime. **Unsoaked Lab CBR increased by 10.12 times and soaked CBR increased by 16.16 times**. **Swell potential decreased by 82.94 %. Field CBR increased by 6.58 times** and **bearing capacity of lime treated soil increased by 160 %** with plate load test. **Direct Shear Test of soil treated with lime increased by 38.89 %**. In the light of the results obtained, it is concluded that 4 % lime can be used efficiently for improvement of weak subgrade (clayey) soils of the area of study.

LIST OF ABBREVIATIONS

AASHTO	– American Association of State Highway & Transportation Official
ASTM	– American Society for Testing and Materials
CAH	– Calcium Aluminate Hydrates
CBR	– California Bearing Ratio
CH	– High Plastic Clay
CL	– Low Plastic Clay
CSH	– Calcium Silicate Hydrates
GSD	– Grain Size Distribution
LL	– Liquid Limit
MDD	– Maximum Dry Density
ML	–Silty Soil
NHA	– National Highway Authority
NLA	– National Lime Association
NS	– Natural Soil
OMC	– Optimum Moisture Content
PI	– Plasticity Index
PL	– Plastic Limit
UCS	– Unconfined Compressive Strength
USCS	– Unified Soil Classification System

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CHAPTER 1

INTRODUCTION

1.1 General

The mobility of forces will play a vital role in outcome of military operations due to high tempo of operations in future battlefield. Provision of requisite logistic support to the forces will also require cross country mob and maintenance of combat roads/ tracks through challenging terrain and in complex battlefield environment. Poor trafficability/ weak soil restricts cross country vehicular move. Though Engineers utilizes available standard road expedients to facilitate move of forces, however ever-increasing volume of mechanized columns in tight timelines necessitates use of additional means to support the move and assembly.

Expansive soils are problematic and now becoming a major issue for the civil Engineers across the globe due to volume change property of such soil. These soils expand with the addition of water and shrinks when these dry out. These soils are usually formed in areas such as Ravi- Chenab corridor. In this region, soil is expansive in nature and exhibits poor bearing capacity especially in wet condition, thereby causing hindrance in mobility of vehicles. These soils have low shear strength, bearing capacity, with higher value of settlements and swelling properties. Lime is the oldest and most common stabilizing agent due to low cost and high stabilizing potential. It significantly increases soil strength and properties. Lime stabilization is achieved through cat-ions exchange, flocculation/agglomeration, lime carbonation and pozzolanic reactions. This reaction continues for years and produce long lasting strength in soil.

This research will help in the stabilization of expansive soil by using the lime material, which is economic and environmentally friendly modification technique.

1.2 Need of Research

Corps of Engineers uses both conventional and unconventional methods and techniques to ensure the mobility of combat forces. However, the job will be much more challenging in current operational environment that demands urgent support with limited resources. Now, there are new technologies, systems and materials that could be used to build and improve combat roads/ tracks, improve vehicle/ soil interaction and traction. Therefore, there is a need to review existing technology and techniques being used by the Corps of Engineers for improving combat roads/ tracks, vehicular/ soil interaction, and propose new technologies and techniques for quick repair and const of combat roads/ tracks.

1.3 Research Objectives

Objectives set-forth for this research study are listed as under:

- **To Investigate** and **classify problematic soils of Ravi-Chenab Corridor** according to the USCS and AASHTO soil classification system.
- **To evaluate Effectiveness** of **stabilizer/** lime with particular focus on the bearing capacity/ strength characteristics of treated soils.
- **To propose construction/ maintenance procedure** for combat roads/ tracks in problematic clayey soils using lime stabilization.

1.4 Scope and Methodology

- This study focuses on review of modern techniques/ technologies for improving trafficability of combat roads/ tracks with special emphasis on Ravi Chenab corridor in Central Comd AOR.
- The research work is primarily a lab-cum-field study for soil improvement using pozzolanic additives especially lime. Identification of the problematic areas and samples collection was carried out in consultation with local formation.
- Wide range of soil modification techniques; including but not limited to geo-synthetics, geo-grids and pozzolanic additives (lime, fly ash, bagasse ash etc) have been reported in literature for soil improvement/ stabilization with varying degree of success.
- However, various research studies have found lime outperforms all other modifiers for clayey soils, thus making it a preferred choice for our study to treat A7-5, Clay, being the most problematic soil found in the study area.

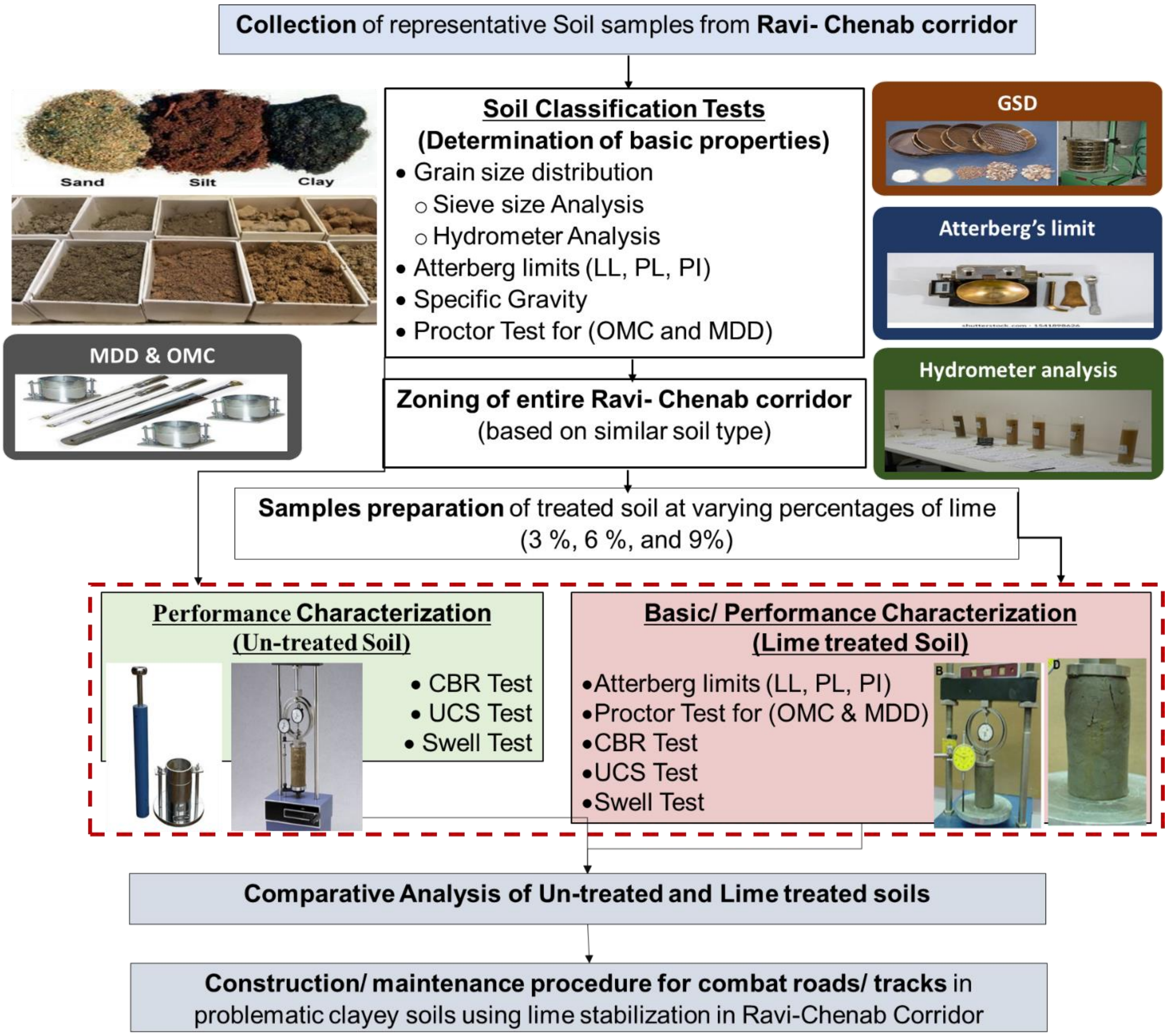


Figure: 1-1, Research Methodology Matrix

1.5 Organization of Research Report

This research report is organized in five chapters; summary of all the chapters is discussed below:

- Chapter 1 includes the introduction to problem statement, research objectives and the scope of the study.
- Chapter 2 describes the literature review of materials and process of stabilization. It also includes past studies carried out by various researchers.
- Chapter 3 describes the research approach taken up to achieve the goals of this study.

It explains in detail the material selection and procedures for determining optimum lime.

- Chapter 4 presents the detail of characterization, and analysis of test performed on lime modified soils at varying percentages of additive, subjected to array of tests in soaked and un-soaked conditions at different curing periods.
- Chapter 5 enlightens the outcomes derived from the current research as well as recommendations for the future research.

CHAPTER 2

LITERATURE REVIEW

2.1 General

Existing ground/ foundation of road/ track commonly termed as Subgrade sustains and transfers vehicular load to the subsurface soil. Subgrade stability depends on soil strength and its behavior under repeated loading. Soil type and moisture content has huge impact on its load carrying/ sustaining capacity. Weak soil like expansive clays, exhibits low bearing capacity, restricts vehicular move, and can result in premature failures of the road structure. Thus, necessitating treatment/ stabilization of these problematic soils to convert them into stable subgrade for road/ track construction.

2.2 Soil Stabilization

Soil stabilization is a collaborative term for physical, chemical, or biological method applied individually or together to improve engineering properties of natural soil (Winterkorn and Fang 1991). Soil stabilization can also be defined as enhancement of required engineering properties of soil by chemical or mechanical means. In-situ soil type and conditions influence suitability/ effectiveness of the stabilization technique/ method.

2.3 Soil Stabilization Techniques

Soil stabilization is generally separated into following two main methods/ techniques.

2.3.1 Mechanical Stabilization

Mechanical stabilization involves physical process that involves compaction, geo-synthetics, ill-suited soil replacement with higher strength material/ soil and adding barriers, nailing, or piling in some cases. Mechanical stabilization is long standing method with its inherent merits, but such methods are expensive and incur higher initial/ construction cost due to replacement of material. Chemical stabilization is new method for enhancing soil strength properties introduced by researchers (Bell 1993, Rogers, Glendinning et al. 1997).

2.3.2 Chemical Stabilization

Chemical stabilization involves improvement of soil strength using different chemical stabilizers. Main types of chemical stabilizers used are lime, cement, bitumen, fly ash etc. are used with different ratio for soil stabilization. Chemical stabilization is done by using two methods ex-situ stabilization and in-situ stabilization. Mechanism of soil stabilization is dependent on type of applied stabilizer (Little and Nair 2009). Same stabilizer cannot be used for all type of soil, so need to check its suitability for target soil and its intended utilization. Chemical stabilizers help in reducing the plasticity, degree of expansion of soil and increase the bearing capacity, shear strength. It significantly increases soil strength, achieved through cat-ions exchange, flocculation/ agglomeration, carbonation and pozzolanic reactions. This reaction continues for years and produce long lasting strength in soil and reduces its moisture susceptibility.

2.3.3 Lime

Lime is the oldest and most common used stabilizing agent (Mallela, Quintus et al. 2004). Soil-Lime mixtures were used to stabilize earth roads in ancient Mesopotamia, Egypt and by Greeks and Romans (McDowell 1959). The appropriate percentage usually ranges from about 3 to 8 percent (Murthy 2002). Lime stabilization is benefit for strength and deformation properties, resilient properties, durability properties, fatigue properties (Little 1998). All strength properties of stabilized soil mixes namely UCS, CBR and shear strength increase with the lime content and curing period (Dahale, Nagarnaik et al. 2016). Lime treated soil is more suitable for warm regions where temperature is very high and for colder regions it is not suitable. Moreover, lime soil stabilization is suitable for soils like clay, silty clay, clayey gravel etc. and is not suitable for granular soil or sandy soil.

2.3.3.1 Lime Stabilization Process

Lime stabilization process undergoes three successive stages:

- **Drying.** During initial mixing of lime and water to the soil the hydration process occurs, soil become dry and its in-situ moisture content reduces.
- **Modification.** After initial mixing Cat-ionic exchange between clay, lime and water occur, which starts flocculation and agglomeration process.
- **Stabilization.** When optimum quantities of lime and water are added the pH of the soil lime mixture quickly increases to up to 12.4, which breaks down clay particles. Cementitious products like Calcium-Silicate-Hydrates (CSH) and Calcium-Aluminate-Hydrates (CAH) are formed due to pozzolanic reaction. These products form a matrix and soil is transformed from weak soil to relative less expansive soil with significant bearing capacity. The matrix formed is permanent, durable, and significantly impermeable, producing a structural layer

that is both strong and flexible.

2.3.3.2 Lime-Soil Chemical Process

Clay and lime mixture reacts in presence of water forming new compounds through the process of cationic exchange, flocculation, carbonation and pozzolanic reaction (Al-Rawas, Hago et al. 2005).

- **Cat-Ionic Exchange.** In this reaction, surplus Ca^{++} cat-ions from hydrated lime are replaced by monovalent cations (Na^{+} or H^{+}) reaction (George, Ponniah et al. 1992). This process makes the modified clayey soil much less affected by moisture (less change in volume) and more resistant to moisture. It is a quick reaction and happens instantly after addition lime in soil.

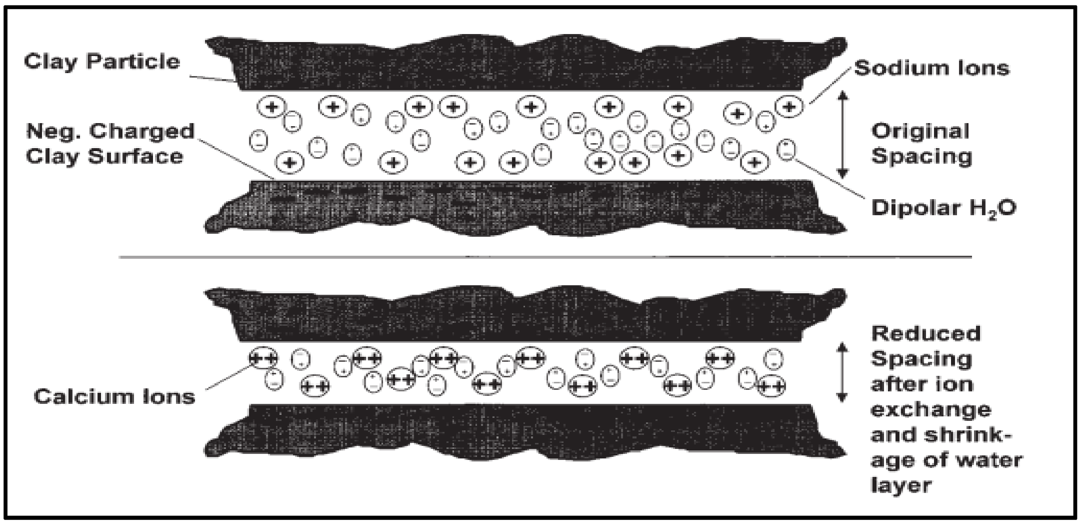


Figure: 2-1, Cat-Ionic Exchange (Prusinski and Bhattacharja 1999)

- **Flocculation-Agglomeration.** A change in texture and gradation is created after cat-ion exchange reaction. Clay particles join forming larger particles/ flocs and this process is called as flocculation. This process plays primary role in modification of engineering properties of lime treated expansive soil (Ghobadi, Abdilor et al. 2014).

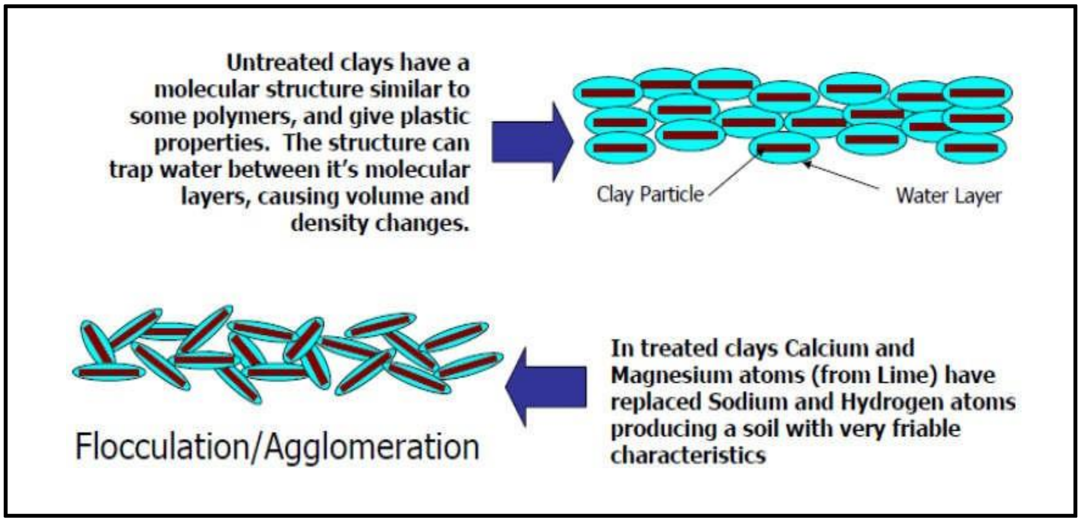


Figure: 2-2, Clay Particles Before and After Lime Stabilization
(Prusinski and Bhattacharja 1999)

- **Carbonation.** Carbonation is an unwanted reaction. In this lime upon addition into soil does not react with soil but reacts with CO2 from air or soil and forms calcium carbonate. Main reason for carbonation reaction is excessive amount of lime content or inadequate amount of pozzolanic clay.

- **Pozzolanic Reactions.** After the initial reaction, alumina and silica in clay mineral become free when pH of 12.4 is reached (Eades and Grim, 1960). Reaction between Ca^{++} cat-ions (available due to hydration of lime) and Silica and Alumina of clay form cementitious materials like Calcium-Silicate-Hydrates (CSH) and Calcium Aluminate Hydrates (CAH) (Eisazadeh, Kassim et al. 2012). These reactions are written as follow:

  Ca(OH)2 + SiO2 → CaO - SiO2

  H2O Ca(OH)2 + Al2O3 → CaO - Al2O3 - H2O

Pozzolanic reactions are time dependent and results in a long-term strength gain. This strength gaining process is called autogenous healing and can continue for years.

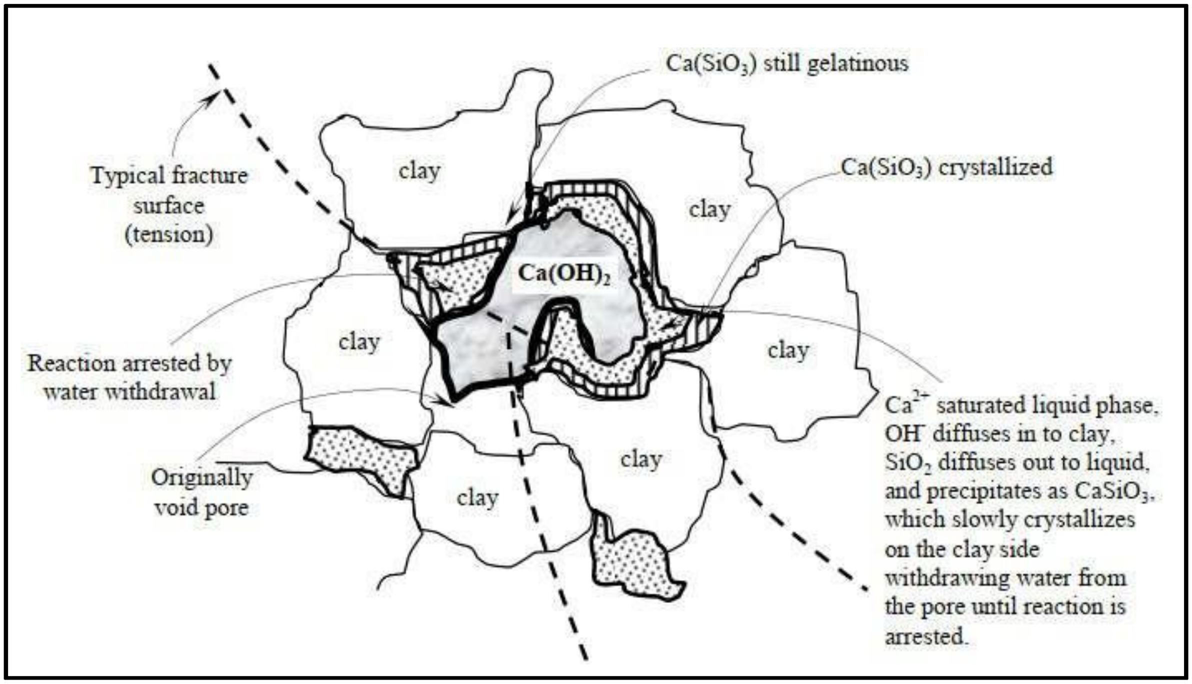


Figure: 2-3, Reaction Mechanism of Stabilization Clay (Ingles and Metcalf 1972)

2.3.3.3 National Lime Association Approach for Lime Stabilization

The mixture design and testing protocol was developed to produce a mixture that has desired structural properties and durability in a road/pavement layer. NLA procedure is used to measure critical engineering properties of subgrade soils stabilized with lime for better performance as pavement layer. This approach was presented by Little 2000, outline of which is presented below:

- Determine optimum lime content.
- To simulate field conditions optimum moisture content and maximum dry density are determined using modified proctor test.
- Unconfined compressive strength tests are conducted as per ASTM D5102. Samples are prepared at optimum moisture content (OMC) and curing is done for 7 days at 40^{o}C. For soaked samples moisture conditioning is done using capillary soak. Samples are subjected to capillary soak for 24 to 48 hours.

2.3.3.4 Effect of Lime on Soil Properties

2.3.3.4.1 Grain Size Distribution

Changes in grain size distribution (GSD) start occurring immediately after addition of lime. Soils become coarser due to agglomeration and flocculation reaction. Lund and

Ramsey (1959) reported decrease in clay content due to increase in particle size with addition of lime.

2.3.3.4.2 Atterberg's Limit

Many researchers reported reduction in plasticity index due to reduction in liquid limit and rise in plastic limit of the soil. However, it depends on the type of soil as different researchers regarding liquid limit have reported conflict behavior. Decrease in PI of soil due to decrease in LL and increase in PL of soil was observed by Jan and Walker (1963).

2.3.3.4.3 Moisture Density Relationship

Optimum moisture content increases due to addition of lime and as a result decreases maximum dry density of the soil. Increase in OMC is due to hydration and pozzolanic reaction with lime. While decrease in MDD is due to flocculation and agglomeration reaction. Hausmann (1990) reported that MDD is reduced by 3-5 lb/ft^3 and OMC increases by 2-4 percent with addition of lime. Increase in OMC enhances lime stabilized soil's moisture resistance.

2.3.3.4.4 Unconfined Compressive Strength

Many researchers reported a significant increase in both soaked and unsoaked UCS of lime soil mixtures. Strength gain in lime soil mixtures may depend on soil type and its mineralogical properties. Little, Thompson et al. (1987) carried out lime stabilization of soils and concluded that strength of lime soil mixture increases more than 100 psi.

2.3.3.4.5 California Bearing Ratio and Swell Potential

CBR test determines bearing capacity and need of subgrade stabilization and overall thickness above subgrade. CBR and swell potential of lime treated soils greatly improves. CBR of soil lime mixture increases from 3-4 times while swell of lime treated soils reduces to less than 0.1% after 96 hours of soaking as mentioned by Little, Thompson et al. (1987).

2.4 Summary of Research Already Carried Out on the Proposed Topic

The following table exhibits the level of research already carried out on the proposed topic as well as the preliminary literature review already done.

Table: 2-1, Summary Finding of the Literature

Author / Journal	**Test Matrix**	**Performance Test Conducted**	**Research Findings**
Dallas N. Little March 2000 (NATIONAL LIME ASSOCIATION)	Lime addition of 5%, 5.5%, 6 % lime in SC, CL, and CH soil respectively.	Unconfined compressive strength test, Plasticity Index	PI decreased • SC- 83.34% • CL- 69% • CH - 73.69% UCS increased • SC 1800% • CL 964.28% • CH 1321%
A.A. Raheem, November 2010. The Pacific Journal of Science and Technology	Cement and lime of 5%, 10%,15%, 20% and 25% in silty soil	Compressive strength test	• Compressive strength 91.41% increased at 10% cement
L.K Sharma Etal 2018 Applied Clay Science	Lime and cement at 1%, 3%, 5%, 7% and 9% in Clayey sand	Unconfined compressive strength test, Atterberg limit test, OMC-MDD	• PI decreased 85% at 9% cement and 60% with lime. • UCS increased 346.7% with lime and 484% with cement. • OMC increased 21.2% at 5% addition of lime and 16.96% at 7% addition of cement. • MDD decreased 26.01% with lime and 23.69% with cement.
Amer Ali Al-Rawasa, 2005 Building and environment 40	Cement, Lime 3%, 6% ,9 %, Cement 3 % + Lime 3%, 6% ,9 %, Cement 5 % + Lime 3%, 6%, 9% in MH soil	LL, PL, PI, and Swell Percentage	• Swell decreased 100% at 6% lime. • PI decreased 60% with combination of cement and lime 3% each.
Amin Soltani etal, 2017 Geotech Geol Engg	28 days lime treatment at 3%, 6%, 9% in CL, 1%, 9.5%, 7.3% in CH 28 days cement 3%, 6%, 9% in CL, 11.6%, 8.8%, 5.4% in CH	PI, OMC, MDD, Swell potential test	• Swell decreased 19% with lime and 21% with cement • PI decreased 9.62% with 3% lime • OMC increased 20.51% at 9% lime • MDD decreased 2.87% with 6% cement.
Asmaa Al-Taie,2021 Procedia Engg	Expansive clay with lime 2-8 % till 28 days curing	OMC, MDD and pH	• OMC increased 13.6% at 8% lime. • MDD decreased 3.35% with 8% lime. • pH increased 52.6 % with 8% lime.
P.P. Dahale, 2016 Construction and Building Materials	Studied effect of combination of 0-10% lime and fly ash on clay soil CH for 7, 28 and 56 days	Atterberg's limit, MDD & OMC, UCCT, CBR	• UCS increased 648.27 %. • Tensile strength 390.4%. • MDD decreased 11.59%. • CBR increased 608%.
Hayder Hassan, 2016 Construction and Building Materials	Studied effect of lime and bagasse ash from 0 -25% on CH at curing period of 3, 7, and 28 days	UCCT, Linear shrinkage	• UCS increased 276.92% at 25 % BA and lime. • Linear shrinkage decreased 83.5% with combination of 25% BA and lime
Azhan Zukri, 2014 Construction and Building Materials	Studied effect of lime from 0 – 9% on clayey soil at 7, 14 and 28 days curing period	Atterberg's limit, MDD& OMC, UCS, CBR	• OMC increased 27.7%. • MDD decreased 13.97%. • UCS increased 1053.3%.
(M.R Asgari, 2013) Construction and Building Materials	CL soil with 3%, 5%,7% and 9% lime and cement on 7, 14, 21, 28, 60 day period	Atterberg's limit, MDD & OMC, UCCT, CBR	• PI decreased 66.6% with lime and 77.7% with cement at 9%. • MDD decreased 58.82% with lime and 47.05 % with cement. • OMC increased 33.3% with lime and 16.66% with cement • UCS increased 1110% with 3% lime and 3500% with cement

2.5 Summary

This chapter presents overview of the studies focusing on soil stabilizers, especially problematic clayey soils. Different techniques/ methods of soil stabilization were discussed. Lime stabilization process and its effect on different geotechnical properties of clayey soils have been discussed in this chapter.

CHAPTER 3

MATERIALS AND METHODOLOGY

3.1 General

Experimental investigation elaborated in this chapter includes characterization of existing soil in the study area, optimization of the modifier/ lime and its effects on treated soil's physical and mechanical properties. To assess the behavior of existing subgrade soil laboratory testing was conducted in three phases. In phase-I, classification of natural material using sieve analysis and Atterberg's limits was determined, and its strength properties were determined using UCS and CBR. In second phase soil properties and response to strength tests was evaluated at various lime contents. Third phase comprises of evaluating soil lime mix.

All the experiments were performed by following ASTM standards. NLA approach was used for soil stabilization using Lime.

3.2 Sample Collection

Soil samples from eight different locations were collected from problematic zones in study in consultation with local formation. Soil samples collection, handling and testing was undertaken in accordance with requisite specifications. Figure: 3-1 illustrates the sampling sites in Ravi-Chenab Corridor, along with their designations as S1, S2, S3, S4, S5, S6, S7 and S8.

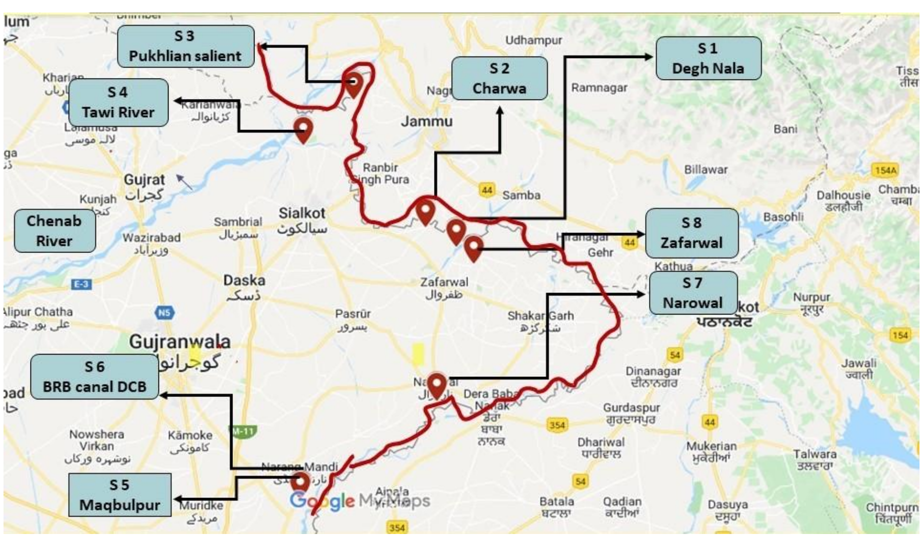


Figure 3-1, Samples collection sites in Area of Study

3.3 Experimental Matrix/ Methodology

Representative soil samples collected from 8x location were subjected to detailed investigation through series of laboratory testing as illustrated in Figure: 3.2 as under:

Phase I: Properties of Natural/ Untreated soil sample

Phase II: Optimization of Lime content

Phase III: Properties and strength of treated soil

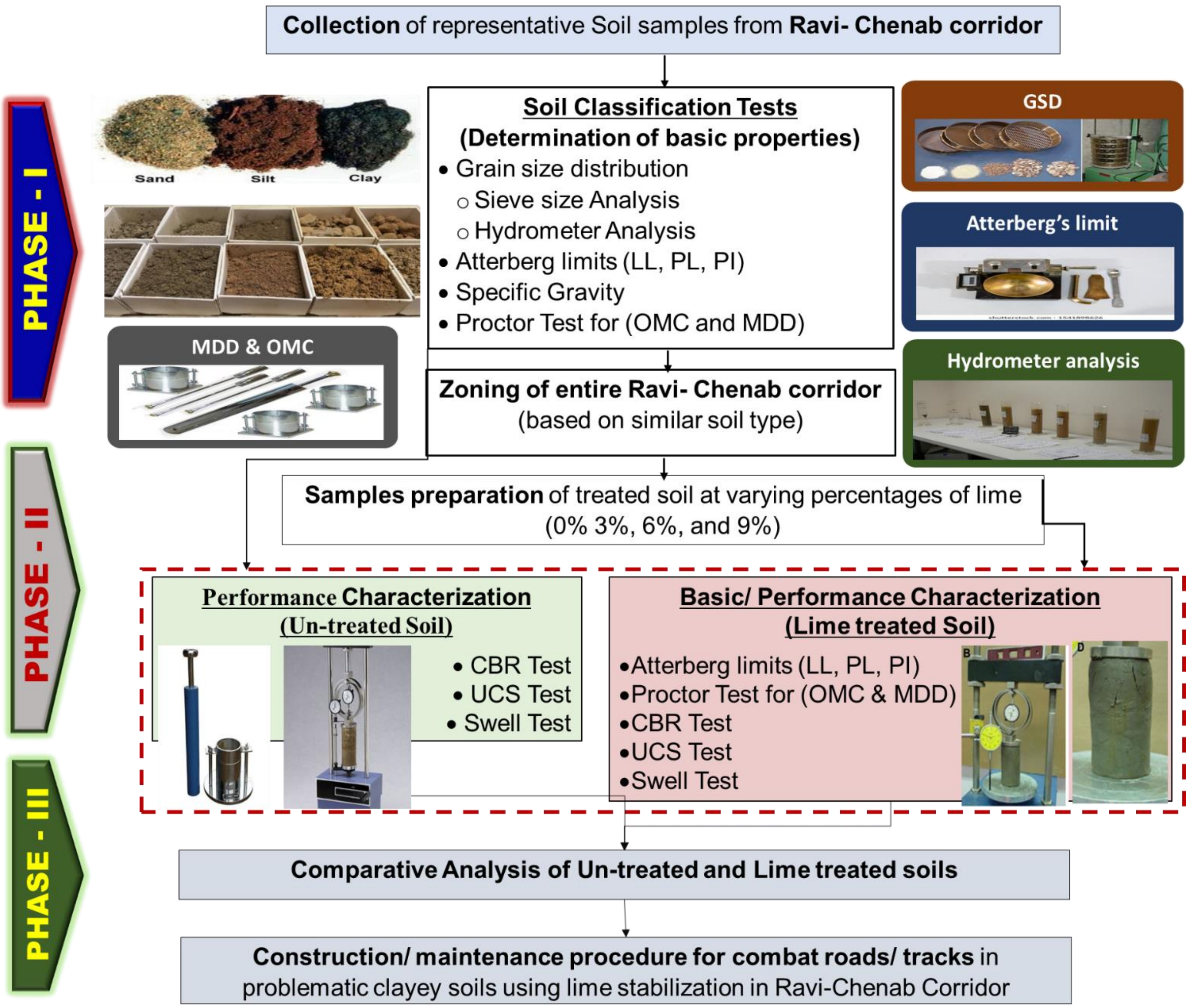
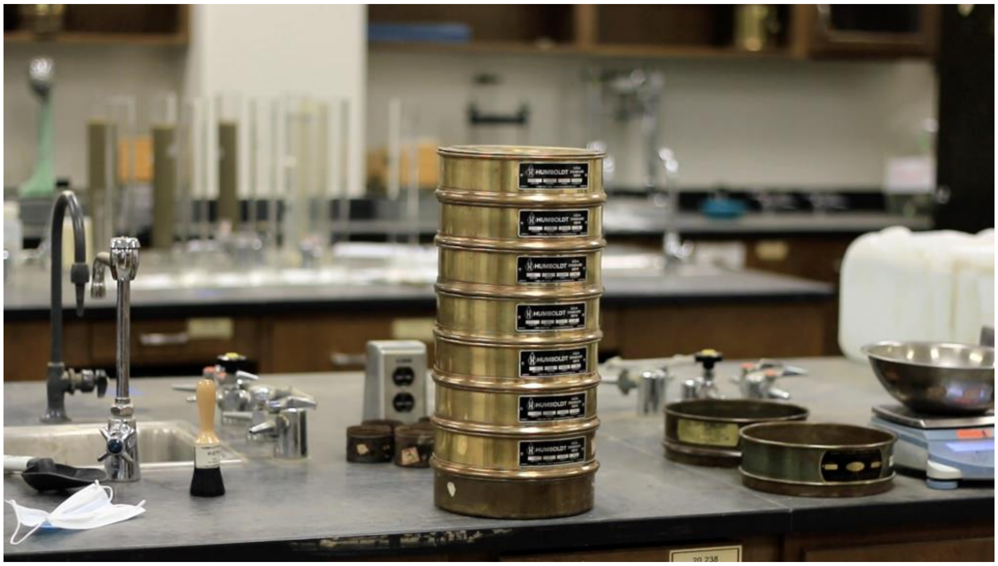


Figure: 3-2, Research Methodology Flow Chart with Phases

3.3.1 Grain Size Distribution

Sieve analysis has been performed by following ASTM D 422 to determine coarse and fine grain soil particles. The size/ particles of soil passed through sieve # 200 are fine grain particles which have been further classified into silt and clay content after hydrometer analysis. Soil retained on sieve#200 are coarse grained soil particles.



Figure; 3-3 Sieve analysis

3.3.2 Hydrometer Analysis

Hydrometer Analysis has been performed to determine silt and clay percentage in fine fraction soil. Sodium hexametaphosphate 5 gm has been mixed with 125 ml water and stirred up properly. Then container has been placed for 24 hrs so it may have complete reaction with water. Then 50 gm soil has been sieved through no 200 sieve and put into the beaker with 1000 ml water and chemical solution. The temperature of the solution measured with thermometer and then hydrometer bulb has been placed inside after mixing the solution properly for minimum 3 minutes. The reading with hydrometer bulb has been taken after 1 min, 2, 4, 8, 15, 30 minutes, 1, 2, 4, 8, 16 and 24 hrs time. The readings are taken minus correction factor and then clay and silt content has been determined of soil samples.

3.3.3 Atterberg's Limits of Soil

Atterberg's limits were determined according to ASTM D 4318. Soil passing through sieve# 40 is used to determine liquid and plastic limits. Plasticity index determined by subtracting the liquid limit from plastic limit which also serves as an indicator of feasibility of soil with lime. Casagrande's apparatus used to determine liquid limit of soil. The mixing of soil with water carried out to form uniform paste after passing through sieve # 40 and pulverization. Groove has been made in the center of soil paste and then rotate the crank with 2 revolution per second until soil contact by 13 mm. Then small amount of soil placed into the container and dried into oven for 24 hrs after its weight determined. The oven dried samples for different moisture content have been again weight and graph plotted between water content with no of blows. The moisture content against 25 no of blow was determined as liquid limit of the soil sample.

Figure 3-4 Liquid Limit limit of soil

The soil sample has been taken and add moisture to make a thread of diameter 3.2 mm. The soil has been rolled on the straight plate so that it should not be sticking with the hands. When thread has been rolled properly into desired size and cracks appeared on whole mass then portion of it has been placed in the container after crubmling. The container has been placed inside oven after weighing then oven dried sample has been weight and finally plastic limit was determined.

Figure 3-5 Sample preparation for Plastic limit

3.3.4 Specific Gravity of Soil

Specific gravity of soil was determined by following ASTM D 854. Soil passing through sieve#4 was used. The flask of 125 ml used in which 50 gm of soil poured after passing through # 200 sieve. Initially weight of empty flask was measured. Then the weight of flask with soil and water has been determined after mixing properly. The soil with water has been half filled for removal of air voids with vacum pump. Then the flask was filled with with water and its weight has been determined for specific gravity of soil samples.

Figure 3-6 Specific gravity of soil

3.3.5 Moisture Density Relationship of Soil

Modified Proctor Test method was used to find moisture density relationship of soil samples. Soil was placed in five layers inside mould and compacted with 25 blows per layer using 10 lb hammer and 18-inch fall height. Test was performed as per ASTM D 1557. The test was conducted for all samples initially and then expansive soil sample with various percentages of lime. The graph plotted between moisture percent and dry density to determine Optimum moisture content and maximum dry density.

3.3.6 Eades and Grim Test to determine optimum lime content.

Optimum amount of lime percent was determined with the help of Eades and Grim Test ASTM D 6276 pH method. Oven dried samples of 25 gm after passing sieve # 40 has been placed inside plastic bottles after drying it properly. Then 100 ml distilled water added in it and stirred up properly along with 2, 3, 4, 5, 6, 8, 10 % lime of dry weight of soil specimen. Then place the specimen for 45 minutes to allow lime soil reaction with water. After shaking period, pH value is determined of soil samples. pH of all samples were noted and the percent of lime which gives max value near 12.4 taken as optimum percent of lime.

3.3.7 Unconfined Compressive Strength of Soil

Unconfined compressive strength test samples were prepared for all samples and then expansive soil sample with 2%, 4%, 6% lime content. Strength tests for both conditions of soaked/unsoaked were performed at 3 hrs, 3 days, 7 days and 14 days. The samples were prepared at OMC and MDD already determined by modified proctor test. All tests were performed in accordance with ASTM D 5102. Height to diameter ratio was kept 2:1. Mold used was of height 10cm and diameter 5cm for UCS testing and no of blows were 25 per layer. All soaked test samples were wrapped up in airtight plastic sheet to prevent moisture loss and cured at 25^{o}C.

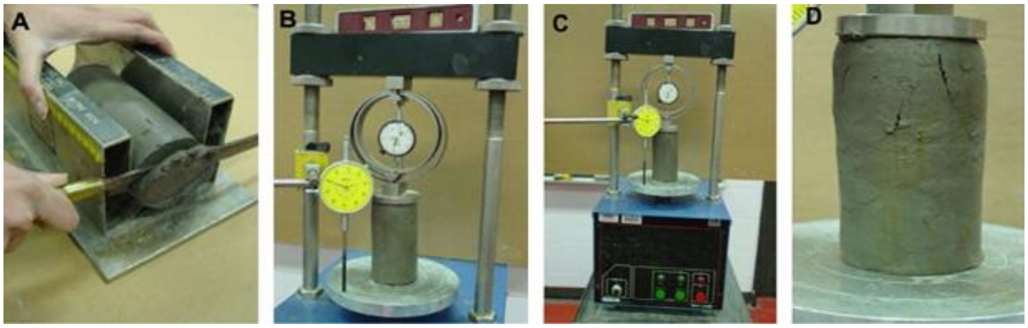


Figure 3-7, UCC Testing of Natural Soil

3.3.8 California Bearing Ratio and Swell Test of Soil

CBR test was performed according to ASTM D 1883. CBR samples were prepared at OMC to achieve maximum dry density and were compacted in five layers with 56 blows per layer. Soaked and unsoaked CBR was conducted in lab at 3 hrs, 3 days, 7 days and 14 days. Soaked CBR sample were soaked for 96 hours in a water tank. A gauge was attached to measure swell potential of the soil.

Figure; 3-8 (a,b) CBR Testing

3.3.9 Field CBR Test

Field CBR has been conducted on soaked field specimen at 0 and 4%lime treated soil. Specimen sample made of 3 ft by 2 ft size and tested after curing for 3 hrs, 3 days, 7 and 14 days time period. Equipment of field CBR placed under the concrete beam to bear upward reaction load. The load was applied by rotating the handle in soaked soil specimen and reading on deformation gauge was noted down to determine CBR value at 0.1 inch and 0.2 inches.

3.3.10 Plate Load Test

The effect of lime stabilization was analyzed by plate load test on field soil specimen. The experiment was performed with 30 cm circular plate. The test completed till the soaked soil further gives no reading or collapses. The selected soil collapsing/ failure criteria to complete the test is to determine the vehicular load that soil can bear in wet period or during inclement weather conditions. Then untreated and treated lime stabilized subgrade soil surface were compared and evaluated. All plate loading test were conducted in soaked condition at 3 hrs, 3 days, 7 days, 14 days curing period.

3.3.11 Direct Shear Test

Direct Shear test was performed for expansive soil samples of untreated and treated soil with 2, 4 and 6% lime of dry weight at 3 hrs, 3 days, 7 days and 14 days curing period. This test conducted to determine shear stress on pre-determined shear failure plane. The soil samples placed inside shear box was having diameter of 63.5 mm and height of 25 mm after passing no 4-sieve size. Filter papers have been placed at bottom and top of each sample inside shear box above porous stone. Consolidation jack with vertical load applied of 50 and 100 Kpa initially and then predetermined shear failure plane was fixed at 10 mm with speed of 0.0254 inches per minute to calculate shear stress.

3.4 Summary

Detailed methodology of research has been presented in this chapter. It described methodology adopted to find out different soil properties of all soil samples and lime treated soil. Last part presents procedure and experiments carried out to analyze geotechnical properties of treated soil. Details about test procedure, test samples, and experimentation setup is also discussed in this chapter

CHAPTER 4

MATERIALS' CHARACTERIZATION AND ANALYSIS

4.1 General

Weak Subgrade soil possess a major problem for pavements. This research was intended to study the use of lime as stabilizers for weak subgrade soil. Detail result analysis is presented below

4.2 Phase I: Properties of Natural/ Untreated soil sample

The first phase in this research was intended to determine the properties of natural or untreated soil or without any stabilizer. Engineering properties were determined, and soils were classified based on GSD and Atterberg's limits. Strength properties of soil were also determined using CBR and UCS. Following tests/procedure was adopted to find properties of natural soil.

4.2.1 Grain Size Distribution

Sieve analysis was performed following ASTM D 422. A 300g Soil samples of each location were oven dried, pulverized and then sieved through stack/ series of sieves. Soil mass retained on each sieve was measured and recorded as shown in Table: 3.1. Gradation plot of all 8x soils have been plotted in Figure: 3.3. Soil mass passed through sieve#200 was used for Hydrometer analysis test.

Table: 4-1, Grain Size Distribution Through Sieve Analysis

Sieve No	Sampling locations/ Soil Mass Retained (g)							
	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-8
# 4	98.18	98.5	99.5	83.5	89.16	94.33	99.76	70.23
# 10	95.85	96.96	98.7	76.92	85.23	91.3	99.68	60.09
# 20	95.35	96.16	97.86	72.25	83.2	88.96	99.6	49.18
# 40	16.49	95.36	96.56	36.88	82.8	87.7	99.51	28.13
# 60	7.3	94.43	93.53	22.36	82.6	86.7	99.42	12.02
# 100	1.6	93.06	87.36	8.77	82.43	84.66	99.36	4.41
# 200	0.4	91.7	79.43	3.36	82.33	81.23	99.33	1.31
Pan	0	0	0	0	0	0	0	0

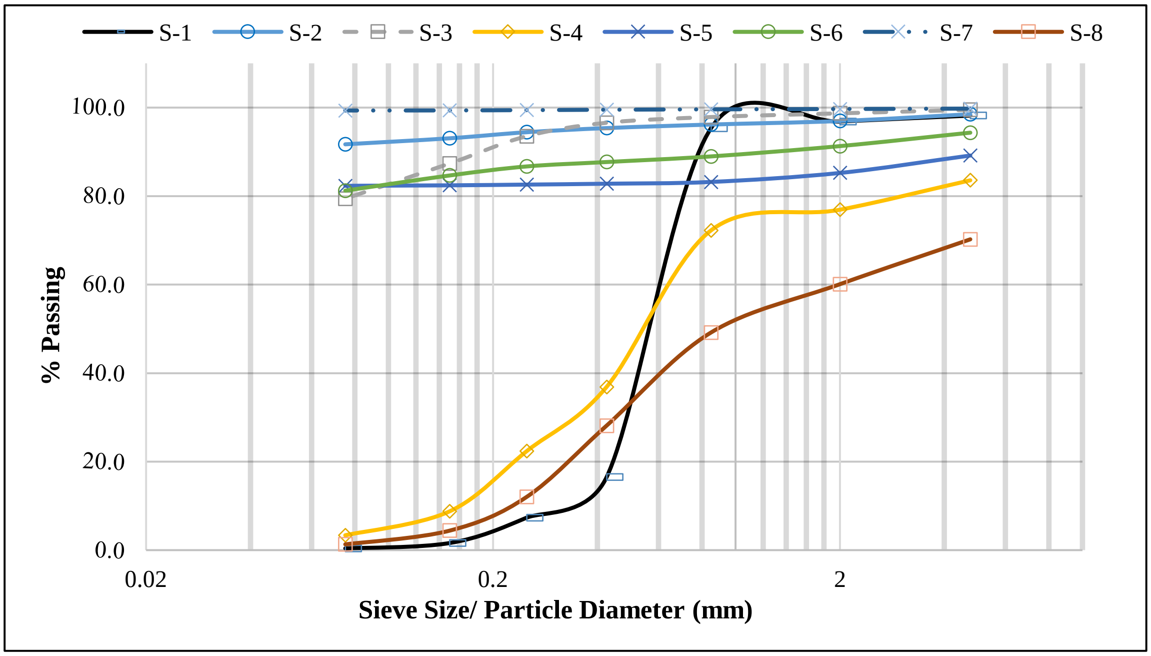


Figure: 4-1; Gradation Plot of Soil Samples from all location

4.2.2 Atterberg's Limits of Soil

Atterberg's limits were determined according to ASTM D 4318. Soil passing through sieve#40 was used to determine liquid and plastic limit. Plastic limit (PL) was determined by making threads of 1/8" thickness at corresponding moisture content. Whereas liquid limit (LL) was determined by finding moisture content at 25 blows using Casagrande apparatus. Plasticity index (PI) of soil is calculated as difference between LL & PL, also indicates soil's suitability for lime treatment/ stabilization.

Table: 4-2, Summary of Atterberg's Limit

Sample ID	Liquid Limit	Plastic Limit	Plasticity Index
S-1	**Non-Plastic Soil**		
S-2	55.10	32.13	22.97
S-3	30.33	22.44	7.89
S-4	**Non-Plastic Soil**		
S-5	35.00	20.90	14.10
S-6	25.50	17.70	7.80
S-7	34.30	23.68	10.62
S-8	**Non-Plastic Soil**		

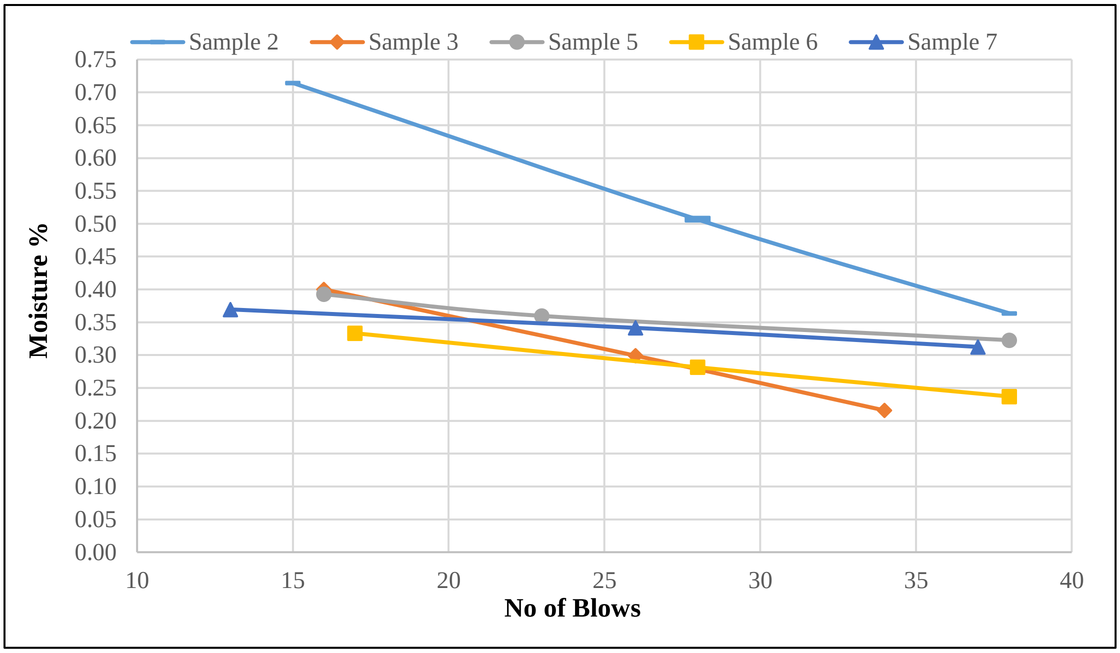
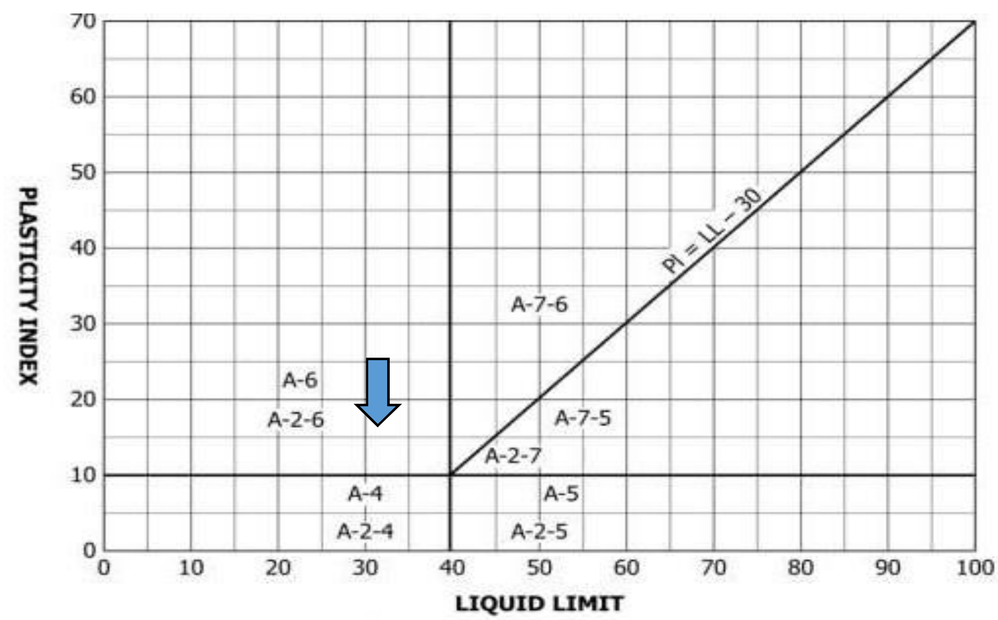


Figure: 4-2, Liquid Limit Measurement using Casagrande Apparatus



(Note: A2 Soils contain less than 35% finer Sieve#200)

Figure: 4-3; Soil Classification (ASTM D3282)

4.2.3 Specific Gravity of Soil

Specific gravity is a significant parameter of soil since it can be associated with the soil mineral composition and weathering. It is also used to derive several parameters such as porosity, dry and saturated density and degree of saturation. Specific Gravity was determined by following ASTM D 854. Soil passing through sieve#4 was used as per ASTM.

Table: 4-3, Specific Gravity of Tested Soils

Sample ID	Specific Gravity
S-1	2.625
S-2	2.636
S-3	2.47
S-4	2.465
S-5	2.577
S-6	2.44
S-7	2.485
S-8	2.526

Figure: 4-4, Soil Specific Gravity Apparatus

4.2.4 Moisture-Density Relationship of Soil

Modified Proctor Test method was used to find moisture-density relationship of natural soil. Soil was placed in five layers and compacted with 25 blows per layer using 10 lb hammer with 18-inch fall. Test was performed as per ASTM D 1557. Different samples were prepared. Optimum moisture content (OMC) and maximum dry densities (MDD) were found for each sample using modified proctor tests, summarized in Table 4-4, and illustrated in Figure 4-5.

Table: 4-4, Moisture Density Relationship

SAMPLE ID	S-1	S-2	S-3	S-4	S-5	S-6	S-7	S-7
MDD (PCF)	118.4	121.8	113.2	123.6	119.8	124.3	124	125.2
OMC %	12.3	11.4	12.7	8.7	10.8	9.9	10.5	8.6

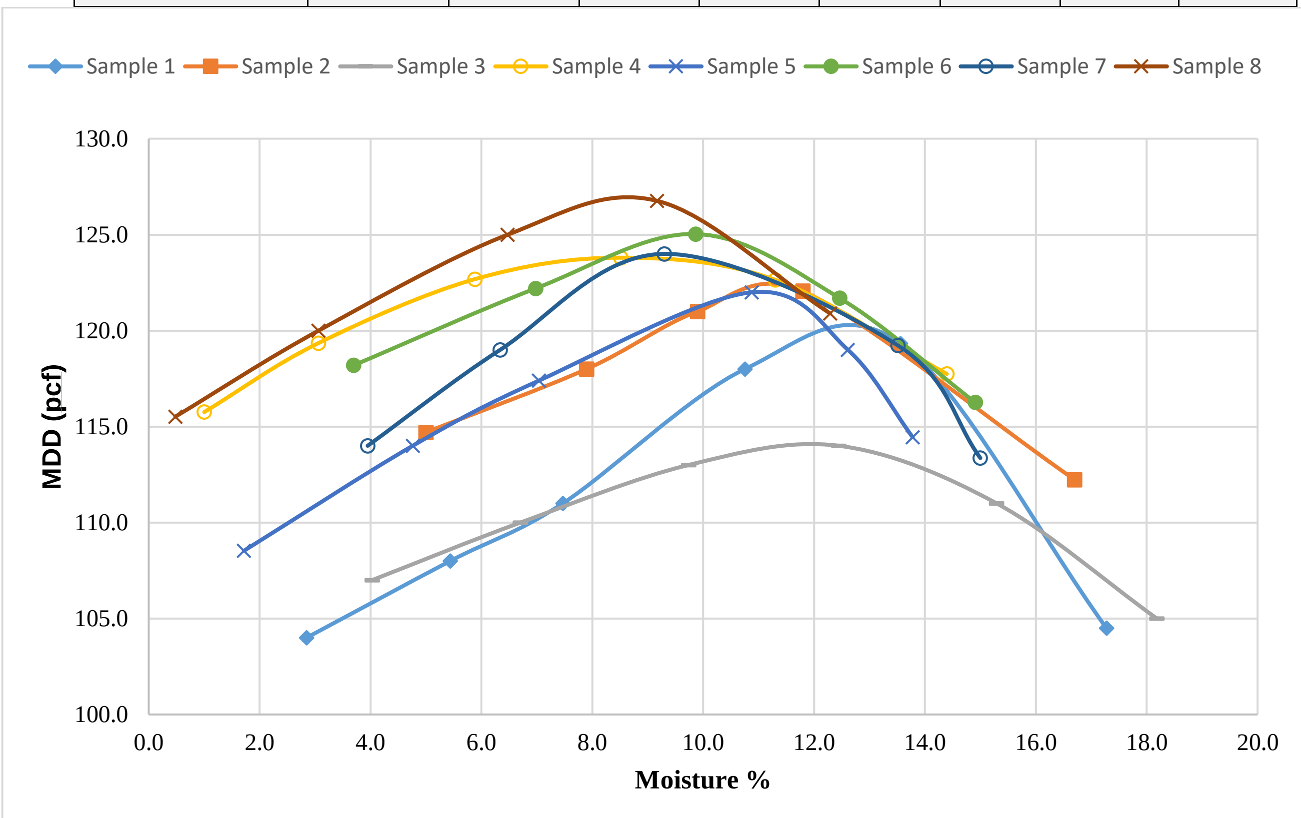


Figure: 4-5, Moisture-Density Relationship Profile of Tested Soils

4.2.5 Unconfined Compressive Strength of Soil

UCCS tests were performed following ASTM D 2166 to determine the compressive strength of untreated soils collected from all 8x sites. According to ASTM D 2166 height to diameter ratio must be 2:1. Mould was of 10cm height and 5cm diameter. Samples were made at optimum moisture content and maximum dry density taken from modified proctor test.

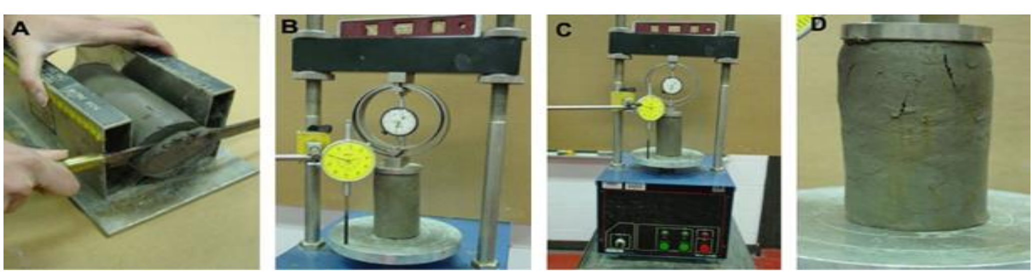


Figure: 4-6, Unconfined Compressive Strength Testing of Natural Soil

Table: 4-5, Results of Unconfined Compression Strength Tests of Silty/ Clayey Soils

Sample ID	S - 1	S – 2		S - 3		S - 4	S - 5		S – 6		S – 7		S - 8
Dial Reading		Strain %	Axial Load	Strain %	Axial Load		Strain %	Axial Load	Strain %	Axial Load	Strain %	Axial Load	
0		0	0	0	0		0	0	0	0	0	0	
25		0.25	0.24	0.25	0.03		0.25	0.05	0.25	0.31	0.25	0.3	
50		0.5	0.41	0.5	0.05		0.5	0.09	0.5	0.46	0.5	0.5	
75		0.75	0.58	0.75	0.06		0.75	0.14	0.75	0.49	0.75	0.74	
100		1	0.73	1	0.08		1	0.17	1	0.63	1	0.98	
125		1.25	0.89	1.25	0.09		1.25	0.2	1.25	0.72	1.25	1.28	
150		1.5	1.03	1.5	0.12		1.5	0.25	1.5	0.84	1.5	1.55	
175		1.75	1.16	1.75	0.14		1.75	0.28	1.75	0.91	1.75	1.83	
200		2	1.28	2	0.19		2	0.32	2	0.94	2	2.07	
225		2.25	1.39	2.25	0.23		2.25	0.37	2.25	0.91	2.25	2.31	
250		2.5	1.48	2.5	0.29		2.5	0.4	2.5	0.83	2.5	2.54	
275		2.75	1.57	2.75	0.36		2.75	0.46	2.75	0.61	2.75	2.72	
300		3	1.62	3	0.44		3	0.51			3	2.91	
325		3.25	1.68	3.25	0.52		3.25	0.57			3.25	3.05	
350	**SANDY SOIL**	3.5	1.71	3.5	0.62	**SANDY SOIL**	3.5	0.62			3.5	3.12	**SANDY SOIL**
375		3.75	1.75	3.75	0.73		3.75	0.68			3.75	3.16	
400		4	1.74	4	0.85		4	0.76			4	3.18	
425		4.25	1.72	4.25	0.98		4.25	0.83			4.25	3.16	
450		4.5	1.66	4.5	1.1		4.5	0.93			4.5	3.08	
475				4.75	1.23		4.75	1.02					
500				5	1.35		5	1.13					
525				5.25	1.44		5.25	1.2					
550				5.5	1.55		5.5	1.31					
575				5.75	1.64		5.75	1.38					
600				6	1.71		6	1.48					
625				6.25	1.76		6.25	1.57					
650				6.5	1.76		6.5	1.62					
675				6.75	1.62		6.75	1.62					
700				7	1.39		7	1.59					
725							7.25	1.55					

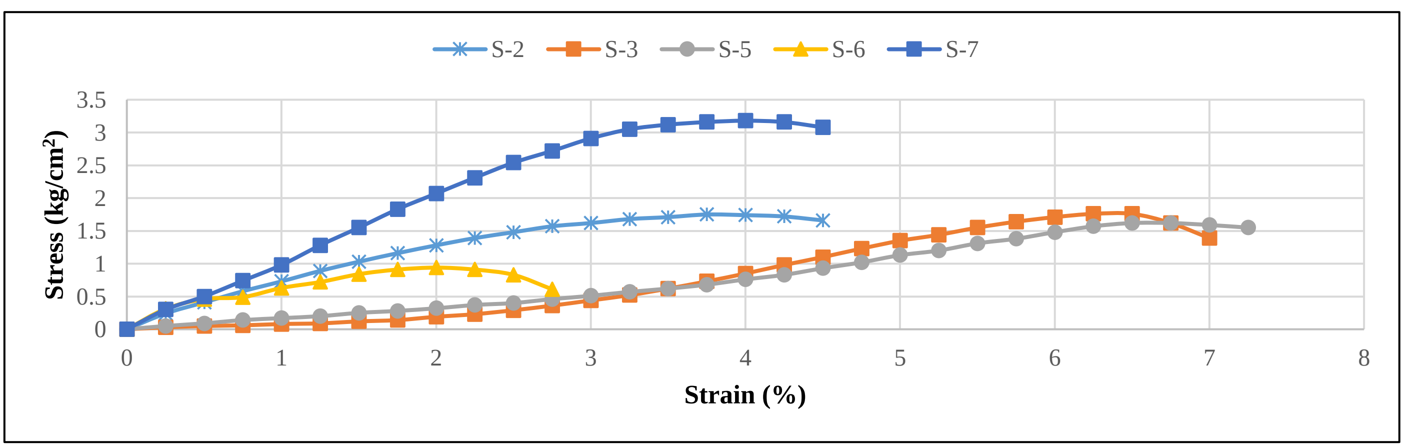


Figure: 4-7, Unconfined Compression Strength Profiles of Silty/ Clayey Soil

Comments on UCS test results performed on untreated silty/ clayey soils illustrated in Table 4-5 and Figure 4-7 are summarized as under:

- The consistency of soil samples 2, 3 & 5 (S-2, S-3 & S-5) have been observed as stiff, having compressive strength from 1-2 kg/cm^2, sample 2 was observed having plastic behavior.
- Sample 6 (S-6) carrying compressive strength of 0.94 kg/cm^2 is identified as firm soil and displayed a ductile behavior.
- Sample 7 (S-7) with a compressive strength of 3.18 kg/cm^2 is observed as very stiff and plastic material.

4.2.6 California Bearing Ratio

California Bearing Ratio (CBR) tests were performed according to ASTM D 1883. CBR samples were prepared at OMC to achieve maximum dry density and were compacted in five layers with 56 blows per layer. Tests for both condition of soaked/unsoaked were performed for natural/untreated soil as per ASTM D 1883.

Table: 4-6, Soak / Un-soak California Bearing Ratio of Untreated Soils

Sample ID	**Soak CBR Test Results**				**Un-Soak CBR Test Results**			
	Stress		**CBR %**		**Stress**		**CBR %**	
Readings	**At 0.1"**	**At 0.2"**	**At 0.1"**	**At 0.2"**	**At 0.1"**	**At 0.2"**	**At 0.1"**	**At 0.2"**
S-1	124	296.3	12.402	**20**	130.9	420.3	13.091	28
S-2	41.3	75.8	4.134	5	181.9	241.2	18.18	16
S-3	44.1	64.8	440	4	246.7	275.6	24.66	18
S-4	385.8	1033.5	38.58	**69**	633.9	1336.7	63.38	89
S-5	46.9	96.5	4.68	6	137.8	249.4	13.78	17
S-6	27.5	62	2.75	4	96.5	166.7	9.64	11
S-7	55.1	95.1	5.12	6	137.8	268.7	13.78	18
S-8	53.7	130.9	5.37	9	100	175	10	12

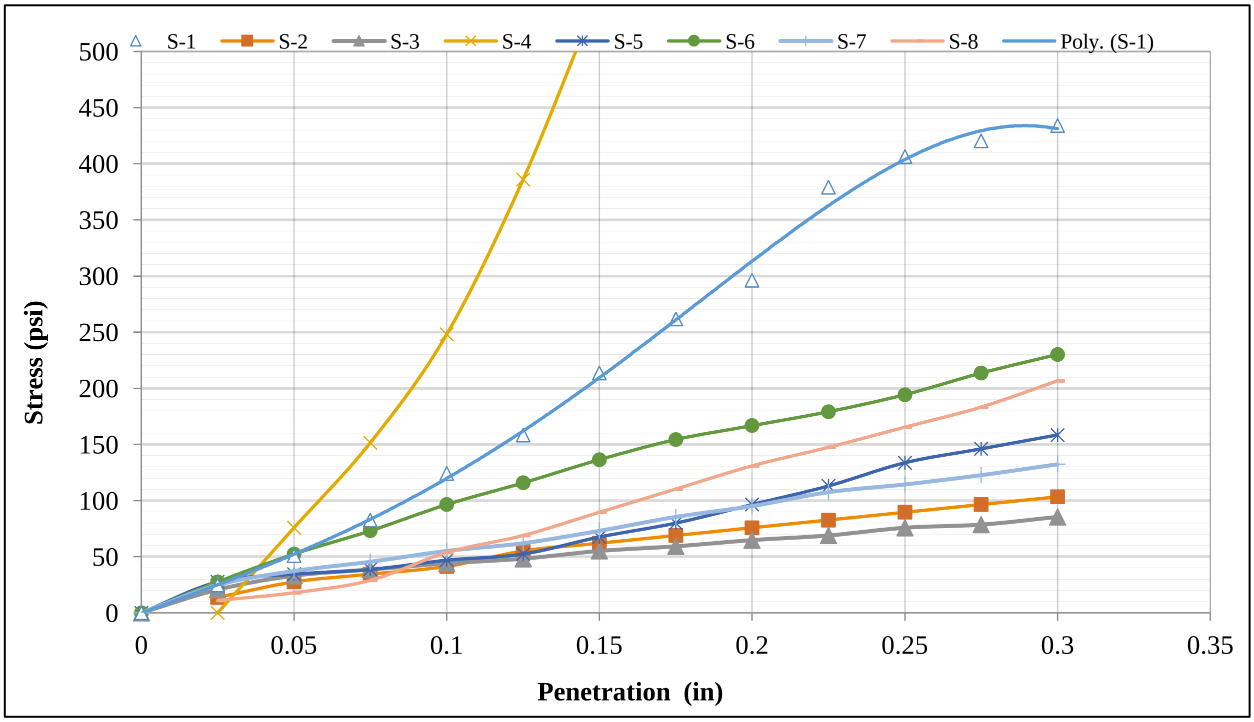


Figure: 4-8, California Bearing Ratio in Soaked Condition

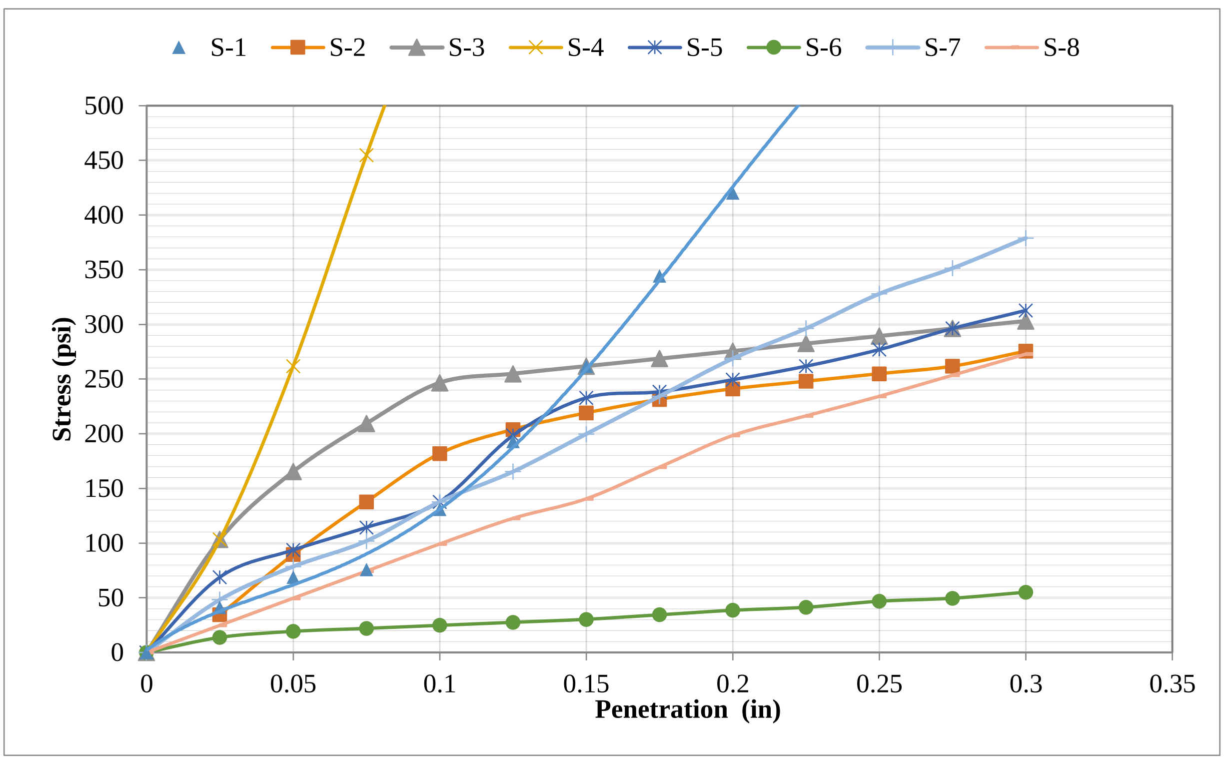


Figure: 4-9, California Bearing Ratio in Un-Soaked Condition

4.2.7 Summary - Properties of Natural/ Untreated Soils

A summary of the tests performed on natural/ untreated soils samples collected from all 8x locations is presented in Table 3.6 alongside their derived soil classification based on the measured responses following USCS and AASHTO specifications/ procedures.

Table: 4-7, Summary of Soil Classification Based on Test Performed

Properties	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
% PASSING SIEVE #200	0.4	91.7	79.43	3.36	82.33	81.23	99.33	1.31
LIQUID LIMIT	**Non-Plastic**	55.1	30.33	**Non-Plastic**	35	25.5	34.3	**Non-Plastic**
PLASTIC LIMIT		22.03	22.44		20.9	17.7	7.8	
PLASTICITY INDEX		22.97	7.89		14.1	7.8	10.62	
OMC	12.3	12.9	12.7	8.7	10.8	9.9	10.5	8.6
MDD (pcf)	118.4	122.8	113.2	123.6	119.8	124.3	124	125.2
SPECIFIC GRAVITY	2.62	2.63	2.47	2.46	2.57	2.44	2.48	2.52
UCCT (kg/cm^2)	**Sandy Soil**	1.75	1.76	**Sandy Soil**	1.62	0.94	3.18	**Sandy Soil**
CBR SOAKED (%)	12.4	6	4	69	6	4	6	9
CBR UNSOAKED (%)	13.09	16	18	89	17	11	18	12
SOIL TYPE AASHTO	**A-1-b**	**A-7-5**	**A-4**	**A-1-b**	**A-6**	**A-4**	**A-6**	**A-1-b**
SOIL TYPE USCS	**SP**	**CH**	**CL**	**SP**	**CL**	**CL**	**CL**	**SP**

Natural soil collected from Charwa location (S-2) was identified as the weakest soil A-7-5/ CH, based on its measured response of various tests performed under different conditions. Being the most problematic soil having lowest bearing capacity, lowest compressive strength was selected for lime stabilization.

4.3 Phase II- Properties of Treated Soil/ Optimization of Lime content

Second Phase of the research was to find optimum lime content. Quick lime from open market was used. Different samples were prepared by adding 2%, 4%, 6% lime content and elaborate laboratory evaluation was carried out to quantify lime stabilization effect, in terms of improvement in physical and mechanical properties of the treated soil under varying post treatment/ healing periods. Eades and Grim test were conducted to measure pH value (lime reactivity potential) of lime-treated soil for approximate optimization of lime.

Table: 4-8, Eades and Grim Test values at various percentage of Lime

Tests	Lime Percentage							
Eades and Grim Test	0%	2%	3%	4%	5%	6%	8%	10%
pH Values	9.64	11.98	11.95	11.87	11.86	11.84	11.76	11.70

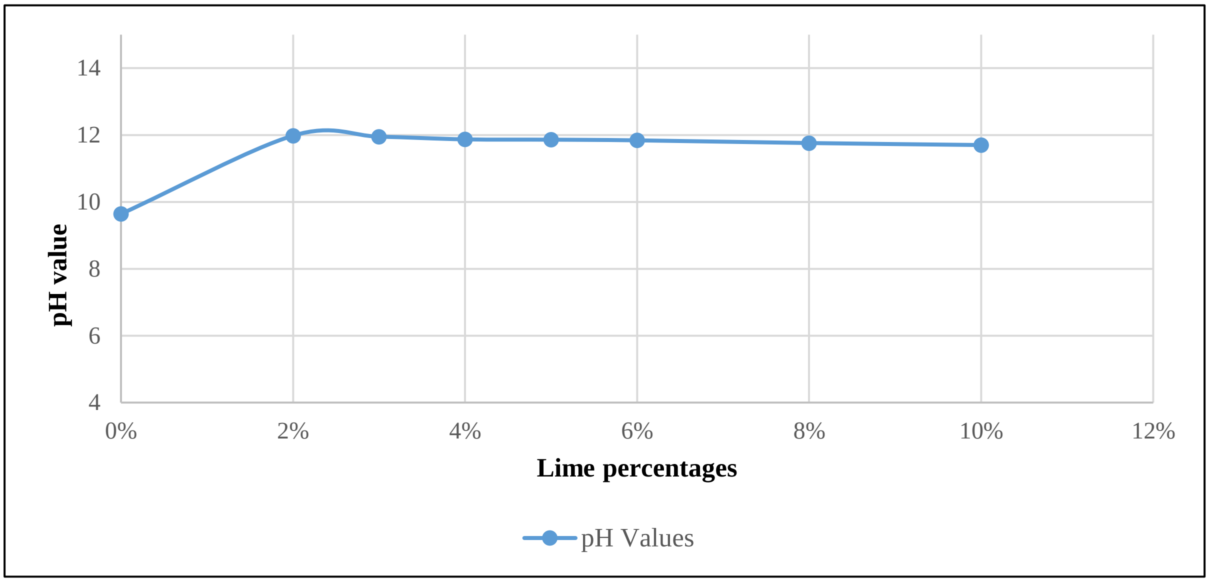


Figure 4-10, Eades and Grim Test ASTM D 6276 pH values with percentage of Lime

4.3.1 Grain Size Distribution at Various Lime Content

Effect of lime on Grain Size Distribution was determined and Sieve analysis was carried out following ASTM D 422 on lime-treated soil at 2%, 4% and 6% lime by weight of soil. Soil passing through sieve#200 and soil retained on sieve#200 was determined. Table 4-9 and Figure 4-11 presents the improved grain size distribution of lime treated soil at different percentages of lime.

Table: 4-9, Sieve Analysis of A-7-5 Lime Treated Soil at Varying Percentages

Sieve No	Percentage of Lime			
	0 %	2%	4%	6%
# 4	98.50	100	100	100
# 10	96.97	99.36	97.9	99.2
# 20	96.17	98.76	95	97.96
# 40	95.37	97.7	93.4	95.9
# 60	94.43	95.96	91.4	92.86
# 100	93.07	92.86	89.4	89.5
# 200	91.70	89.4	88.2	87.5

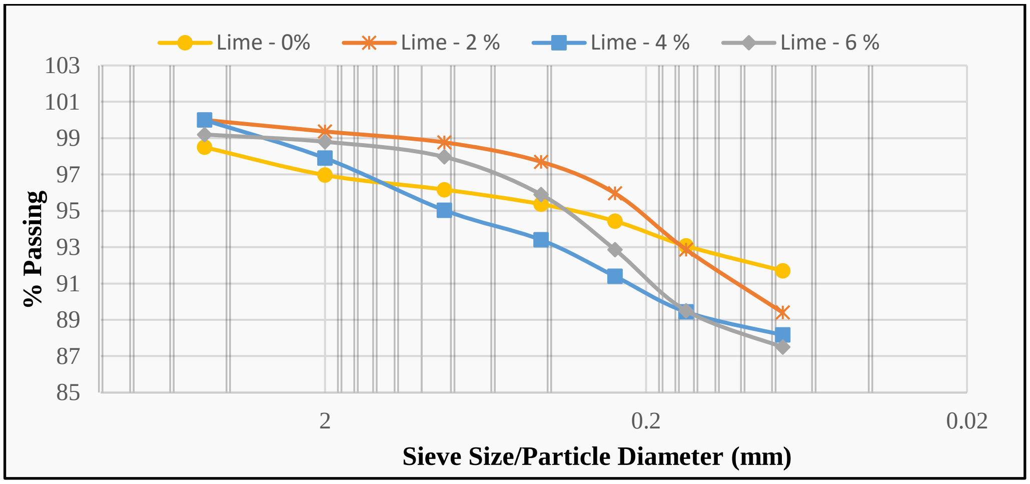


Figure: 4-11, Grain Size Distribution of Lime Treated Soil

4.3.2 Atterberg's Limit of Treated Soil

Effect of lime on Atterberg's limit was determined and test performed according to ASTM D 4318. Soil passing through sieve#40 was mixed with 2%, 4% and 6% lime and used to determine liquid and plastic limits. Table 3.8 and Figure 3.12 presents the improved LL, PL and PI of lime treated soil at different percentages of lime.

Table: 4-10, Atterberg's Limit Based on Lime %

LIME %	LIQUID LIMIT	PLASTIC LIMIT	PLASTICITY INDEX
0	55.1	32.13	22.97
2	45.10	30.0	15.10
4	37.01	32.27	4.74
6	32	22.03	9.97

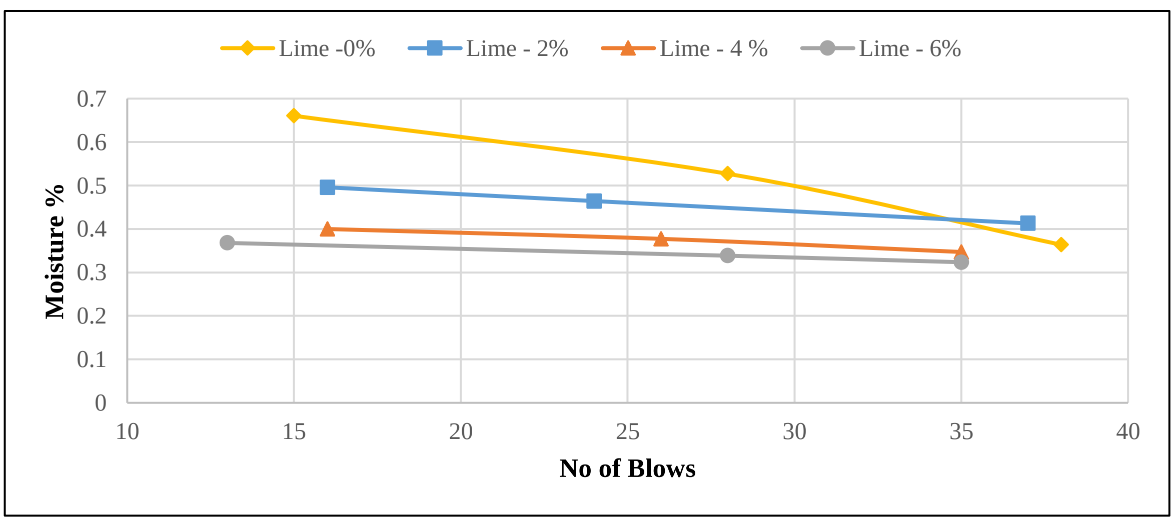


Figure 4 - 12, Liquid limit with varying percentage of Lime

4.3.3 Moisture Density Relationship of Treated Soil

Sample A-7-5 was prepared by adding 2%, 4%, 6% lime. OMC and MDD were found for each lime content using modified proctor tests. All experiments were carried out as per ASTM D 1557. Moisture-Density test results of lime treated soil at varying percentages are shown in table 4-11 and figure 4-13.

Table: 4-11, Moisture Density Relationship Soil-Lime Mix

LIME	MDD (pcf)	OMC (%)
0%	122.8	11.4
2%	114.7	12.6
4%	112.2	12.9
6%	115.5	9.8

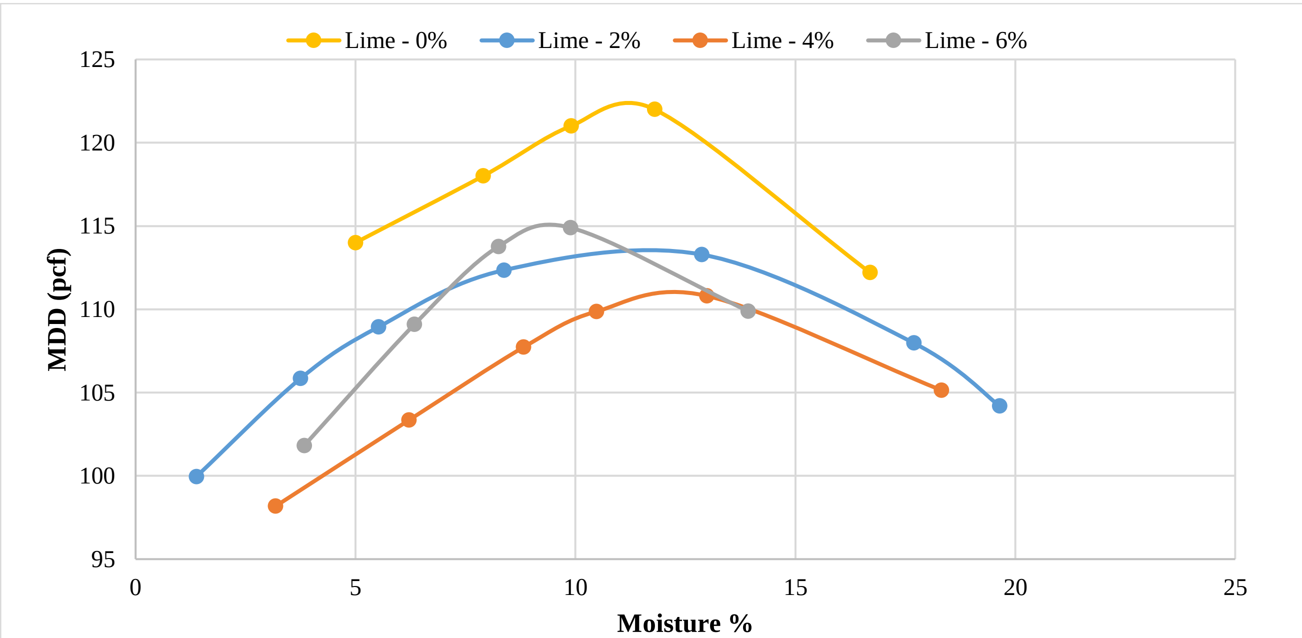


Figure: 4-13, Moisture-Density Profile of Lime-Treated Soil

4.3.4 Unconfined Compressive Strength of Treated Soil

Unconfined compressive strength tests in both soaked and unsoaked conditions were carried out on samples after 3 hrs, 3 and 7 and 14 days curing periods. Soaked testing was carried out to assess the behavior of soil in moist condition. Test results for both conditions of unsoaked/soaked for untreated and treated soil at various lime content are shown below in table 4-12 and figure 4-14 and 4-15.

Table: 4-12, UCS Results Based on varying percentages of Lime/ Curing Periods

Curing Period	**3 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**
% LIME	**0%**	**2%**				**4%**				**6%**			
UCC UN-SOAKED (KG/CM^2)	1.75	4.89	7.44	7.27	6.29	5.76	8.97	7.72	13.57	2.78	6.67	5.17	6.91
UCC SOAKED (KG/CM^2)	1.62	2.45	6.23	4.59	4.30	5.18	7.27	4.70	6.86	1.90	5.33	3.43	2.94

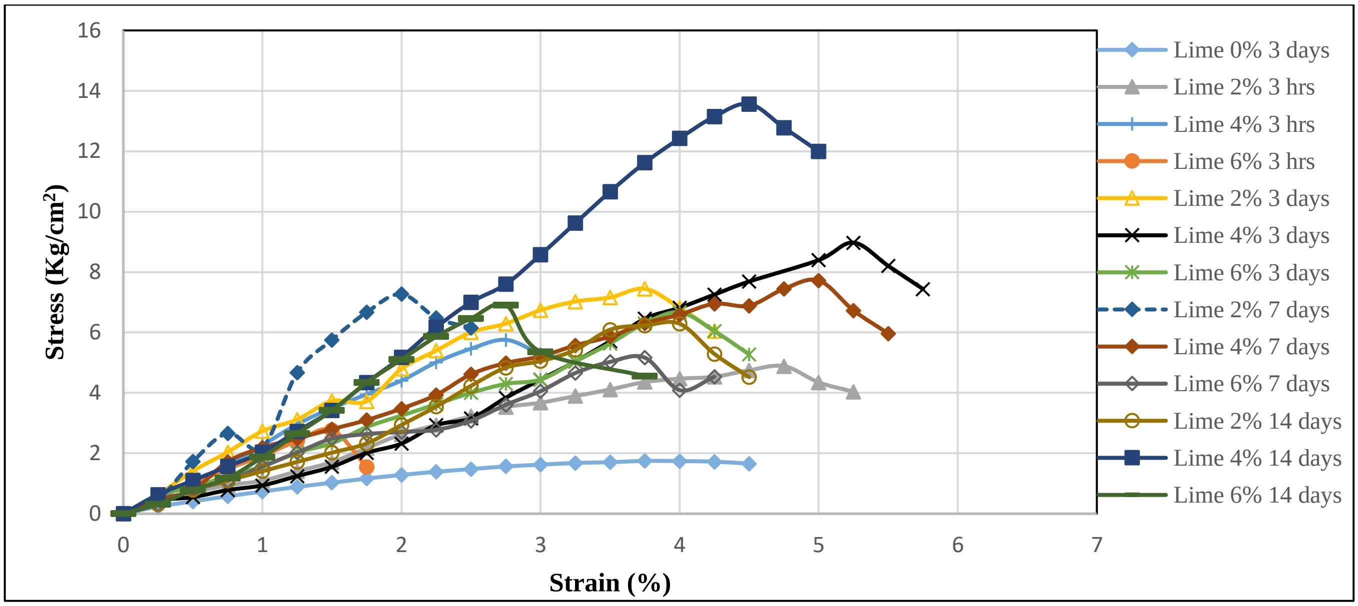


Figure 4-14, UCS unsoaked with Lime percentages

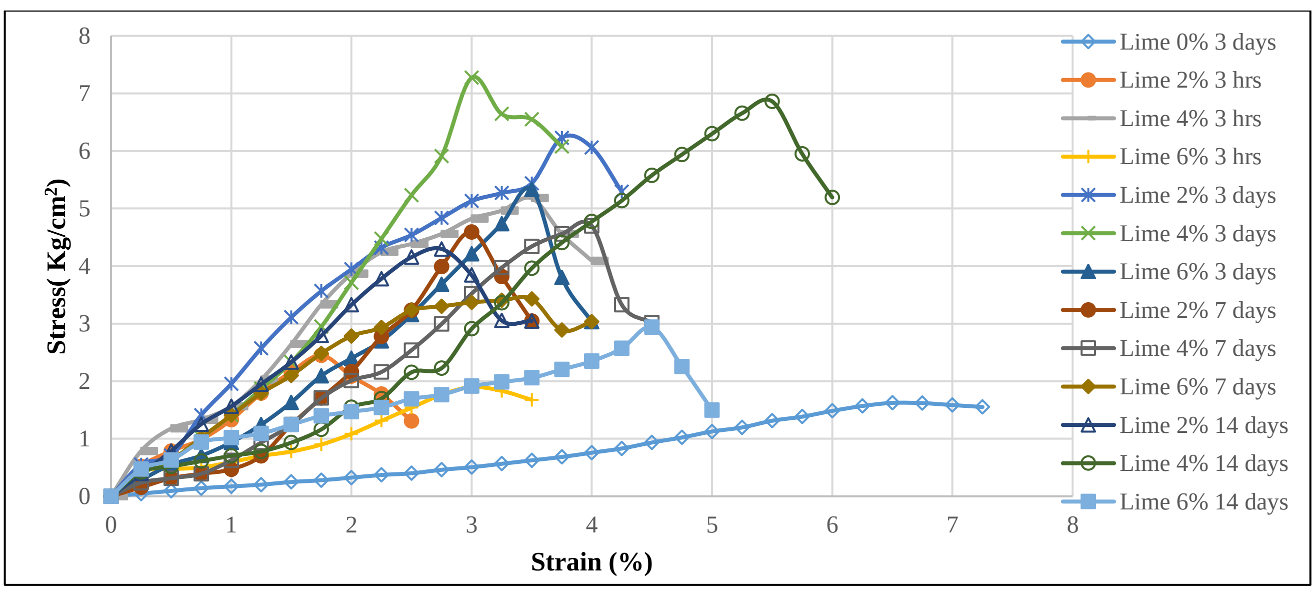


Figure 4-15, UCS soaked with Lime percentages

4.3.5 California Bearing Ratio of Treated Soil:

California Bearing Ratio tests in both soaked and unsoaked conditions were carried out on samples after 3 hrs, 3, 7 and 14 days curing periods. Soaked testing was carried out to assess the behavior of soil in moist condition. California bearing ratio and swell potential tests result for untreated and treated soil at various lime content are shown in table 4-13 and figure 4-16 , 4-17 and 4-18.

Table: 4-13, CBR Results Based on varying percentages of Lime/ Curing Periods

Curing Pds	**3 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**
% LIME	**0%**	**2%**				**4%**				**6%**			
CBR un-soaked	16	54	57	64.7	100	69	75	84	110	73	80	94	178
CBR soaked	6	33	40	48	48	36	41.3	47	57.8	18	47	57	103
Free swell	2.99	1.06	1.58	2.39	2.40	0.51	1.62	2.52	2.52	1.6	2.16	2.39	2.42

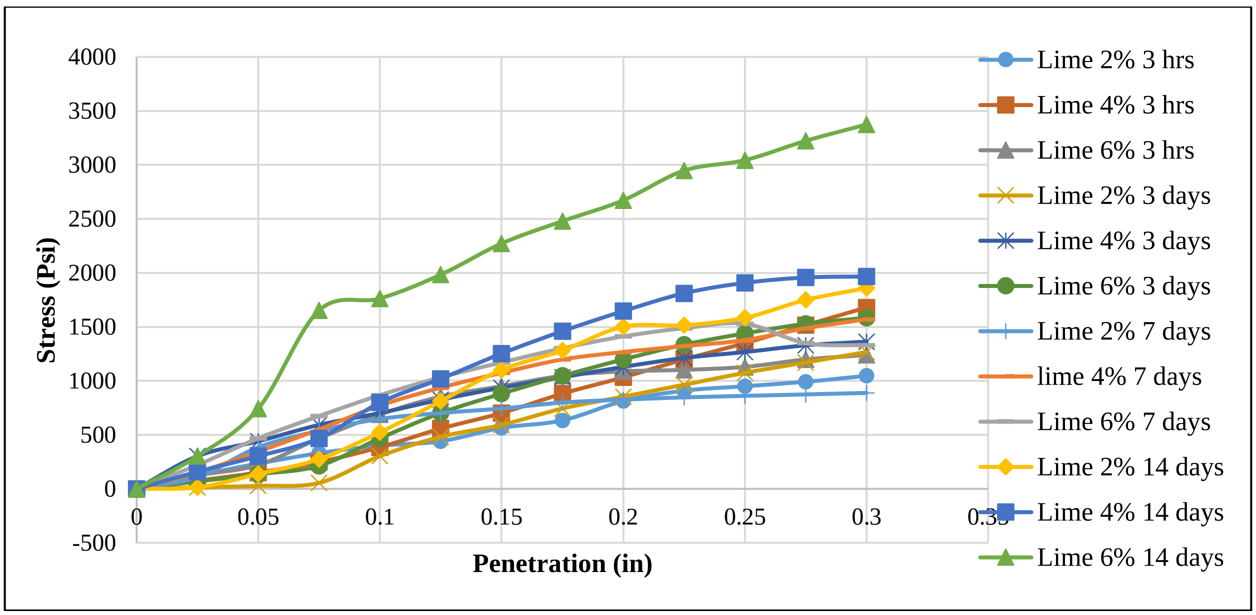


Figure 4-16, CBR unsoaked with Lime percentages

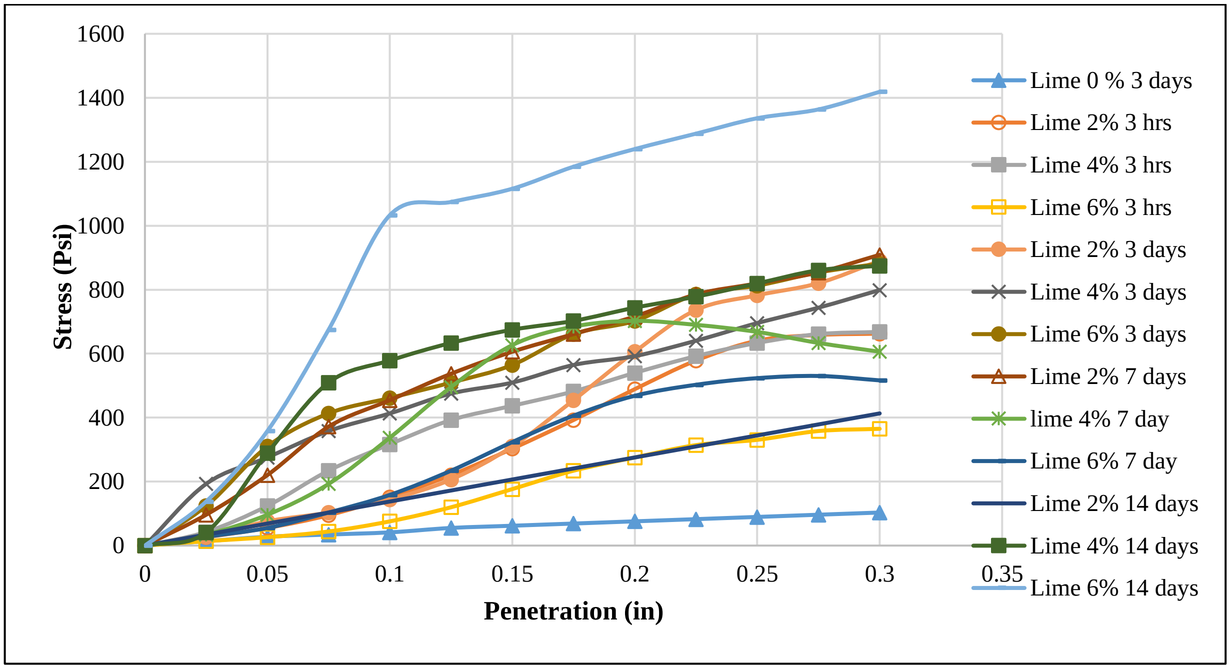


Figure 4-17, CBR soaked with Lime percentages

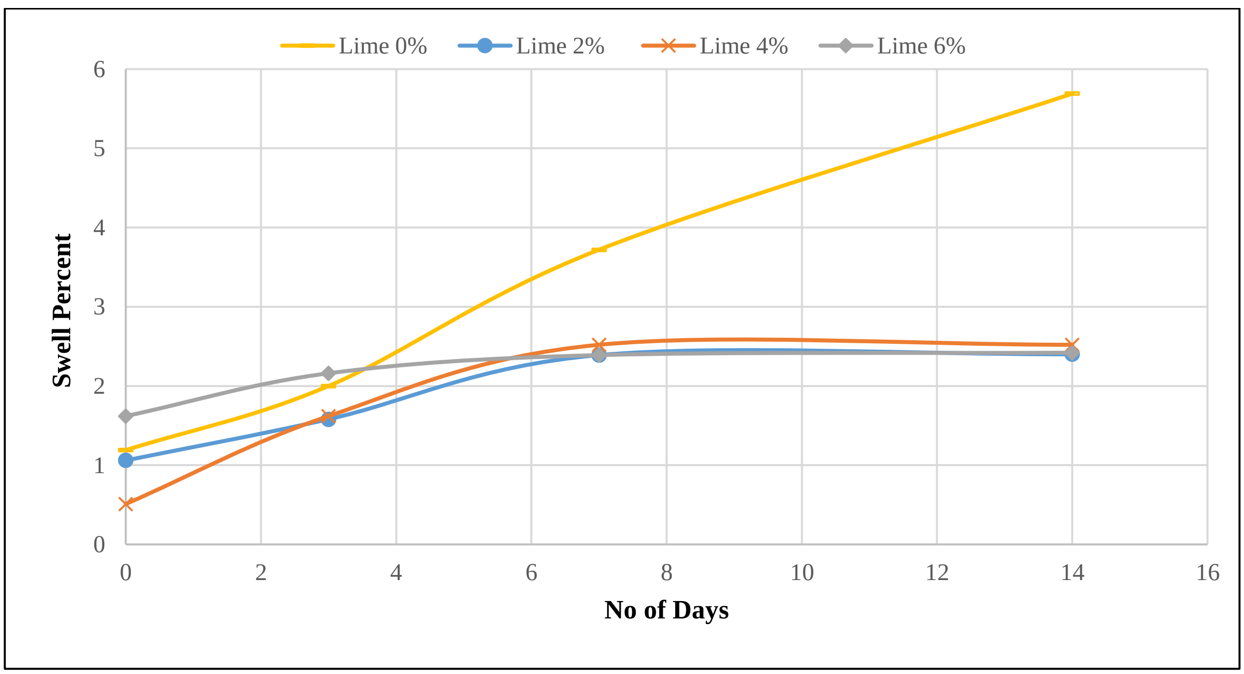


Figure 4-18, Swell Index with Lime percentages

4.4 Design of Experiment for Soaked and Unsoaked CBR

Statistical analysis method called experimental design combines substantial number of factors with goal of analyzing how they affect response variable. To ensure that independent elements are considered simultaneously and then their effects on response variable of Lab CBR are considered, the experimental method was adopted.

Two level factorial design for this study was created using the statistical programmed Minitab. Each factor has two level of values high or low. This study choses lab CBR as dependent variable, lime, curing period with condition of soaked / unsoaked as independent variables. These all-independent variables have been considered significant with this Minitab software having direct effect on strength of CBR values.

The low- and high-level values for soaked and unsoaked conditions are 0 and 1 respectively. The low-level value or minimum value for lime percent is 2 % and high-level value is 6%. Then low-level value for the curing duration is 0 day and high-level value is 14 days. The findings of the factorial design carried out in Minitab 21 software for main and interaction effects are displayed in Table below. Lab CBR increased with the portion of lime increased in soaked and unsoaked conditions.

Lab CBR of lime stabilized soil shows the outcome of variance ANOVA. It has also been noted that three factors Lime %, curing with no of days and soaked unsoaked conditions of clay are responsible to determine Lab CBR variation. A factors significance is determined by comparing its p value to 0.05 and factors F value more than 10. Since p value is less than 0.05 and F value is more than 10, it is seen that major influence is significant in statistical analysis.

Table 4-14, Analysis of Variance

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Model	7	54596.6	7799.5	7799.52	0.000
Linear	3	46117.1	15372.4	15372.38	0.000
s/us	1	15453.4	15453.4	15453.38	0.000
Lime	1	7038.4	7038.4	7038.38	0.000
Days	1	23625.4	23625.4	23625.38	0.000
2-Way Interactions	3	8434.1	2811.4	2811.38	0.000
s/us*Lime	1	1218.4	1218.4	1218.38	0.000
s/us*Days	1	975.4	975.4	975.38	0.000

Lime*Days	1	6240.4	6240.4	6240.38	0.000
3-Way Interactions	1	45.4	45.4	45.38	0.000
s/us*Lime*Days	1	45.4	45.4	45.38	0.000
Error	16	16.0	1.0		
Total	23	54612.6			

Three-way interaction of lime percent, curing and soaked / unsoaked conditions are marginally significant according to above Tables 4-14. This is due to the reason that F is minor and p value is not statically significant. The model is sound as its R square is 99.97%. The principal effect has degree of freedom of 3. A three-way interaction has one DOF and one or two interactions has DOF 3.

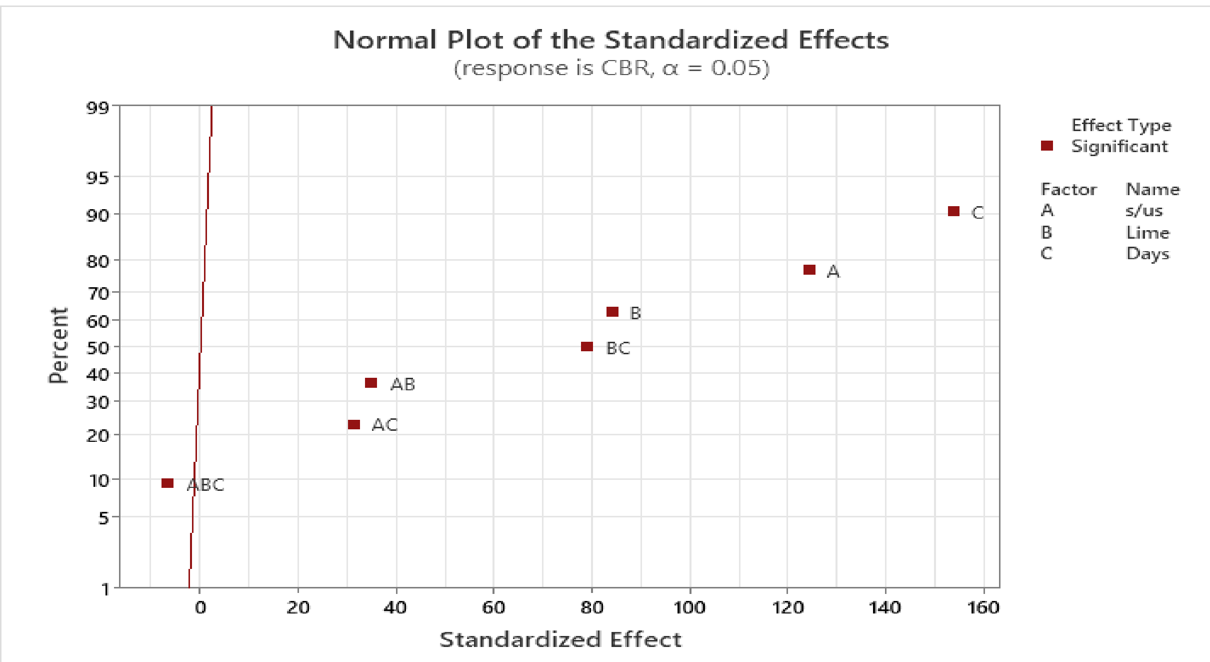


Figure 4-19, Normal Plot of Standardized Effects

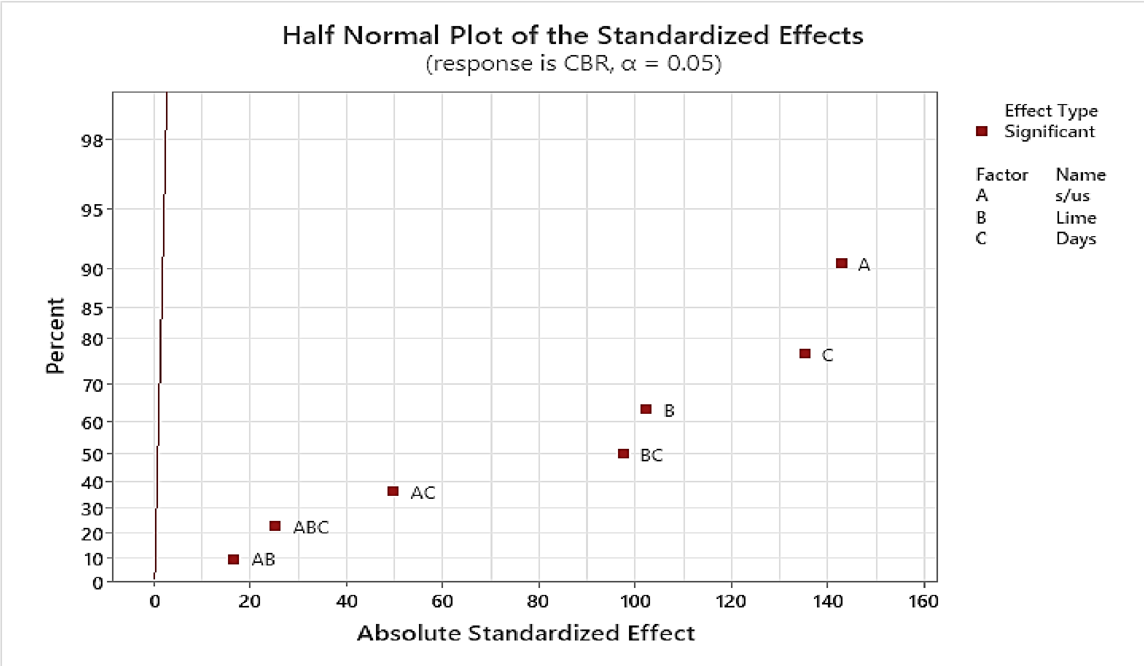


Figure 4-20, Half Normal Plot of Standardized Effects

The factors taken into account for a study of lime stabilized expansive soil are significant as shown in figures 4-19 and 4-20. The degree to which the Lab CBR is impacted by soaked /unsoaked state, lime concentration and curing time may be measured from distance away from red line. While percentage lime, soaked/ unsoaked conditions near red line and the combination of curing period, lime percent, and soaked/ unsoaked condition is on the negative side of the line that has an inverse relationship or least significant.

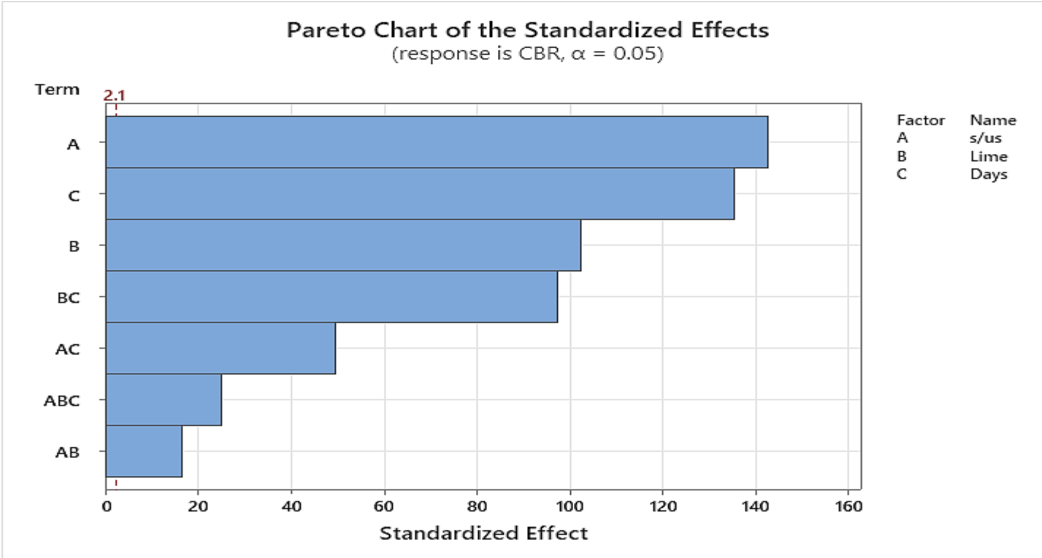


Figure 4-21, Pareto Chart for Standardized Effects

Figure 4-21 displays the chart of lime treated expansive soil and its effect on Lab CBR results. The Pareto figure shows the importance of variables and how they interact to affect results. The pareto chart also shows the significance of the factor effected relatively. The summation of factors for the mean response and the determined significance level which is 5% as well as 95% confidence interval for t critical value. This is known as standardized effect of each factor. The graphics include the reference red dot that indicates the importance of bars crossing it. Their bars crossed the t critical line as shown in figure 4-21 demonstrating that they have an impact on it. Each of these factors lime percent, curing period and soaked unsoaked condition affect the Lab CBR results.

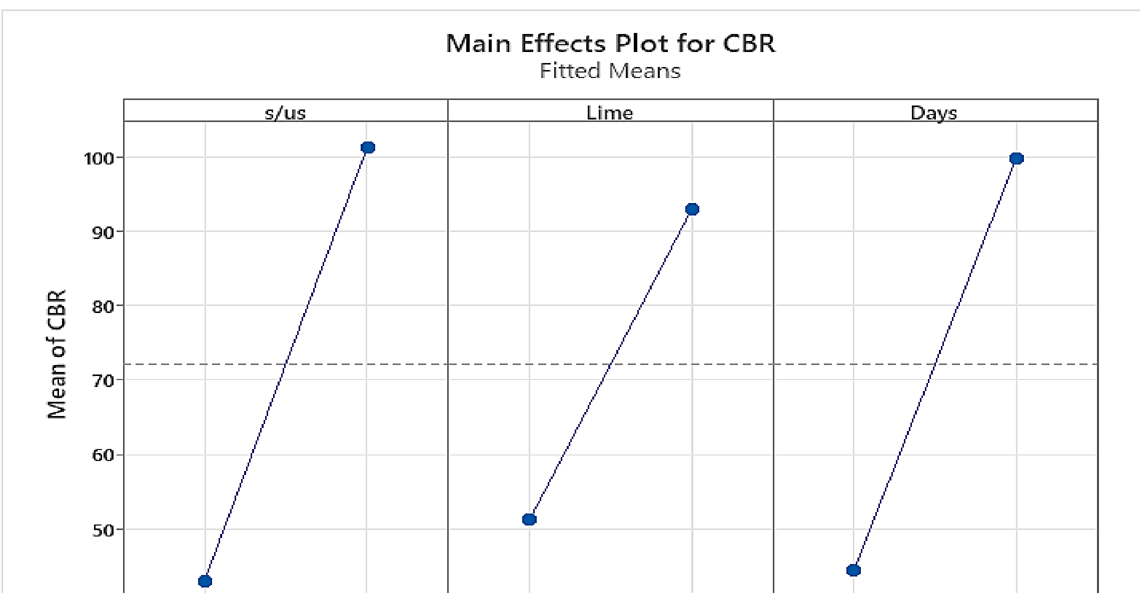


Figure 4-22, Main effects plot for CBR

Figure 4-22 shows the main effect of graphs of lime treated soil. It displays the steepness of the slope of the line denotes direct relationship with CBR and other independent variables. The major effect is drawn against both low- and high-level factors examined for the study. The line abrupt slope makes it obvious that state of being soaked or not is a key factor. Furthermore, percentage of lime and curing time have direct correlation with results and steep slope of line indicating higher relevance. The crisp line ascends indicating direct relationship between percentage lime, soaked/unsoaked condition and curing time for lab CBR results.

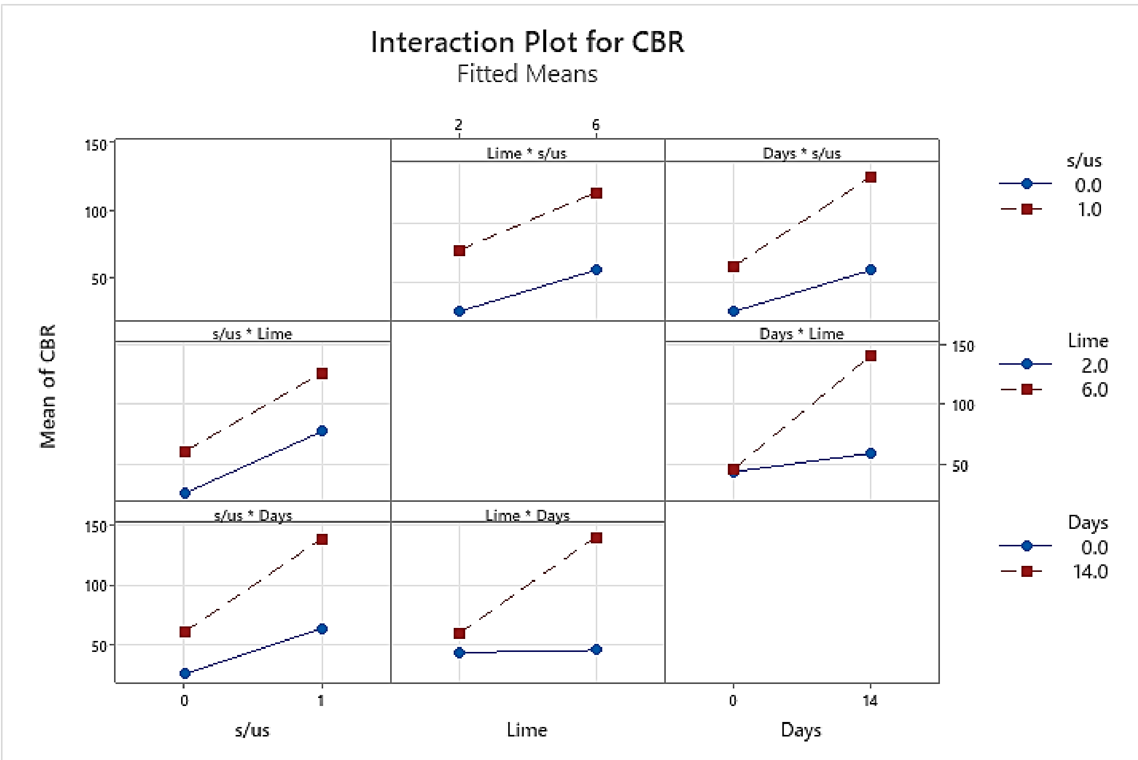


Figure 4-23, Interaction Plot for CBR

The interaction impact on the soil sample treated with lime in the lab is shown in figure 4-23. The impact of one component on both values of elements may be used to describe how two components interact for the mean response. A non-parallel line denotes the presence of substantial interaction between two factors denotes the significance of interaction. The interaction has significant impact because of steepness of slope. The above figures indicates that percent lime, soaked/unsoaked conditions and curing period have a significant impact on lab CBR results.

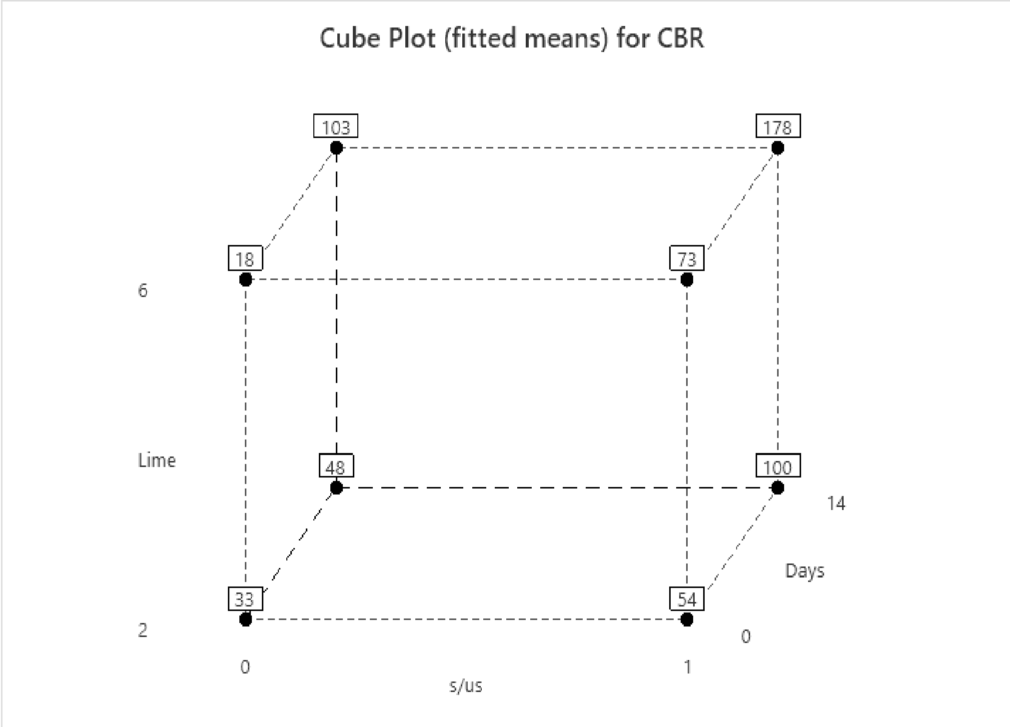


Figure 4-24, Cube Plot for CBR

The cube plot for the expansive soil sample treated with lime is shown in figure 4-24. The plot shows that that 6% lime for both soaked and unsoaked conditions with 14 days curing period gives highest strength. 6% lime for 0 day and 2% lime for 14 day curing period produces the lowest CBR results.

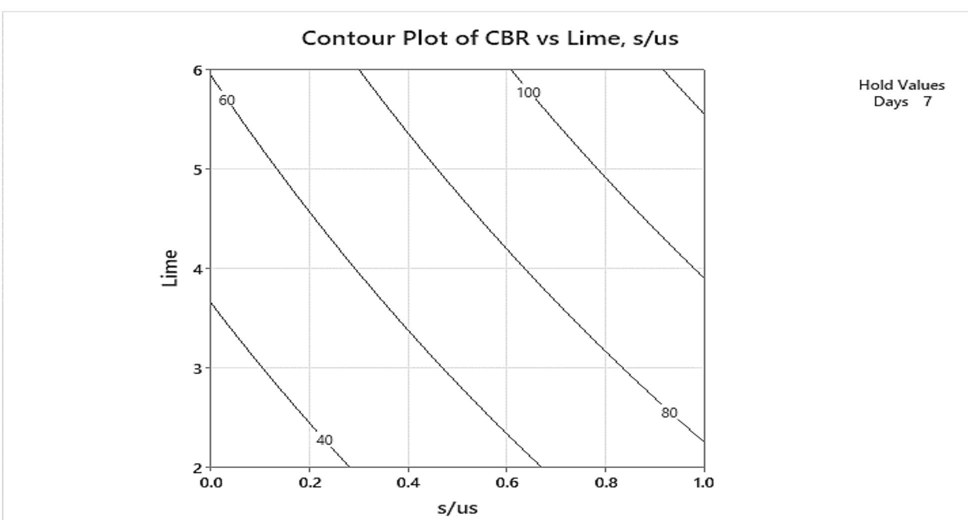


Figure 4-25, Contour Plot of CBR vs Lime, soaked/unsoaked

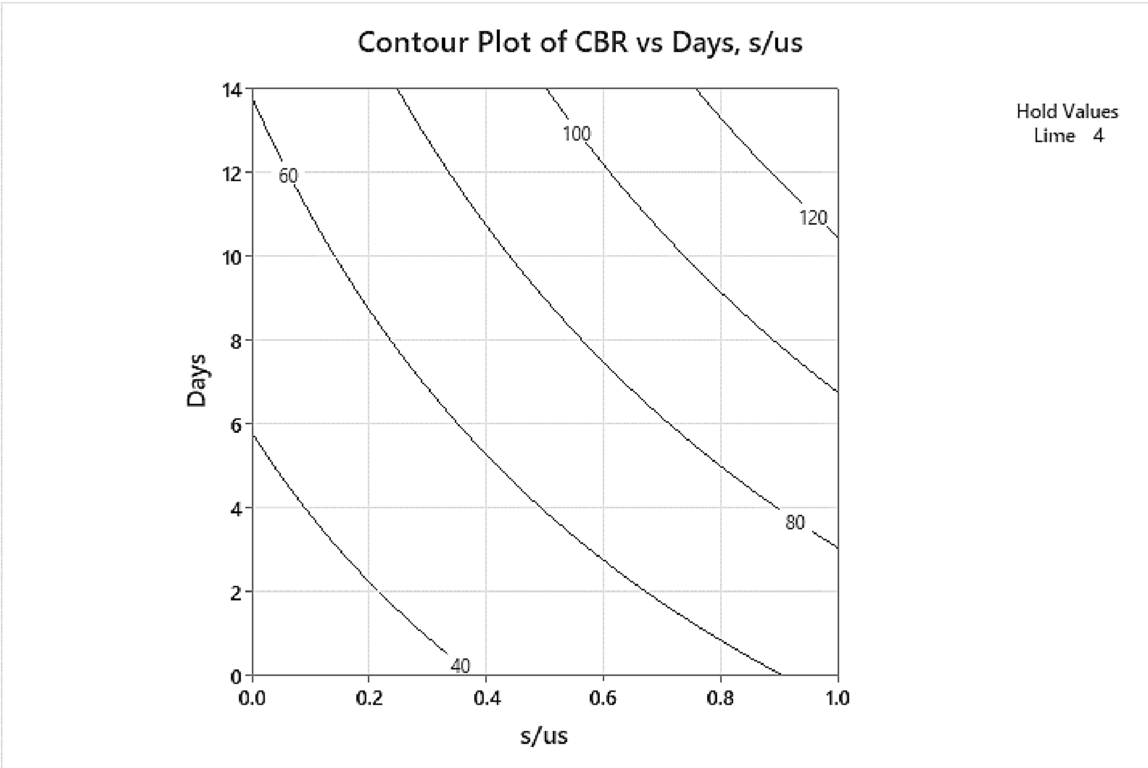


Figure 4-26, Contour Plot of CBR vs Days soaked and unsoaked

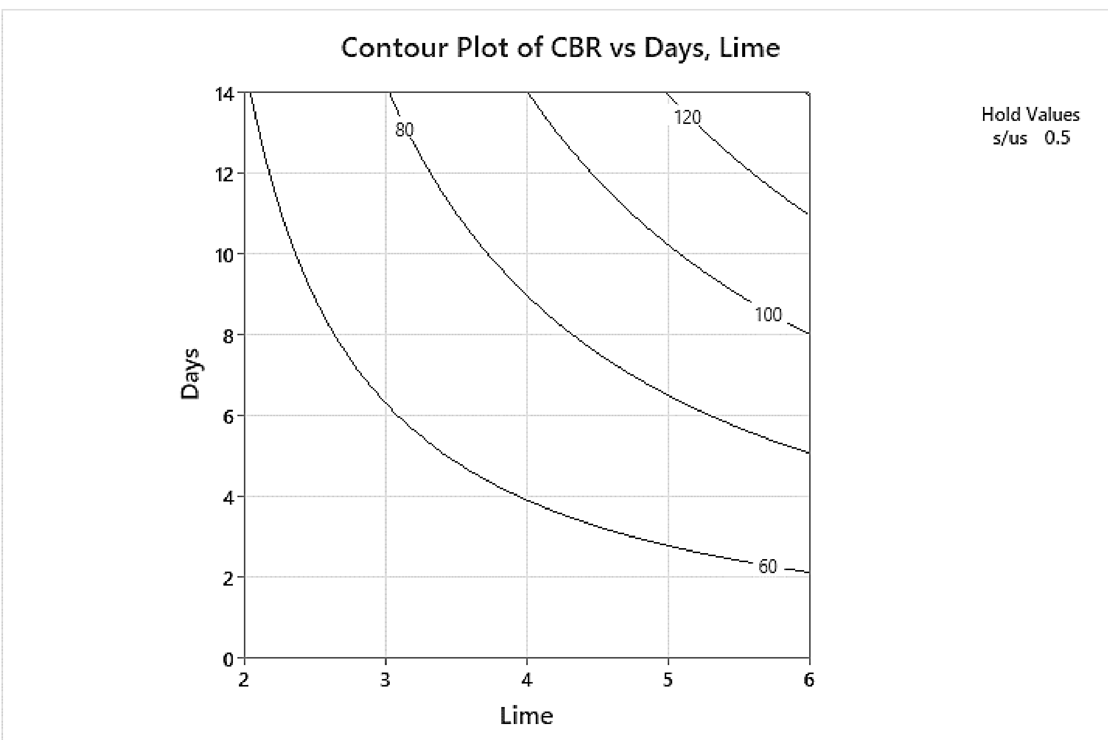


Figure 4-27, Contour Plot of CBR vs Days, Lime

Based on variety of factors, Lab CBR values are shown in figures 4-25, 4-26 and 4-27. It depicts the Lab CBR surface of expansive soil cured with lime with low and high percentages together with curing period. These numbers represent series of experiments with various percentage of lime and shows the reaction plot. The percentage increase of lime and curing time are both directly correlated with lab CBR soaked and unsoaked samples. These lines which can be seen as contour lines as topological map indicate the Lab CBR in the plot. The curve of the surface illustrates the relationship between the curing period and different levels of lime percentage.

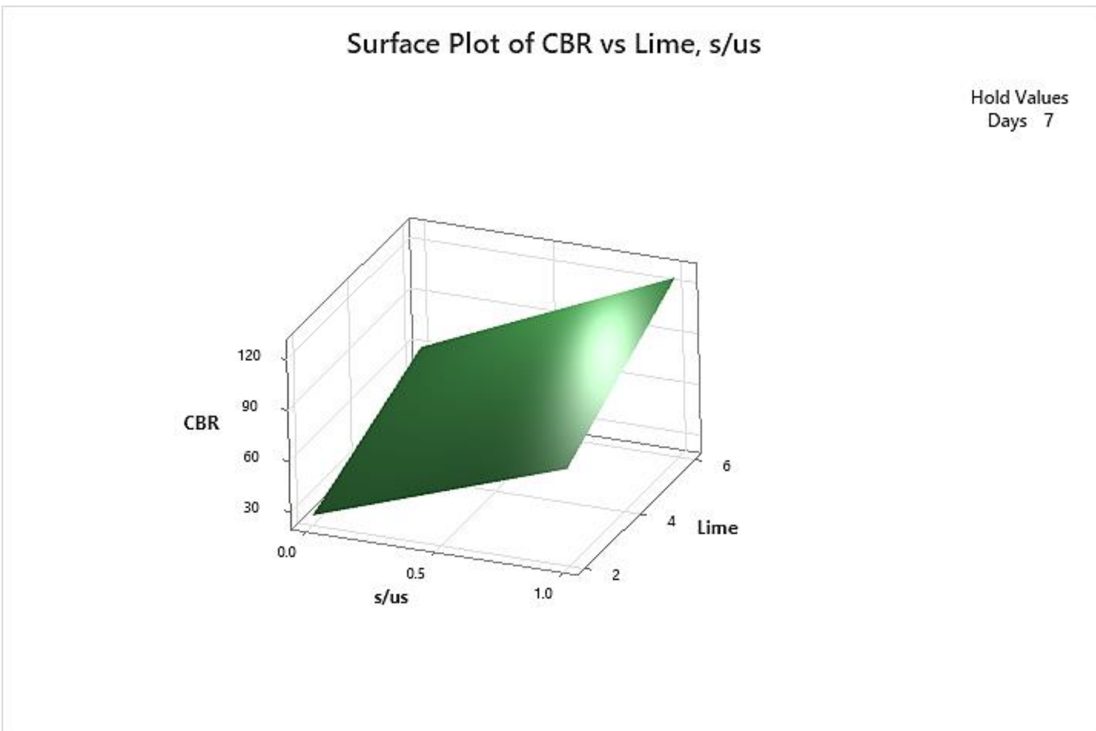


Figure 4-28, Surface Plot of CBR vs Lime soaked and unsoaked

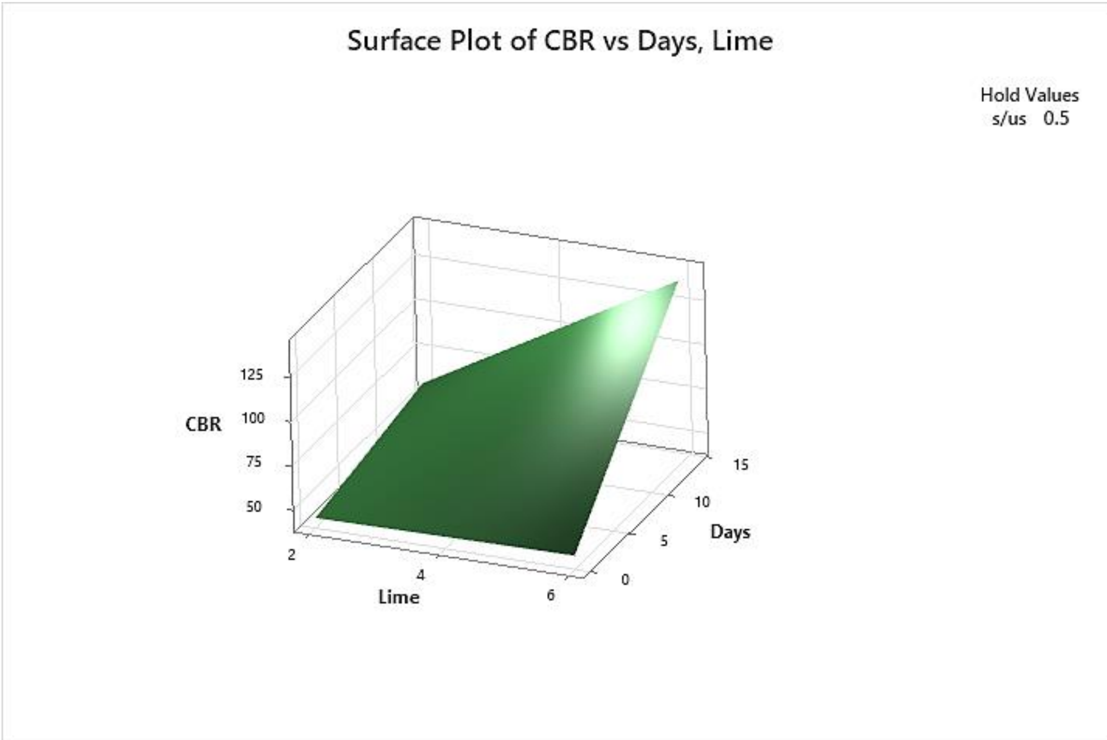


Figure 4-29, Surface Plot of CBR vs Days, Lime

A 3D depiction of the response variable, Lab CBR vs curing period and percent lime with soaked and unsoaked conditions of treated expansive soil sample is shown in figures 4-28 and 4-29. This plot shows that Lab CBR rises with curing time and lime percentage. Lab CBR may be anticipated by necessary curing time and lime percentage. It is feasible to determine the transitional and ideal values using this data.

4.4.1 Regression Analysis for CBR of Lime treated Expansive Soil.

Regression analysis of Lab CBR test data has been performed for different proportions of Lime, conditioning and curing time by considering CBR as response variable and percent Lime, conditioning, and curing time as predictors. The general form of regression model is as follow:

CBR = f (% Lime, Curing & Conditioning)

Where,

- CBR = Dependent Variable
- % Lime = Independent Variable
- Curing = Independent Variable
- Conditioning = Independent Variable

The regression equation for CBR data is presented below:

CBR = 40.500 + 4.00 s/us - 3.750 Lime - 1.4286 Days + 8.500 s/us*Lime + 2.607 s/us*Days + 1.2500 Lime*Days – 0.1964 s/us*Lime*Days

- CBR = Percentage
- Conditioning = Soaked or Unsoaked
- Lime = Percentage (2%, 4% & 6%)
- Curing = Days (0,3, 7 &14 days)

Table 4-15, T- Statistics

	Coefficient	**SE Coefficient**	**T-test**	**p Value**
Constant	72.125	0.204	353.34	0.000
Conditioning (A)	29.125	0.204	142.68	0.000
Lime (%) (B)	20.875	0.204	102.27	0.000
Curing (C)	27.625	0.204	135.33	0.000

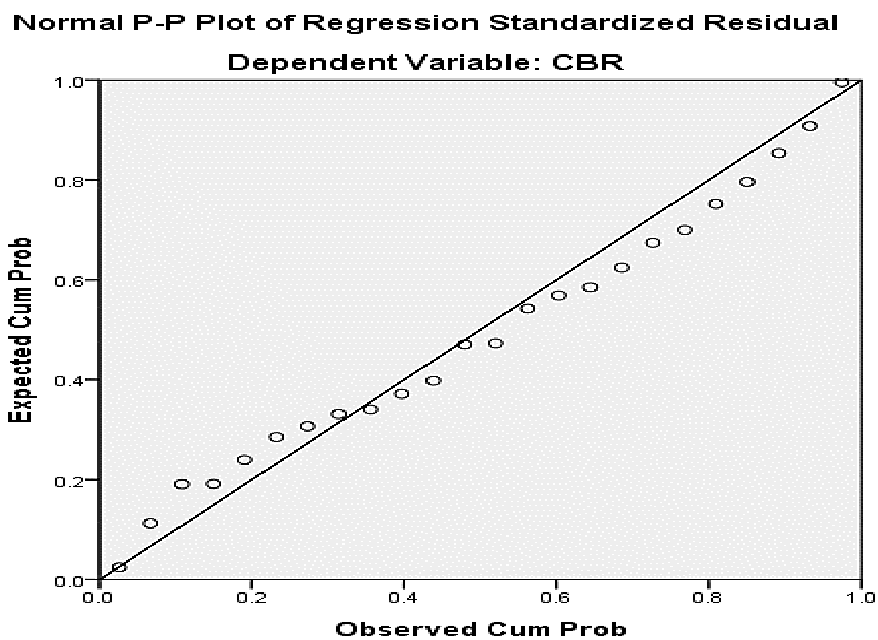


Figure 4-30, Normal plot of Regression standardized Residual

Table 4-16, Model Summary in SPSS Linear Regression

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.896[a]	.802	.773	15.9451	.802	27.06	3	20	.000

a. Predictors: (Constant), days, lime, sus

The value of R^2 for this model is 80.2% which is good. Figure 4-30 shows the normal probability plot of residuals, the normality assumption is satisfied because the plot resembles a straight line which shows that the errors are normally distributed. The observed versus predicted values were plotted as shown in figure above demonstrates the predictive capability of model. The model for which predicted data points were located close to the 100% validation line were considered the best predictive.

4.5 Field CBR and Plate load Tests of Treated Soils.

California Bearing Ratio and Plate load tests in moist field conditions were carried out on field specimen. Soaked testing was carried out to assess the behavior of soil in moist condition. Tests result for untreated and treated soil at optimum lime content are shown below in table 4-16, figure 4-31, 4-32 and 4-33.

Table: 4-17, Field Tests Results Based on varying percentages of Lime/ Curing Periods

Curing Period	**3 Hrs**	**3 Days**	**7 Days**	**14 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 days**
% LIME	**0%**				**4%**			
Field CBR (%)	2.1	2.07	1	1	2.4	3	4	7.58
Plat Load Test (Ton/ft^2)	0.7	0.60	0.58	0.50	0.98	1.2	1.3	1.31

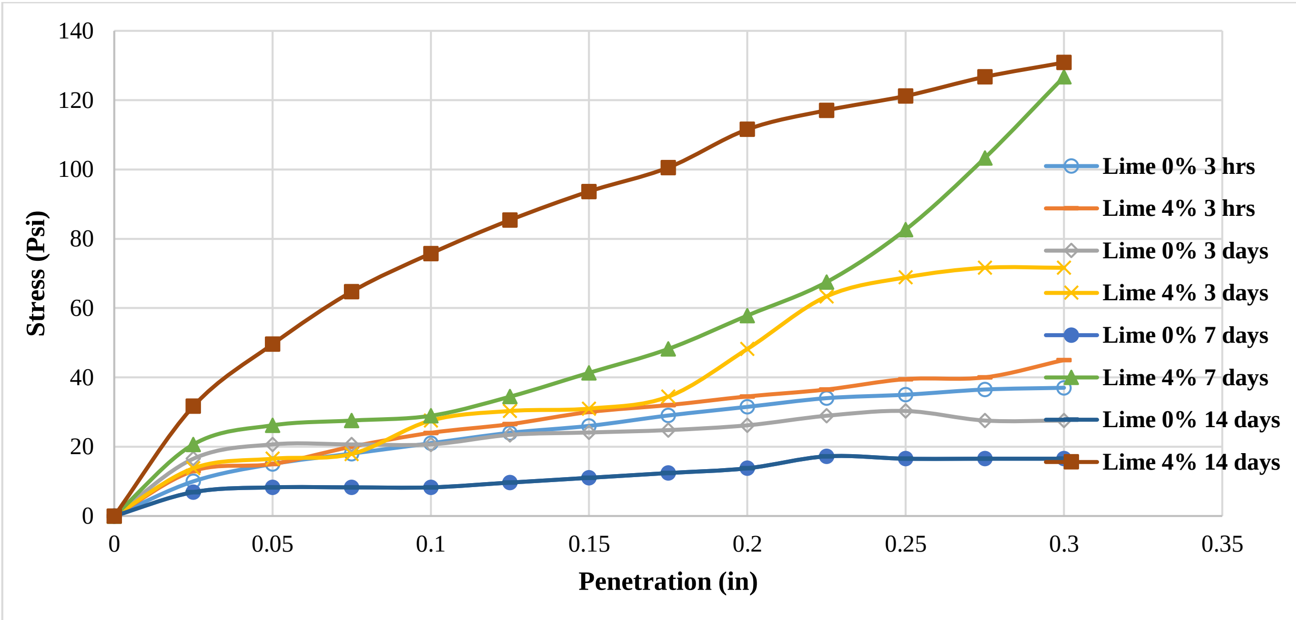


Figure 4-31, Field CBR-soaked values with Lime

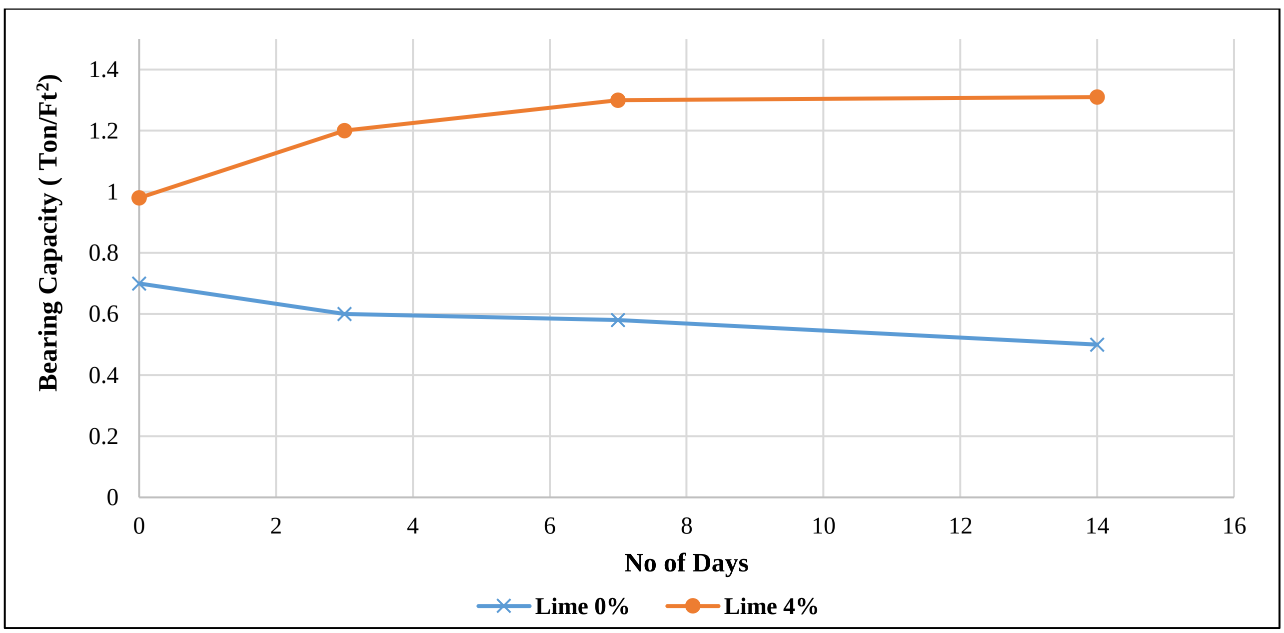


Figure 4-32, Plate Load Test Result with Lime

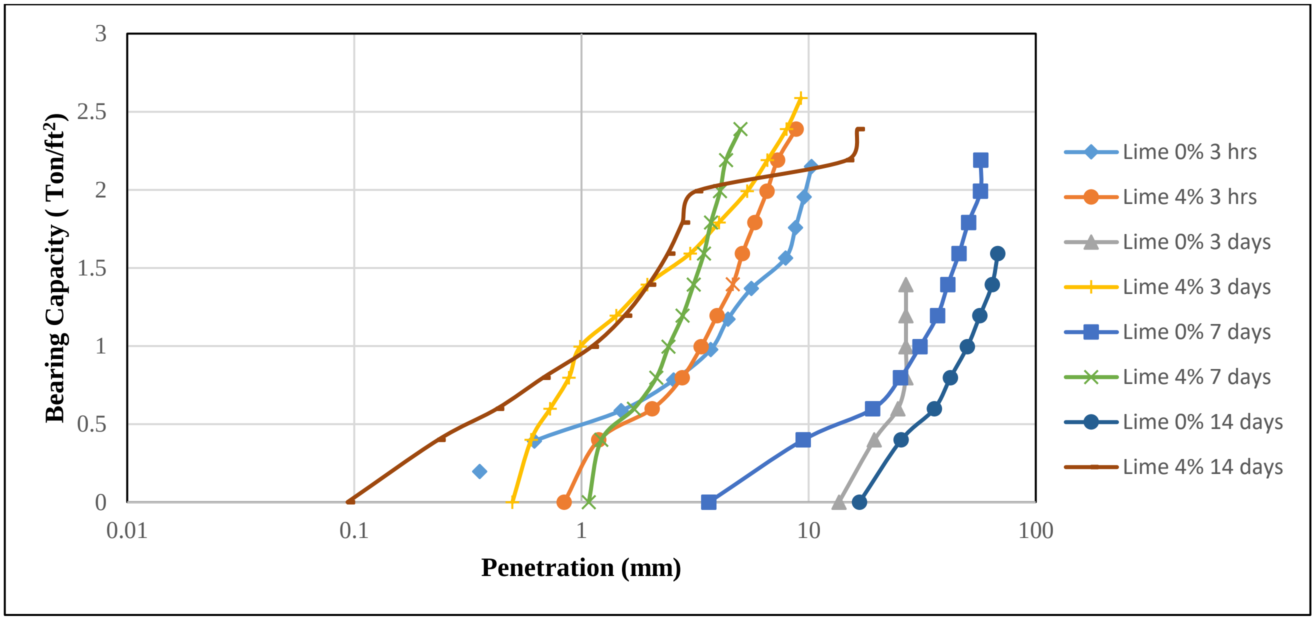


Figure 4-33, Plate load test result with Lime percentage

4.6 Direct Shear test of Treated Soil.

Direct Shear tests were carried out on samples after 3 hrs, 3, 7 and 14 days curing periods. Direct shear result for untreated and treated soil at optimum lime content are shown below in table 4-17 and figure 4-34.

Table: 4-18, DST Results Based on varying percentages of Lime/ Curing Periods

Curing Pds	**3 Days**	**3 Hrs**	**3 Days**	**7 Days**	**14 days**	**3 Hrs**	**3 Days**	**7 Days**	**14 days**	**3 Hrs**	**3 Days**	**7 Days**	**14 days**
% LIME	**0%**	**2%**				**4%**				**6%**			
Cohesion (Kpa)	4.63	0.84	0.78	0.54	1.04	1.04	0.71	0.87	0.01	2.31	0.07	0.01	2.03
Angle Of Friction (Degree)	45.9	43.92	43.43	43.29	43.1	43.11	43.7	43.17	43.5	42.16	43.53	43.52	42.3
Shear Stress (Kpa)	109.9	108	70.14	90.64	98.8	102.1	101.07	83.62	104	98.01	96.98	152.51	100

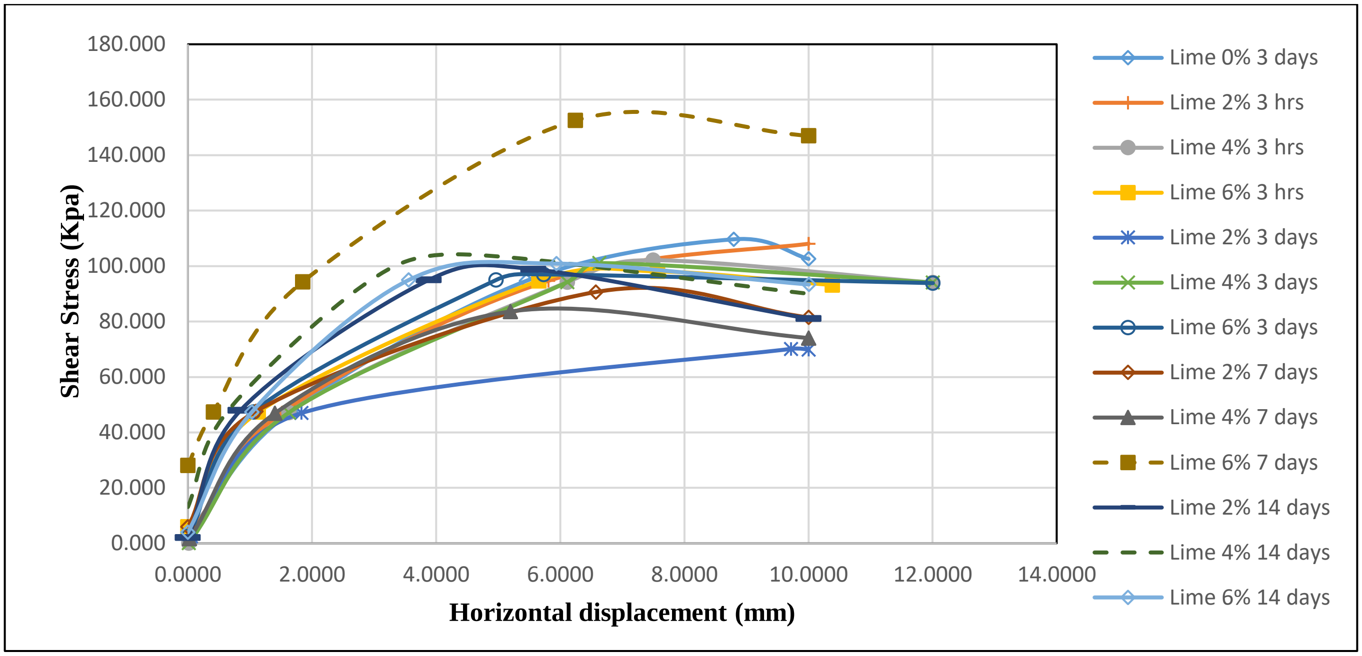


Figure 4-34, Direct shear test results with Lime percentages

Table: 4-19, Summary of Lime-Treated A-7-5 Soil Tests Results

Ser No.	Lab Tests	Min values at 0 %	Max Values at varying percentage of lime	Percentage Difference
1	Course Fraction (%)	8.3	12.5 (6%)	50.60 ↑
2	Fine fraction (%)	91.71	87.5 (6%)	↓ 4.59
3	Liquid limit (%)	55.1	32.0 (6%)	↓ 41.92
4	Plastic limit (&)	32.13	22.03 (6%)	↓ 31.43
5	Plasticity Index (%)	22.97	4.74 (4%)	↓ 79.36
6	Max Dry Density (pcf)	122.8	112.2 (4%)	↓ 8.63
7	Optimum Moisture Content (%)	11.4	12.9 (4%)	13.15 ↑
8	Specific Gravity	2.63	2.29 (2%)	↓ 12.92
9	Eades and Grim test (pH values)	9.64	11.98 (2%)	24.27 ↑
11	Unconfined Compressive strength test unsoaked(kg/cm^2)	1.75	13.57 (4%)	675.42 ↑
12	UCS soaked (kg/cm^2)	1.62	7.27 (4%)	348.76 ↑
12	CBR Unsoaked (%)	16	178 (6%)	1012.5 ↑
13	CBR soaked (%)	6	103 (6%)	1616.66 ↑
14	Free Swell index (%)	2.99	0.51 (4%)	↓ 82.94
15	Field CBR (%)	1	7.58 (4%)	658 ↑
16	Direct Shear test (Kpa)	109.8	152.51 (6%)	38.89 ↑
17	Plate load test Bearing capacity (Ton/ft^2)	0.5	1.31 (4%)	160 ↑

Table: 4-20, Summary of Lime-Treated A-7-5 Basic Soil Tests Results

LAB TESTS WITH LIME %		**0%**	**2%**	**4%**	**6%**
SIEVE ANALYSES	Coarse Fraction	8.3	10.6	11.8	12.5
	Fine Fraction	91.71	89.4	88.2	87.5
HYDROMETER ANALYSIS	Silt %	82.2	80.0	78.9	78.5
	Clay %	9.50	9.44	9.38	9.06
LIQUID LIMIT		55.1	45.1	37.01	32
PLASTICITY LIMIT		32.13	30.0	32.27	22.03
PLASTICITY INDEX		22.97	15.10	4.74	9.97
MDD (pcf)		122.8	114.7	112.2	115.5
OMC (%)		11.4	12.6	12.9	9.8
SPECIFIC GRAVITY		2.63	2.29	2.49	2.44
IMPROVED SOIL CLASSIFICATION	**(AASHTO)** **(USCS)**	A-7-5 CH	A-7-5 CL	A-4 CL-ML	A-4 CL

Table: 4-21, Validation of Research with Literature Results

Ser No.	**Tests**	**Literature inc/dec (%)**	**Research inc/dec (%)**	**Author/ Journal**
1	Plasticity Index	↓ 73.69	↓ 79.36	Dallas N Little 2000 National Lime Asso-ciation
2	Max Dry Density	↓ 8.60	↓ 8.63	Hesham A.H Ismaiel etal 2013 Geo Sciences
3	Optimum Moisture Content	↑ 13.6	↑ 13.15	Asmaa Al-Taie,2021 Procedia Engg
4	Unconfined Compressive strength	↑ 3.54 times	↑ 3.48 times	L.K. Sharma etal , 2018 Applied clay sciences
6	CBR strength	↑ 18 times	↑ 16.6 times	Aydm Kavak etal 2007 Environ Geol
9	Plate load settlement	↓ 76.0	↓ 75.91	Aydm Kavak etal 2007 Environ Geol

4.7 Summary

In this chapter, detailed results and discussions were presented. The results of all lab experiments carried out are presented with the help of graphs. The curves showing trend and effect of lime on clay soil are discussed in detail.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

Experimental study concludes a **significant decrease in Atterberg's limit (**plasticity index **reduced by 79.96 %)** of soil by lime modification. Classification of soil changed from AASHTO **A-7-5 soil to A-4** soil and its behavior from **clayey to silty** soil, thus improving its trafficability class. In the light of the results obtained, it can be concluded that 4% lime can be efficiently used for improvement of weak subgrade (clayey) soils of the area of study.

5.2 Conclusions

- Significant improvement of UCS of soil in soaked and unsoaked condition with the use of lime. There was **675.42 % increase in unsoaked UCS and 348.76% in soaked condition with 4% lime**. This improvement in strength is due to cat-ionic exchange, flocculation agglomeration and pozzolanic reactions between soil and lime.
- The **loss of strength in untreated soaked and unsoaked UCS soil sample is 0.13 kg/cm^2** whereas after optimum lime content addition, **max loss of strength between soaked and unsoaked is 6.30 kg/cm^2.**
- **Plasticity index** reduced to **80% with increase of lime content**. This change is associated with the flocculation and agglomeration of soil particles. Classification of soil changed from **AASHTO A-7-5 soil to A-4 soil. Soil behavior changed from clayey to silty soil.**
- **MDD of the treated soil decreased by 7.88% after using lime and OMC value increased by 13.15%**. Decrease in dry density is due to flocculation of soil particles. While the rise in optimum moisture content indicates decrease in soil moisture susceptibility.
- In the light of the results obtained, it can be concluded that 4% lime can be

efficiently used for improvement of weak subgrade (clayey) soils.

The results achieved from the experimental work can be useful in gaining a good understanding of the performance of Lime soil improved subgrade and mechanism of Lime reaction with soil.

5.3 Recommendations

- It is recommended to determine strength parameters such as **cohesion, internal angle of friction and shear strength with triaxial test** as well**.**
- **Field investigations** should be carried out to implement the findings of research. Trial sections can be planned in coordination with **HQ Engrs 30 Corps and NHA.**

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Appendix - I

SOIL-LIME STABILIZATION PROCEDURE

Wide range of soil modification techniques; including but not limited to geo-synthetics, geo-grids and pozzolanic additives (lime, fly ash, bagasse ash etc) are reported in literature for soil improvement/ stabilization with varying degree of success. However, various research studies have found lime outperforms all other modifiers for clayey soils, thus making it a preferred choice for our study to treat A-7-5, Clay, being the most problematic soil found in the study area.

Identification/ selection of tracks/ routes with poor/ weak being capacity/ trafficability of lime treatment for trials. The method of mixing lime into soil for stabilization is enumerated in following steps:

- **Soil Preparation**. The soil which needs stabilization is *scarified and pulverized* by suitable plough/ grader upto a depth of 25–35 cm with removal of larger than 3 inches material i.e., roots, aggregates etc.
- **Addition of Lime**. *Add 3-5% lime* to the pulverized soil either in powder form (wet soils) or in the form of slurry (dry soils) and mix using disc plough/ grader. If lime powder is used, water should be sprayed before mixing to achieve a moist soil-lime mix, closer to (OMC ~ 15%).
- **Leveling & Compaction**. Spread/ level the soil to require grade and compact it using rollers. compaction should get required maximum dry density, preferably >95%.
- **Curing**. The compacted lime-soil layer is allowed for moist curing for one week if time & situation permits.
- Testing (desirable). In-situ Bearing capacity can be measured using field CBR test.

Appendix - II

DIRECT SHEAR TEST RESULTS WITH 2% LIME AT 3 HOURS

		Peak Point	1.0921	10.0028	108.067
Elapsed Time (min.)	Horizontal Load (N)	Vertical Load (N)	Vertical Disp. (mm)	Horizontal Disp. (mm)	Shear Stress (kPa)
0.00	6.73	284.15	0.0000	0.0000	2.125
0.05	7.67	314.40	0.0071	0.0109	2.423
0.10	8.22	316.23	0.0040	0.0244	2.595
0.15	7.43	316.32	0.0025	0.0366	2.347
0.20	8.86	316.23	0.0043	0.0502	2.799
0.25	16.44	315.11	0.0072	0.0623	5.191
0.30	19.26	315.40	0.0106	0.0757	6.080
0.35	21.46	315.10	0.0132	0.0890	6.776
0.40	22.83	315.73	0.0076	0.1023	7.210
0.45	24.35	315.75	0.0087	0.1158	7.690
0.52	25.93	315.53	0.0165	0.1281	8.187
0.57	28.79	315.74	0.0330	0.1415	9.090
0.62	30.73	316.02	0.0306	0.1549	9.705
0.67	31.36	317.19	0.0287	0.1683	9.901
0.72	36.86	316.28	0.0331	0.1816	11.638
0.77	42.14	314.95	0.0294	0.1951	13.307
0.82	45.29	316.40	0.0383	0.2084	14.301
0.87	48.39	315.33	0.0411	0.2207	15.278
0.92	50.27	315.12	0.0442	0.2343	15.872
0.97	51.82	315.66	0.0548	0.2464	16.361
1.03	53.47	315.07	0.0690	0.2598	16.883
1.08	54.96	315.77	0.0709	0.2732	17.353
1.13	56.41	315.89	0.0818	0.2854	17.811
1.18	58.04	315.57	0.0914	0.2988	18.327
1.23	59.60	317.01	0.0919	0.3121	18.819
1.28	60.01	315.16	0.0992	0.3255	18.950
1.33	60.96	315.84	0.1032	0.3390	19.250
1.40	62.83	316.17	0.1073	0.3524	19.840
1.45	63.16	315.25	0.1115	0.3659	19.944
1.50	64.68	316.27	0.1156	0.3782	20.424
1.55	66.10	315.99	0.1195	0.3917	20.872
1.60	67.26	315.42	0.1316	0.4050	21.238
1.65	68.29	315.67	0.1400	0.4183	21.565
1.70	69.54	315.38	0.1468	0.4318	21.957
1.75	71.28	314.51	0.1564	0.4453	22.509
1.82	72.27	316.91	0.1553	0.4588	22.819
1.87	72.70	315.99	0.1623	0.4722	22.957
1.92	74.80	317.36	0.1764	0.4845	23.618
1.97	74.78	316.28	0.1833	0.4981	23.614
2.02	76.30	315.94	0.1927	0.5101	24.091

Elapsed Time (min.)	Horizontal Load (N)	Vertical Load (N)	Vertical Disp. (mm)	Horizontal Disp. (mm)	Shear Stress (kPa)
2.07	77.42	315.99	0.1959	0.5236	24.447
2.12	78.19	315.41	0.2010	0.5371	24.689
2.17	79.34	315.78	0.2091	0.5504	25.052
2.22	80.77	315.39	0.2127	0.5639	25.504
2.28	81.98	316.03	0.2270	0.5773	25.886
2.33	83.42	319.53	0.2270	0.5908	26.343
2.38	84.04	316.57	0.2332	0.6030	26.538
2.43	85.25	316.71	0.2376	0.6164	26.920
2.48	86.53	316.44	0.2435	0.6297	27.324
2.53	87.21	317.03	0.2510	0.6430	27.538
2.58	88.21	316.12	0.2514	0.6563	27.853
2.63	88.98	315.87	0.2531	0.6696	28.095
2.80	91.63	314.78	0.2786	0.7080	28.934
2.95	95.03	315.63	0.2840	0.7465	30.006
3.10	97.78	315.72	0.3021	0.7847	30.875
3.25	100.70	316.20	0.3177	0.8231	31.796
3.40	104.44	317.08	0.3284	0.8614	32.979
3.55	108.04	316.53	0.3418	0.8997	34.116
3.70	111.75	316.03	0.3504	0.9382	35.286
3.85	114.73	317.20	0.3713	0.9765	36.227
4.00	117.06	316.42	0.3750	1.0150	36.964
4.15	120.18	316.72	0.3835	1.0534	37.949
4.30	123.08	316.52	0.3968	1.0918	38.865
4.45	125.78	316.94	0.4131	1.1303	39.716
4.60	127.88	316.91	0.4345	1.1691	40.378
4.75	130.90	317.66	0.4526	1.2074	41.334
4.92	133.86	317.57	0.4512	1.2457	42.269
5.07	135.10	316.28	0.4608	1.2843	42.660
5.22	138.06	316.61	0.4746	1.3230	43.594
5.37	140.34	316.53	0.4817	1.3628	44.314
5.52	142.99	319.27	0.4955	1.3998	45.151
5.67	144.76	316.04	0.4945	1.4383	45.710
5.82	147.22	317.23	0.4970	1.4766	46.488
5.97	149.16	316.87	0.4955	1.5148	47.100
6.12	151.69	317.42	0.5120	1.5532	47.899
6.27	153.29	317.45	0.5216	1.5917	48.404
6.42	154.96	316.87	0.5283	1.6301	48.931
6.57	157.24	316.82	0.5449	1.6686	49.651
6.73	159.66	316.85	0.5515	1.7072	50.414
6.88	161.55	316.88	0.5807	1.7453	51.011
7.03	162.99	317.33	0.5849	1.7837	51.467
7.18	165.39	317.41	0.5887	1.8220	52.225
7.33	166.79	316.49	0.5917	1.8604	52.667
7.48	168.74	317.10	0.5945	1.8989	53.283
7.63	170.89	316.80	0.5988	1.9372	53.962
7.78	173.11	316.98	0.5972	1.9757	54.663
7.93	174.70	317.15	0.6143	2.0140	55.165

Elapsed Time (min.)	Horizontal Load (N)	Vertical Load (N)	Vertical Disp. (mm)	Horizontal Disp. (mm)	Shear Stress (kPa)
8.08	175.98	316.93	0.6130	2.0526	55.568
8.23	177.84	316.12	0.6220	2.0911	56.156
8.38	180.14	317.24	0.6351	2.1296	56.881
8.53	181.02	316.60	0.6507	2.1679	57.160
8.70	182.89	316.68	0.6587	2.2067	57.749
8.85	181.57	316.85	0.6677	2.2450	57.335
9.00	185.74	316.67	0.6649	2.2834	58.651
9.15	187.68	316.68	0.6775	2.3217	59.263
9.30	189.23	316.73	0.6826	2.3603	59.754
9.45	190.62	317.14	0.6848	2.3988	60.191
9.60	192.36	316.55	0.6931	2.4372	60.741
9.75	194.27	316.47	0.7024	2.4760	61.345
9.90	195.97	317.00	0.7071	2.5144	61.882
10.05	197.21	316.83	0.7246	2.5528	62.272
10.20	198.89	315.49	0.7226	2.5911	62.802
10.50	201.63	317.37	0.7439	2.6679	63.668
10.80	203.74	316.69	0.7404	2.7447	64.335
11.12	206.72	316.22	0.7562	2.8219	65.275
11.42	209.43	316.20	0.7689	2.8968	66.129
11.72	212.13	316.09	0.7730	2.9734	66.983
12.02	214.59	316.29	0.7821	3.0498	67.761
12.32	217.46	317.12	0.7982	3.1264	68.667
12.62	220.61	316.44	0.8104	3.2032	69.661
12.92	223.72	316.37	0.8154	3.2802	70.643
13.22	225.69	315.82	0.8328	3.3574	71.264
13.52	229.11	316.46	0.8372	3.4330	72.346
13.82	232.17	316.91	0.8472	3.5097	73.312
14.12	234.32	316.94	0.8689	3.5865	73.991
14.42	237.41	316.71	0.8830	3.6629	74.967
14.73	240.38	316.56	0.8908	3.7396	75.903
15.03	242.83	316.81	0.8975	3.8165	76.678
15.33	245.24	316.72	0.9030	3.8934	77.436
15.63	247.28	316.36	0.9273	3.9698	78.084
15.93	250.48	316.83	0.9146	4.0466	79.092
16.23	253.21	316.83	0.9285	4.1232	79.953
16.53	255.22	316.19	0.9352	4.2002	80.590
16.83	258.16	316.45	0.9445	4.2774	81.518
17.13	260.57	316.41	0.9578	4.3525	82.279
17.45	262.42	316.85	0.9590	4.4294	82.862
17.75	265.43	317.04	0.9746	4.5062	83.814
18.05	267.72	316.78	0.9857	4.5828	84.536
18.35	269.59	317.04	1.0024	4.6597	85.127
18.65	272.49	316.86	1.0094	4.7367	86.042
18.95	275.21	317.02	1.0156	4.8138	86.900
19.25	277.04	316.32	1.0231	4.8892	87.479
19.55	278.82	317.15	1.0178	4.9662	88.040
19.85	281.53	317.06	1.0187	5.0430	88.896

Elapsed Time (min.)	Horizontal Load (N)	Vertical Load (N)	Vertical Disp. (mm)	Horizontal Disp. (mm)	Shear Stress (kPa)
20.17	283.32	316.95	1.0224	5.1196	89.461
20.47	285.60	317.20	1.0250	5.1965	90.181
20.77	287.63	316.91	1.0338	5.2731	90.822
21.07	289.44	317.32	1.0309	5.3501	91.394
21.37	291.02	316.78	1.0314	5.4270	91.895
21.67	293.15	317.19	1.0367	5.5039	92.566
21.97	294.67	316.68	1.0432	5.5807	93.046
22.28	296.18	317.02	1.0384	5.6570	93.524
22.58	297.83	316.77	1.0434	5.7340	94.044
22.88	299.89	317.23	1.0522	5.8099	94.694
23.18	301.25	316.95	1.0553	5.8866	95.125
23.48	302.48	316.68	1.0556	5.9634	95.513
23.78	304.08	316.78	1.0628	6.0404	96.019
24.08	305.59	316.87	1.0591	6.1171	96.493
24.38	306.90	317.03	1.0550	6.1938	96.909
24.68	308.16	316.83	1.0582	6.2708	97.306
24.98	309.16	316.85	1.0691	6.3464	97.623
25.30	310.40	316.76	1.0623	6.4232	98.013
25.60	311.74	317.04	1.0697	6.5002	98.436
25.90	312.88	316.70	1.0637	6.5771	98.795
26.20	313.91	316.91	1.0724	6.6538	99.122
26.50	315.65	316.97	1.0745	6.7308	99.670
26.80	316.73	316.65	1.0722	6.8075	100.012
27.10	317.68	316.87	1.0795	6.8843	100.312
27.42	318.97	316.91	1.0834	6.9611	100.719
27.72	319.91	316.83	1.0824	7.0382	101.016
28.02	320.75	316.69	1.0860	7.1135	101.282
28.32	321.71	316.73	1.0790	7.1905	101.583
28.62	323.12	316.78	1.0857	7.2676	102.030
28.92	323.97	316.85	1.0786	7.3447	102.299
29.22	324.59	316.65	1.0838	7.4219	102.495
29.52	325.66	316.63	1.0852	7.4976	102.832
29.82	326.88	316.80	1.0876	7.5743	103.216
30.12	327.41	316.78	1.0874	7.6517	103.384
30.43	328.20	316.66	1.0855	7.7272	103.633
30.73	328.80	316.44	1.0902	7.8044	103.822
31.03	329.76	316.95	1.0841	7.8800	104.126
31.33	330.73	317.35	1.0927	7.9569	104.432
31.63	331.35	316.70	1.0871	8.0341	104.629
31.93	331.65	317.04	1.0916	8.1110	104.723
32.23	332.26	317.11	1.0886	8.1876	104.915
32.53	332.70	317.11	1.0878	8.2644	105.054
32.85	332.95	316.68	1.0877	8.3412	105.135
33.15	333.46	316.83	1.0952	8.4179	105.294
33.45	334.35	316.41	1.0903	8.4943	105.574
33.75	334.41	316.64	1.0899	8.5712	105.594
34.05	334.83	316.80	1.0902	8.6484	105.727

Elapsed Time (min.)	Horizontal Load (N)	Vertical Load (N)	Vertical Disp. (mm)	Horizontal Disp. (mm)	Shear Stress (kPa)
34.35	335.16	316.42	1.0943	8.7256	105.831
34.65	335.93	316.69	1.0853	8.8005	106.075
34.95	335.96	316.57	1.0940	8.8776	106.084
35.25	336.82	316.99	1.0907	8.9533	106.356
35.55	337.35	317.08	1.0885	9.0304	106.522
35.85	337.59	316.70	1.0931	9.1059	106.600
36.15	337.82	316.63	1.0920	9.1828	106.670
36.45	337.93	316.45	1.0825	9.2599	106.706
36.75	338.62	316.61	1.0864	9.3369	106.924
37.07	339.18	316.68	1.0906	9.4121	107.101
37.37	339.68	316.84	1.0856	9.4890	107.259
37.67	339.55	316.06	1.0841	9.5659	107.217
37.97	339.66	316.53	1.0898	9.6425	107.254
38.27	340.40	316.66	1.0878	9.7195	107.485
38.57	340.89	317.05	1.0939	9.7951	107.640
38.87	340.96	316.61	1.0918	9.8720	107.664
39.17	341.49	316.77	1.0855	9.9492	107.831
39.38	342.24	316.56	1.0921	10.0028	108.067

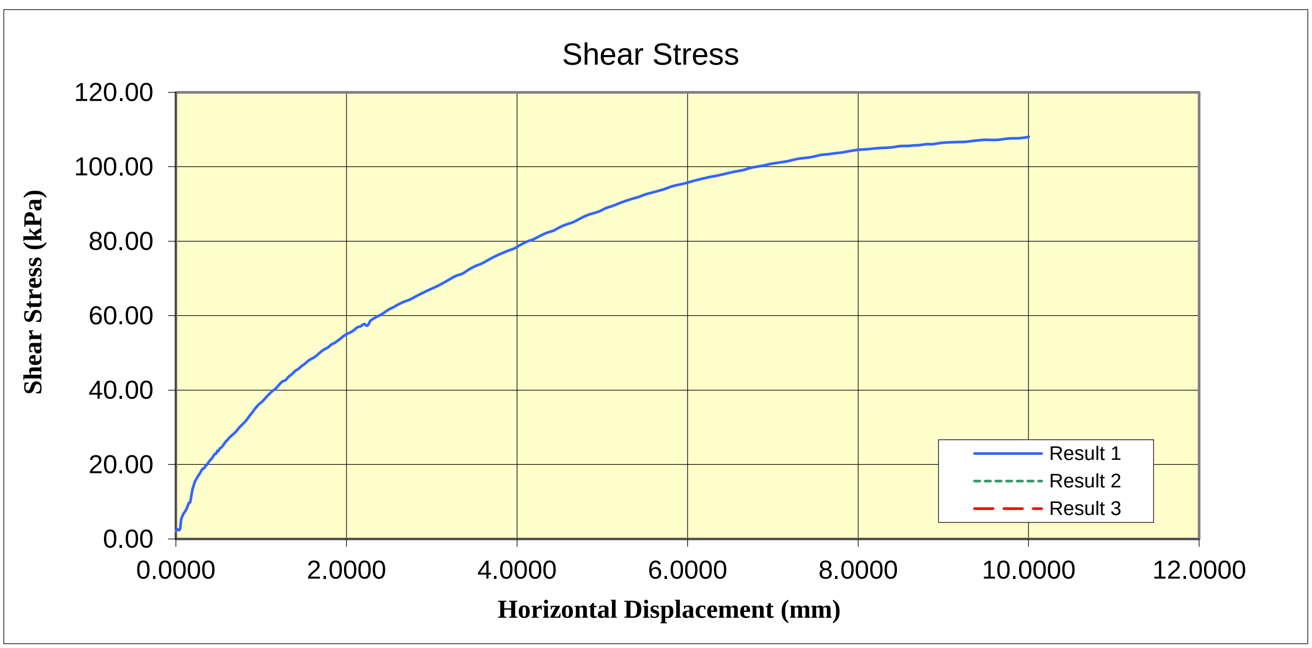

Figure 1, DST Result Shear Stress vs Horizontal displacement

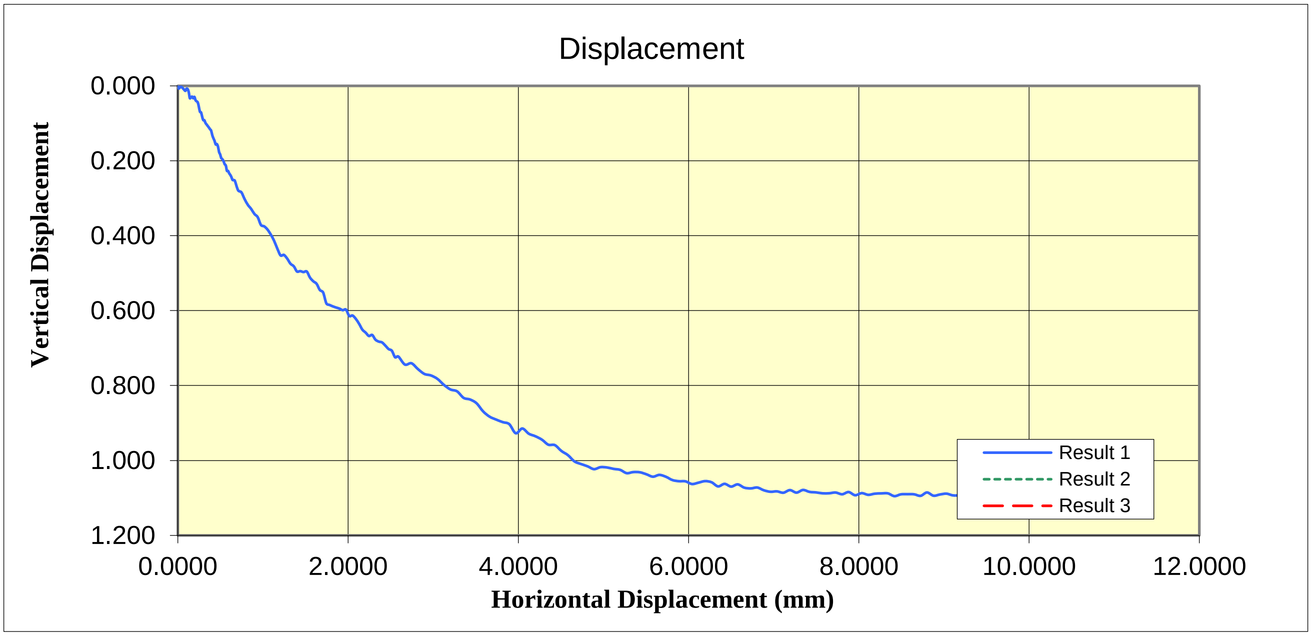

Figure 2, DST Result Vertical displacement vs Horizontal displacement

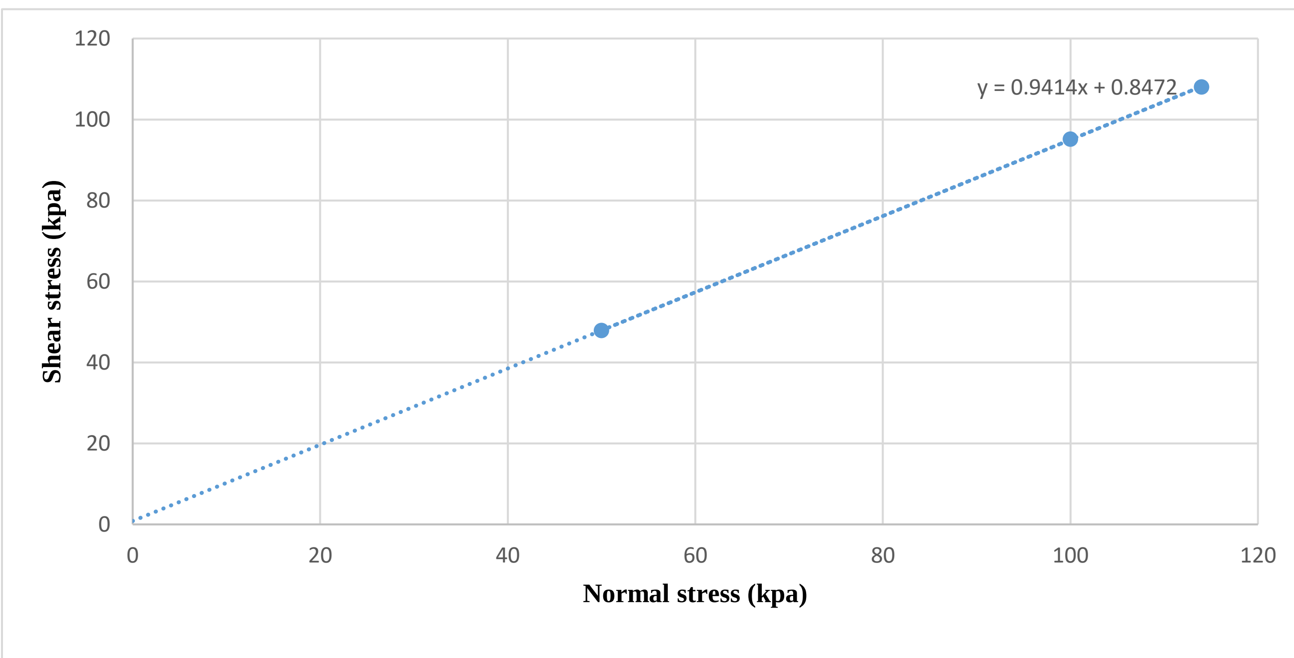

Figure 3, DST Result Cohesion and Angle of Friction