STABILIZATION OF LOW PLASTIC AND HIGH PLASTIC SOIL USING GYPSUM AND RICE HUSK ASH

By

Hasib ur Rehman

(NUST-2016-MS GEOTECH- 00000170563)

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science

In

Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)

School of Civil and Environmental Engineering (SCEE)

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THESIS ACCEPTANCE CERTIFICATE

Certified that final copy of MS thesis written by **HASIB UR REHMAN** (**Registration No. NUST 2016 MS GEOTECH 00000170563)**, of **NUST INSTITUTE OF CIVIL ENGINEERING (NICE)** has been vetted by undersigned, found complete in all respects as per NUST Statutes/Regulations, is free of plagiarism, errors, and mistakes and is accepted as partial fulfillment for award of MS degree. It is further certified that necessary amendments as pointed out by GEC members of the scholar have also been incorporated in the said thesis.

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This is to certify that the

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STABILIZATION OF LOW PLASTIC AND HIGH PLASTIC SOIL USING GYPSUM AND RICE HUSK ASH

Submitted by

Hasib ur Rehman

has been accepted towards the partial fulfillment

of

the requirements

for

Master of Science in Geotechnical Engineering

____

Dr. Liaqat Ali

Associate Dean

NUST Institute of Civil Engineering (NICE)

DEDICATED

TO

MY LOVING PARENTS

FOR THEIR SUPPORT, LOVE, AND ENCOURAGEMENT

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SYMBOLS AND ABBREVIATIONS

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ABSTRACT

Construction on clays is mostly found problematic due to their despoiled properties, i.e., low bearing capacity, low Unconfined Compressive Strength (UCS), high swell potential, high compressibility, and low permeability. Problems associated with clays are mainly foundation failures, floors upheave, diagonal cracks in the walls and cracks in canal linings. The best suitable and economical way to tackle the problem is soil stabilization. This study is conducted to check the potential of Gypsum and Rice Husk Ash (RHA) as soil stabilizers for low plastic clay (CL) and high plastic clay (CH). Gypsum is locally available in abundance while RHA is agricultural waste produced by burning of rice husk which is also available in abundance all over Pakistan. Atterberg limits, compaction properties, Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR) and swell potential of untreated and treated soils were analyzed.

Liquid Limit (LL) and Plasticity Index (PI) of both CL and CH decreased by the use of Gypsum and RHA. Optimum Moisture Content (OMC) of the treated soil increases while Maximum Dry Density (MDD) decreases due to flocculation of soil particles. UCS of CL treated with Gypsum and RHA increases 18 and 5.5 times while that of CH increases 20 and 4.45 times under soaked and unsoaked conditions respectively. The value of CBR for CL for untreated soil lies within the range of poor subgrade material while after treatment, soil was considered as good subgrade material. One dimensional swell potential of CL was reduced 6 times when treated with Gypsum and RHA while the reduction in the swell potential of CH was 40 times. The results of this study concluded that Gypsum and RHA are effective soil stabilizers.

Chapter 1

INTRODUCTION

1.1 GENERAL

The performance of structures depends upon the soil on which they are constructed. The soil with good strength and durability responds adequately to the structural loads. Clay is one of the type of soil, which we as civil engineer encounter in everyday life. Clayey soils are challenging in nature, because its interaction with water is troublesome; clay swells when it absorbs the moisture and shrinks when it loses the moisture. The extent of the swelling depends upon the type of the mineral in the soil. Mainly three types of minerals are present in the clayey soil, i.e., Montmorillonite, Illite, and Kaolinite. Montmorillonite is classified as a three-layer structure with expanding nature and kaolinite expands the least, having secondary hydrogen bonding between particles (Grim, 1953). The problems to the structure due to the presence of clays are of different nature, they can be experienced in the form of diagonal cracks, heaved concrete, differential settlements of the structures and cracking of pavement, sewage pipes, and water supply pipes. In the year 1973-74 cost of damages caused by the expansive soil in United States was 2.2 billion Dollars, more than any other natural hazard (Jones and Holtz, 1974).

Need for the stabilization of soil is as old as construction on the soil. Soil stabilization practice was started in late 60’s and 70’s when replacement of the weaker soil with stronger soil was considered a waste of resource (Chen, 1975). There are different methods of stabilizing expansive clays. Various methods practiced for the stabilization of the expansive clays in Colorado, United States are; replacing weak soil by the strong one, low-grade explosive treatment, chemical stabilization, pre-wetting of soil, heavy pressure application, avoiding weak soils and mechanical stabilization (Ardani, 1992).

1.2 NEED FOR RESEARCH

Soil can be improved by the various methods as discussed above. Method to be adopted for the improvement of the soil depends on the availability of the technology, time constraint, expense, and expertise, etc.

Chemically soil is stabilized using different pozzolanic materials such as cement, lime, gypsum and agricultural waste, etc. (Yilmaz and Civelekoglu, 2009) used phosphogypsum and natural gypsum for the stabilization of expansive soil. The conclusion of the study was that using 10 percent gypsum and phosphogypsum increases the strength of the soil. Uniformity of the material was enhanced along with water resisting property of the soil.

(Gulleria and Dutta, 2011) used fly ash, lime, and gypsum composite mixed with tire chips was applied for strengthening of UCS. The study concluded that by use of reference mix along with carbon tetrachloride (CCl_4) and sodium hydroxide (NaOH), UCS of the soil was increased with curing period. After a certain percentage of the reference mix, the value of UCS started decreasing.

(Ahmad and Ugai, 2011) used recycled gypsum along with waste plastic trays were applied to check their effect on the ground improvement. The study concluded that by increasing gypsum quantity, OMC of the soil was increased but no considerable change was observed in MDD. Curing of fourteen days of soil treated with gypsum increases the UCS.

(Sabat and Kumar, 2011) studied the effect of marble dust on RHA-stabilized expensive soil. (Basha *et al*., 2005) studied stabilization of residual soil with RHA and cement. (Alhasan, 2008) checked the potential of RHA as a soil stabilizer.

Gypsum and RHA are cheap and available in abundance in Pakistan and are not tested as potential stabilizers of soil. The suitability of these additives as soil stabilizers should be checked.

1.3 RESEARCH OBJECTIVES

The main objective of the research is to check the appropriateness of Gypsum and RHA as soil stabilizers. This research will present the geotechnical analysis of Gypsum and RHA as soil stabilizers. Following properties of soil will be studied: -

- Index properties
- Moisture and density relationship of soil
- UCS of soil
- CBR of Soil
- Swell potential of soil

1.4 SCOPE AND METHODODLOGY

The scope of this research is to perform a comparative analysis of the GSD, Atterberg Limit, OMC, MDD, UCS, CBR, and Swell Potential of the untreated and treated soil. The research was conducted in four phases as given below:

1.4.1 Phase I: (Properties of Untreated Soil)

- Field moisture of soil
- Grain Size Distribution of soil (GSD)
  - Hydrometer analysis
- Specific gravity of natural soil (G_S)

- Atterberg limits
  - Liquid limit test (Casagrande Apparatus)
  - Plastic limit test
  - Plasticity index
- Standard Proctor test of soil
  - Optimum Moisture Content (OMC)
  - Maximum Dry Density (MDD)
- Unconfined Compressive Strength (UCS)
  - Unsoaked
  - Soaked
- California Bearing Ratio (CBR) test
  - Unsoaked
  - Soaked (96 hours soaking)
- Swell potential test of soil

1.4.2 Phase II: (Optimization of Gypsum Content)

- Standard Proctor tests at different percentages of Gypsum
  - Optimum Moisture Content (OMC)
  - Maximum Dry Density (MDD)
- UCS at different percentages of Gypsum at 7 days of curing
- Excessive moisture optimization

1.4.3 Phase III: (Optimization of RHA Content)

- Standard Proctor tests at different percentages of RHA
  - Optimum Moisture Content (OMC)
  - Maximum Dry Density (MDD)

- UCS at different percentages of RHA at 7 days of curing
- Excessive moisture optimization

1.4.4 Phase IV: (Optimization of RHA with Optimum Gypsum Content)

- Standard Proctor tests at optimum Gypsum and different percentages of RHA
    - Optimum Moisture Content (OMC)
    - Maximum Dry Density (MDD)
- UCS at optimum Gypsum and different percentages of RHA at 7 days of curing
- Excessive moisture optimization

1.4.5 Phase V: (Properties of Treated Soil)

- Atterberg limits with optimum Gypsum
    - Liquid limit test (Casagrande apparatus)
    - Plastic limit test
    - Plasticity index
- Atterberg limits with optimum RHA
    - Liquid limit test (Casagrande apparatus)
    - Plastic limit test
    - Plasticity index
- Atterberg limits with optimum Gypsum and optimum RHA
    - Liquid limit test (Casagrande apparatus)
    - Plastic limit test
    - Plasticity index
- UCS at 2, 7, 14, and 28 days of curing with optimum Gypsum

  - Unsoaked
  - Soaked
- UCS at 2, 7, 14, and 28 days of curing with optimum RHA
  - Unsoaked
  - Soaked
- UCS at 2, 7, 14, and 28 days of curing with optimum Gypsum and optimum RHA
  - Unsoaked
  - Soaked
- CBR and swell potential of soil with optimum Gypsum
  - Unsoaked
  - Soaked (96 hours of soaking)
- CBR and swell potential of soil with optimum RHA
  - Unsoaked
  - Soaked (96 hours soaking)
- CBR and swell potential of soil with optimum Gypsum and optimum RHA
  - Unsoaked
  - Soaked (96 hours of soaking)

Chapter 2

REVIEW OF LITERATURE

2.1 GENERAL

Clays are well known for their expansive nature and degraded properties like low bearing capacity, low shear strength, low permeability, and high plasticity, high shrink and swell potential and lower values of CBR. Most problems encountered with clays are foundation cracks, breakage of roads, cracks in underground tanks, pipes, sewers, and canal linings. Lightly loaded structures are more affected by clayey soil due to swelling pressure of clay (Jones and Holtz, 1973). The swelling behavior of clay is controlled by the presence of clay minerals: mostly minerals found in clays are Montmorillonite, Illite, and Kaolinite. Montmorillonite mineral is the one which swells the most and kaolinite is the one which swells the least.

2.2 CLAYEY SOILS

Clay is the naturally occurring material formed by the weathering of rocks. The size of the clay particle is less than 0.002 mm (USCS and AASHTO classification); the size of clay particles is so small that there are no gravitational forces between them as they stick together due to electrostatic forces (Chen, 1975). The main difference between clay and silt apart from the particle size is plasticity. Clays exhibit considerable plasticity when meets water and become hard and rigid upon drying. Clays become sticky, when sufficient amount of moisture is present in it (Terzaghi *et al*., 1996).

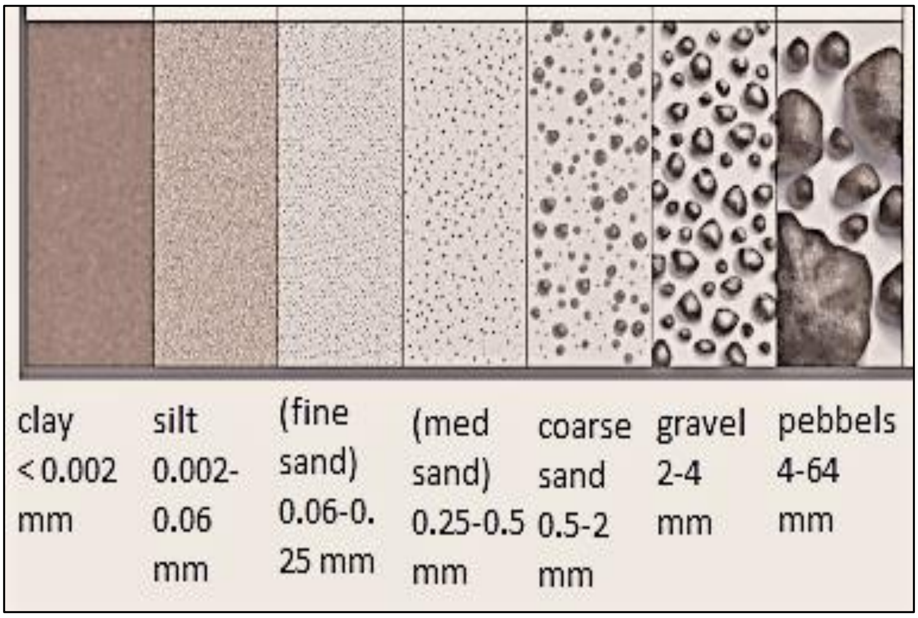

Figure 2.1: Classification based on particle size (Holtz and Kovacs, 1981)

2.2.1 Clay Minerals and their Properties

2.2.1.1 General

Clay minerals are mainly formed either by weathering of parent mineral into clay-rich material (Kaolinite) or by hydrothermal modification of parent rock (Cornish china clay). Mostly clay minerals are found as Montmorillonite, Illite, and Kaolinite. Clay minerals greatly influence the chemical and physical properties of the clays. Swelling of the clay is associated with the presence of montmorillonite while kaolinite is the non-swelling clay mineral. On the basis of structure, clay minerals ae classified as: amorphous and crystalline minerals.

Amorphous clay minerals are generally found in the form of Allophane group which is unstable form of clay minerals while crystalline structure is the stable form which is further divided into two-layer type and three-layer type.

The two-layer type mainly consists of one unit of silica tetrahedron and one unit of the aluminium octahedron. Kaolinite is the best example of the two-layer type. Three-layer type consists of two layers of silica tetrahedron and one layer of the aluminium octahedron. They are further divided into expanding and non-expanding type. Montmorillonite comes under the expanding type while Illite comes under non-expanding type.

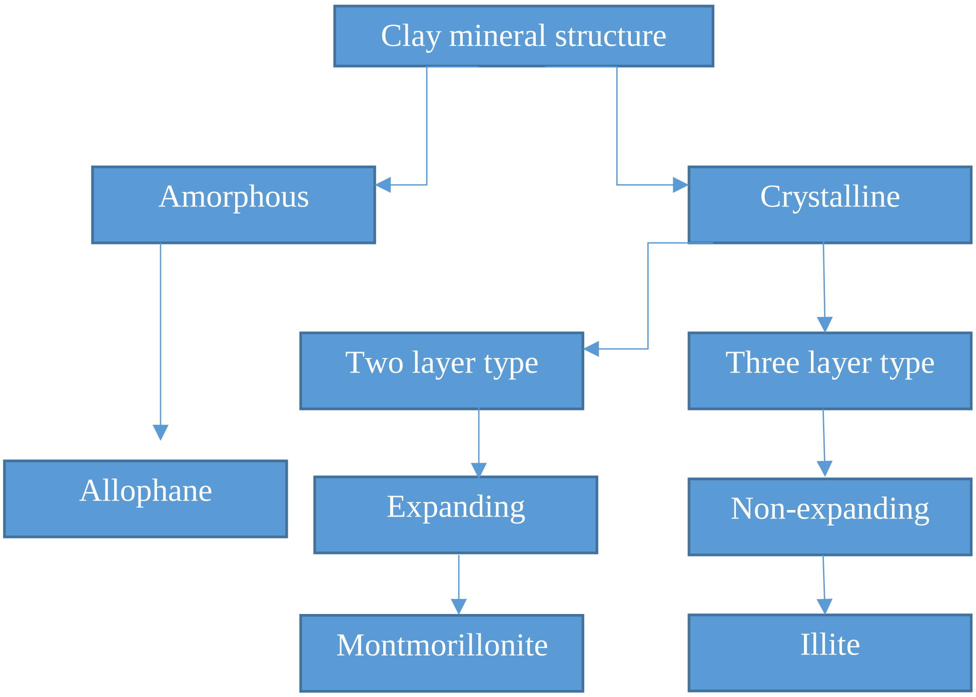

Figure 2.2: Classification of clay minerals structure

2.2.1.2 Kaolinite

Kaolin comes from Chinese background which refers to "Kauling" a hill in the China where it was found centuries ago. The structure of kaolinite consists of one unit of aluminium octahedron and one unit of silica tetrahedron. They are mostly found clay minerals with layer structure of 1:1. Brindley proposed a triclinic structure of kaolinite. They are the most stable clay minerals possessing hydrogen bonding between the sheets. The reaction below shows the formation of kaolinite from potassium feldspar (Grim, 1953).

$$2KAlSi_3O_8 + H_2O \longrightarrow Al_2Si_2O_5\,(OH)_4 + 4SiO_2 + 2K\,(OH)$$

(Kaolinite)

Kaolinite is used in paper coating, fillers, ceramics, and pigments and used as raw material in cement and fiberglass (Thair and Olly, 2008).

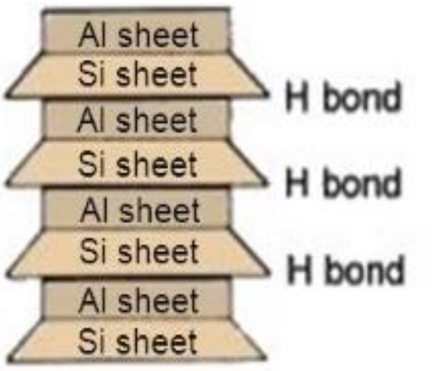

Figure 2.3: Hydrogen bonding (Grim, 1962)

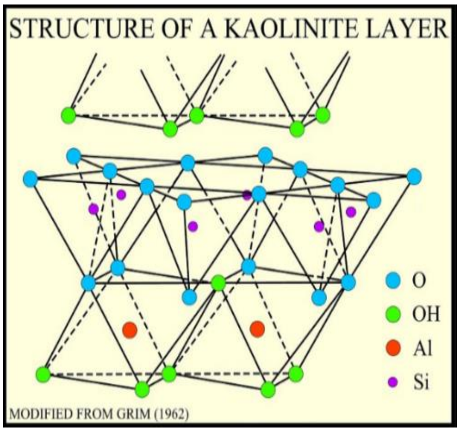

Figure 2.4: Sheet of Kaolinite (Grim, 1962)

2.2.1.3 Illite

Illite was named after the state of Illinois, US, as it was discovered there. The structure of Illite comes under three-layer type classification of crystalline structure and further categorized as a non-expanding lattice. Structure of Illite is composed of one aluminum octahedral sheet crammed between two silicon tetrahedral sheets. Illite is the weathering product of feldspar and felsic silicates. The properties of Illite minerals are the intermediate of the kaolinite and montmorillonite minerals. It has relatively weaker hydrogen bonding as compared to kaolinite, and relatively stronger bonding as compared to montmorillonite (Grim, 1953).

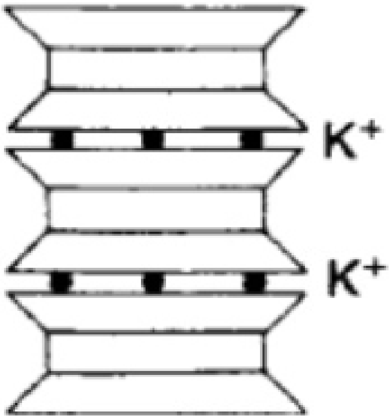

Figure 2.5: K bonding (Grim, 1962)

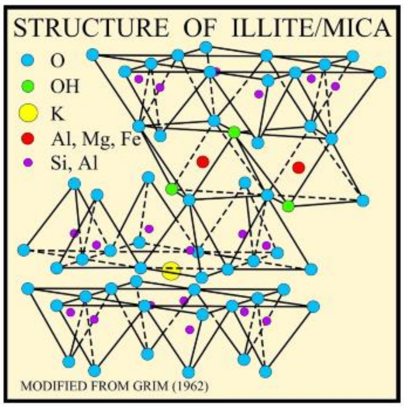

Figure 2.6: Structure of Illite (Grim. 1962)

2.2.1.4 Montmorillonite

The name of montmorillonite mineral comes from Montmorillon, France. The mineral was classified as the three-layer type with expanding lattice. It consists of one aluminium octahedral sheet between two silicon tetrahedral sheets. The expanding lattice of montmorillonite is because of the weak inter particle forces, that allows the water to percolate between the particles and expand it. The dominant forces in montmorillonite are Van der Wall forces. Montmorillonite is the weathered product of the mafic silicates (Grim, 1953).

Montmorillonite is used in oil industry, drilling muds, clay liners, preventing groundwater contamination, seepage prevention, lubrication, civil engineering, chemicals, and as bentonite (Thair and Olly, 2008).

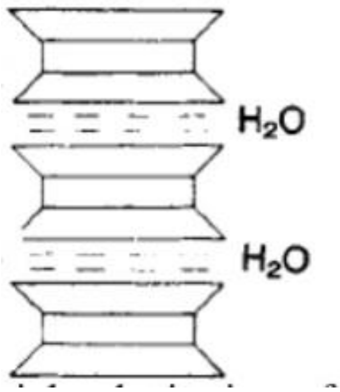

Figure 2.7: Bonding in Montmorillonite

(Grim, 1962)

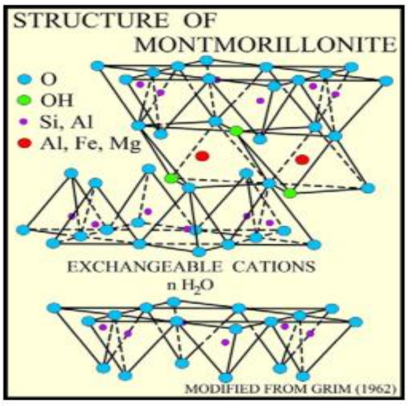

Figure 2.8: Structure of Montmorillonite

(Grim, 1962)

2.3 SOIL STABILIZATION

Soil stabilization is a process in which any chemical or mechanical method is applied to improve the engineering properties of the soil. Soil stabilization helps improve the strength, permeability, swell potential, and compressibility of the soil.

2.3.1 Methods for Stabilization

Many methods are used for the stabilization of soil, some of them are explained in Chapter 1. Soil is stabilized mechanically, chemically, or by using agricultural waste products.

Mechanically soil is stabilized by compaction (dynamic compaction, deep dynamic compaction, and impact compaction), pre-loading and vibro-floatation.

The oldest and mostly adopted method for soil stabilization is the use of chemicals. The vast amount of research is already conducted on the use of different chemicals for soil stabilization. Cement, lime, Gypsum, marble dust, RHA, fly ash and different other chemicals are used as soil stabilizers. These chemicals in reaction with soil, produce the cementitious products which help improve the properties of the soil.

The main theme of chemical stabilization of soil is to replace the weaker cations with stronger cations e.g., sodium (Na^+) possess only one valence electron so, it can only form a single bond with soil particles but when it is replaced by divalent calcium (Ca^{++}) ions, which have two valence electrons and can form a stronger bond then sodium with soil particles and stabilize the soil particles.

Now a days, synthetically prepared bio-enzymes are also used as soil stabilizers. They have excellent power to react with the soil and improve its properties e.g., Terrazyme extracted from sugar cane is used as a bio-enzyme stabilizer of the soil.

2.3.2 Soil Stabilization using Lime

(Bell, 1996) used lime to check its effect on the properties of clays. By the addition of lime: workability and strength of the clays is increased, PI of the soil is reduced, OMC of the soil increases and MDD of the soil is decreased, strength and CBR of the soil is also increased, increase in strength was observed for curing of 7 days.

(Rizvi *et al*., 2018) used lime on black cotton soil to check its effect on the CBR. The study concluded that CBR of treated soil was much improved as compared to that of untreated soil. Optimum percentage of lime was calculated as 2-3 percent.

(Negi et al., 2013) used to check its effect on properties of soil. The study concluded that: lime immediately reacts with soil producing cementitious products. Resistance of soil to shrinkage during moist conditions, reduction in plasticity index, and increase in CBR value and increase in the compression resistance with the time was observed for the soil treated with lime.

2.3.3 Soil Stabilization using Cement

(Basha *et al*., 2005) used cement along with RHA for the stabilization of residual soil. The study concluded that 6-8 percent cement and 10-15 percent RHA are the optimum percentages to be added. By the use optimum percentage of additives plasticity of the soil was reduced, OMC was increased, MDD was reduced and CBR was improved up to 60 percent.

(Yin *et al*., 2006) used Portland cement and RHA for the stabilization of lead contaminated soils. The study concluded in improved values of UCS of treated soils after 28 days of curing.

(Alam and Rayhan, 2015) used cement and glass dust for the stabilization of soil. Liquid limit was decreased by the use of both additives in combination. Significant increase in the UCS of treated soil was observed.

2.3.4 Soil Stabilization using Bagasse Ash

(Ramirez *et al*., 2012) used bagasse ash and lime to improve the durability and mechanical properties of compacted soil blocks. The study concluded that 10 percent bagasse ash along with 10 percent lime significantly improves the durability and mechanical properties of the blocks. Compressive and flexural strength of lime treated blocks was improved.

(Ali and Shah, 2014) studied the stabilization of expansive soil by the use of marble dust and bagasse ash. The study concluded that consistency limits of the soil were improved by the use of these additives. Uplift pressure of the treated soil was reduced by the use of 12 percent marble dust and 12 percent bagasse ash.

(Sadeeq *et al*., 2015) studied effect of bagasse ash on lime stabilized lateritic soil. (Osinubi *et al*., 2009) studied Lime stabilization of black cotton soil using bagasse ash as admixture. (Gandhi, 2012) studied expansive soil stabilization using bagasse ash.

2.3.5 Soil Stabilization using Fly Ash

(Kolias *et al*., 2005) studied stabilization of clayey soils with high calcium fly ash and cement. Combined use of these additives improves strength (compressive tensile and flexural), modulus of elasticity and CBR of treated soil.

(Edil *et al*., 2006) studied the stabilizing soft fine-grained soils with fly ash. With the addition of fly ash CBR and resilient modulus of the soil was significantly enhanced. Effect of curing on the resilient modulus was significant in between 14 and 56 days.

(Tastan et al., 2011) used fly ash for the stabilization of organic soils. (Kumar *et al*., 2007) studied the influence of fly ash, lime, and polyester fibers on compaction and strength properties of expansive soil. (Consoli et al., 2001) studied the behavior of compacted soil-fly ash-carbide lime mixtures.

2.3.6 Soil Stabilization using Cement Kiln Dust (CKD)

(Upma and Kumar, 2015) studied the effect of CKD and chemical additives on the expansive soil at subgrade level. Up to 10 percent of CKD consistency limits of the soil are improved. OMC is increased and MDD is decreases by the use of CKD. UCS, shear and CBR of the CKD treated soil were improved significantly.

(Mosa, *et al*., 2017) studied the improvement of poor subgrade material by the use of CKD. CBR and subgrade resilient modulus was enhanced which enables to design the pavements with less thickness thus making construction cost effective.

2.3.7 Soil Stabilization using Terrazyme

Terrazyme is a safe, effective and non-corrosive liquid enzyme which is used for soil stabilization all over the world. Following are some of the studies that used Terrazyme as soil stabilizers.

(Saini and Vaishnava, 2015) studied soil stabilization using Terrazyme. The study concluded that compounds formed by the addition of Terrazyme are biodegradable but effect on the soil is permanent. In long term cost analysis Terrazyme is cost effective stabilizer.

(Rajoria and Kaur, 2014) studied soil stabilization using Terrazyme. The study concluded that by the use of Terrazyme, liquid limit of the soil was decreased and UCS of the treated soil was increased.

(Eujine *et al*., 2014) studied the enzyme stabilization of the soil. (Venkatasubramanian and Dhinakaran, 2011) studied the effect of bio-enzymatic soil stabilization on unconfined compressive strength and California bearing ratio.

2.3.8 Soil Stabilization using Perma-Zyme

Perma-Zyme is a compaction enzyme, in reaction with soil it improves rate of compaction. Perma-Zyme is a natural organic compound, similar to proteins, which acts as a catalyst (Rajoria and Kaur, 2014).

(Khan and Sarkar, 1993) studied enzyme enhanced stabilization of soil and fly ash for soil improvement. The study concluded that less compactive effort was required for soil to reach its maximum density. It reduces the optimum moisture up to 25 percent.

2.3.9 Soil Stabilization using Fujibeton

Fujibeton is an inorganic polymer that chemically binds with all compounds, when blended with ordinary Portland cement.

(Chandrasekhar, 2006) studied innovative rural road construction techniques. The study concluded that Fujibeton stabilized road are not only economical but also proven effective under constraints of traffic diversions.

2.4 GYPSUM STABILIZATION

2.4.1 General

Gypsum word is of Greek origin "*Gypsas*" meaning "plaster". Gypsum is the sulphate mineral with chemical formula $CaSO_4.2H_2O$ and is mostly found in white color all around the world in an abundant state. In 2015 total production of Gypsum around the globe was 258000 thousand metric tons, Pakistan produced 1300 thousand metric tons (USGS Mineral Resource Program, 2015). Gypsum is composed of different ions and oxides. The percentage of ions and oxides in Gypsum according to (Yilmaz and Civelekoglu, 2009) are presented in table below:

Table 2.1: Percentages of ions and oxides in Gypsum (Yilmaz and Civelekoglu, 2009)

Ions	Percentage	Oxides	Percentage
Ca ++	23.28	CaO	32.57
H+	2.34	H_2O	20.93
S--	18.62	SO_3	46.50
O--	55.76		

2.4.2 Properties of Gypsum

Gypsum is the true source of calcium, which is the divalent cation having two electrons to offer for bonding, and along with this calcium has a strong replacement and flocculating power (Sumner and Naidu, 1998). Gypsum, when mixed with soil will replace the weak cation and flocculate the soil particles, thus making the soil strong by improving strength, angle of internal friction, and reduces plasticity and swell potential of the soil. The binding power of cations in decreasing order is shown below (Terzaghi *et al*., 1996).

$$Al^{+3} \rightarrow Ca^{+2} \rightarrow Mg^{+2} \rightarrow NH_4^{+} \rightarrow K^{+} \rightarrow H^{+} \rightarrow Na^{+} \rightarrow Li^{+}$$

Table 2.2: Flocculation power of cations (Sumner and Naidu, 1998)

Flocculation Power of Cations			
Cations	**Charge**	**Hyd. Radii**	**Flocc. Power**
Sodium	1	0.79	1.0
Ptassium	1	0.53	1.7
Magnesium	2	1.08	27.0
Calcium	2	0.96	43.0

2.4.3 Reaction of Gypsum with Soil

Gypsum needs water for the initiation and completion of the reaction with soil. Gypsum and soil reaction completes in following three stages:

1. Cation exchange
2. Agglomeration/ Flocculation
3. Pozzolanic reaction

2.4.3.1 Cation exchange

When soil is mixed with Gypsum in the presence of water calcium will replace the weak cations within the soil, either hydrogen or sodium. The reaction proceeds in the following manner:

$$(H^{+} \text{ or } Na^{+})\text{-Clay} + CaSO_4.2H_2O \longrightarrow \text{Ca-Clay} + H^{+} + Na^{+} + SO_4^{-2}$$

2.4.3.2 Flocculation

Once exchange of cations is completed, calcium with flocculation power 43 times as strong as sodium will start flocculation and makes soil particles much coarser than before. Calcium silicate is produced during the process which is a cementitious product and helps in improving the properties of soil (Sumner and Naidu, 1998).

2.4.3.3 Pozzolanic reaction

Pozzolanic reaction depends on the long-term availability of calcium ions. Gypsum being rich in calcium, will keep the pozzolanic reaction active for a longer period of time. The pozzolanic reaction is the main source of long-term strength gain of soil.

2.4.4 Fittingness of Gypsum as a Soil Stabilizer

Gypsum has been used all around the world for soil stabilization. The brief summaries of some of the work done, using Gypsum along with other additives is presented below:

(Yilmaz and Civelekoglu, 2009) applied Gypsum for stabilization of swelling clays. The study concluded significant change in the UCS of the soil with time. The major strength gain was during the first seven days of curing. The swelling potential of the soil was reduced using Gypsum.

(Degirmenchi, 2008) applied phosphogypsum, fly ash, and cement for the stabilization of CH and MH. The study resulted in improvement in the plasticity of the soil, increase in OMC and decrease in MDD of the soil, UCS of the soil was increased significantly, and results of cement treated soil were better as compared to that of fly ash.

(Ahmed *et al*., 2011) used phosphogypsum along with waste plastic trays for the stabilization of soil. Increase in OMC and decrease in MDD was observed, UCS of soil was improved, improvement was significant during first 14 days of curing, and the capillary rise of the soil is reduced by the use of above mentioned additives.

(Seco *et al*., 2011) used lime, gypsum, MgO, RHA, fly ash, coal fly ash, coal bottom ash, steel fly ash, and aluminium filler to draw a comparison of their effects on engineering properties of the soil. The effect of magnesium as compared to calcium in reducing swell potential was more effective. Material rich in sulphates reduce the swell potential significantly. The effect of material having monovalent cation on swelling of soil was less as compared to divalent cation. UCS of the soil increases 2-4 times with all the additives used. RHA is the waste produced in developing countries and has good effect on the swelling and mechanical properties of soil.

(Kolay and Pui, 2010) used gypsum and fly ash for the stabilization of peat. OMC of the soil was increased, MDD was decreased, and increase in UCS of the soil was observed as soil was cured up to 28 days.

(Sleiman *et al*., 2015) used phospogypsum for the stabilization of non-plastic clay and its CBR value was studied. The optimum percentage of phosphogypsum was 21.4 percent. UCS was significantly increased by the use of phosphogypsum. The depth of the pavement was sufficiently reduced by the use of phosphogypsum.

2.4.5 Effect of Gypsum on Soil Properties

2.4.5.1 Grain size distribution (GSD)

Addition of Gypsum changes the GSD of soil. Due to the flocculation of the particles, the size of the soil particles increases (Yilmaz and Civelekoglu, 2009).

2.4.5.2 Atterberg limits

Liquid limit by the addition of the Gypsum may or may not increase depending on the nature of the soil. Plasticity index of the soil will reduce due to flocculation and coarseness of the soil particles (Degirmenchi, 2008).

2.4.5.3 Density and moisture relationship

OMC will increase and MDD will decrease by the addition of Gypsum. The rise in the OMC is due to the smaller size of Gypsum powder then soil which has a greater surface area and requires more water for lubrication. Increase in OMC can also be due to the pozzolanic reaction, which requires more water for completion of the chemical reaction. MDD will fall because of flocculation which makes compaction difficult. Flocculation causes the size of soil particles to increase which increases the amount of voids in the soil sample which will cause the reduction of MDD (Ahmed *et al*., 2011).

2.4.5.4 Unconfined compressive strength (UCS)

UCS of the Gypsum-treated soils will increase, due to flocculation and production of cementitious products. Greater particle size and cementitious products helps improve the UCS of the soil (Yilmaz and Civelekoglu, 2009).

2.4.5.5 California bearing ratio (CBR)

CBR of the treated soil increases due to flocculation and production of cementitious products. As soil becomes coarser, CBR of the soil will increase (Sleiman *et al*., 2015).

2.4.5.6 Swell potential

Due to increase in coarseness, the water holding capacity of the soil will reduce thus plasticity index of the soil will decrease. Plasticity has a direct relation with swell potential of the soil, reduction in plasticity and water holding capacity causes the swell potential of the soil to decrease (Seco *et al*., 2011).

2.4.6 Uses of Gypsum

Gypsum is used in a great many products. Some of the major applications of Gypsum are as follows:

- Gypsum is used in the manufacturing of hard boards.
- Used in manufacturing of cement and Plaster of Paris.
- Used as a hardness preventer in Portland cement.
- Gypsum is used for ornamental purposes.
- Gypsum is used in making surgical and orthopedic cases.
- The primary ingredient of toothpaste.
- Used as a fertilizer in the soil.

2.5 RICE HUSK ASH (RHA) STABILIZATION

2.5.1 General

Rice husk ash is an agricultural waste produced by the burning of covering of rice husk at 600-700°C for 2 hours (Okafor, 2009). Rice Husk is used for different industrial purposes.

2.5.2 Production of RHA in Pakistan

Pakistan is the 11th largest rice production country of the world. In 2017, Pakistan produced 6.7 million tons of rice, 4 million tons were exported, and 2.7 million ton was consumed domestically (Pakistan Economic Survey, 2016-17). Out of the total weight of the rice, 28 percent is the weight of husk (Della, 2002), which gives 0.756 million ton of husk. Dumping of rice husk in rice producing country is a big problem, it is either pile burnt or dumped carelessly.

In Pakistan RHA is produced by burning it in brick incinerators (CSIR, Pakistan). Other sources of RHA production are step grate furnace (industrial combustion system used for burning solid waste), steam gasification (treating a material at temperature greater than 700˚C) and brick suspension burner (Klieh and Hillingdon, 1993). RHA has many technical and commercial applications. RHA can be utilized as insulation material, reinforcing agents and fillers, fertilizers, chemicals and building material component.

2.5.3 Composition of RHA

Rice husk ash is mainly composed of silica, plants extract silicon from soil and deposit it in the covering of rice (husk). The content of silica changes from soil to soil depending upon the type of the soil. The chemical composition of RHA is given in the table below:

Table 2.3: Chemical composition of RHA (Alhasaan, 2008)

Chemical Composition of Rice Husk Ash (RHA)	
Oxides	**Percentage**
SiO_2	90.16
Fe_2O_3	0.41
Al_2O_3	0.11
CaO	1.01
MgO	0.27
SO_3	0.12
$Al_2O_3 + Fe_2O_3$	0.52
$Al_2O_3 + Fe_2O_3 + SiO_2$	0.93
Na_2O	0.01
K_2O	0.65

2.5.4 Reaction of RHA with Soil

RHA is mainly composed of silicon dioxide (SiO_2), which plants extract from the ground and deposit it in the outer shell of the rice. When this shell is burnt organic material escapes in the air and silicon dioxide (SiO_2) is left behind. The reaction of soil with RHA in the presence of calcium Ca^{++}, produces calcium silicate $CaSiO_3$ which is a cementitious product giving strength to the soil and reduces the sulphate and chemical attack on the soil (Alhasaan, 2008).

$$Ca(OH)_2 \longrightarrow Ca^{++} + OH^-$$

$$Ca^{++} + SiO_2 + OH^- \longrightarrow CaSiO_3 + H_2O$$

(Cementitious product)

2.5.5 Fittingness of RHA as a Soil Stabilizer

Previous studies conducted on the RHA as soil stabilizers concluded that RHA is a cheap, and reliable source of soil stabilization. Many researchers concluded that use of RHA for soil stabilization gives good results of strength gain, reduction in the plasticity and increase in the CBR of the soil.

(Islam, 2012) used RHA to check its effect on the geotechnical properties of cohesive soil. The results of the study were good regarding the improvement of soil. Addition of RHA to the soil produces cementitious products due to pozzolanic nature of the RHA. Flocs are formed, and the soil becomes coarser thus improving the strength and reduces the plasticity of the soil.

(Alhasaan, 2008) studied the potential of RHA as a soil stabilizer and the conclusion of the study was improved values of UCS and CBR at 6 percent of RHA. The effects on the moisture and density relation were that MDD was decreased due to flocculation and OMC was increased by the addition of RHA due to the pozzolanic reaction.

(Okafor, 2009) applied RHA on lateritic soils to study the effects on geotechnical properties of the soil. Reduction in the plasticity of the soil was observed by adding RHA, and CBR was improved, volume stability was attained, and 10 percent RHA was considered as an optimum percentage.

(Rao *et al.*, 2011) checked the effect of gypsum, lime, and RHA on expansive soil. UCS, CBR, and swell potential of the soil was checked. Optimum percentage of additives was 20 percent RHA, 5 percent lime, and 3 percent gypsum. Swell index was reduced 88 percent by the use of optimum percentage, UCS was increased 548 percent after 28 days of curing and CBR was increased 1350 percent after 14 days of curing.

(Sarkar *et al*., 2012) checked the effect of RHA on the properties of cohesive soil and the study concluded that 10 percent RHA was the optimum percentage for UCS and shear strength of soil. Plasticity, swell potential, and compression index of the treated soil was reduced, and UCS was increased significantly.

2.5.6 Uses of RHA

Rice husk ash has different industrial and domestic uses, some of the main uses of RHA are as follows:

- Used for stabilization of soil and cement.
- RHA is used in toothpaste.
- It can also be used as pet food.
- One of industrial use of RHA is that it is used in fertilizers.
- RHA is used in insulating material and fireworks.

Chapter 3

MATERIALS AND METHODOLOGY

3.1 GENERAL

This study is conducted to check the suitability of Gypsum and RHA as soil stabilizers. CL and CH soils were treated with Gypsum, RHA, and the combination of `Gypsum and RHA to check the improvement in the engineering properties of these soils.

3.2 MATERIAL

Soils used in this study were of two type i.e. CL and CH. CL was taken from village Ballewla near Nandipur Power Plant, Gujranwala. The site was 32°15’58.8” N and 74°14’13.28” E. Picture below shows a satellite image of the site from where sample was collected. CH was made artificially in the lab by mixing 25 percent bentonite with CL.

Figure 3.1: Satellite image of soil site

Figure 3.2: Soil sample passed through sieve #4

3.2.1 Gypsum

Gypsum used was taken from Arish Gypsum Products Karachi, Pakistan. Gypsum is identified under the name ProCaster^{TM}. The properties of ProCaster is given in the table below:

Table 3.1: Properties of Gypsum (Arish Pro Caster)

Specifications	**ProCaster^{TM}**
Chemical composition	Calcium sulphate hemihydrates $CaSO_4.1/2\ H_2O$
Fineness	Only 4 to 5 percent remains on sieve no 200
Initial setting time	From 3 minutes for speedo plaster to 10 minutes
Final setting time	From 12 minutes for speedo plaster to 30 minutes
Compressive strength	>1525 MN/m^2 or 1525 psi
Density	1100 kg/m^3

Figure 3.3: Gypsum used in the study

3.2.2 Rice Husk Ash (RHA)

RHA was taken from Punjab Oil Mills Private Limited Islamabad. The sample was oven dried and passed through sieve #100 and kept in impermeable plastic bags.

Figure 3.4: Site from where RHA was taken

Figure 3.5: RHA used in the study

3.2.3 Bentonite

Bentonite was obtained from Ittefaq Tiles Corporation, Lahore, Pakistan. Bentonite used in this study was high swelling sodium bentonite. The purpose of the use of bentonite was to make the CH from CL in the lab.

Figure 3.6: Bentonite used in the study

Table 3.2: Chemical composition of bentonite (Na bentonite,Ittefaq Tiles).

SiO_2	55-65
Al_2O_3	18-22
Fe_2O_3	3-5
MgO	1-3
CaO	0.7-1.32
Na_2O	0.13-1.2
K_2O	0.2-0.56
TiO_2	0.15-0.35

3.3 METHODOLOGY

The research was carried out in the five phases as follow:

- Phase I: Properties of untreated soil
- Phase II: Optimization of Gypsum content
- Phase III: Optimization of RHA content
- Phase IV: Optimization of RHA with optimum Gypsum
- Phase V: Properties of treated soils

3.3.1 Phase I: Properties of Natural Soil

In the first phase of the research, soil sample was collected and properties of natural soil like in situ moisture content, Atterberg limits, MDD, OMC, UCS, CBR and swell potential of both CL and CH were calculated.

3.3.1.1 Sample collection

The soil sample CL was taken from village Ballewala, near Nandipur Power Plant Gujranwala. The sample was collected from the depth of 3 feet so that impurities can be avoided, while CH was prepared in the lab by mixing 25 percent bentonite with CL.

3.3.1.2 Insitu moisture content

The site moisture content was calculated according to ASTM 2216-13. The sample was kept in the oven for 24 hours and the difference in the soil mass was calculated as the in situ moisture content of the soil.

3.3.1.3 Grain size distribution (GSD)

Sieve analysis was performed according to ASTM D422-07. Soil sample of 300 grams was taken, pulverized and then passed through sieve set and percentage retained on sieve #200 was weighted.

3.3.1.4 Hydrometer analysis

Hydrometer analysis was performed on soil sample passed through sieve #200, according to ASTM standard D7928-16. The percentage of silt and clay particles were calculated through hydrometer analysis.

3.3.1.5 Atterberg limits

Atterberg limit was calculated according to the ASTM standard D4318-10. LL, Plastic Limit (PL) and PI of both CL and CH were calculated. Soil sample of 200 grams passing through sieve #40 was used to perform the test. The test was performed for the classification of the soil.

3.3.1.6 Specific gravity (G_s)

The specific gravity test for both CL and CH was performed according to ASTM D854-14. The test was performed with the soil sample passing through sieve #16.

3.3.1.7 Compaction characteristics of soil

Standard Proctor test was performed for both CL and CH to plot a relation between OMC and MDD. The test was performed according to ASTM standard D698-07.

3.3.1.8 Unconfined compressive strength

UCS of the untreated soil was calculated using ASTM standard D2166-13. Two samples for both CL and CH were made at 95 percent of OMC and MDD and their average value was reported. The test was performed both under soaked and unsoaked conditions.

Unsoaked samples were prepared and then cured for 2, 7, 14, and 28 days and then tested. Test was performed according to ASTM D5102-019. Curing was done by covering the samples in airtight plastic bags and then kept in an oven at 30 degrees Celsius for the desired time period before testing.

Soaked samples were tested to check the effect of moisture on the strength of the clays. Test was performed according to ASTM D5102-019. Samples were wrapped in absorption fabric and kept in the desiccator for soaking. Care should be taken to avoid the direct contact of water with the samples. Soaking was done for 48 hours prior to testing.

The mold of height 8 cm and a diameter of 4 cm was used. The soil sample was compacted completely within the mold and care was taken not to over compact the soil sample.

Figure 3.7: Curing of UCS samples in an oven

Figure 3.8: Soaking of UCS samples in a desiccator

3.3.1.9 California bearing ratio (CBR) and swell potential of the soil

CBR test was performed according to ASTM standard D1883-14 and AASHTO standard T193-13. One-point CBR test was performed for both CL and CH. The test was performed both under soaked and unsoaked conditions. In both soaked and unsoaked conditions, samples were prepared at OMC and were compacted in five layers with 65 blows per layer. Soaking is done for 96 hours in a soaking tub. The mold of diameter 6”, height 7”, and spacer disk of 2” was used.

The swell potential of the both CL and CH was calculated using soaked CBR samples. Samples were soaked for 96 hours along with surcharge load of 5 kg which is the least requirement of the standard. The difference between the heights of the soil was calculated as swell potential of the soil.

Figure 3.9: CBR apparatus

Figure 3.10: Soaking of CBR samples

3.3.2 Phase II: Optimization of Gypsum Content

In this phase, samples were prepared and tested by adding 9, 12, 15, and 18 percent of Gypsum by weight of soil. Gypsum was optimized for both CL and CH.

3.3.2.1 Compaction characteristics at different percentages of Gypsum

Samples were prepared by mixing soil with 9, 12, 15 and 18 percent of Gypsum. Standard Proctor test was performed according to ASTM D698-07, to plot moisture and density relation. Samples were compacted in 3 layers with 25 blows per layer with a hammer of 5.5lb.

3.3.2.2 Unconfined compressive strength at different percentages of Gypsum

UCS samples were prepared at 9, 12, 15, and 18 percent of Gypsum with soil. Samples were prepared at 95 percent of OMC and MDD obtained from Standard Proctor test. The samples were cured in an oven in airtight plastic bags for 7 days at 30 degrees Celsius, prior to testing. Two samples were tested for each percentage of Gypsum. The average strength of the two samples was noted and the percentage of Gypsum giving highest strength was considered an optimum percentage.

3.3.2.3 Excessive moisture optimization

Gypsum needs water for the initiation and hydration of the chemical reaction with soil. Two UCS samples with moisture 1 percent, 2 percent and 3 percent more than optimum moisture were prepared with each percentage of Gypsum. The samples were cured for 7 days in an oven at 30 degrees Celsius and then tested. The average value of the two-specimen giving the highest UCS was considered as the optimum extra moisture.

3.3.3 Phase III: Optimization of RHA

In this phase, samples were prepared and tested by adding 4, 8, 12, and 16 percent of RHA with soil. RHA was optimized for both CL and CH.

3.3.3.1 Compaction characteristics at different percentages of RHA

Samples were prepared by mixing soil with 4, 8, 12, and 16 percent of RHA. Standard Proctor test was performed according to ASTM D698-07, to plot relation between moisture and density. Samples were compacted in 3 layers with 25 blows per layer with a hammer of 5.5lb.

3.3.3.2 UCS at different percentages of RHA

UCS test samples were prepared at 4, 8, 12, and 16 percent of RHA with soil. Two samples were prepared at 95 percent of OMC and MDD as calculated previously in Proctor test. These samples were cured in an oven for 7 days wrapped up in airtight bags at 30 degrees Celsius. The percentage of RHA giving the highest value of UCS was considered as optimum RHA content.

3.3.3.3 Excessive moisture optimization

Extra moisture was added to the samples prepared at OMC to check their effect on the strength. Two UCS samples were prepared at moisture 1 percent, 2 percent, and 3 percent greater than the OMC and then tested after curing them for 7 days in airtight bags in an oven at 30 degrees Celsius. The average value of the samples giving the highest value was considered as the optimum extra moisture.

3.3.4 Phase IV: Optimization of RHA with Gypsum

In this phase, samples were prepared with optimum Gypsum content and 3, 6, 9, and 12 percent RHA by weight of soil and then tested. Testing was conducted for both CL and CH.

3.3.4.1 Compaction characteristics at different percentages of RHA with optimum Gypsum

Samples were prepared with optimum Gypsum content and 3, 6, 9, and 12 percent of RHA by weight of soil. The sample was compacted in 3 layers with 25 blows per layer with 5.5 lb. hammer dropping from a height of 12 inches. Moisture and density relation was plotted for each trial.

3.3.4.2 Unconfined compressive strength at different percentages of RHA with optimum Gypsum

UCS test samples were prepared at optimum Gypsum content and 3, 6, 9, and 12 percent of RHA. The samples were prepared at 95 percent of OMC and MDD as calculated in the compaction test. Two samples were prepared, cured in an oven covered in airtight plastic bags for 7 days at 30 degrees Celsius and then tested. The average of the two samples giving the highest strength was considered as optimum percentage of RHA with optimum Gypsum.

3.3.4.3 Excessive moisture optimization

Two UCS samples were prepared at moisture content greater than OMC by 1, 2, and 3 percent and then tested after curing in an oven in airtight plastic bags at 30 degrees Celsius for 7 days. The average of the two samples giving the highest value was considered as the optimum extra moisture.

3.3.5 Phase V: Properties of Treated Soil

As optimum contents for both Gypsum and RHA and optimum of their combination are calculated. Using these percentages Atterberg limits, UCS, CBR, and swell potential of the treated soils were calculated and the effect of curing on the strength was marked. Curing was done for 2, 7, 14, and 28 days. All the above-mentioned tests were performed for both CL and CH.

3.3.5.1 Atterberg limits of treated soil

Atterberg’s limits were calculated according to ASTM D4318-10 LL, PL, and PI were calculated for soils treated with Gypsum and RHA.

3.3.5.2 Compaction characteristics of treated soil

Standard Proctor test was performed for the soil treated with optimum Gypsum, optimum RHA and optimum Gypsum and optimum RHA to draw relationship between OMC and MDD.

3.3.5.3 Unconfined compressive strength of treated soil

Two UCS samples were prepared with optimum Gypsum, optimum RHA and optimum Gypsum and optimum RHA. These samples were prepared at 95 percent of OMC and MDD as calculated in Proctor test. Samples were wrapped in air tight plastic bags and were cured for 2, 7, 14, and 28 days at 30 degrees Celsius in an oven before testing. The average value of the two specimens was recorded.

3.3.5.4 California bearing ratio of treated soil

CBR test was performed with optimum Gypsum, optimum RHA, and optimum Gypsum and optimum RHA in combination. Both soaked and unsoaked tests were performed for treated soils.

3.3.5.5 Swell potential of treated soil

Swell potential test was performed according to AASHTO standard T193-13. Surcharge weight of 5 kg was kept on the CBR sample and sample was kept in a soaking tub for 96 hours. Change in the heights of the soil level was calculated as the percent swell.

Chapter 4

RESULTS AND DISCUSSIONS

4.1 GENERAL

This chapter explains the results obtained, based on the testing performed to check the suitability of Gypsum and RHA as soil stabilizers.

4.2 PHASE I: PROPERTIES OF NATURAL SOIL

4.2.1 Insitu Moisture Content of Soil

In-Situ moisture content was calculated using oven dry method of ASTM D2216-98 for CL. The in-situ moisture content was determined as 13.47 percent. As CH was made artificially so, its moisture content was not possible to find.

4.2.2 Grain Size Distribution (GSD)

GSD was calculated for both the soils, following ASTM standard D422-07. For CL, 95.60 percent of soil passed through sieve #200 and for CH, 96.48 percent sample passed through sieve #200.

4.2.3 Hydrometer Analysis

Hydrometer analysis was done according to ASTM standard D7928-16. The hydrometer test results showed that in the case of CL, 18 percent was less than 2 microns while for CH, 32 percent was less than 2 microns.

4.2.4 Atterberg Limits of Soil

Casagrande apparatus was used to calculate the LL of soils and for PL, 1/8” threads were made according to ASTM standard D4318-10.

The LL for CL was determined as 46 percent while PL and PI were 22.36 percent and 23.75 percent respectively. According to USCS the soil was classified as "low plastic clay" and as per AASHTO classification system the soil was classified as A-7-6.

In the case of CH, LL was increased from 46 to 59 percent, plastic limit came out to be 23 percent while PI was increased from 23.75 to 36 percent. By the addition of 25 percent of bentonite plasticity of soil was increased due to a greater percentage of fines. Results are shown in figure below:

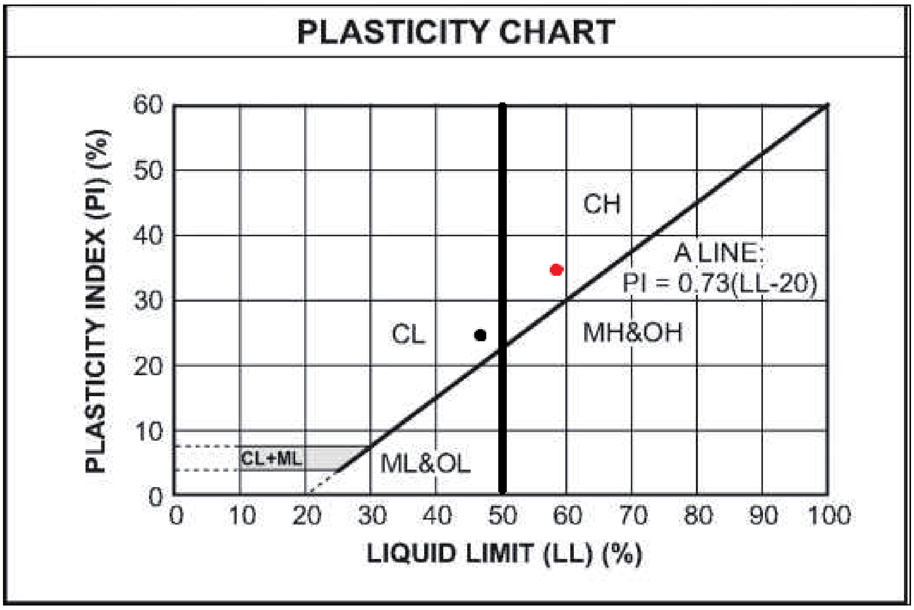

Figure 4.1: Classification of soil USCS (CL and CH)

4.2.5 Specific Gravity (G_s)

Specific gravity test was performed for both CL and CH using ASTM standard D854-14. The value of specific gravity for CL was determined as 2.67 while that of CH was 2.70.

4.2.6 Moisture-Density Relation of Soil

The values of MDD and OMC for CL were determined as 1.702 g/cm^3 and 18.25 percent respectively. Similarly, the values of MDD and OMC for CH were determined as 1.676 g/cm^3 and 21.7 percent respectively. Moisture-density curves for both soils are given in the figure below:

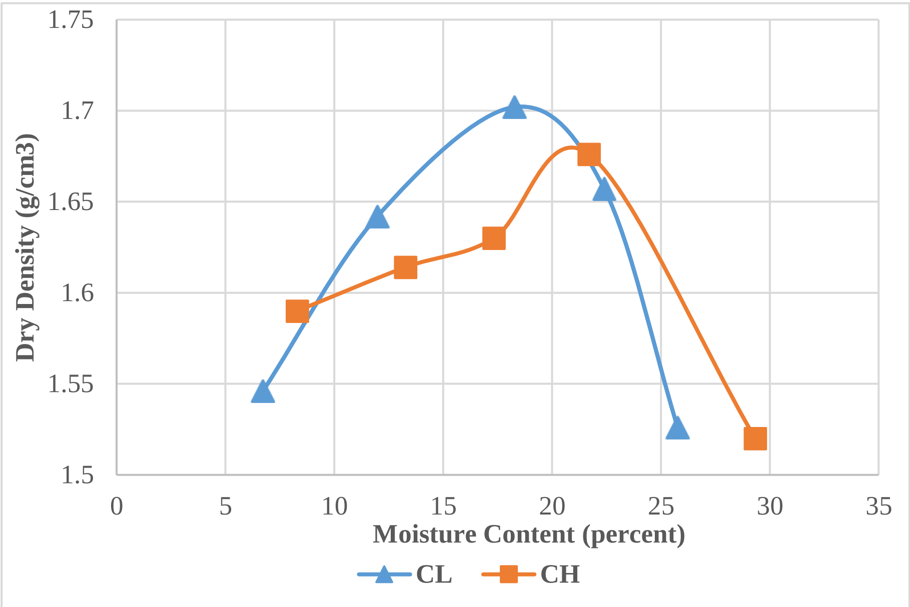

Figure 4.2: Comparison of compaction curves of (CL) and (CH)

4.2.7 Unconfined Compressive Strength of Soil

The UCS of both CL and CH was calculated following ASTM standard D2166-13. The UCS of CL was calculated as 127.6 kPa for unsoaked conditions while for soaked conditions, the UCS was reduced to 23.7 kPa. The reduction in strength of the soil is due to contact of soil with moisture. Results of unsoaked testing is shown in the Figure 4.3, while results of soaked test for CL is shown in the Figure 4.4.

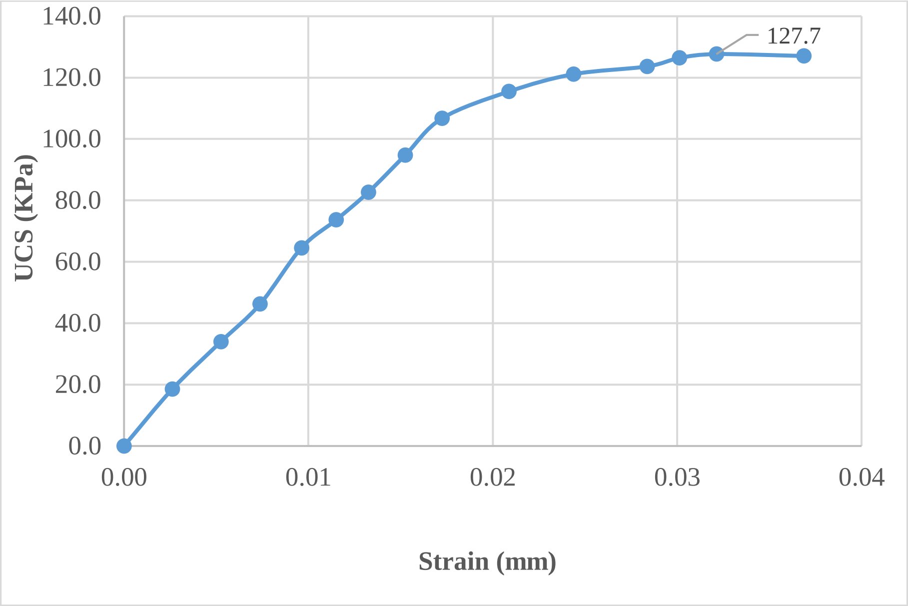

Figure 4.3: UCS test results of CL soil (unsoaked)

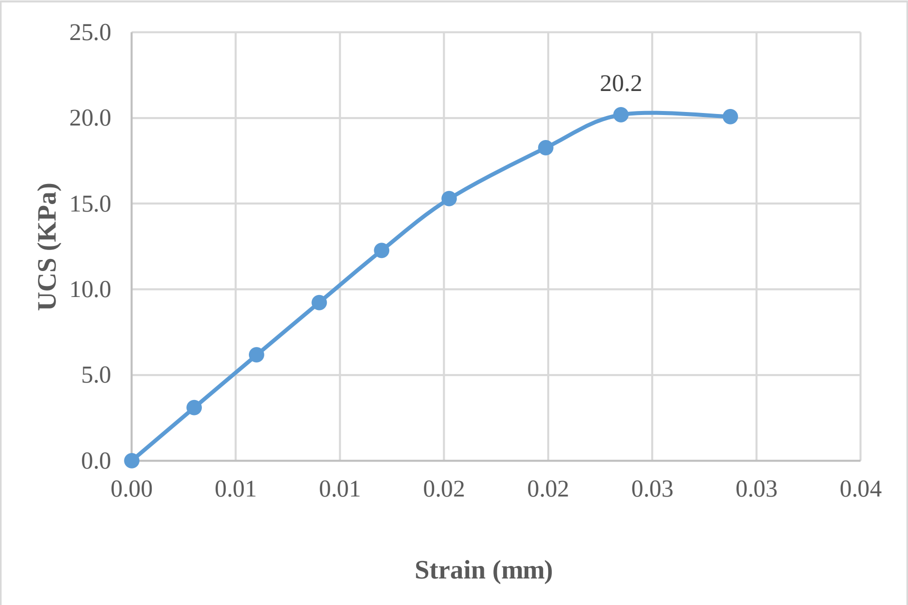

Figure 4.4: UCS test results of CL soil (soaked)

Similarly, UCS for CH was calculated as 151.3 kPa for unsoaked conditions while when the soil was soaked for 48 hours the value was reduced to 20.2 kPa. In the case of CH, the effect of soaking was more severe as compared to that of CL because of the presence of bentonite, which is a highly swelling clay. Unsoaked and soaked test results are shown in Figure 4.5 and Figure 4.6 respectively.

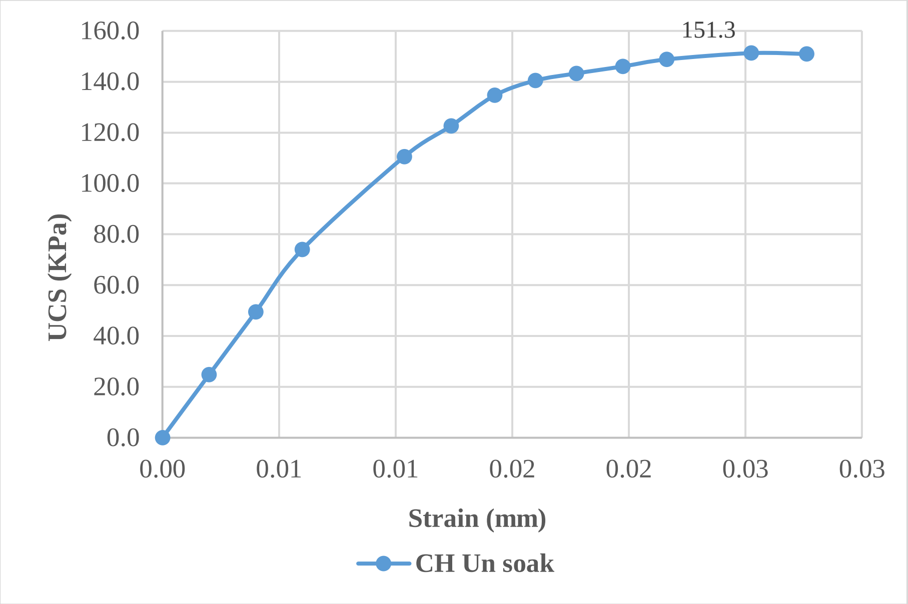

Figure 4.5: UCS test results of CH soil (unsoaked)

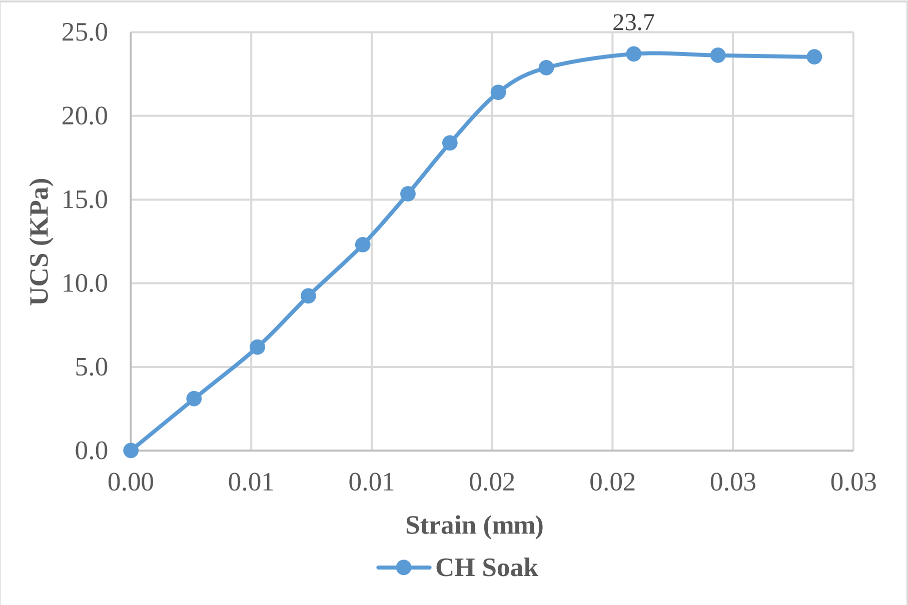

Figure 4.6: UCS test results of CH soil (soaked)

4.2.8 California Bearing Ratio (CBR)

The value of unsoaked CBR was 3.1 percent and that of soaked CBR was 1.7 percent for CL, while in case of CH, unsoaked CBR was 1.5 percent and soaked CBR was 1 percent. Both CL and CH were classified as poor subgrade materials according to the standard (TRH, 1996). Results of the CBR test performed for CL and CH are shown in Figure 4.7 and Figure 4.8 respectively.

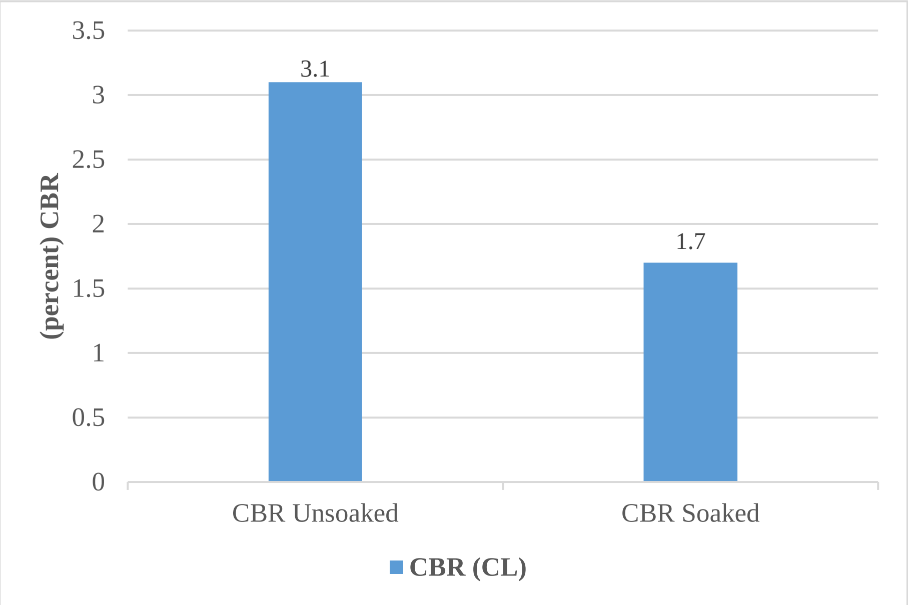

Figure 4.7: Unsoaked vs soaked CBR (CL)

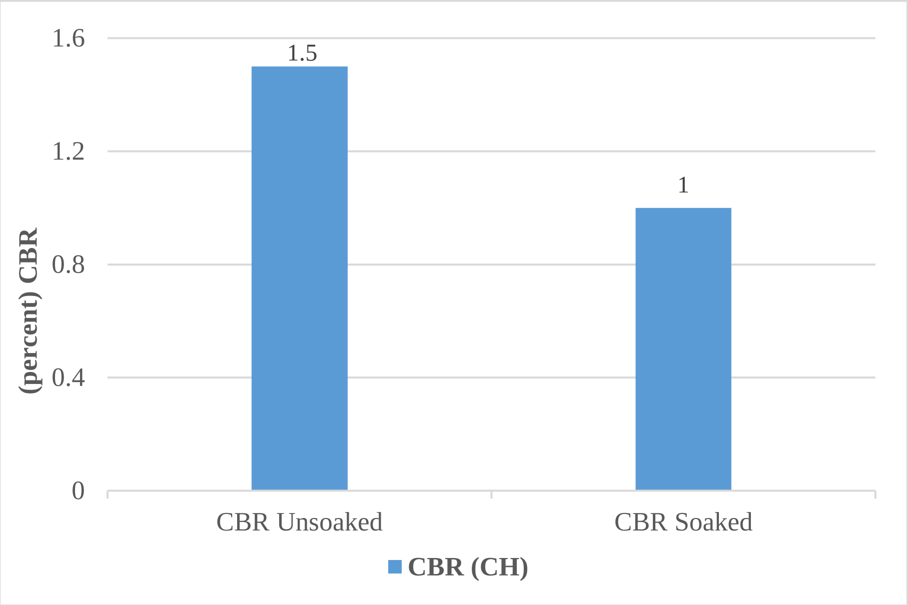

Figure 4.8: Unsoaked vs soaked CBR (CH)

4.2.9 Swell Potential of Soil

The swell potential was calculated from soaked CBR samples according to AASHTO standard T193-13. Samples were prepared at OMC and MDD and kept for soaking for 96 hours and change in the heights of soil was calculated as percent swell of the soil. The one-dimensional swell potential of CL was 6.01 percent and that of CH was 8.04 percent. Results of swell potential test for CL and CH are shown in the Figure 4.9.

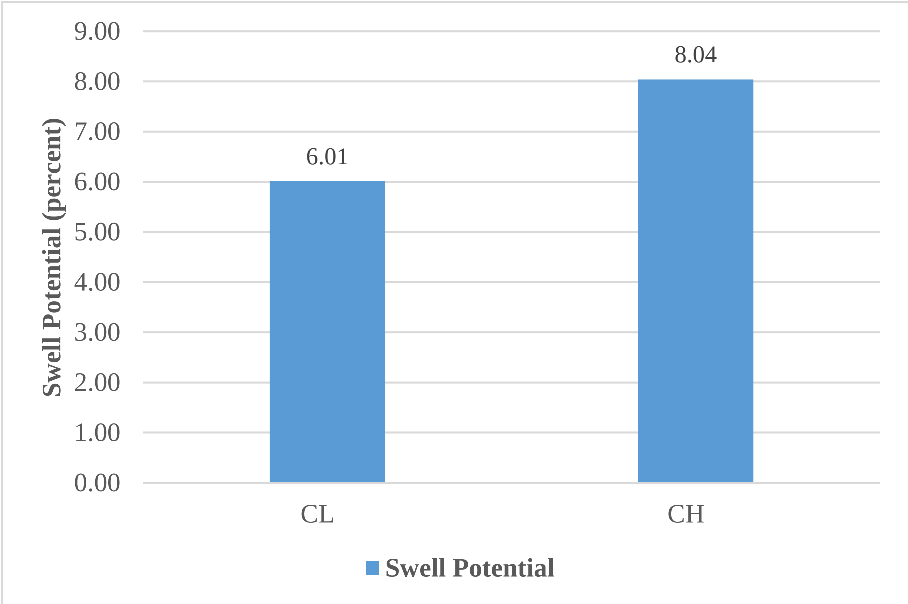

Figure 4.9: Swell potential comparison for CL and CH

Table 4.1: Summary of properties of natural soil (CL and CH)

Summary of Properties of Natural Soil				
Property	**CL**		**CH**	
Liquid Limit (percent)	46.11		59.03	
Plastic Limit (percent)	22.36		23.1	
Plasticity Index (percent)	23.75		35.9	
Percent Passing Seive #200	95.60		96.48	
Silt (percent)	37		27	
Clay(percent)	63		73	
Soil Type	USCS	CL	USCS	CH
	AASHTO	A-7-6	AASHTO	A-7-6
Natural Moisture Content (percent)	13.21		-	
Specific Gravity Of Soil	2.67		2.70	
Maximum Dry Density g/cm3	1.702		1.676	
Optimum Moisture Content (percent)	18.28		21.7	
UCS (kPa)	Unsoaked	127.6	Unsoaked	151.3
	Soaked	23.7	Soaked	20.2
CBR (percent)	3.1		1.7	
One Dimensional Swell Potential (percent)	6.01		8.04	

4.3 PHASE II: OPTIMIZATION OF GYPSUM CONTENT

In this stage, both soils under study were tested with different percentages of Gypsum to check its effect on the engineering properties of the soil. The optimum percentage of the Gypsum is the one which gives the highest value of UCS.

4.3.1 Moisture-Density Relation at Different Percentages of Gypsum

Standard Proctor tests were performed by adding 9, 12, 15, and 18 percent of Gypsum by mass to both CL and CH.

For CL with 12 percent Gypsum, there is the maximum change in moisture content and dry density of the soil. OMC with 12 percent Gypsum was calculated as 23.13 percent and MDD was calculated as 1.62 g/cm^3. Similarly for CH, maximum effect on dry density and moisture content was observed by adding 15 percent Gypsum. OMC was calculated as 24.99 percent while MDD was 1.60 g/cm^3. The variation of MDD and OMC with different percentages of Gypsum are shown in the Figure 4.12 and Figure 4.13 respectively.

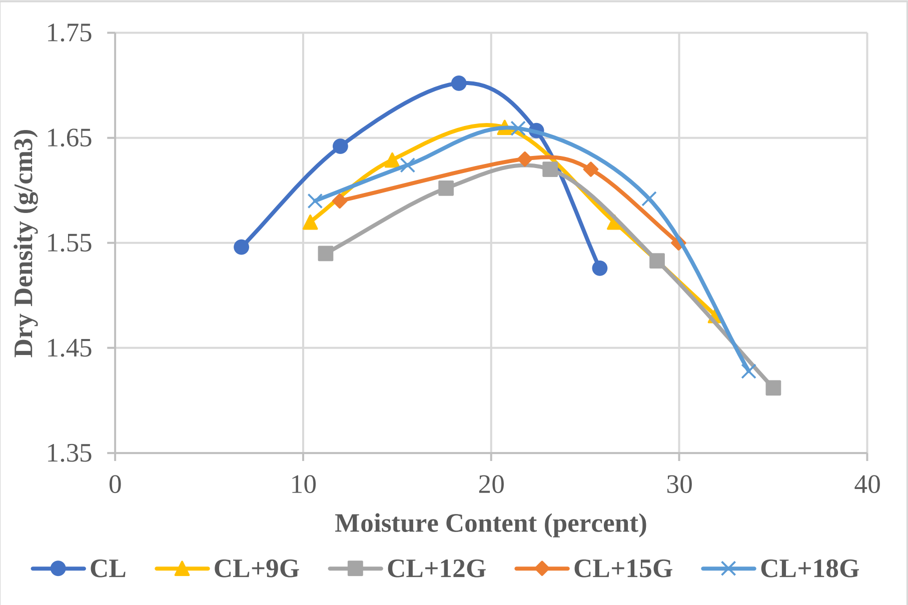

Figure 4.10: Compaction curves at different percentages of Gypsum (CL)

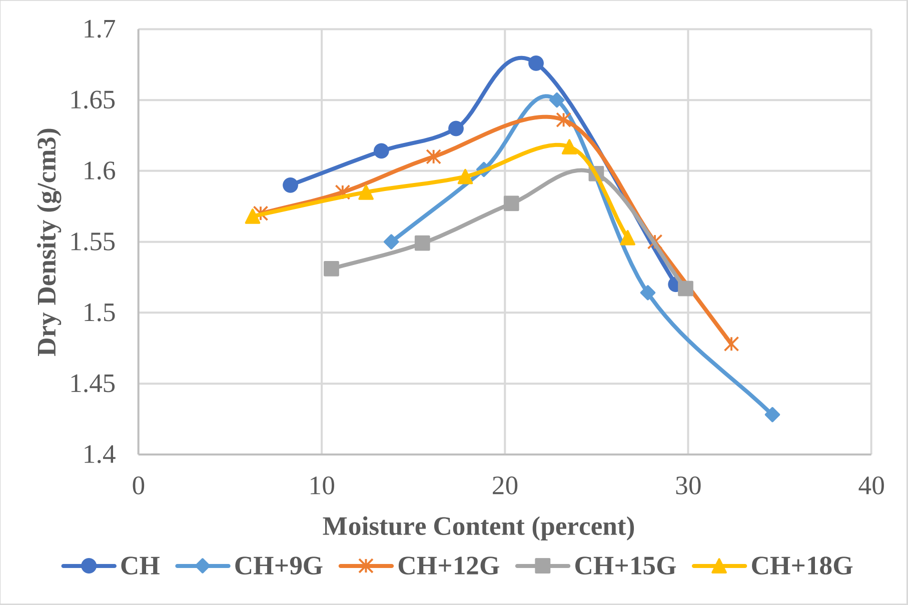

Figure 4.11: Compaction curves at different percentages of Gypsum (CH)

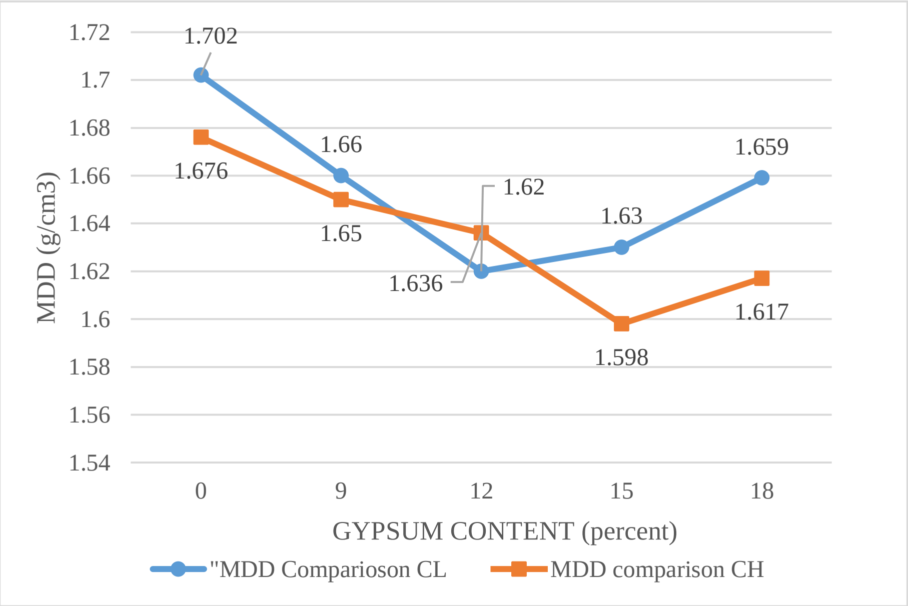

Figure 4.12: Comparison of MDD at different percentages of Gypsum (CL and CH)

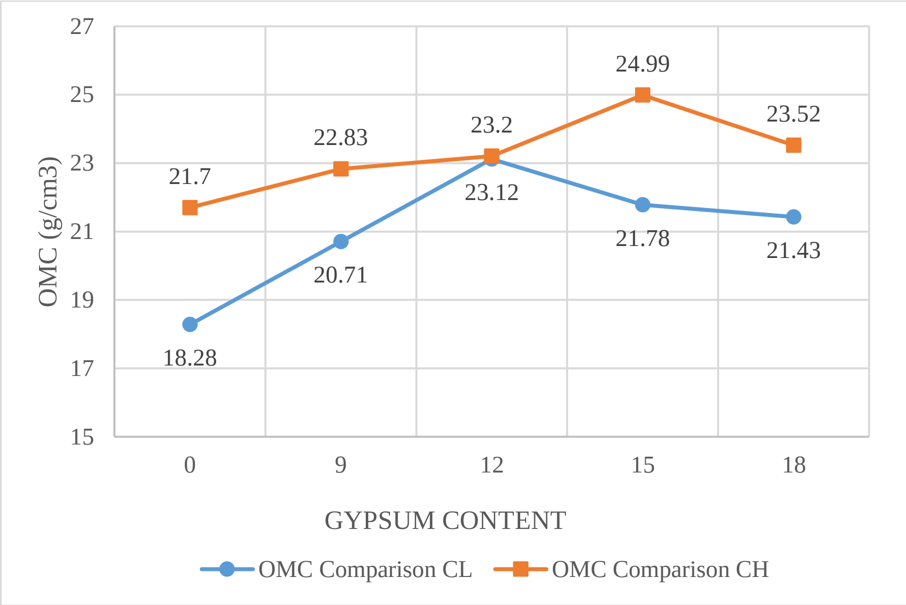

Figure 4.13: Comparison of OMC at different percentages of Gypsum (CL and CH)

The decrease in MDD and increase in OMC can be observed for both CL and CH. The increase in the MDD can be explained by flocculation of the soil particles upon the addition of Gypsum. If soil particles are large, it will occupy more space, and the amount of voids in the soil will increase which will reduce the MDD of soil. The MDD of the soil also decreases because compaction becomes difficult when the size of soil particle increases. The increase in the OMC can be explained on basis of the size of Gypsum particles. As size of Gypsum powder is smaller than the size of soil particles, so its surface area will be more and will require more water to lubricate the soil particles. The increase in the OMC is also due to the pozzolanic reaction between Gypsum and soil. Pozzolanic reaction results in long-term strength gain of the soil and greatly depends on the availability of Ca^{2+} ions.

4.3.2 Unconfined Compressive Strength at Different Percentages of Gypsum

UCS samples were prepared at 95 percent of OMC and MDD obtained from compaction test. The samples were cured for 7 days and then tested for both CL and CH. The percentage of Gypsum giving the maximum UCS was considered as the optimum percentage of Gypsum.

From the testing, it was concluded that for CL, 12 percent Gypsum was considered as the optimum percentage, as it gives UCS of 272.4 kPa while in case of CH, 15 percent Gypsum was the optimum percentage giving the highest values of the UCS i.e. 369.8 kPa. The results of UCS performed for CL and CH at different percentages of Gypsum are shown in the Figure 4.14 and Figure 4.15respectively.

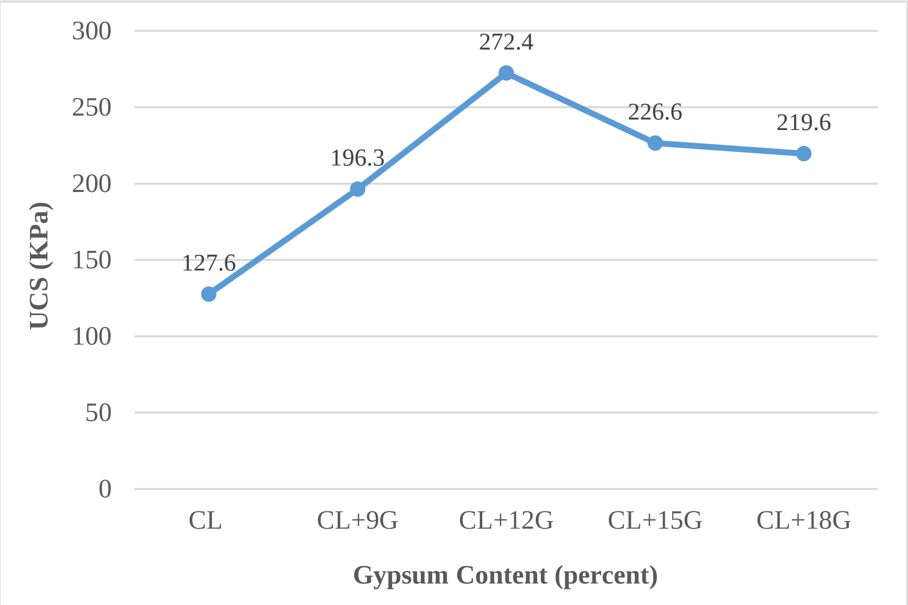

Figure 4.14: Comparison of UCS at different percentages of Gypsum (CL)

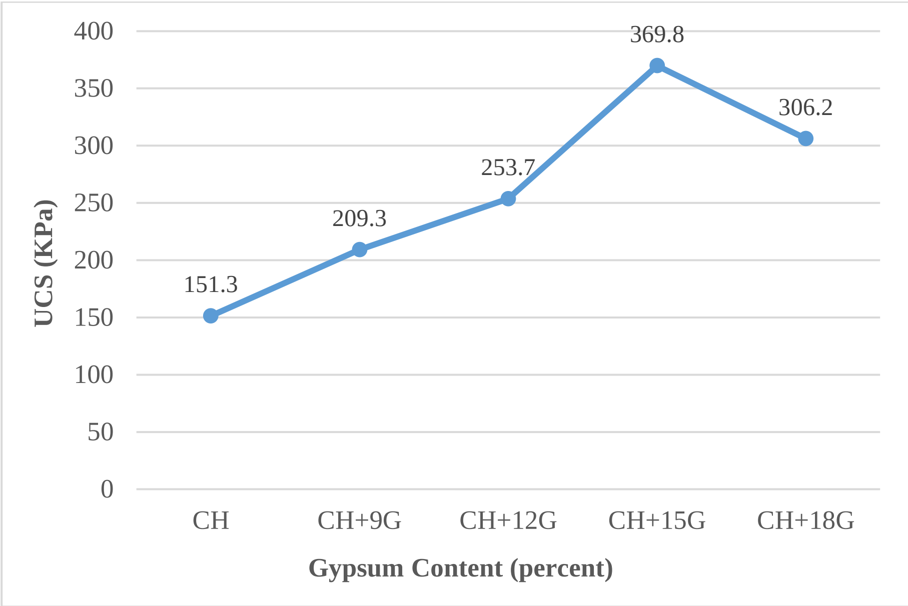

Figure 4.15: Comparison of UCS at different percentages of Gypsum (CH)

4.3.3 Excessive Moisture Optimization

Gypsum needs water for initiation as well as hydration of the chemical reaction with soil. So, for chemical reaction to proceed some extra water is added to check its effect on the UCS of soil, but the addition of too much water reduces the strength of the soil sample.

Samples were prepared with moisture 1 percent, 2 percent, and 3 percent greater than that of OMC and their strengths were checked. The optimum percentage of extra moisture for CL treated with Gypsum is 1 percent which gives the highest value of UCS i.e. 289.6 kPa while for CH, 2 percent of extra moisture gave 402.5 kPa strength which is highest value of UCS, as shown in the Figure 4.16 and Figure 4.17 respectively.

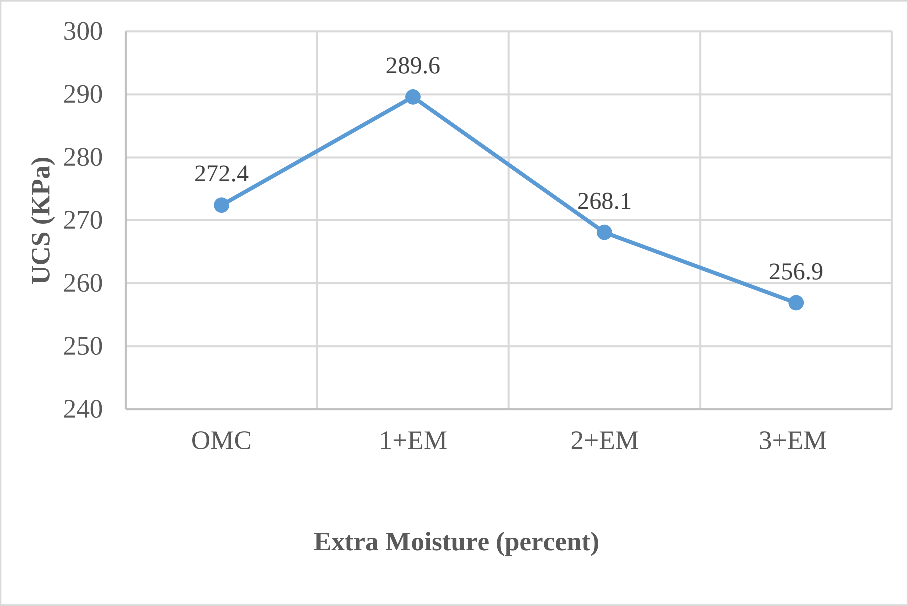

Figure 4.16: Effect of extra moisture on the Gypsum-treated soil (CL +12 Gypsum)

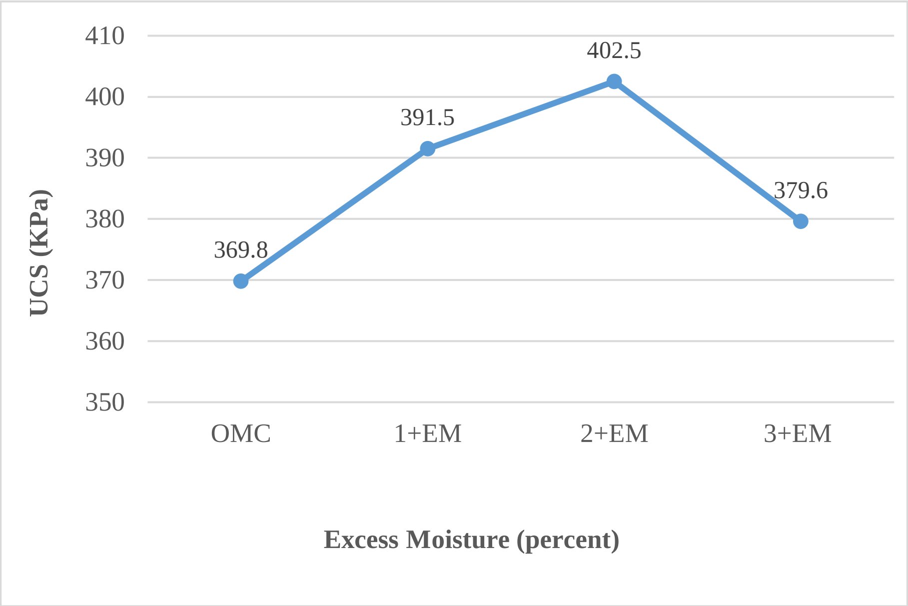

Figure 4.17: Effect of extra moisture on the Gypsum-treated soil (CH + 15 Gypsum)

Table 4.2: Summary of test results for the optimization of Gypsum

Summary of Optimization of Gypsum		
Property	**CL (12 percent Gypsum)**	**CH (15 percent Gypsum)**
OMC (percent)	23.13	24.99
MDD g/cm^3	1.62	1.60
UCS (unsoaked) (kPa)	272.4	369.8
UCS Excess Moisture (kPa)	1 (percent) 289.6	2 (percent) 402.5

4.4 PHASE III: OPTIMIZATION OF RHA

In this phase both the soils under study were tested with different percentages of RHA to check its effect on the engineering properties of CL and CH. The optimum percentage of the RHA is the one which gives the highest value of UCS.

4.4.1 Moisture-Density Relation at Different Percentages of RHA

For moisture density relation Standard Proctor tests were performed by adding 4, 8, 12, 16, and 20 percent of RHA by mass to both CL and CH. MDD and OMC of both the soils were calculated.

For CL maximum effect on moisture content and dry density was observed by adding 12 percent RHA. OMC with 12 percent RHA was calculated as 23.54 percent and MDD was calculated as 1.565 g/cm^3 Figure 4.18.

For CH, maximum effect on moisture content and dry density was observed by adding 16 percent RHA. OMC was calculated as 24.43 percent while MDD was 1.452 g/cm^3 Figure 4.19.

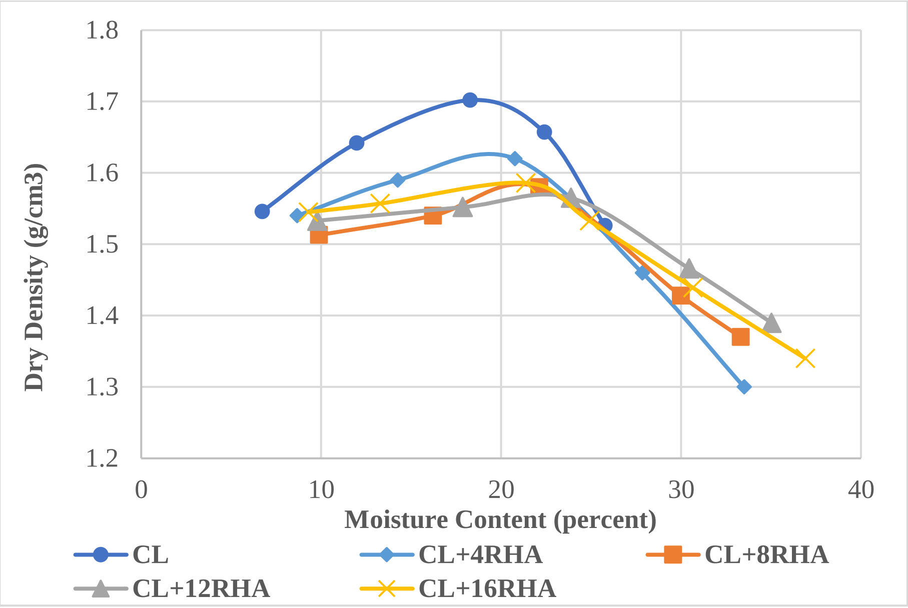

Figure 4.18: Compaction curves at different percentages of RHA (CL)

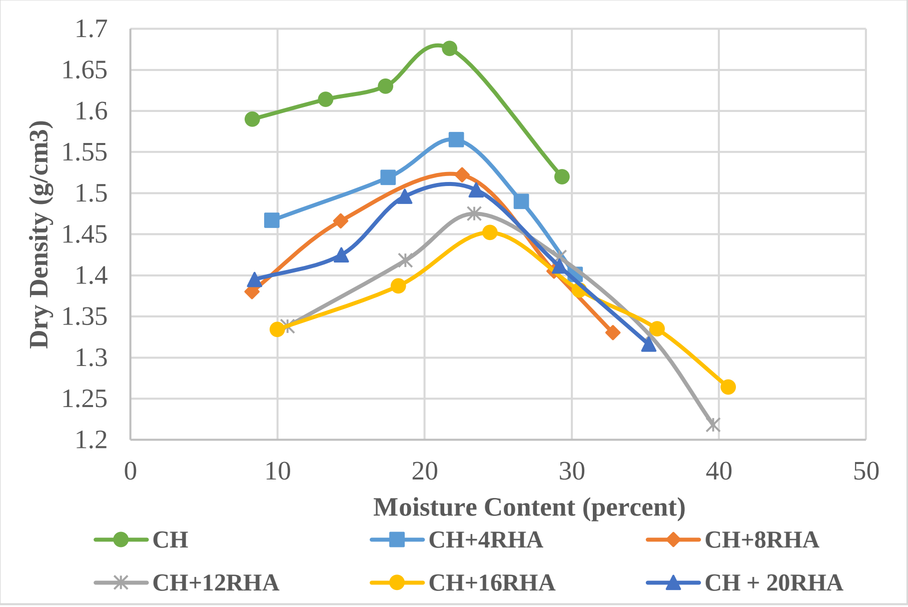

Figure 4.19: Compaction curves at different percentages of RHA (CH)

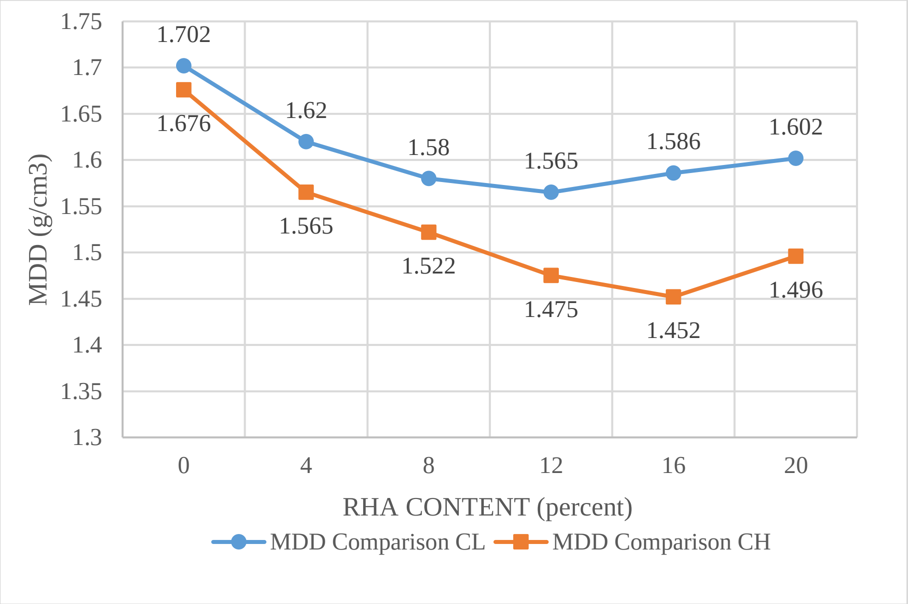

Figure 4.20: Comparison of MDD at different percentages of RHA (CL and CH)

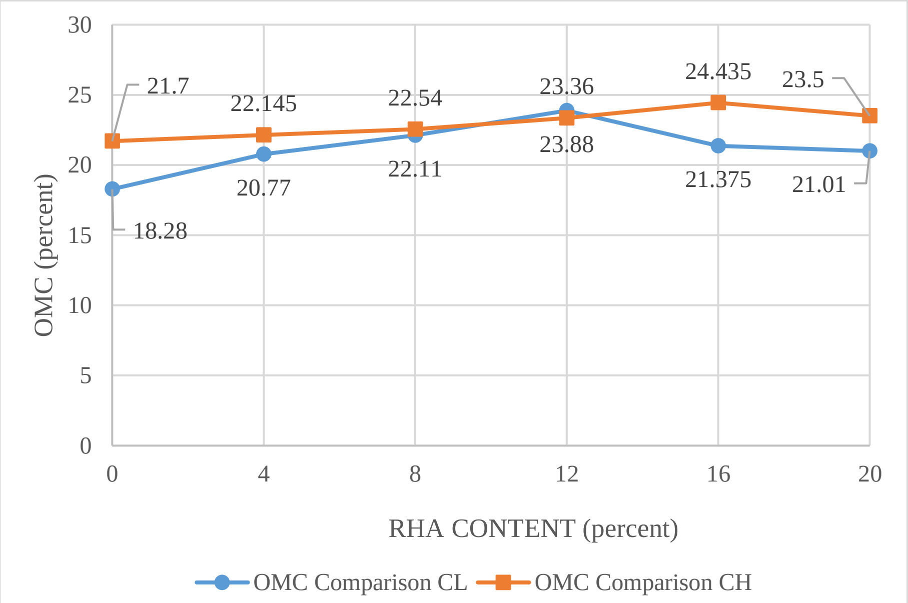

Figure 4.21: Comparison of OMC at different percentages of RHA (CL and CH)

The reduction in MDD with the addition of RHA can be seen in the Figure 4.20. The reduction in MDD can be explained based on flocculation and agglomeration as RHA is added to the soil. If soil particles are large, it will occupy more space, and the amount of voids in the soil will increase which will reduce the MDD of soil. The MDD of the soil also decreases because compaction becomes difficult when the size of soil particle increases. The rise in OMC can be explained on the basis that RHA is finer than soil and their surface area is greater due to which they require a greater amount of water for lubrication Figure 4.21.

4.4.2 Unconfined Compressive Strength at Different Percentages of RHA

Samples of UCS were prepared at the 95 percent OMC and MDD as obtained from compaction tests. These samples were cured for 7 days, covered in airtight plastic bags at 30 ºC in an oven and then tested. Two samples were prepared for each percentage of RHA and their average value was reported. The percentage of RHA which gives the highest value for UCS was considered as the optimum percentage of RHA.

After conducting the testing, results showed that for CL, 12 percent RHA was considered as optimum percentage giving 234.1 kPa strength while for CH, 16 percent RHA was considered as optimum percentage giving 331.2 kPa strength. The results of UCS performed for CL and CH with different percentages of RHA are shown in the Figure 4.22 and Figure 4.23 respectively.

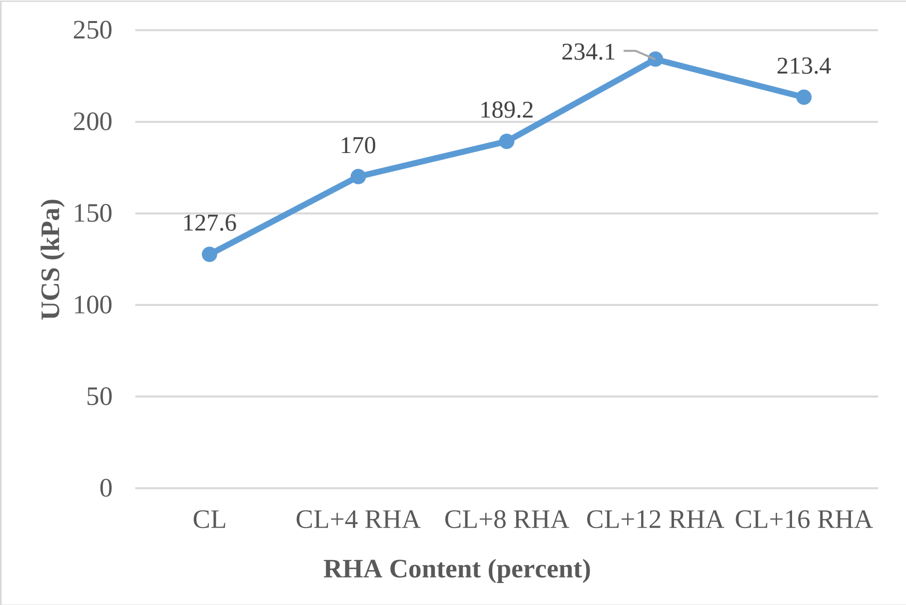

Figure 4.22: Comparison of UCS at different percentages of RHA (CL)

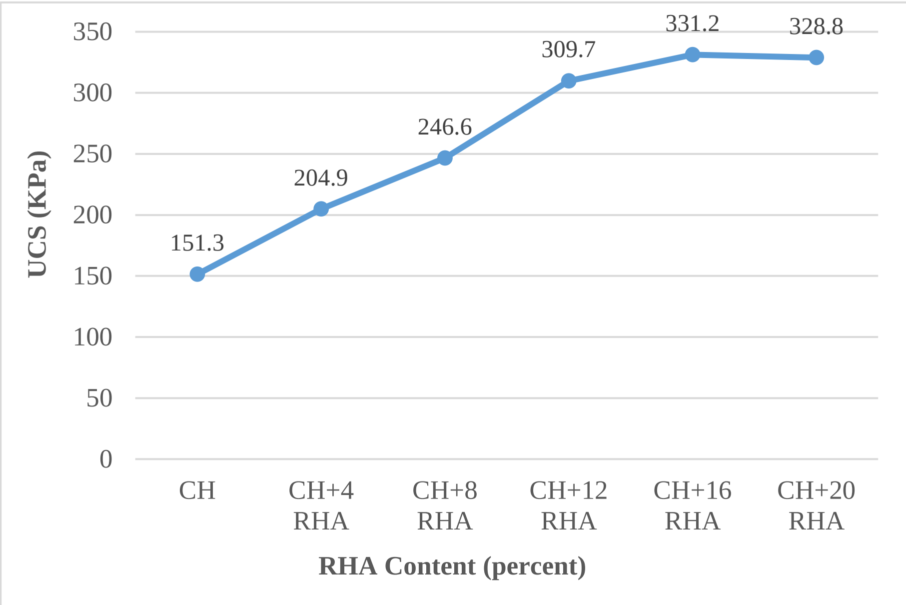

Figure 4.23: Comparison of UCS at different percentages of RHA (CH)

4.4.3 Excessive Moisture Optimization

RHA needs water for the hydration and as well as the initiation of a chemical reaction with soil, therefore some extra water is added to check its effect on the strength of soil, but if too much water is added it can reduce the strength of soil.

Samples were prepared with extra moisture of 1 percent, 2 percent, and 3 percent more than OMC. CL with 1 percent of extra moisture gave the value of 241.6 kPa while CH with 2 percent of extra moisture gave the value of 342.5 kPa as shown in the Figure 4.24 and Figure 4.25 respectively.

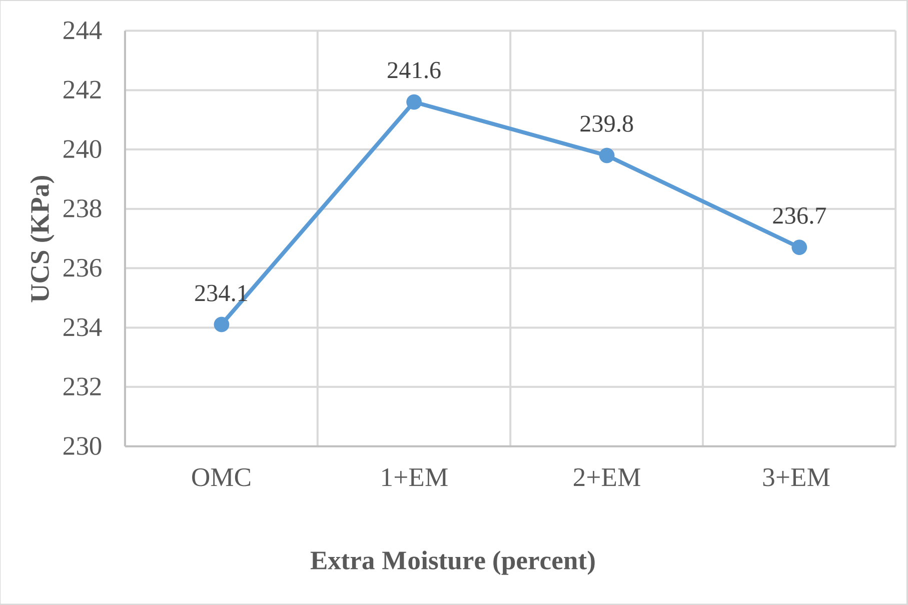

Figure 4.24: Effect of extra moisture on the RHA treated soil (CL+12 RHA)

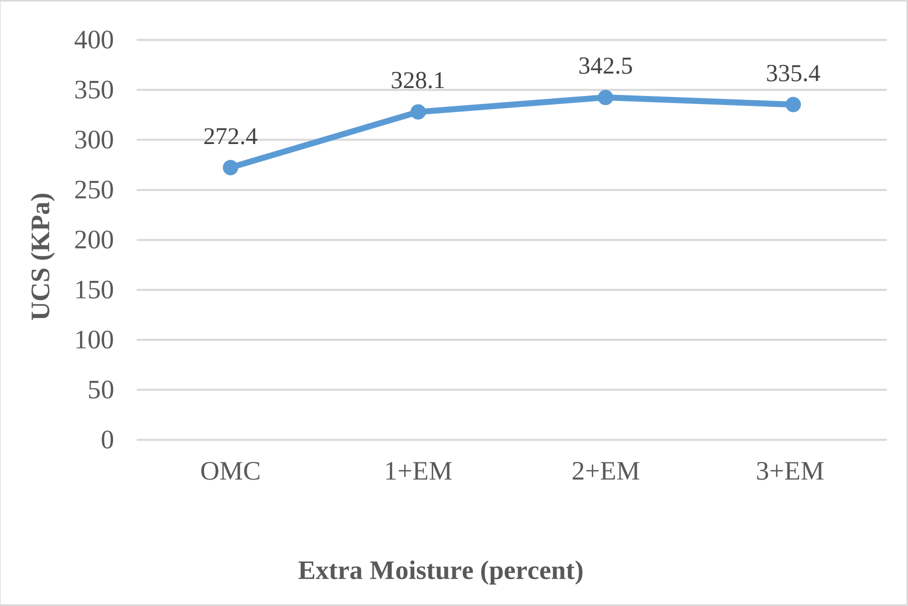

Figure 4.25: Effect of extra moisture on the RHA treated soil (CH+ 16 RHA)

Table 4.3: Summary of test results for the optimization of RHA

Summary of Optimization of RHA		
Property	**CL (12 percent RHA)**	**CH (16 percent RHA)**
OMC (percent)	23.54	24.43
MDD (g/cm^3)	1.565	1.452
UCS (Unsoaked) (kPa)	234.1	331.2
UCS Excess Moisture (kPa)	1 (percent) 241.6	2 (percent) 342.5

4.5 PHASE IV: OPTIMIZATION OF RHA WITH GYPSUM

In this phase, the optimum percentage of Gypsum for CL and CH was treated with 3, 6, 9, 12, and 15 percent RHA to optimize the percentage of RHA with Gypsum. Criteria for optimization of RHA with Gypsum was the same, the percentage which will give the maximum value for UCS will be considered as the optimum percentage of RHA with Gypsum.

4.5.1 Moisture-Density Relation at Different Percentages of RHA with Gypsum

Standard Proctor tests were performed at optimum Gypsum along with 3, 6, 9, and 12 percent RHA by mass for CL and 3, 6, 9, 12, and 15 percent RHA by mass for CH. Relation between dry density and moisture content were plotted for both the soils. Graphs below shows that for CL, 12 percent Gypsum and 9 percent RHA has maximum effect on the dry density and moisture content. While for CH, 15 percent Gypsum and 12 percent RHA has the maximum impact on the dry density and moisture content of the soil. MDD and OMC for CL were calculated as 1.502 g/cm^3 and 23.58 percent Figure 4.26. In case of CH, MDD and OMC were calculated as 1.433 g/cm^3 and 25.57 percent respectively Figure 4.29.

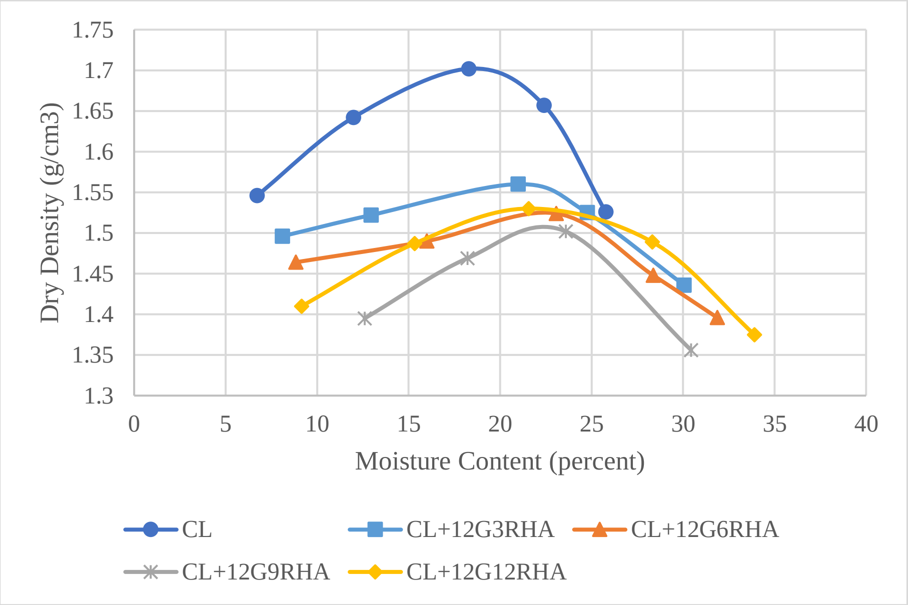

Figure 4.26: Compaction curves of optimum Gypsum with different percentages of RHA

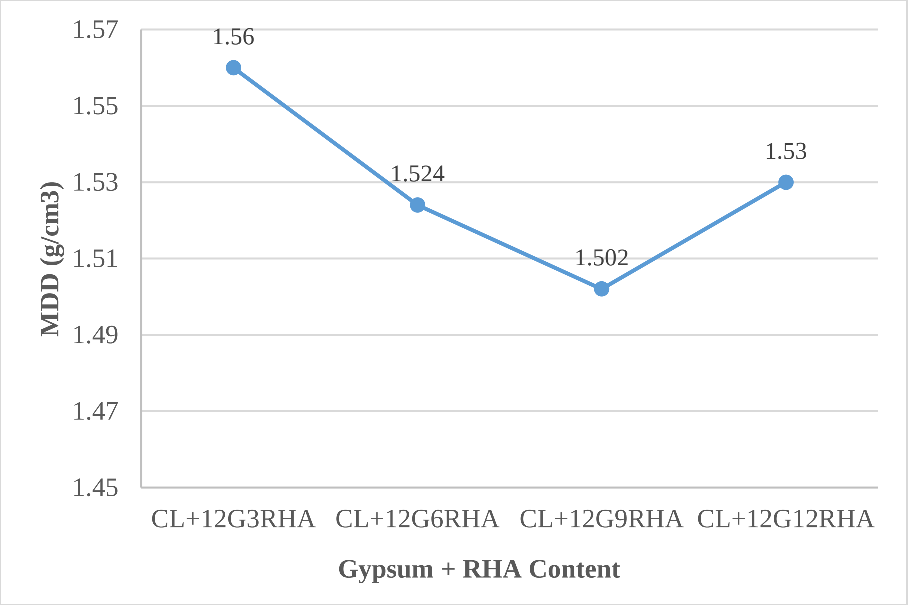

Figure 4.27: MDD at optimum Gypsum and different percentages of RHA (CL)

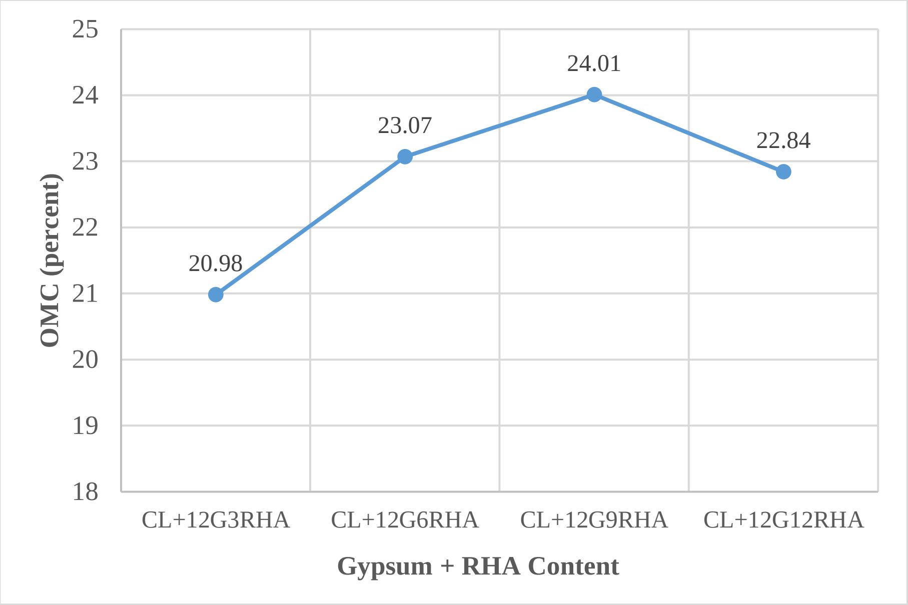

Figure 4.28: OMC at optimum Gypsum and different percentages of RHA (CL)

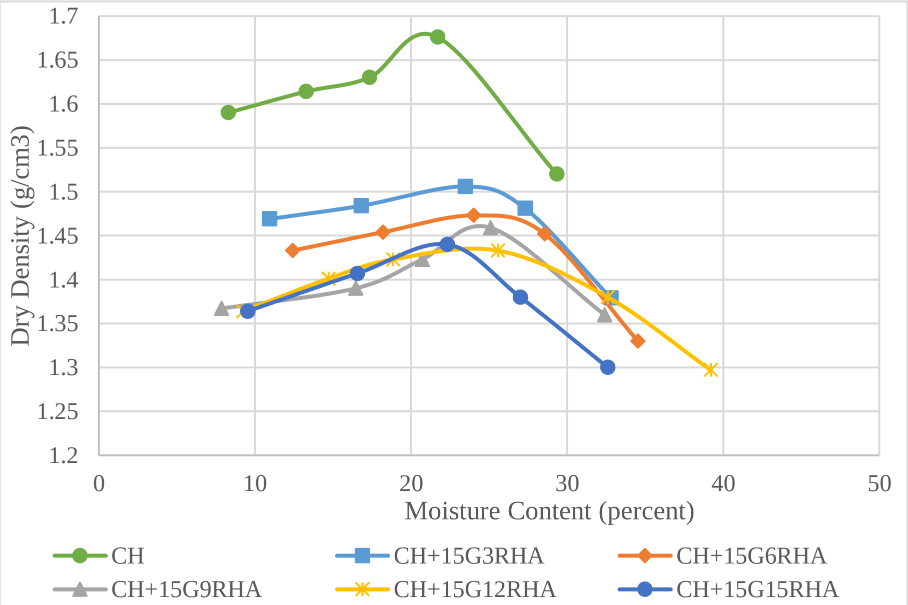

Figure 4.29: Compaction curves of optimum Gypsum with different percentages of RHA

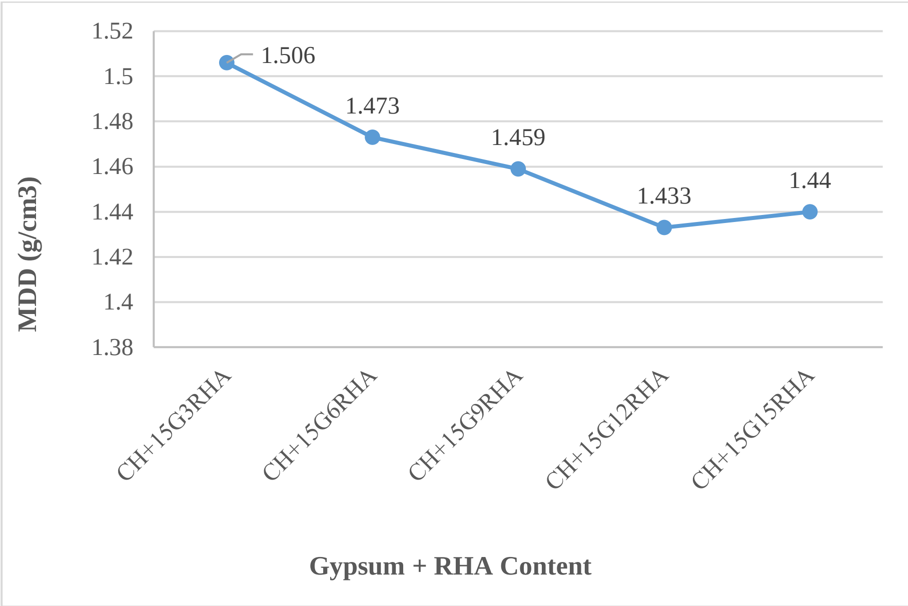

Figure 4.30: MDD at optimum Gypsum and different percentages of RHA (CH)

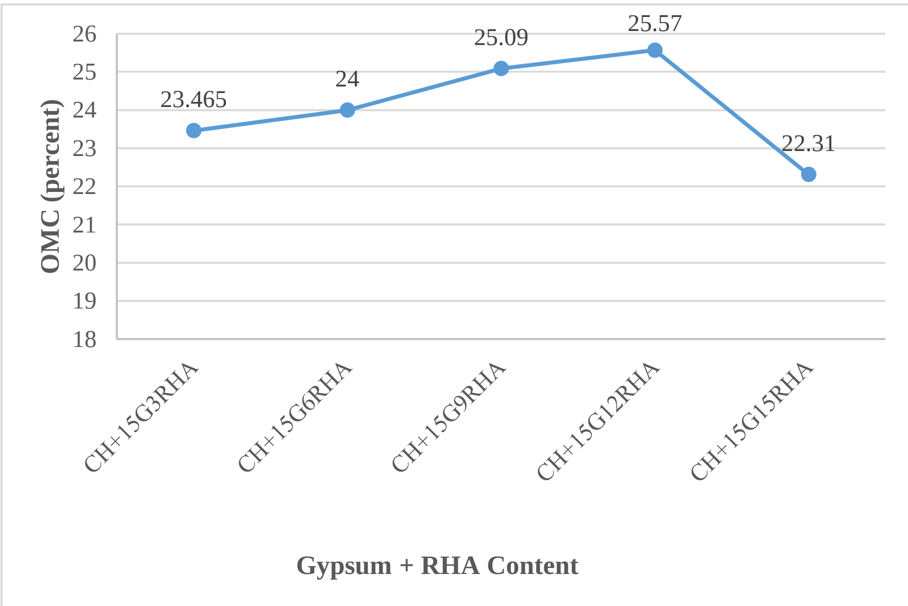

Figure 4.31: OMC at optimum Gypsum and different percentages of RHA (CH)

The reduction in MDD with the addition of RHA and Gypsum can be seen in the Figure 4.30. The reduction in MDD can be explained based on flocculation and agglomeration of the soil particles, as RHA and Gypsum are added to the soil. If soil particles are large, it will occupy more space, and the amount of voids in the soil will increase which will reduce the MDD of soil. The MDD of the soil also decreases because compaction becomes difficult when the size of soil particle increases. The rise in OMC can be explained on the basis that RHA is finer than soil and their surface area is greater due to which they require a greater amount of water for lubrication Figure 4.31.

4.5.2 Unconfined Compressive Strength at Different Percentages of RHA with Gypsum

UCS samples were prepared with optimum Gypsum and different percentages of RHA at 95 percent OMC and MDD as obtained from compaction tests. These samples were cured for 7 days coated in airtight plastic bags at 30 ºC in an oven and then tested. Two samples were prepared for each combination of Gypsum and RHA and their average value was calculated. The percentage of RHA which gives the highest UCS was optimum percentage of RHA with optimum Gypsum.

After conducting the test, results concluded that for CL, along with 12 percent Gypsum, 9 percent RHA gave the maximum value of UCS i.e. 364.5 kPa Figure 4.32 and was considered as the optimum percentage of RHA with Gypsum. Similarly for CH, along with 15 percent Gypsum, 12 percent RHA gave the maximum value of UCS i.e. 462.4 kPa Figure 4.33 and was considered as the optimum percentage of RHA with Gypsum.

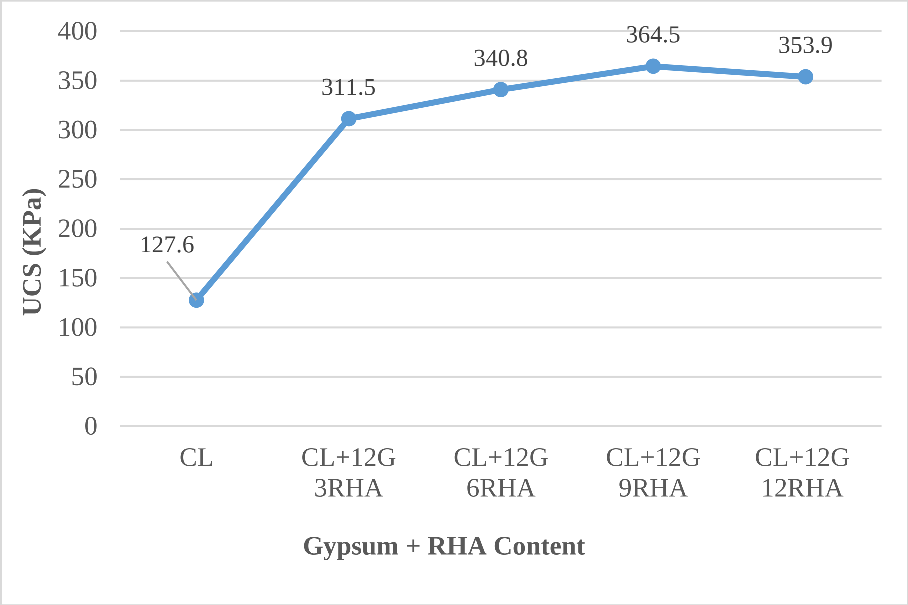

Figure 4.32: Comparison of UCS at optimum Gypsum and different percentages of RHA

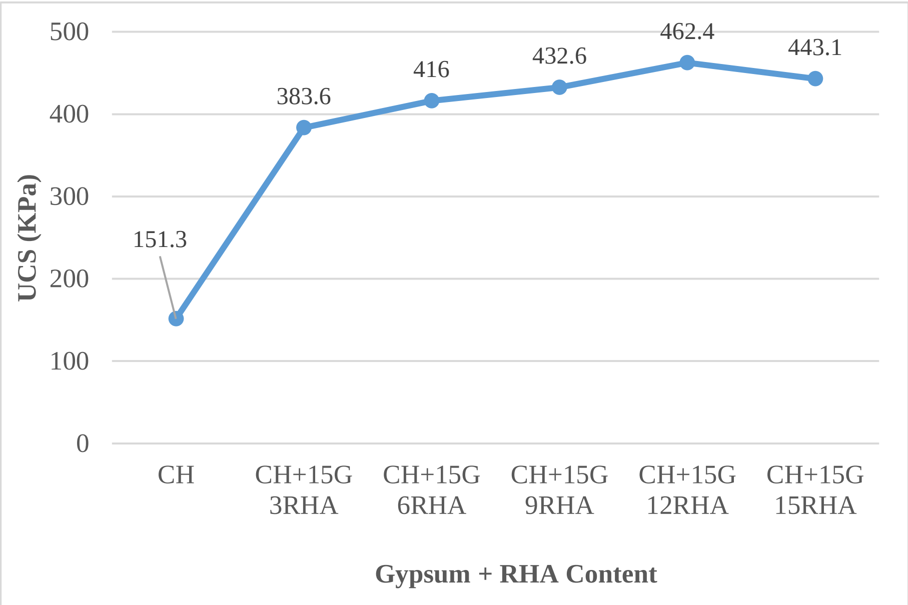

Figure 4.33: Comparison of UCS at optimum Gypsum and different percentages of RHA

4.5.3 Excessive Moisture Optimization

Gypsum, as well as RHA, need water for the hydration and as well as the initiation of a chemical reaction between soil, Gypsum, and RHA. So, for chemical reaction to proceed some extra water is added to check its effect on the UCS of soil, but too much water can reduce the UCS of soil.

Samples were prepared with 1 percent, 2 percent, and 3 percent of extra moisture above OMC. CL with 1 percent of extra moisture gave the value of 398.2 kPa while CH with 2 percent of extra moisture gave the value of 501.2 kPa as shown in the figures below:

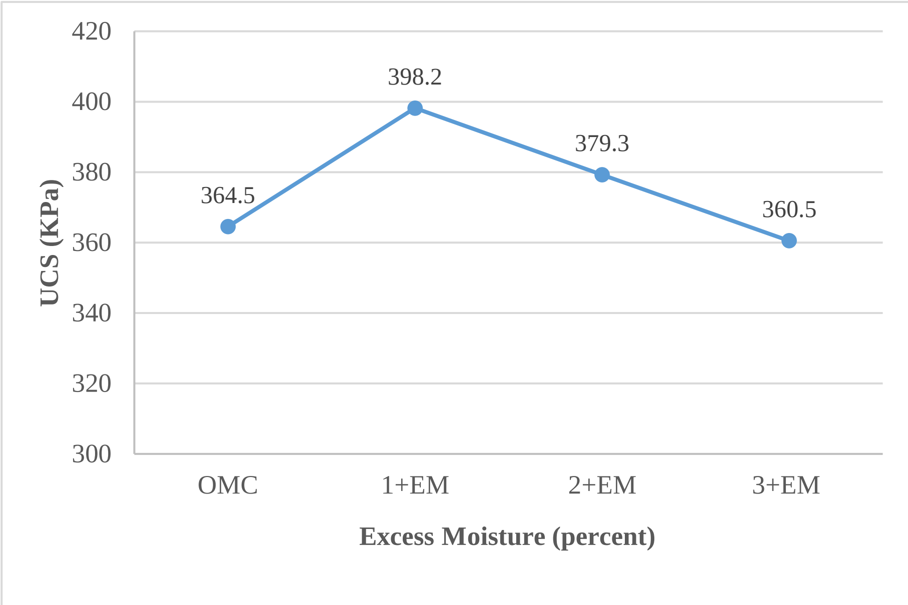

Figure 4.34: Effect of extra moisture on the Gypsum and RHA treated soil (CL + 12G + 9RHA)

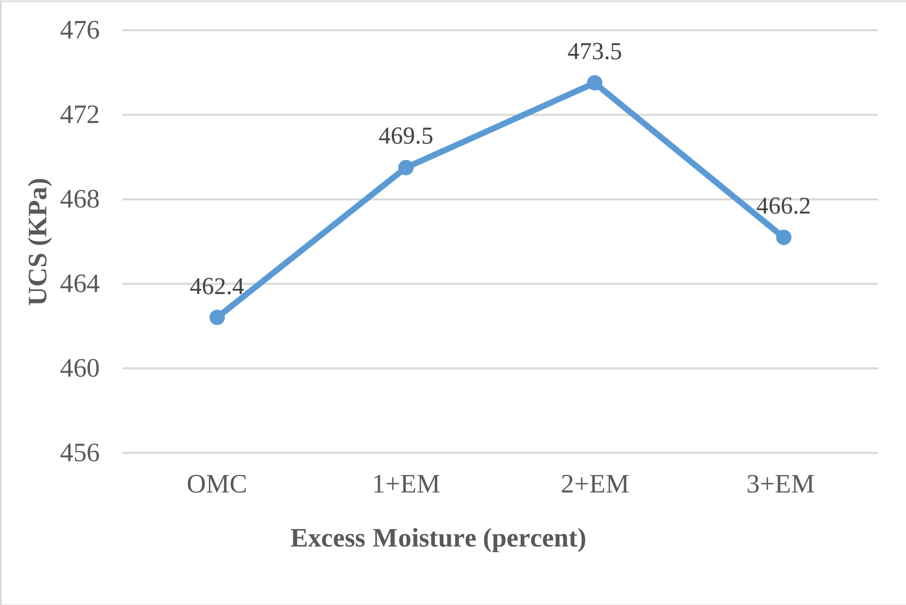

Figure 4.35: Effect of extra moisture on the Gypsum and RHA treated soil (CH + 15G +12RHA)

4.6 PHASE V: PROPERTIES OF TREATED SOIL

Once optimum percentages of Gypsum and RHA were known for CL and CH then testing was conducted to calculate: Atterberg limits, UCS, CBR, and swell potential of the soil. Curing was done for 2, 7, 14, and 28 days to check its effect on the properties of soil. This phase will decide that weather Gypsum and RHA are potential soil stabilizers or not.

4.6.1 Atterberg Limits of Soil

Classification of soils is done based on Index properties, they are calculated using Casagrande apparatus. The testing was conducted in three stages:

In first stage, both the soils were treated with optimum Gypsum, in the second stage both the soils were treated with optimum RHA, and in the third and final stage both the soils were treated with optimums of Gypsum and RHA.

When CL is treated with 12 percent Gypsum, LL was reduced from 46 to 39 percent Figure 4.36, PL was reduced from 22.36 to 22 percent, and PI was reduced from 23.64 to 17 percent Figure 4.37. Similarly, when CH was treated with 15 percent Gypsum LL was reduced from 59 to 52.7 percent Figure 4.38, PL was reduced from 23.1 to 22.5 percent and PI was reduced from 35.9 to 30.2 percent Figure 4.39.

When CL was treated with 12 percent of RHA, LL was reduced from 46 to 40.55 percent Figure 4.36, PL was reduced from 22.36 to 22.2 percent, and PI was reduced from 23.64 to 18.35 percent Figure 4.37. Similarly, when CH was treated with 16 percent RHA, LL was reduced from 59 to 53.29 percent Figure 4.38. PL was reduced from 23.1 to 23 percent and PI was reduced from 35.9 to 30.3 percent Figure 4.39.

In the final stage maximum effect was observed when both CL and CH were treated with combined Gypsum and RHA, LL of CL was reduced from 46 to 36.4 percent Figure 4.36, PL was reduced from 22.36 to 21.74 percent, and PI was reduced from 23.64 to 14.66 percent Figure 4.37. Similarly in case of CH, LL was reduced from 59 to 39.21 percent Figure 4.38, PL was reduced from 23.1 to 22.8 percent, and PI was reduced from 35.9 to 19.45 percent Figure 4.39.

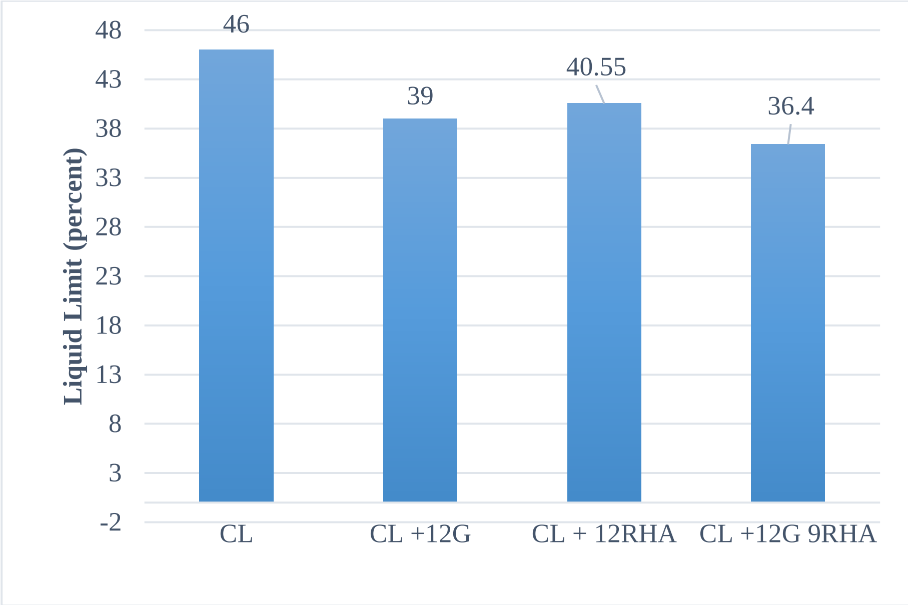

Figure 4.36: Comparison of liquid limit of treated soil (CL)

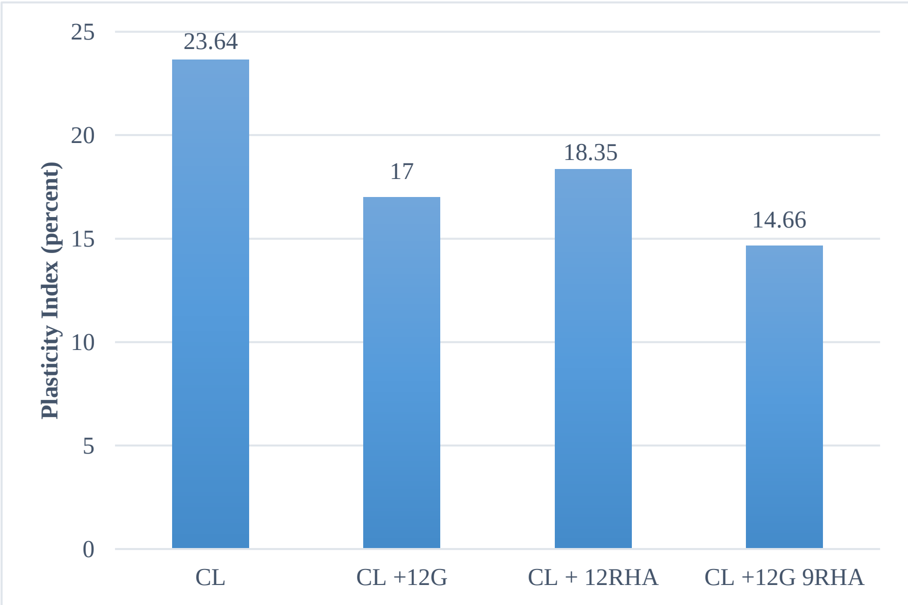

Figure 4.37: Comparison of the plasticity index of treated soil (CL)

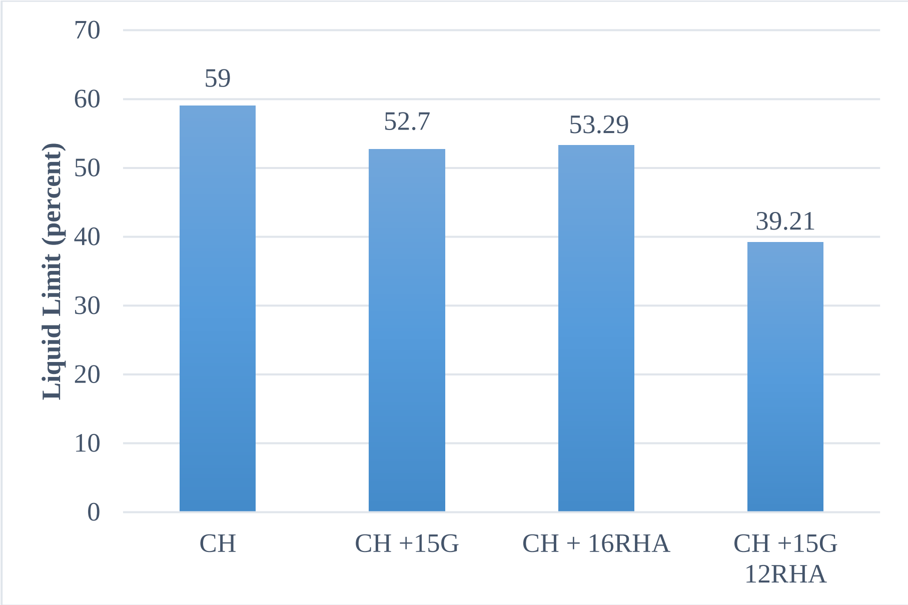

Figure 4.38: Comparison of liquid limit of treated soil (CH)

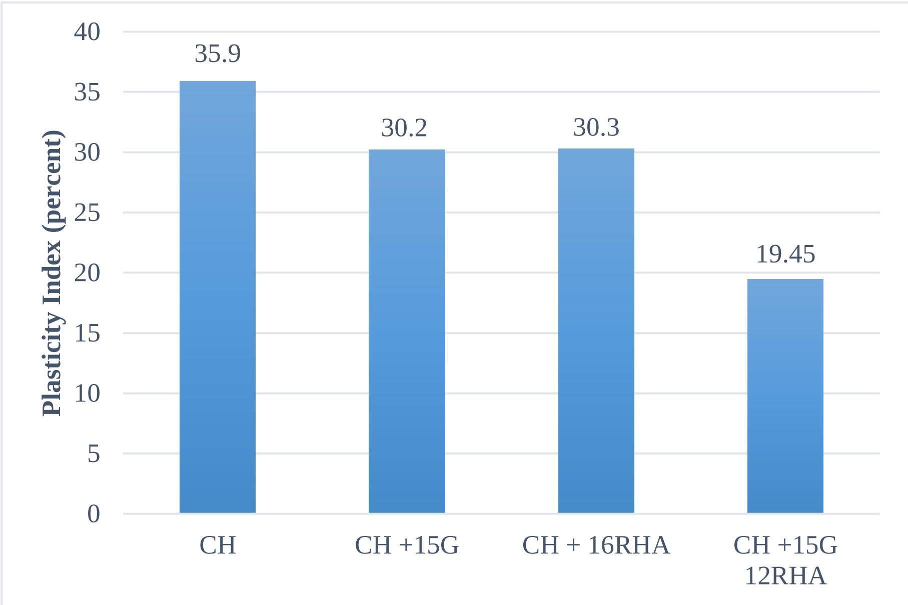

Figure 4.39: Comparison of the plasticity index of treated soil (CH)

With addition of Gypsum and RHA, LL and PI of both the soil reduces while PL of both the soils somehow remained same. The reduction in PI is attributed with reduction of LL. The process behind reduction of LL and PI is flocculation and agglomeration which increases the silty behavior of soil. Increase in coarseness of soil reduces the water holding capacity of soil. The effect on CH is more evident as compared to that of CL.

4.6.2 Moisture-Density Relation of Treated Soil

Compaction properties of treated soils are explained in phase IV Figure 4.26 and Figure 4.29. The figures show a decrease in the values of MDD and increase in the values of OMC.

4.6.3 Unconfined Compressive Strength of Treated Soil

As optimum percentage of Gypsum and RHA were obtained in phase IV for both CL and CH. Samples were prepared for testing at 95 percent of OMC and MDD for curing period of 2, 7, 14, and 28 days to monitor the increase in the strength with time. Testing was conducted both for soaked and unsoaked condition. Soaking was done by covering the samples in airtight bags and keeping them in a desiccator for 48 hours before testing. Soaked samples were tested to check the behavior of soil in moist conditions.

Figure 4.40 and Figure 4.41shows the comparative analysis of UCS of CL, CL + 12 percent Gypsum, CL + 12 percent RHA, and CL + 12 percent Gypsum + 9 percent RHA with time. The graphs indicates increase in the value of UCS with time when treated with additives.

When CL is treated with 12 percent Gypsum, its UCS value for 2 days is 154.5 kPa while after curing it for 28 days its UCS value is raised up to 430.5 kPa. Similarly, when CL is treated with 12 percent RHA, 2 days strength of the soil is 147.8 kPa while 28 days strength is 375.6 kPa. Maximum gain in strength is observed in case of combined addition of Gypsum and RHA i.e., 2 days strength of CL treated with optimum Gypsum and RHA is 182.2 kPa while that of 28 days strength is 698.7 kPa Figure 4.40.

In the case of soaked samples, the improvement in the strength with time is very high as compared to that of unsoaked strength. When CL is treated with 12 percent Gypsum, after soaking it for 2 days the UCS value comes out to be 42.4 kPa and after 28 days, the value rises to 268.5 kPa. Similarly when the soil is treated with 12 percent RHA, after soaking it for 2 days UCS value of the soil comes out to be 36.3 kPa while 28 days strength of sample was calculated as 225.7 kPa. The effect on the strength of the soil treated with 12 percent Gypsum and 9 percent RHA was the highest, 2 days-soaked strength of the soil was 62.3 kPa while that of 28 days strength of the CL was 401 kPa Figure 4.41.

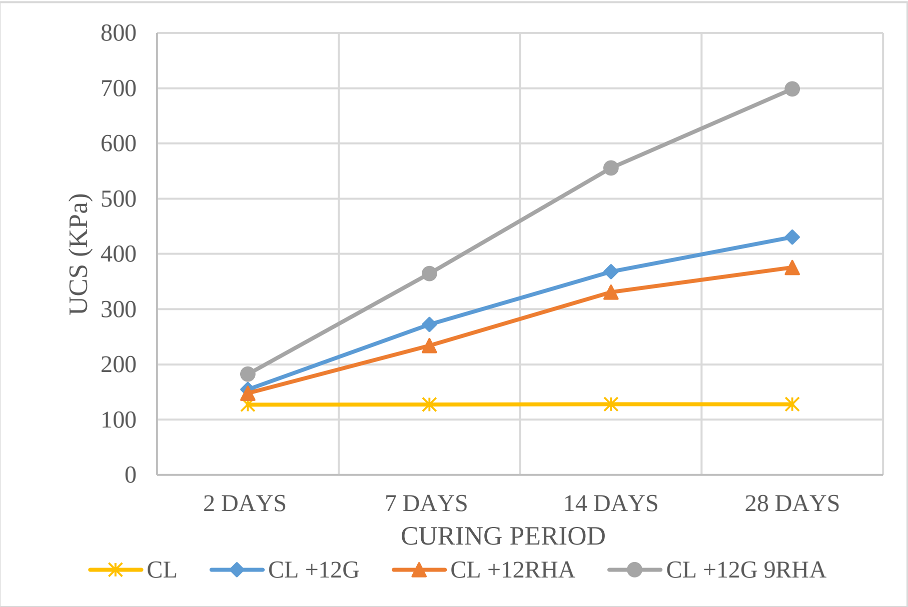

Figure 4.40: Unsoaked comparison of UCS of treated soils (CL)

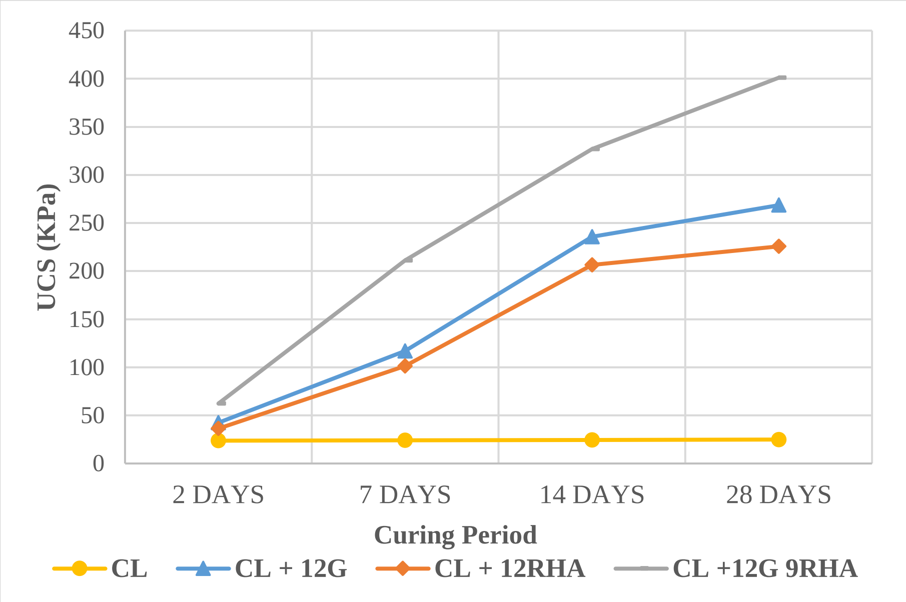

Figure 4.41: Soaked comparison of UCS of treated soils (CL)

The same behavior of strength gain was observed for CH as that of CL, the rise in UCS value was observed with curing time. The Figure 4.42 and Figure 4.43 shows the comparison of strength gain for CH, CH + 15 percent Gypsum, CH + 16 percent RHA, and CH + 15 percent Gypsum + 12 percent RHA with time both under soaked and unsoaked conditions.

When CH was treated with 15 percent Gypsum under unsoaked conditions 2 days strength of the soil was 226.2 kPa while 28 days strength was 581.2 kPa. Similarly CH treated with 16 percent RHA, 2 days strength was 223.1 kPa while 28 days strength was 521.3 kPa. The strength gain was maximum when CH was treated was both 15 percent Gypsum and 12 percent RHA, 2 days strength of the soil was 299.3 kPa while 28 days strength was 674.2 kPa Figure 4.42.

CH when treated with 15 percent Gypsum under soaked conditions, 2 days strength of the soil was 76.2 kPa while 28 days strength of the soil was 290.8 kPa. CH, when treated with 16 percent of RHA, 2 days strength of the soil was 72.1 kPa and 28 days strength was 261.3 kPa. When Gypsum and RHA combined were added to the soil under moist conditions, 2 days strength of the soil was 100.3 kPa while 28 days strength of the soil was 403.6 kPa as shown in the Figure 4.43.

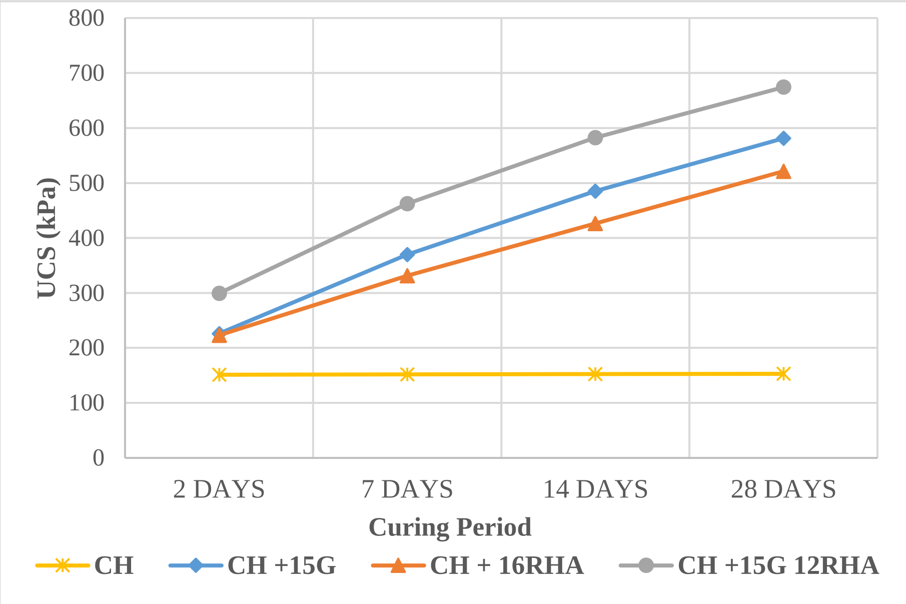

Figure 4.42: Unsoaked comparison of UCS of treated soils (CH)

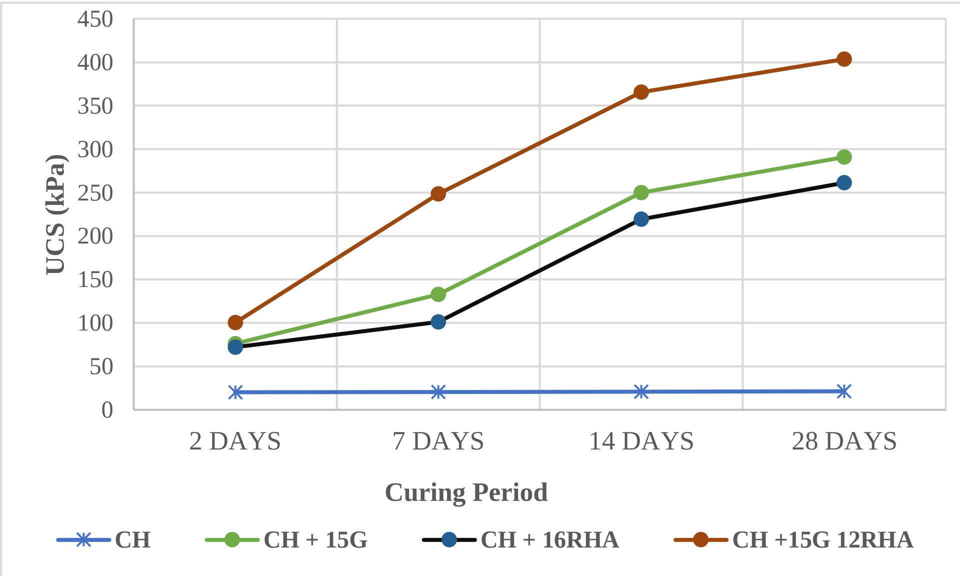

Figure 4.43: Soaked comparison of UCS of treated soils (CH)

4.6.4 California Bearing Ratio of Treated Soil

CBR test was performed for both CL and CH at optimum Gypsum, optimum RHA, and their combination. Values of CBR for both CL and CH lies within the range of poor material for subgrade material in untreated conditions. When both the soil were treated with the additives, the value of CBR is somehow improved. The reason for the improvement in the CBR of the soil is the reaction of Gypsum and RHA with soil produces cementitious products which increases the CBR.

Under soaked conditions CBR of CL was 1.7 percent, when treated with optimum Gypsum the value of CBR was increased to 2.1 percent. Similarly when CL was treated with optimum RHA, the value of CBR was increased to 1.9 percent, and maximum improvement was observed when CL was treated with combined Gypsum and RHA, the value of CBR was increased to 3.3 percent. Under unsoaked conditions, CBR of CL was 3.1 percent, when treated with optimum Gypsum, the value of CBR was increased to 6.3 percent, with optimum RHA, the value of CBR was increased to 5.8 percent, and maximum improvement was observed when CL was treated with combined Gypsum and RHA, the value of CBR was increased to 12.7 percent Figure 4.44.

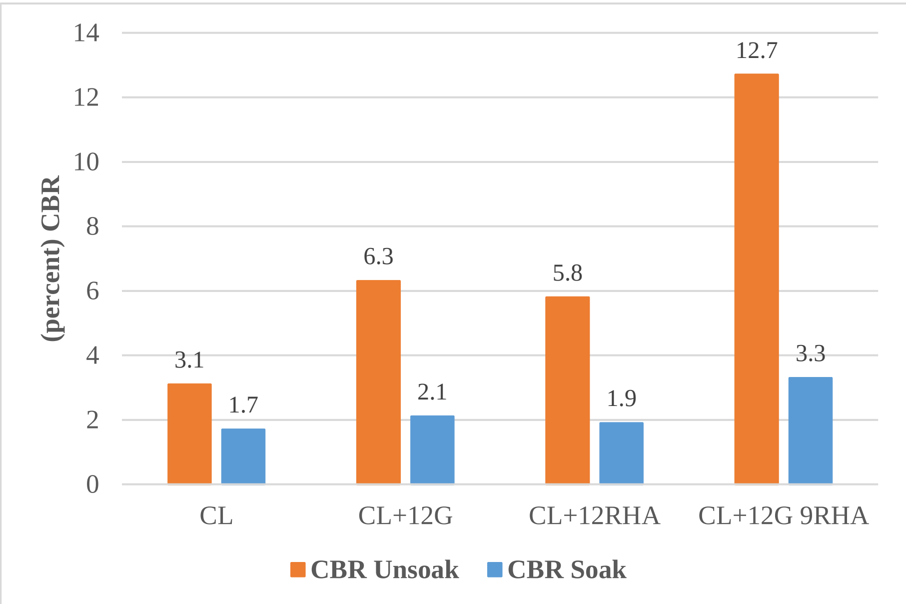

Figure 4.44: Comparison of soaked and unsoaked CBR (CL)

Under soaked conditions CBR of CH was 1 percent, when treated with optimum Gypsum the value of CBR was increased to 1.7 percent, similarly when treated with optimum RHA, the value of CBR was increased to 1.6 percent, and maximum improvement was observed when CH was treated with combined Gypsum and RHA, the CBR was increased to 3.1 percent. Under unsoaked conditions, CBR of CH was 1.5 percent, when treated with optimum Gypsum, the value of CBR was increased to 1.9 percent, with optimum RHA, the value of CBR was increased to 1.8 percent, and maximum improvement was observed when CH was treated with combined Gypsum and RHA, the value was increased to 4.8 percent Figure 4.45.

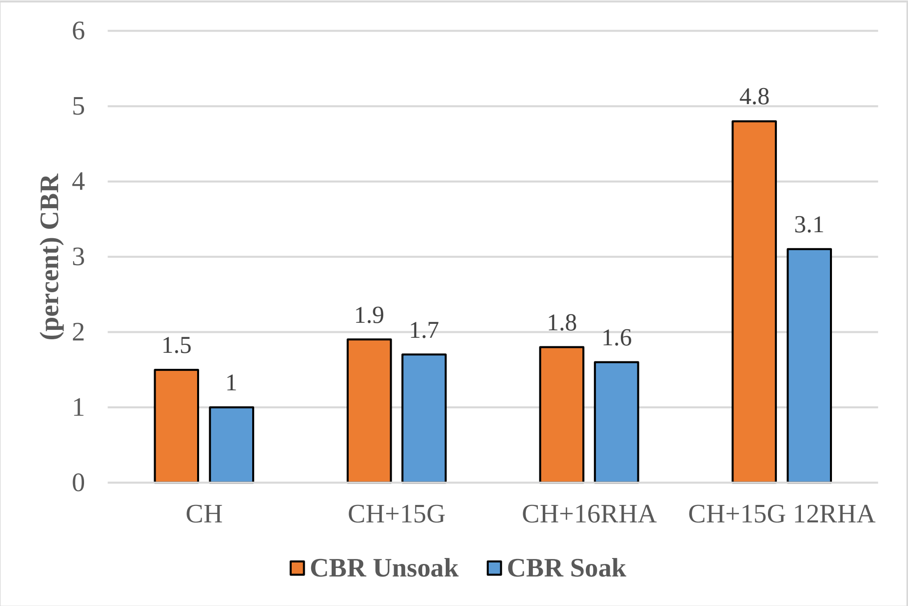

Figure 4.45: Comparison of soaked and unsoaked CBR (CH)

4.6.5 Swell Potential of Treated Soil

One dimensional swell potential test was conducted for both CL and CH and their results are shown in the Figure 4.46 and Figure 4.47.

The swell potential of CL was 6.01 percent, when soil was treated with optimum Gypsum, the value was reduced to 2.10 percent, with optimum RHA swell potential was reduced to 2.40 percent, and maximum improvement was observed when CL was treated with combined Gypsum and RHA, the swell potential was reduced to 1.01 percent Figure 4.46, making a high swelling clay to a low swelling clay.

The swell potential of CH was 8.04 percent, when soil was treated with optimum Gypsum, the value was reduced to1.08 percent, with optimum RHA swell potential was reduced to 1.34 percent, and maximum improvement was observed when CH was treated with combined Gypsum and RHA, the swell potential was reduced to 0.20 percent Figure 4.47, making a high swelling clay to a low swelling clay.

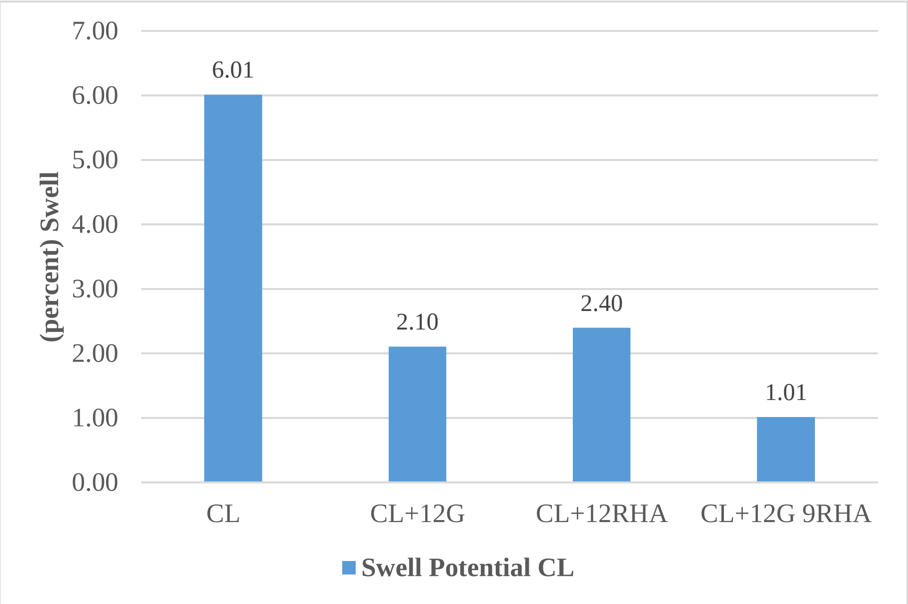

Figure 4.46: Comparison of the swell potential of treated soil (CL)

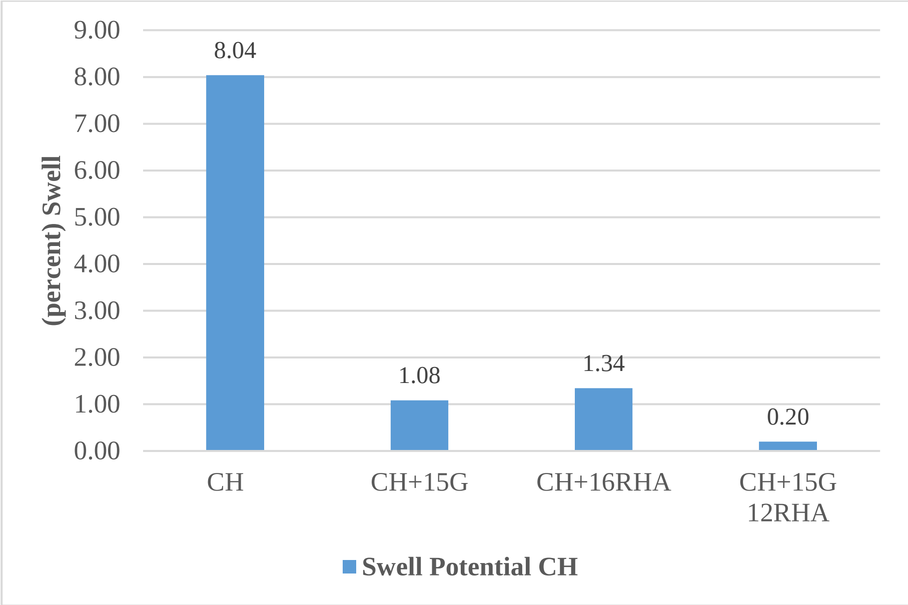

Figure 4.47: Comparison of the swell potential of treated soil (CH)

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The study was conducted on CL and CH to check the feasibility of Gypsum and RHA as potential soil stabilizers. The soil was first treated separately with Gypsum, then with RHA, and then tested with a combination of RHA and Gypsum. Based on the test conducted during the study following conclusions were drawn.

- The optimum percentage of RHA for CL was 12 percent and that for CH was 16 percent, while optimum percentage of Gypsum for CL was 12 percent and that for CH was 15 percent. When gypsum and RHA were used in combination for CL, their optimum percentages were 12 percent Gypsum and 9 percent RHA while in case of CH, 15 percent Gypsum and 12 percent RHA were the optimum percentages.
- Decrease in the values of liquid limit was observed when Gypsum and RHA were added to the soil samples as compared to untreated soil samples. In case of RHA alone, least improvement was observed in the liquid limit, liquid limit was decreased by 11.95 percent. Combination of Gypsum and RHA gave the best results, liquid limit was decreased by 20.8 percent. Gypsum alone gave the intermediate results, liquid limit was decreased by 15.21 percent. Similar trends were observed in the case of the Plasticity Index (PI). The decrease in PI was 22.4, 27.9, and 38.1 percent by the use of RHA, Gypsum and their combination respectively. The decrease in the values of PI can be explained on the basis of flocculation. Due to flocculation, particle

size increases and the soil becomes coarser, thus the water retention property of the soil is reduced. The reduction in PI led to the reduction of the LL.

- Addition of the Gypsum and RHA to CL and CH causes the MDD to decrease and increases the value of OMC. The decrease in the value of MDD is due to the flocculation causing soil particles to cluster, thus making compaction difficult. The reduction in the MDD can also be explained in the manner that when the soil particles cluster, the empty spaces between the soil particles increases, causing MDD to fall. The rise in the value of OMC is due to increase in the number of fines by the addition of Gypsum and RHA. Smaller the particle size greater will be its surface area thus more water will be required for lubrication.
- Addition of Gypsum and RHA effectively increases the value of UCS for both CL and CH. Improvement in case of soaked samples was much higher as compare to unsoaked samples. In case of unsoaked CL samples, treated with optimum RHA, improvement in the UCS after 28 days of curing was 194.3 percent while in the soaked condition the improvement was 852.3 percent. Improvement in soaked and unsoaked CL samples treated with optimum Gypsum after 28 days of curing was 1033 and 237.4 percent respectively. Similarly, when CL was treated with an optimum of both Gypsum and RHA, improvement in the soil after 28 days under unsoaked conditions was 447.5 percent and that of soaked samples was 1592 percent. In case of soaked and unsoaked CH samples treated with optimum RHA after 28 days, improvement in the soil was 1193.5 and 244.5 percent respectively. Improvement in CH treated with optimum Gypsum after 28 days under

soaked and unsoaked conditions was 1340 and 284.1 percent respectively. Similarly, improvement in CH treated with both Gypsum and RHA under soaked and unsoaked conditions were 1898 and 345.6 percent respectively.

- Significant gain in UCS was during the first fourteen days of curing. Later a small increase in the values of UCS was observed.
- The results of CBR for untreated soils lies within the range of poor material for subgrade but when CL was treated with Gypsum and RHA the improved value of CBR was in the range of good material for subgrade. Improvement in CBR under soaked and unsoaked conditions was 94.12 and 309.6 percent respectively. The improvement in CBR for CH under soaked and unsoaked conditions was 210 and 220 percent respectively.
- Less improvement was observed in the swell potential of CL as compared to that of CH. CL, when treated with optimum RHA, decrease in the swell potential of soil was 60 percent. Gypsum-treated soil decreases the swell potential of soil by 65 percent, and when CL was treated with an optimum of Gypsum and RHA, decrease in the swell potential of the soil was 83.2 percent. CH sample treated with optimum RHA decreases the swell potential of the soil by 83.3 percent. CH treated with optimum Gypsum decreases the swell potential of soil by 86.6 percent, when CH was treated with optimum Gypsum and RHA, decrease in the swell potential of the soil was 97.5 percent.

5.2 RECOMMENDATIONS

- As both Gypsum and RHA produces cementitious products so, suitability of these materials should be checked as stabilizers for granular soils and soils rich in silt.
- CBR tests conducted in this study were one-point CBR test, CBR tests should be performed at different moisture contents to check the suitability of the soil as a subgrade material.
- RHA in this study was collected only from one source, the chemical composition of RHA may vary from soil to soil in which rice was grown. The percentage of silicon in the RHA greatly depend on the type of soil, so to regulate the use of RHA as pozzolanic material testing should be conducted for RHA from different sources (rice grown in different soils) in the country.
- One dimensional swell potential test was performed during this study to study the swell behavior, the free swell potential of the soil should be studied.
- This study was completely based on lab testing, field studies should be conducted to check the suitability of Gypsum and RHA as soil stabilizers.
- As with the use of Gypsum and RHA, the PI of the soil was reduced, which means the water retention capacity of the soil is reduced. The study should be conducted to check the effect of improvement on the permeability of the soil.

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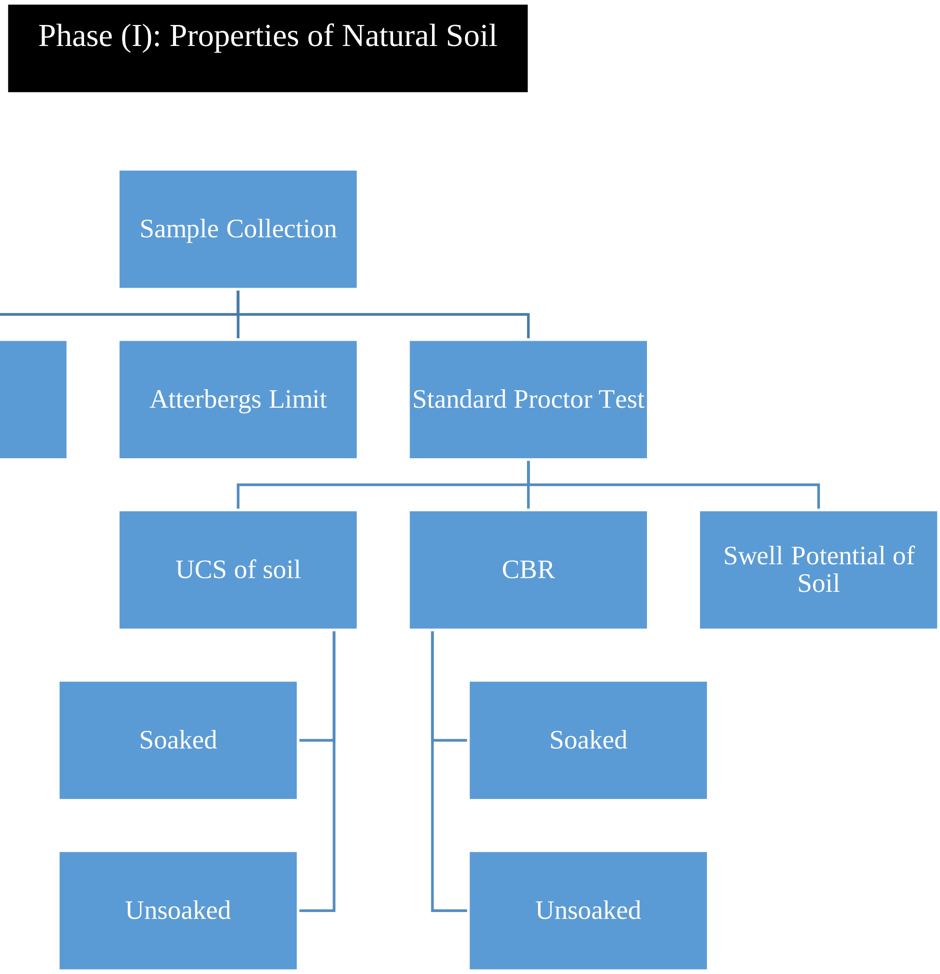
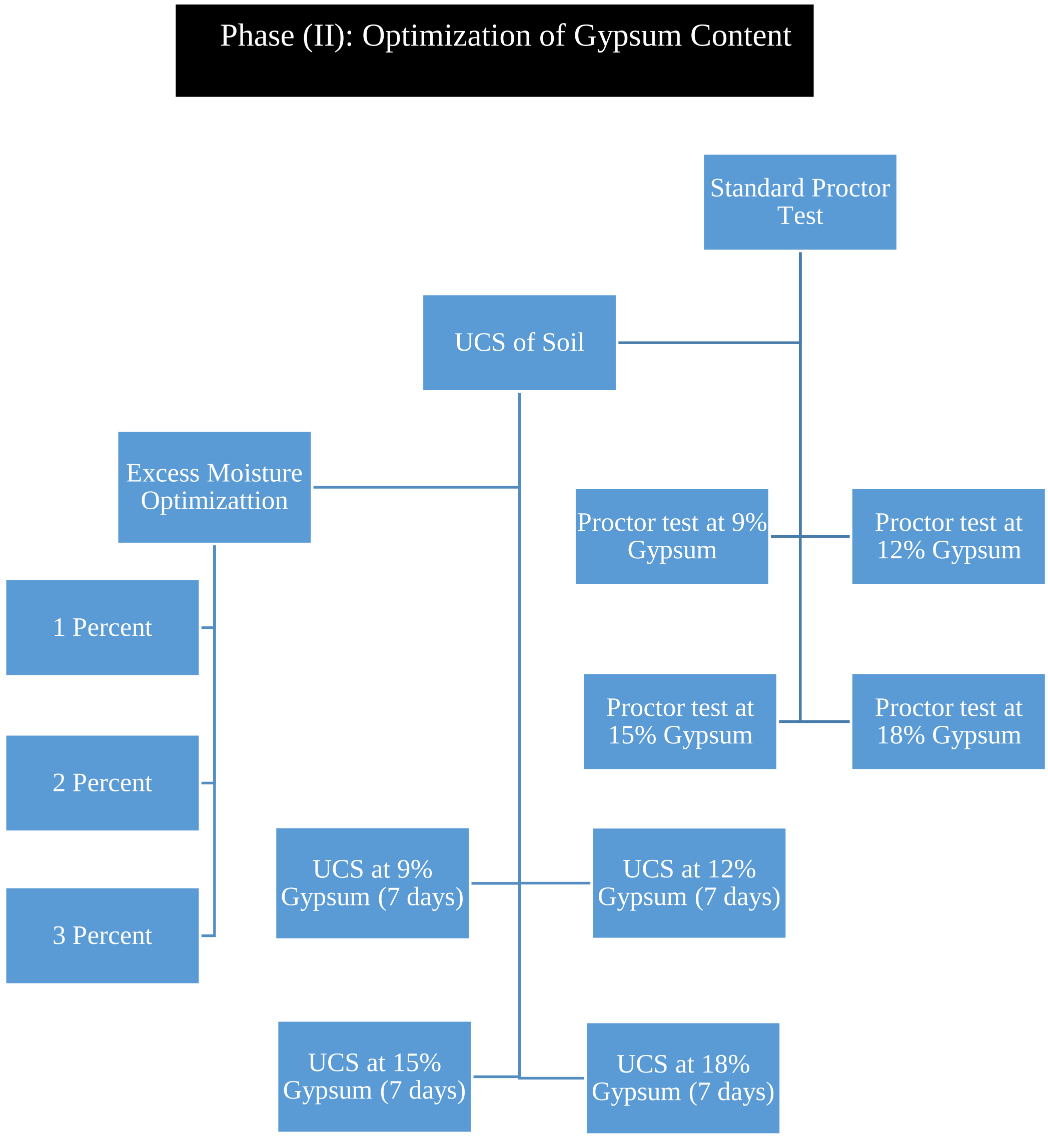
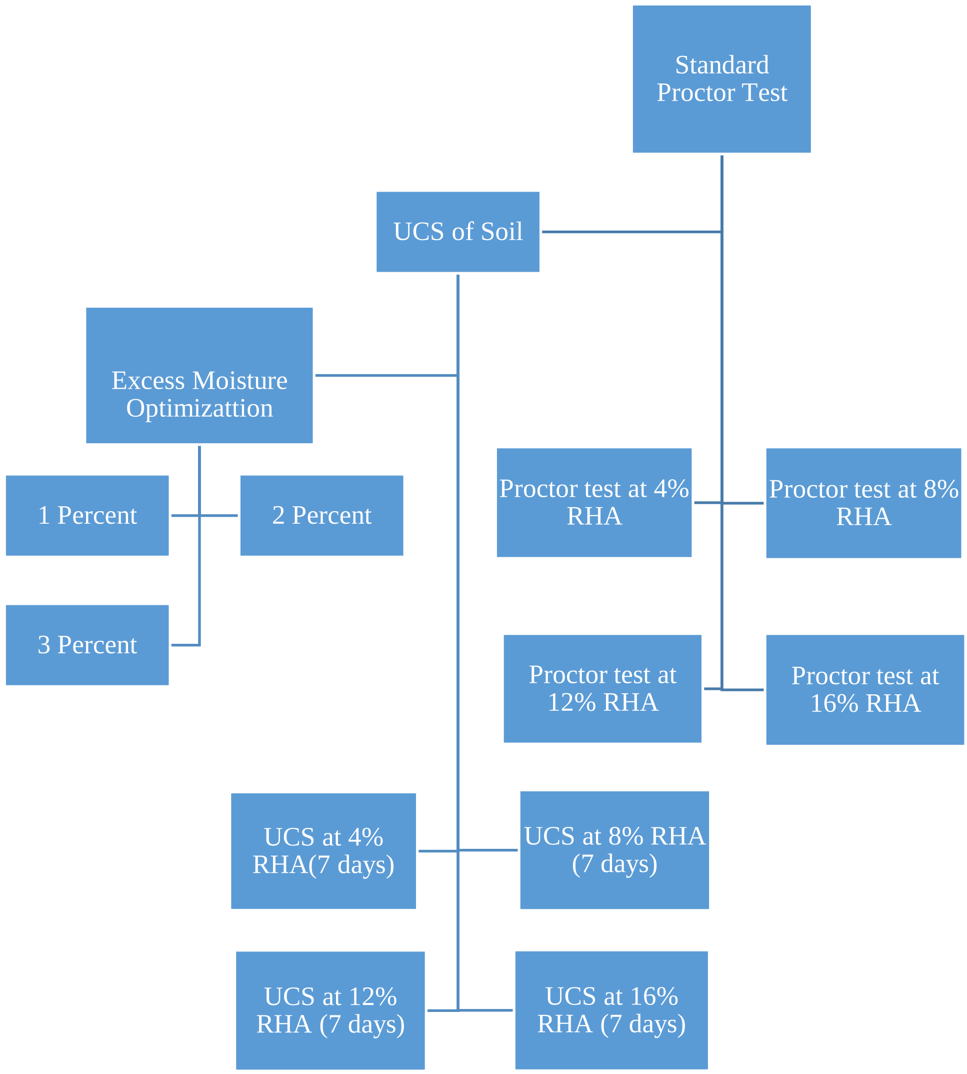
Appendix A

Experimental Sequence

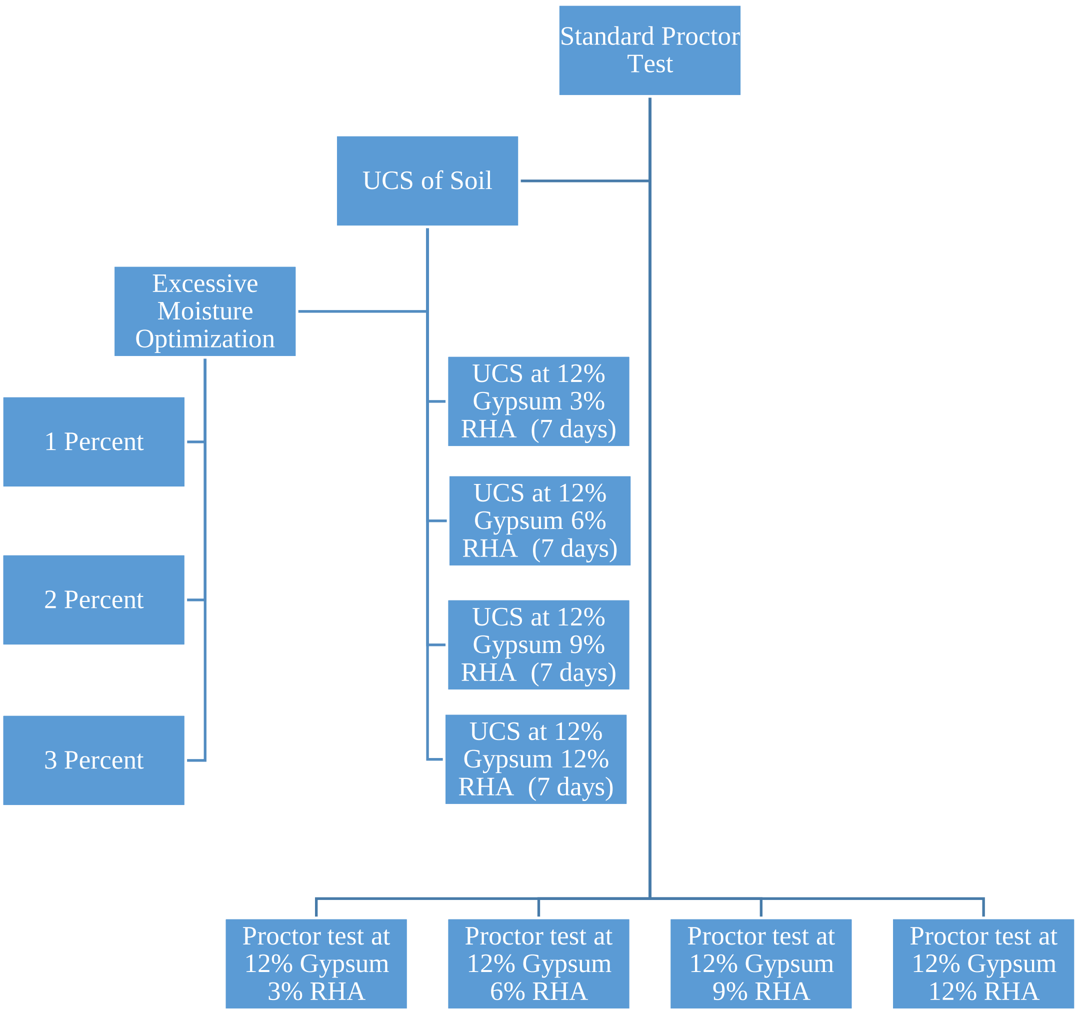


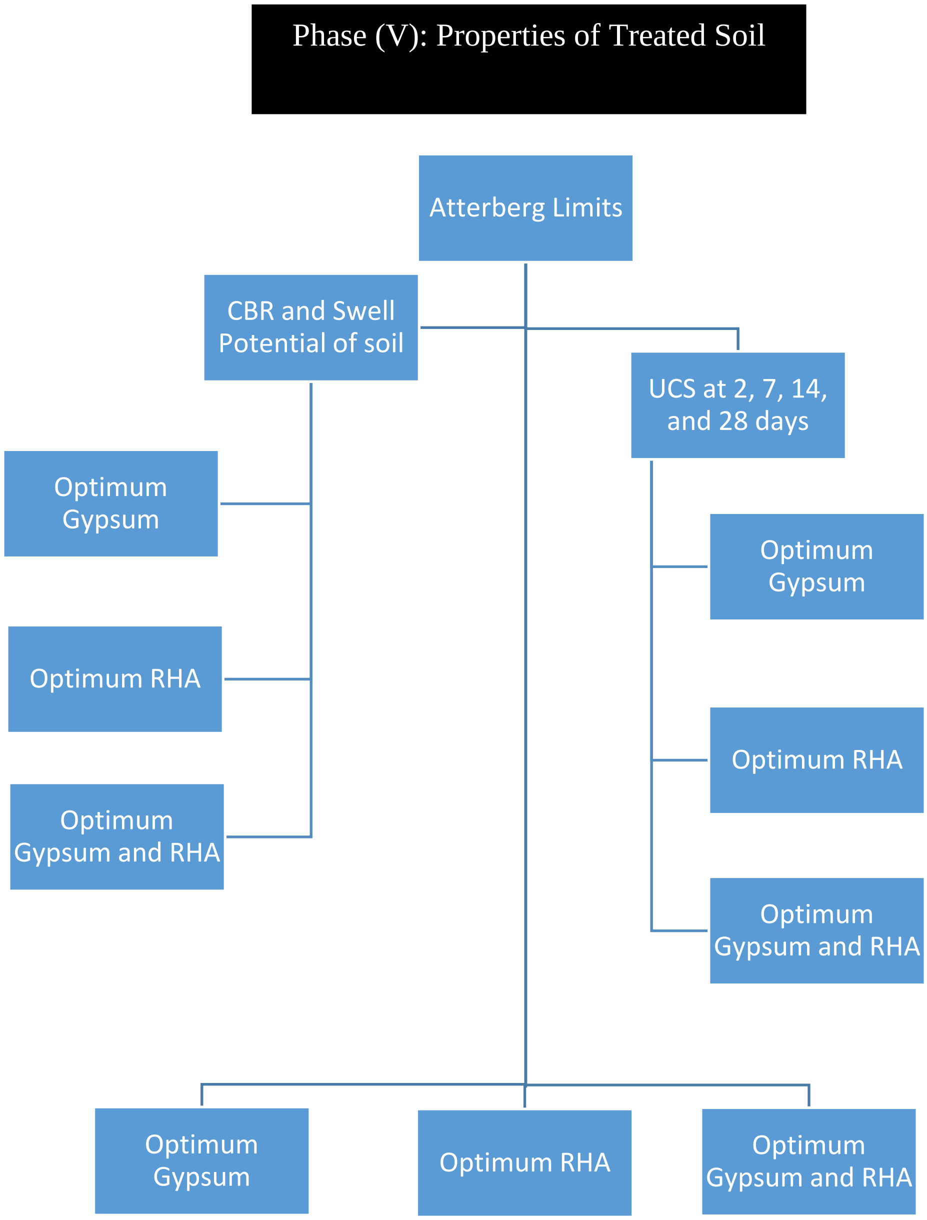

Phase (II): Optimization of Gypsum Content
Standard Proctor Test
UCS of Soil
Excess Moisture Optimizattion
Proctor test at 9% Gypsum
Proctor test at 12% Gypsum
1 Percent
Proctor test at 15% Gypsum
Proctor test at 18% Gypsum
2 Percent
UCS at 9% Gypsum (7 days)
UCS at 12% Gypsum (7 days)
3 Percent
UCS at 15% Gypsum (7 days)
UCS at 18% Gypsum (7 days)

Phase (III): Optimization of Rice Husk Ash (RHA)



Phase (IV): Optimization of Gypsum and RHA




Phase (V): Properties of Treated Soil
Atterberg Limits
CBR and Swell Potential of soil
UCS at 2, 7, 14, and 28 days
Optimum Gypsum
Optimum RHA
Optimum Gypsum and RHA
Optimum Gypsum
Optimum RHA
Optimum Gypsum and RHA
Optimum Gypsum
Optimum RHA
Optimum Gypsum and RHA