STABILIZATION OF MEDIUM PLASTIC AND HIGH PLASTIC CLAY USING GYPSUM AND BAGASSE ASH

By

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A thesis submitted in partial fulfillment of
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STABILIZATION OF MEDIUM PLASTIC AND HIGH PLASTIC CLAY USING GYPSUM AND BAGASSE ASH

Submitted by

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Has been accepted towards the partial fulfillment

of

the requirements

for

Master of Science in Geotechnical Engineering

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DEDICATED

TO

HOLY PROPHET (P.B.U.H)

MINERAT OF KNOWLEDGE

AND

MY LOVING PARENTS & INSTITUTE

WHO GAVE ME A LOT OF INSPIRATION,

COURAGE &

SUPPORTED MORALLY &

FINANCIALLY FOR MY STUDIES

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TABLE OF CONTENTS

CHAPTER 3: MATERIALS AND METHODOLOGY

CHAPTER 4: RESULTS AND DISCUSSIONS

LIST OF TABLES

LIST OF FIGURES

ABBREVATIONS

AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Standards of Testing Materials
BA	Bagasse Ash
CAH	Calcium Alumina Hydrates
CBR	California Bearing Ratio
CEC	Cation Exchange Capacity
CH	High Plastic Clay
CH	High Plastic Clay
CL	Medium Plastic Clay
CL	Medium Plastic Clay
CSH	Calcium Silica Hydrates
EC	Soil Electrical Conductivity
ESR	Exchangeable Sodium Percentage
G	Gypsum
GC	Clayey Gravel
GM	Silty Gravel
GP	Poorly Graded Gravel
G_s	Specific Gravity
GSD	Grain Size Distribution
GW	Well Graded Gravel
LL	Liquid Limit
MDD	Maximum Dry Density
MH	High Plastic Silt
ML	Non Plastic Silt
OH	Organic Clay

OMC	Optimum Moisture Content
PI	Plasticity Index
PL	Plastic Limit
SAR	Sodium Absorption Ratio
SC	Clayey Sand
SCBA	Sugarcane Bagasse Ash
SM	Silty Sand
SP	Poorly Graded Sand
SW	Well Graded Sand
UCS	Unconfined Compressive Strength
USCS	Unified Soil Classification System
W	Moisture Content

ABSTRACT

Clays have a tendency to undergo volumetric changes on their interaction with water. These soils are a very common reason for most of the foundation failures due to their degraded properties like low shear strength, low bearing capacity, high shrink-swell potential and high compressibility. With the growing need of infrastructure development, avoiding these soils for future constructions is not possible. Engineering properties of these soils must be improved by chemical or mechanical means to meet structural requirements. The present research is intended to examine the effect of gypsum and bagasse ash on the properties of swelling clays and evaluate their potential use for the stabilization and improvement of engineering properties of these soils. Gypsum is naturally occurring mineral and bagasse ash is a waste product produced by sugar-mills. Two types of swelling clays, medium plastic, and high plastic clay, are used. Atterberg's limits, compaction characteristics, unconfined compressive strength, California bearing ratio and swell potential of these soils are determined in untreated and after treatment with gypsum and bagasse ash.

Soils treated with gypsum and bagasse ash exhibit a decrease in plasticity index and liquid limit, decrease in maximum dry density and an increase in optimum moisture content. Medium plastic clay had almost 6 times higher unsoaked compressive strength in treated form as compared to untreated form. While the improvement was around 27 times when tests were performed in soaked condition. High plastic clay exhibited 5.5 times higher unsoaked compressive strength than untreated soil while the improvement in soaked condition was around 30 times. Comparison of results between soaked and unsoaked strength tests results shows that the loss in strength due to soaking was much less in the soils treated with gypsum and bagasse ash as compared to untreated soils. California bearing ratio increased almost 3 times and one-dimensional swell potential also reduced to less than 1% changing soil nature to low swelling when these soils were treated with gypsum and bagasse ash. The improvement observed with the combination of gypsum and bagasse ash is more significant as compared to the individual effect of gypsum. The results indicate that gypsum and bagasse ash can provide an effective and economical method for the treatment of medium and high plastic clays.

Chapter 1

INTRODUCTION

1.1 GENERAL

Clayey soils take an important place among soils with special behavior due to their expansive nature. Expansive soils are those soils which has a tendency to undergo significant volume changes with the change in water contents. This volumetric variation potential of a soil depends upon the mineralogy and percentage of expansive clayey minerals present in the soil. Common clay minerals are semectite, bentonite, montmorillonite, beidellite, vermiculite, attapulgite, nontronite, illite, chlorite, etc. These soils can easily absorb moisture and expand because of fine particles and weak inter-particle bonding.

Damage caused due to expansion of clays is more than twice than the combined damage from other natural hazards, i.e., floods, hurricanes, earthquakes and tornados (Jones and Holtz, 1973). Expansive soils result in cracking and breaking up of pavements, building foundations, channel linings, irrigation systems, water pipelines, sewer lines and gas pipeline. Expansion of soil also results in pressure on the verticals face of retaining wall, foundation and basement which results in lateral movement of soil. This shrinkage and swelling results in loss in strength or capacity of soil making it unstable and causing various forms of foundation problems and slop failures.

In the conjunction with infrastructural development, the demand for land is ever growing and avoiding these soils for infrastructural development won't be possible in near future. Expansive soils are normally present in arid and semi-arid regions of the world. Expansive soils are well established for their downgraded properties like low shear strength, high shrink and swell, high compressibility and low bearing capacity etc. these soils are not suitable for engineering development. Therefore, various stabilization techniques have been developed to improve these soils which include mechanical, chemical or by use of geo synthetics in soil. Mechanical techniques include compaction, pre-wetting, and surcharge loading etc, and Chemical methods include the addition of some chemical admixture to the soil which improves soil strength by directly reacting with soil. These reactions are either chemical or pozzolanic in nature. Most commonly used chemicals include sodium silicates, lime, gypsum, fly ash, etc.

1.2 NEED OF RESEARCH

Soil stabilization provides an economical and technically feasible solution to many engineering problems associated with expansive soils. However, there is always an uncertainty associated with the subsurface conditions. So a technique suitable for one case might not be suitable for the other. Most of the solutions in geotechnical engineering are site specific, thus a recommended treatment for a particular site may not be applicable at a different location. It is therefore recommended that detailed field and laboratory investigations be carried out before recommending a specific stabilization technique.

Researchers have been working on trying different chemical admixtures and evaluating their effect on the engineering properties like compressibility, durability, permeability, particle size gradation and consistency limits of soil. Negi, et al., (2013) used lime for stabilization of highly expansive soils. They found out that lime is an excellent soil stabilizing materials for such soils. Lime immediately reacts with soil and improves most of the engineering properties like plasticity, bearing capacity and California Bearing Ratio (CBR) of soil. Basha et al., (2005) monitored the effect of rice husk ash and cement on the strength properties of residual soils. They observed that there was a reduction in soil plasticity and dry density of soil, while an increase in optimum moisture content (OMC), CBR value, and compressive strength. Alavéz-Ramírez, et al. (2012) has used sugarcane bagasse ash and lime as soil stabilizers. Kolay, P. K., and Pui, M. P. (2010) has used gypsum and fly ash for the stabilization of peat soils. Osinubi, et al. (2009) has used sugarcane bagasse ash for the stabilization of lateritic soils. Rajakumaran, K. (2015) studied the effect of steel slag and fly ash and she found out that steel slag and fly ash can be used effectively to improve the engineering properties of soil. Nsaif, A. L. M. H. (2013) has studied the effect of the addition of plastic waste materials on the strength of soils. She observed that an increase in strength parameters was observed due to the increase in internal friction, but there was no significant increase in cohesion. She also found out that the addition of plastic waste results in an increase in OMC and a decrease in maximum dry density MDD of soil.

So far, a vast number of chemical and natural materials have been used as the soil stabilizers. But no efforts have been made to study the suitability of combined effect of gypsum and sugarcane bagasse ash as the soil stabilizers. So, this research study is intended to fill this gap in the field of soil stabilization. Sugarcane Bagasse Ash is a waste material produced by sugar mills. Gypsum is also readily available in Pakistan. So using these materials for the soil stabilization would provide a feasible and economical solution for improving the engineering properties of expansive soils.

1.3 RESEARCH OBJECTIVES

The main objective of this research is to check the suitability of Gypsum and Sugarcane Bagasse Ash as soil stabilizers. This research will be mainly focused on how Gypsum and Sugarcane Bagasse Ash will help improve the following properties of soil: -

- Soil Plasticity
- Compaction Characteristics of soil
- Unconfined Compressive Strength of soil
- CBR and Swell potential of Soil

1.4 SCOPE AND METHODOLOGY

The soil has been characterized by finding out its consistency limits, gradation, mineralogy and cation exchange capacity (CEC). The effect of moisture, density, and stabilizer type is evaluated by conducting CBR and unconfined compressive strength (UCS) tests on treated and untreated soils. Detailed methodology has been covered in Chapter 3, however, scope and brief methodology is given below:

- Phase I (Properties of Untreated / Natural Soil)
    - Atterberg's Limits
    - Specific Gravity of Soil
    - Grain Size Distribution of Soil
    - In-Situ Density and Moisture Content of Soil
    - Compaction Characteristic of Soil
    - UCS (soaked)
    - UCS (unsoaked)
    - CBR and Swell Potential of Soil
- Phase II (Optimization of Gypsum Content)
    - Compaction tests at various Gypsum contents
    - UCS at various Gypsum contents at 7 days of curing
    - Optimization of excess moisture
- Phase III (Optimization of Bagasse Ash Content)

    - Chemical Composition of Bagasse Ash
    - Compaction tests at optimum Gypsum and various Bagasse Ash contents
    - UCS at optimum Gypsum and various Bagasse Ash Contents at 7 Days of curing
    - Optimization of excess moisture
- Phase IV (Properties of treated / stabilized Soil)
    - Atterberg's Limits with Optimum Gypsum
    - Atterberg's Limits with Optimum Gypsum and Optimum Bagasse Ash
    - UCS at 2, 7, 14 and 28 Days of curing (soaked) with Optimum Gypsum
    - UCS at 2, 7, 14 and 28 Days of curing (unsoaked) with Optimum Gypsum
    - UCS at 2, 7, 14 and 28 Days of curing (soaked) with Optimum Gypsum and Optimum Bagasse Ash
    - UCS at 2, 7, 14 and 28 Days of curing (unsoaked) with Optimum Gypsum and Optimum Bagasse Ash
    - CBR and Swell Potential of Soil with Optimum Gypsum
    - CBR and Swell Potential of Soil with Optimum Gypsum and Optimum Bagasse Ash
- Analysis and Discussion of test results
- Conclusions and Recommendations

Chapter 2

LITERATURE REVIEW

2.1 GENERAL

Expansive soils or swelling soils are well known for their significant potential to undergo volume changes as the moisture content changes. Presence of swelling soils underneath the foundation of lightly loaded civil engineering structures has resulted in some serious damages around the globe due to their heave up potential. The increase in moisture content will cause these soils to swell which in turn will cause the heaving or lifting of the structures founded on them. On the contrary, a decrease in moisture content will shrink these soils causing excessive settlements of the structures. Swelling soils are highly plastic soils typically consisting of clay minerals, i.e., montmorillonite which have potential to absorb significant amount of water. The percentage and variety of clay mineral present in soil play a vital role in swelling potential of soil. Montmorillonite group is identified as highest swelling and kaolinite group as the least swelling clay minerals.

Improving the on-site properties of soil is called soil improvement or soil stabilization. Stabilization is the permanent change in engineering properties, i.e., plasticity, swelling potential, compressibility and bearing capacity of soil.

2.2 CLAYEY SOILS

The term clay is associated both with mineralogy and the size of the soil particles. In terms of size, it is the material which has particle size smaller than 0.002 mm. In terms of mineralogy, it is referred as a material which does possess a net negative charge, plasticity, cohesion and shows resistance to weathering. Clayey soils are the formed by the chemical weathering of rocks. Most common clay minerals include kaolinite, illites, montmorillonites, vermiculites, etc.

2.2.1 Clay Structure

The properties which determine the composition of a mineral depend upon its chemical composition, the geometric arrangement of atoms and ions, and the electrical forces that bind them together (Barton, C. D. 2002). Clay structure means that how different particles join each other to form a clay crystal. Bonding between ions creates molecules. These molecules join each other to form sheets. A sheet upon sheet is termed as Layer. While a layer upon layer is called Crystal. Clay minerals are made up of two basic structural units or sheets which are silicon tetrahedron (silica) and aluminum (alumina) octahedron (Figure 2.1).

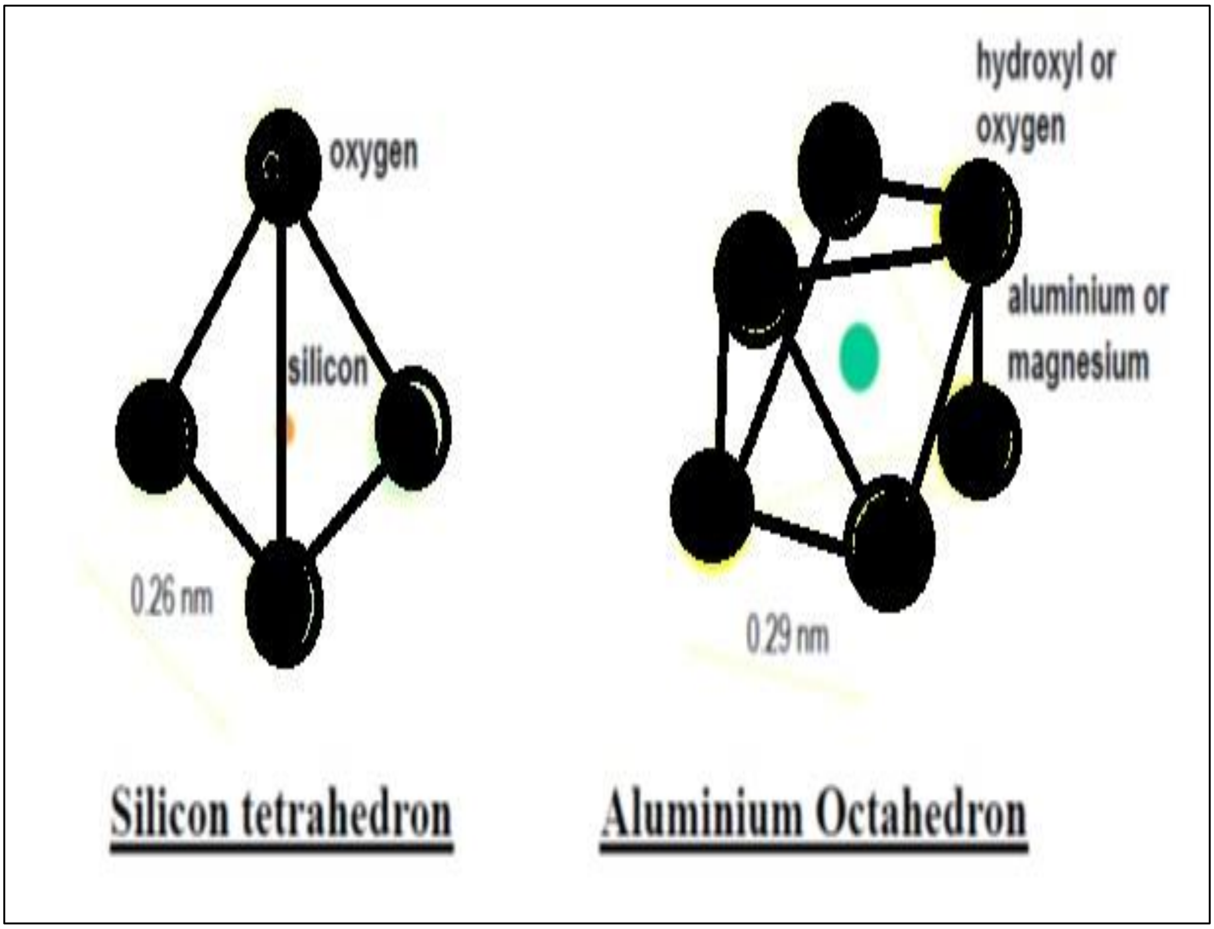

Figure 2.1: Structural Units of Clay Minerals (TSUYUZAKI Shiro, N. D)

In clay minerals, a tetrahedral sheet does not exist by itself. It will always be combined with Octahedral sheet. Layering silicon tetrahedron and aluminum octahedron sheets in different combinations results in different clay minerals.

2.2.2 Cation Exchange

Clay particle are normally negatively charged. Similarly charged particles repel each other and cause a dispersion in soil. These negatively charged clay particles can be held together with positively charged cations. The process is termed as flocculation. Different cations have different flocculation power. From Table 2.1, it is clear that sodium is weakest and calcium the strongest flocculator. Cation exchange is the process in which weak flocculator cations are replaced with cations of high flocculating power. The main ions associated with cation exchange capacity (CEC) in soils are the exchangeable cations, i.e., calcium (Ca^{2+}), magnesium (Mg^{2+}), sodium (Na^{+}) and potassium (K^{+}) (Rayment and Higginson 1992), and are generally referred to as the base cations. During cation exchange, either a fraction or all of the exchangeable ions can be replaced.

Table 2.1: The Relative Flocculating Power of Major Soil Cations (Rengasamy and Sumner, 1998)

Cation	Charges per Molecule	Hydrated Radius (nm)	Relative Flocculating Power
Sodium	1	0.79	1.0
Potassium	1	0.53	1.7
Magnesium	2	1.08	27.0
Calcium	2	0.96	43.0

2.2.3 Sources of cation exchange

There are three main sources of cation exchange in soils.

2.2.3.1 Isomorphs substitution

It is the process of substitution of one element in clay structure with another element of similar ionic radii and valence state (Holtz et al. 1981). This process leads to net negative charge in the clay mineral. Examples of the process are the substitution of Al3+ for Si4+ in the tetrahedral sheets and Mg2+, Fe2+, Fe3+, and others for Al3+ in octahedral sheets within clay minerals. Isomorphs substitution is the main source of net negative charge in the clay minerals and it produces a permanent charge on the clay sheet.

2.2.3.2 Broken bonds

Electronegativity of clay particles and potential to absorb cations is due to the presence of surface and broken - edge -OH groups. In most soils, it is a combination of constant and variable charge (Mitchell 1993). Cation are either acidic (acid forming) or alkaline in nature. The Hydrogen Cation H+ and the Aluminum cation Al3+ are acidic.

2.2.3.3 Ionization of hydroxyl groups

pH-dependent charges are mainly due to the Ionization of hydroxyl groups on the surface of other soil colloids and organic matter (Mitchell 1993). pH-dependent charges are variable and increase with increasing pH, unlike permanent charges developed by isomorphs substitution.

2.2.3.4 Cation exchange capacity (CEC)

Cation exchange capacity of soil represents the amount of exchangeable cations in the clay mineral which can be replaced by the cations of higher replacing power than the absorbed cations. CEC is an inherent property, and it is difficult to significantly alter it. The CEC of a soil is a function of the amount and type of soil colloids present. Cation exchange capacity of different clay minerals is listed in Table 2.2.

Table 2.2: Typical Values of CEC for Various Clay Minerals (Mitchell 1993)

Colloid Type		CEC (meq/100gm)
Kaolinite		2-15
Montmorillonite		80-150
Chlorite		10-40
Hydrous Mica (Illite)		10 – 40

2.2.4 Properties of Clays

Clayey soils are well established for their downgraded properties like high plasticity, high shrink and swell potential, high compressibility, low shear strength and low bearing capacity. A brief description of some basic properties of clayey soils is given below.

2.2.4.1 Grain size distribution

Particle size distribution or Grain size distribution means the percentage of different sizes present in a soil sample. Particle size of clays is normally less than 0.002 mm.

2.2.4.2 Cation exchange capacity

Cation exchange capacity is termed as the amount of exchangeable cations present in a soil fraction.

2.2.4.3 Atterberg’s limits

Based on Liquid Limit, clays are classified as

Low Plastic Clay LL < 30

Medium Plastic Clay 30< LL <50

High Plastic Clay LL > 50

2.2.4.4 Compaction characteristics

A brief description of compaction characteristics, i.e. maximum dry density (MDD) and optimum moisture content (OMC), of various soil types is presented in Table 2.3.

Table 2.3: Typical Values of MDD and OMC (Lindeburg, M. R., 2012)

Soil (USCS)	Maximum Dry Density (lb/ft^3)	Optimum Moisture Content (%)
Well Graded Gravel ,GW	125 – 135	8 - 11
Poorly Graded Gravel, GP	115 – 125	11 - 14
Silty Gravel, GM	120 – 135	8 - 12
Clayey Gravel, GC	115 – 130	9 - 14
Well Graded Sand, SW	110 – 130	9 - 16
Poorly Graded Sand, SP	100 – 120	12 - 21
Silty Sand, SM	110 – 125	11 - 16
Clayey Sand, SC	105 – 125	11 - 19
Non Plastic Silt, ML	95 – 120	12 - 24
Medium Plastic Clay, CL	95 – 120	12 - 24
High Plastic Silt, MH	70 – 95	24 - 40
High Plastic Clay, CH	75 – 105	19 - 36
Organic Clay, OH	65 – 100	21 - 45

2.2.4.5 Swell potential

Swell potential is the measure of volumetric change in various soils on their interaction with water. Different experimental and empirical methods have been developed to determine swell potential of clayey soils. Seed et al. (1962) developed the correlation between swell potential and Plasticity index of soil.

$$S = K (M) (PI)^{2.44}$$ Seed et al. (1962)

$$K = 3.6 \times 10^{-5}$$

M= 60 for Natural soil, 100 for Artificial soils

PI = Plasticity Index

He proposed a soil classification on the basis of swell potential of soil

Yilmaz, I. (2004) developed correlation between liquid limit and cation exchange capacity of soil. He proposed a soil classification based on swell potential of soil.

$$CEC = e^{(2.63 + 0.002\ LL)} \qquad \text{Yilmaz, I. (2004)}$$

CEC = Cation Exchange Capacity

LL = Liquid Limit

Table 2.4: Soil Classification Based on Swell Potential (Seed et al., 1962)

Soil Type	Swell Potential
Very High	> 25
High	5 – 25
Medium	1.5 – 5
Low	< 1.5

Table 2.5: Soil Classification Based on Cation Exchange Capacity (Yilmaz, I. (2004)

Soil Type	Swell Potential
Very High swelling	> 55
High swelling	37 – 55
Medium swelling	27 – 37
Low swelling	< 27

2.2.4.6 California bearing ratio (CBR)

CBR is the measure of quality of subgrade material.

Table 2.6: Subgrade Classification Based on CBR (TRH4, 1996)

Material Quality	CBR (%)
Good	>15
Moderate	7 – 15
Fair	3 – 7
Poor	< 3

2.3 SOIL STABILIZATION

Soil Stabilization is the permanent improvement in the nature of soil to meet the engineering requirements by physical, chemical, biological or a combination of these techniques.

Soil Stabilization can: -

- Reduce compressibility of soil
- Reduce plasticity
- Increase bearing capacity
- Increase shear strength

Mechanical stabilization involves techniques like compaction, pre loading, drainage, etc.

Chemical stabilization is the process in which different chemical substances are added to the soil to improve its engineering properties. The chemicals directly react with soil particles. These reactions are either cementitious or pozzolanic in nature.

Biological methods involve addition of biological substances, i.e., bio–enzymes.

Chemical stabilization is achieved by adding various chemical substances to the soil. These chemicals react with soil particles. These reactions are either cementitious or pozzolanic in nature.

Clay particles are generally negatively charged. These negatively charged particles repel each other and cause a dispersion in soil. They can be held together by positively charged cations. This process is termed as flocculation or agglomeration. Flocculating power of various soil cations is given in Table 2.1. Higher is the flocculating power of cation, stronger will be the bonding in clay particles and better will be the engineering properties of soil. So, the basic mechanism of chemical stabilization is replacement of weak flocculaters with cations of higher flocculating power by the process of cation exchange.

Table 2.1 shows that the calcium ions have the highest flocculating power. So replacing weak sodium ions with calcium ions can provide a sufficient improvement in soil properties. Gypsum and lime are most common sources of calcium ions in soil.

2.4 GYPSUM STABILIZATION

Gypsum is a naturally occurring mineral and abundantly available in many parts of the world. Gypsum is hydrated calcium sulfate and the chemical name of gypsum is calcium sulfate dihydrate. Gypsum is chemically represented as Ca (SO4)•2(H2O). In its pure form, gypsum contains 23.28% calcium (Ca) and 18.62% sulfur (S) in the promptly accessible sulfate frame (SO4). Gypsum possesses the possibility to tie and concrete the soil particles and helps improve soil strength. Clay particles are normally negatively charged. These negative charges repel each other and cause a dispersion in soil structure. The dispersed particles clog the void spaces and prevent the drainage of water. These negatively charged clay particles can be bound together forming clumps or aggregates by positively charged ions or cations. This process is termed as flocculation. Flocculation helps improve the water drainage and strength parameters of soil (Walworth, J. 2012). The table 2.1 shows the flocculation power of some dominant cations in soil from which Ca is clearly the cation of choice for flocculation of soils. The most commonly used Ca resources include gypsum, lime, and a few calcium based salts.

2.4.1 Reaction of Gypsum with Soil

Most of the soils contain Silica and Alumina in sufficient quantity, which in presence of water, can react with Gypsum and form some cementitious products. The chemistry of Gypsum-Soil reaction is still not clear. Some theories suggest that gypsum is absorbed onto clay surface and reacts with other surfaces and precipitates to form cementitious products while other theories suggest that gypsum directly reacts with clay edges and forms a cementitious network. The summary of the reactions taking place between gypsum and soil is given below

2.4.1.1 Cation exchange

This is a fast reaction and reacts instantaneously as soon as gypsum is added to the soil. Gypsum creates a surplus of Ca^{+2} ions in the soil which replace monovalent cations (Na^{+1} or H^{+1}) in soil.

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

2.4.1.2 Flocculation-Agglomeration

In this process, smaller clay particles start to join together and create flocs or groups which increase the particle size. Soil texture changes, particle size increases, change in gradation is observed, clay particles become more friable and start to behave sand-like. This is also a fast process and occurs immediately as soon as gypsum is added to the soil.

2.4.1.3 Pozzolanic reaction

This is a long-term reaction, and it depends on the amount of Ca^{+2} ions available to replace silica and alumina of soil. Cementitious products are formed in this process which results in long-term strength gain of soil. This reaction can continue for years.

2.4.2 Suitability of Soil for Stabilization with Gypsum

The addition of gypsum can improve the aggregate structure of some types of soil and it might not be as effective in other soils. So it is important to understand the process which occurs when gypsum is added to the soil.

Soil particles are negatively charged so they repel each other. These particles are held together by cations. This process of binding soil particles together to form aggregates is called flocculation. Not all cations do possess the same flocculating power (Table 2.1). Sodium (Na^{+1}) is the weakest and Calcium (Ca^{+2}) and Magnesium (Mg^{+2}) are one of the best flocculaters. The concentration of these cations together determines the stability of soil. This is done by calculating the Sodium Absorption Ratio (SAR) and Exchangeable Sodium Percentage (ESP) (Walworth, J.,2012).

$$\text{SAR} = \frac{[Na^{+1}]}{\sqrt{[Ca^{+2}] + [Mg^{+2}]}} \qquad \text{ESP} = \frac{[Na^{+1}]}{Cation\ Exchange\ Capacity}$$

Cations are always accompanied by negatively charged anions and together they are called salts. Salts have the potential to conduct electricity and their electrical conductivity (EC) and Sodium Absorption Ratio (SAR) can be used to predict the instability of soil structure as shown in Figure 2.2.

In soils with unstable structure, gypsum can help stabilize structure by providing a good source of calcium. Calcium has high flocculating power and acts as a “glue” that holds soil particles together into aggregates and stabilizes soil structure.

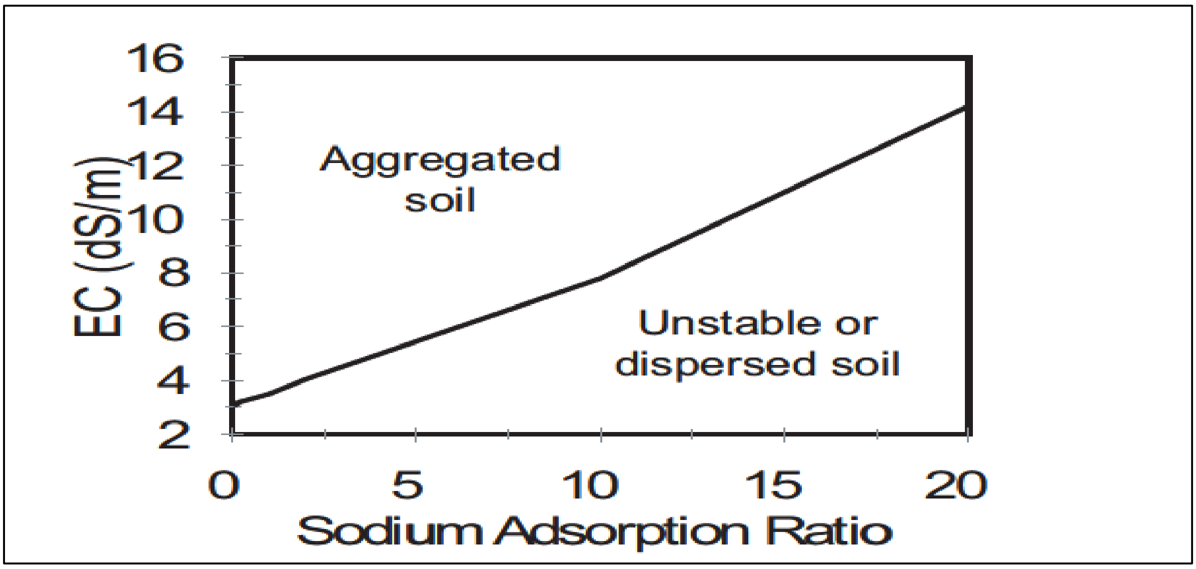

Figure 2.2: Soil Electrical Conductivity (EC) and Sodium Adsorption Ratio (SAR) Determine Aggregate Stability. (Walworth, J.,2012).

2.4.3. Modes of Stabilization

2.4.3.1 Soil modification

Gypsum is an excellent source for the modification of different properties of soil. This modification occurs as a result of replacement of monovalent cations present in the soil with calcium ions. Soil modification reduces plasticity, improves compaction characteristics, maximizes use of low-cost on-site materials and enables us speed construction with the stable working platform.

2.4.3.2 Soil improvement/stabilization

Soil stabilization or soil improvement is the result of long-term strength gain due to the Pozzolanic activity. This reaction produces cementitious products i.e. calcium silicates and calcium aluminates and the process continues for years. Soil stabilization chemically modifies clay so a permanent increase in strength, reduction in cracking, excellent resistance in the freeze-thaw phenomenon and a reduction of expansion properties of soil is observed.

2.4.3.3 Drying of soils

As gypsum is added to the soil, it reacts with water present in the soil and dries up the soil. Moreover, the addition of gypsum increases the moisture holding capacity of soil which reduces the free water and further dries up the soil. This process completes within hours and one of the best ways to dry up the wet soils on construction sites.

2.4.4 Effect of Gypsum on the Properties of Soil

2.4.4.1 Grain size distribution

Due to the flocculation of soil with the addition of gypsum, particle size increases and soil becomes coarser than the original soil. This aggregation of soil particles helps improve the workability of soil (Krishnan, K. D, 2016).

2.4.4.2 Atterberg's limits

Plasticity index of the soil reduces as gypsum is added to the soil. When gypsum is added to the soil, soil becomes coarser due to the flocculation and water-holding capacity of the soil reduces. As a result, plasticity index also reduces. Liquid limit of soil may increase or decrease depend upon the nature of the soil. Change in plasticity index can be as significant as the soil might become non-plastic from plastic (James, J., and Pandian, P. K. 2016).

2.4.4.3 Compaction characteristics (Moisture-Density Relationship)

Gypsum increases the optimum moisture content (OMC) while reduces the maximum dry density (MDD) of soil. The reduction in dry density is due to flocculation and cementation of soil which makes the compaction difficult, so the maximum dry density of soil is reduced (PRT, P. 2011).

2.4.4.4 Unconfined Compressive Strength (UCS)

A significant improvement in the unconfined compressive strength (UCS) of soil is observed due to the addition of gypsum. The improvement may be variable due to a number of factors involved. This increase is due to the increase in the cementitious behavior of soil (Krishnan, K. D, 2016).

2.4.4.5 California Bearing Ratio (CBR)

CBR test is used to determine the suitability of a subgrade as a pavement material. Lesser the CBR value, higher will be the thickness required of subgrade or subbase material. Gypsum can help improve the CBR value thus reducing the required thickness of subgrade or subbase and reducing the cost factor of the project (PRT, P. 2011).

2.4.4.6 Swell Potential of Soil

Gypsum increases the flocculation of soil, which increase the permeability of the soil. Thus water holding a capacity of soil is reduced which in turn reduces the swell potential of the soil. The swell potential of the soil is significantly reduced by the addition of gypsum (James, J., and Pandian, P. K. 2016).

2.3.4.7 Durability of Soil

Prolonged exposure to water does have significant detrimental effects on the soaked strength of soil. Gypsum reduces the detrimental effects of soaking and helps improve the ratio of soaked to the unsoaked strength of soil (Ahmed, A., and Issa, U. H. 2014).

2.5 BAGASSE ASH

2.5.1 Pozzolans

According to ASTM, a pozzolan is defined as

> *"A siliceous or siliceous and aluminous material, which in itself possesses little or no cementitious value, but will, when in finely divided form and in the presence of moisture, chemically reacts with calcium hydroxide at ordinary temperature to form compounds possessing cementitious properties." ASTM, C618, (2005).*

ASTM classifies pozzolans into Class C, Class F, and Class N fly ash. Class F and Class C fly ashes are those which are produced from bituminous and sub-bituminous coals, respectively. Whereas, a Raw or natural pozzolan are classified as Class N pozzolan. ASTM requirement for Class N pozzolan is that it must be containing at least 70% of mixture of Silicon dioxide (SiO2) plus Aluminum oxide (Al2O3) plus iron oxide (Fe2O3), a maximum of 3% moisture and/or 4% of Sulfur-tri-oxide (SO3) and a maximum loss of 10% on ignition ASTM C618, (2005).

2.5.1.1 Sources and Types of Pozzolanic Materials

Pozzolanic materials can be divided into the following categories according to their properties and origin

2.5.1.1.1 Volcanic origin

These materials are formed from a combination of minerals which are ejected from volcanoes. They are very finely divided vitreous material and mainly consist of silica and alumina with fractional quantities of other minerals containing calcium, magnesium, iron, potassium, and sodium), Basalt is also a vitreous material exhibiting mild pozzolanic properties in finely grounded form.

2.5.1.1.2 Calcined clay products

Clay tiles or bricks, in lightly fired and finely crushed form result in pozzolanic additives. These materials are possessing high reactivity and immediately react with calcium hydroxide to form calcium silicate hydrates and calcium alumina-silicate hydrates which have cementitious properties.

2.5.1.1.3 Mineral slag

Furnace slag is a by-product of process i.e. smelting, vitrified in nature, not reactive in raw form but develops reaction characteristics when grounded into a fine material. It contains silica, alumina, lime and other minerals in various proportions and, in modern practice, is more commonly used as an additive in Portland cement concretes**.**

2.5.1.1.4 Organic origin

Coal ashes have been utilized as a pozzolan because of their sensible balance of siliceous and alimonies constituents. Coal ash has been generally utilized as an added substance to cementitious mortars and in lime-based grouts as (pummeled fuel powder). The buildup of fills from lime smoldering, whether from coal-, cokes, or wood-let go furnaces, known as lime-cinder, is outstanding verifiably as a pozzolan is still accessible. Other vegetable ashes, for example, rice husk ash and bagasse ash, are utilized as pozzolans in different parts of the world. Bone ash is additionally known to have been utilized.

2.5.1.2 Pozzolanic Reaction

The pozzolanic reaction is the reaction between silica or silica and alumina with calcium hydroxide. This reaction is normally abbreviated as

$$CH + SH \rightarrow C\text{-}S\text{-}H$$

$$CH + AH \rightarrow C\text{-}A\text{-}H$$

Calcium silica hydrates (CSH) and calcium alumina hydrates (CAH) are cementitious products which do possess very good cementitious properties.

2.5.1.3 Pozzolanic activity

Pozzolanic activity is defined as the measure of Pozzolanic reaction over time in presence of water. The reaction rate is dependent upon particle properties i.e. specific surface area of the pozzolan, chemical composition of the pozzolan and the reaction conditions.

2.5.2 Sugarcane Bagasse Ash (SCBA) as Pozzolan

Sugarcane bagasse is an industrial waste produced in sugar industry, which in same sugar industry, is used as fuel and the ashes produced from combustion of sugarcane bagasse are known as sugarcane bagasse ash (SCBA) which contain high amounts of unburnt matter, oxides of silica and aluminum are most important components of these ashes Díaz-Pinzón, L., & Ordóñez, L. M. (2002). SCBA does have excellent pozzolanic characteristics and is widely used as the pozzolanic material.

2.5.2.1 Production of bagasse ash in Pakistan

Pakistan is an agro-based country which is positioned as the fifth biggest sugarcane delivering nation on the planet creating more than 52 million tons of sugarcane every year (WADE 2004). Around 81% of the sugarcane is utilized as a part of sugar industry (Akbar et al. 2006). Every ton of sugarcane deliver around 26% of bagasse (at a dampness substance of half) and 0.62% of residual ashes (Cordeiro et al. 2004). In this manner, considering usage of roughly 42 million tons of sugarcane in the sugar producing industry, Pakistan creates around 11 million tons of bagasse, with a limit of producing more than 0.26 million tons of bagasse ash.

2.5.2.2 Potential uses of bagasse ash in Pakistan

Bagasse ash possesses very good pozzolanic characteristics and is cheaply available in Pakistan. Which makes it as an excellent and attractive material for its use in engineering applications. Major engineering applications of bagasse ash are: -

a. Soil stabilization
b. Partial replacement of cement in concrete mixes.
c. Manufacturing of low-cost mud blocks for building construction.

Khan, S., Kamal, M., & Haroon, M. (2015) summarized that there is a significant potential of SCBA to be used for road construction. Its market potential will depend on the financial value of resources saved, along with its transportation cost.

Amin, N. U. (2010) showed via his research that up to 20% of high-strength Portland cement can be optimally replaced with well-burnt bagasse ash without any adverse effect on the desirable properties of concrete. The specific advantages of such replacement are the development of high early strength, reduction in water permeability, and appreciable resistance to chloride permeation and diffusion.

Akram. T, Khan. A, Memon. S, (2007) observed that the results of unconfined compression test show an increase in soil strength of almost 50 times with lime and 64 times with combination of lime-bagasse ash. The California Bearing Ratio (CBR) increased by 3.5 and 4.5 times with lime and lime-bagasse ash combination, respectively. Swell potential of the soil reduced from 2.5 percent to almost zero. Bagasse ash with high silica and alumina contents reacts with calcium to form cementitious calcium silicate and aluminate hydrates. Therefore, use of bagasse ash in combination with lime significantly improves the strength and durability properties of low plastic clayey subgrade soils, and provides an environment friendly disposal of this agro-industry waste product.

2.5.3 Effect of Bagasse Ash on Properties of Soil

2.5.3.1 Atterberg's Limits

Gandhi, K. S, (2012) successfully used bagasse ash to reduce plasticity index of expansive clays. He reported that addition of 10 percent bagasse ash results in decrease in liquid limit from 72 percent to 52 percent, plasticity index from 42 percent to 27 percent and shrinkage limit reduced from 21 percent to 15 percent. Ashish et al, (2015) used bagasse ash to stabilize locally available medium plastic clay and he reported that for addition of 10 percent bagasse ash, liquid limit of soil reduced from 35 percent to 26 percent and plasticity index reduced from 13 percent to mere 9 percent.

2.5.3.2 Compaction Characteristics

Chhacchia & Mittal, (2015) utilized bagasse ash for the stabilization of clayey soils. They used up to 28 percent of bagasse ash in soil. They reported an increase in OMC from 22.42 percent to 27.9 percent and a reduction in MDD from 1.82 g/cm^3 to 1.34 g/cm^3. Ashish et al, (2015) studied the effect of bagasse ash on the properties of locally available medium plastic clay. With addition of 10 percent bagasse ash, they observed an increase in OMC from 15.3 percent to 18 percent and a decrease in MDD from 1.793 g/cm^3 to 1.692 g/cm^3.

2.5.3.3 Unconfined Compressive Strength of Soil

Osinubi et al, (2009) successfully used bagasse ash for the stabilization of lateritic soils. The UCS increased from 366 kN/m2 for the natural soil to 836, 842 and 973 kN/m2 for specimens treated with 2% bagasse ash content and cured for 7, 14 and 28 days, respectively.

The improvement in strength of bagasse ash-treated soil has been attributed to soil-bagasse ash reactions, which result in the formation of cementitious compounds that bind soil aggregates.

2.5.3.4 California Bearing Ratio and Swell Potential of Soil

Bagasse ash can produce a significant improvement in CBR and swell properties of soil. Ahmed et al, (2015) reported that addition of bagasse ash 0 percent, 1 percent, 3 percent, 5 percent, 7 percent and 9 percent to the soil samples caused an increase in CBR value at the rate of 6.47 percent, 8.63 percent, 10.97 percent, 12.05 percent, 13.5 percent, 13.85 percent respectively and at the addition of 11 percent bagasse ash, CBR value decreased to 13.28 percent. So 9 percent was selected as optimum percentage of bagasse ash. Chhacchia & Mittal, (2015) observed that untreated medium plastic clay had a CBR of 2.1 percent. It increased to 9.8 percent with the addition of 24 percent bagasse ash. But further addition of bagasse ash up to 28 percent reduced the CBR value to 6.7 percent. So they selected 24 percent bagasse ash as optimum percentage for the soil under study. Gandhi, K. S, (2012) reported a reduction of free swell index from 150 percent to 80 percent with the addition of 10 percent bagasse ash.

Chapter 3

MATERIALS AND METHODOLOGY

3.1 GENERAL

The research work is intended to check the suitability of gypsum and bagasse ash to help improve and stabilize expansive soils. Two types of expansive soils were used, medium plastic and highly plastic clays. All tests were carried out according to ASTM standards.

3.2 MATERIALS

Details about soil, gypsum, bagasse ash and bentonite used in this research are given in this section.

3.2.1 Soil

Two types of soils were used in this research, medium plastic clay, and high plastic clay. Medium plastic clay samples were collected from Ballewale village near Nandipur, Gujranwala. Figure 3.1 show the location of sample collection point.

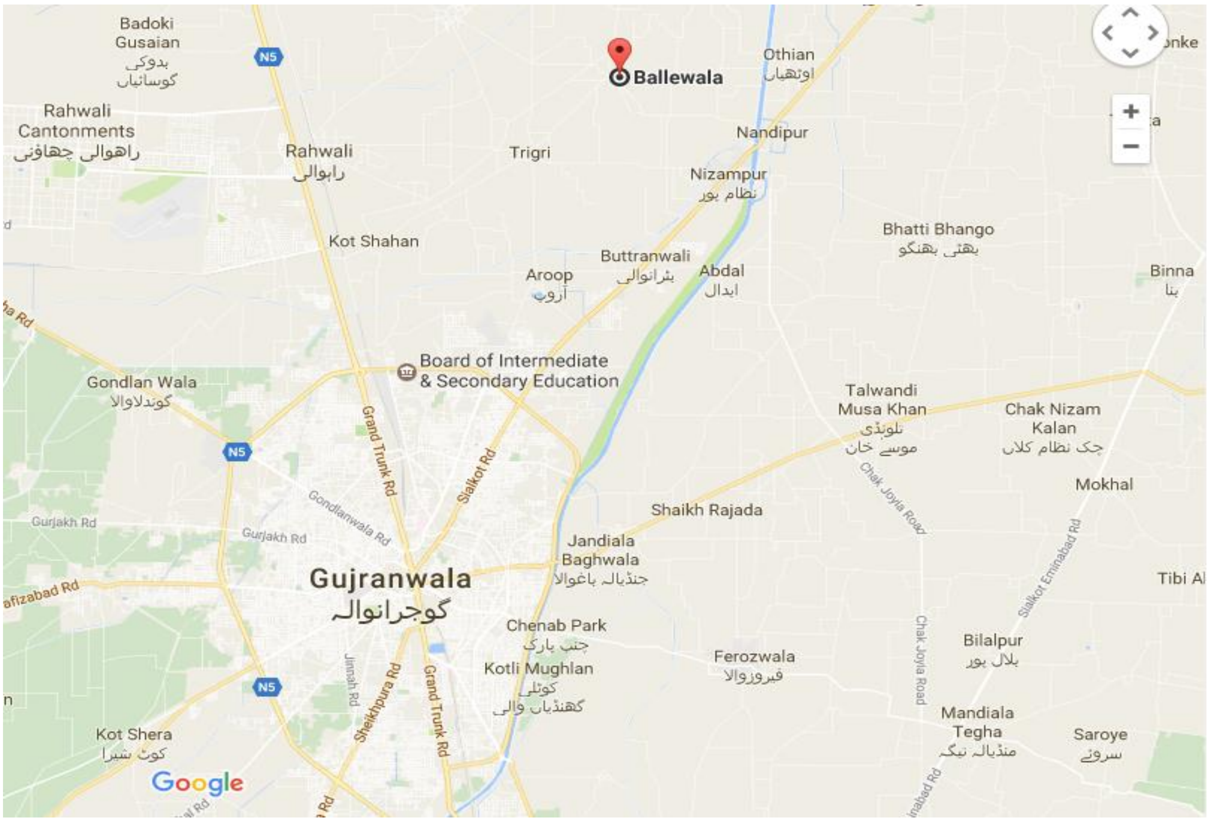

Figure 3.1: Satellite View of Sample Collection Point in Ballewale Near Nandipur

Then bentonite was added to this soil to make it high plastic. Oven dried soils were used throughout the research process. After performing multiple trials, 25 percent bentonite was selected as a suitable percentage to prepare high plastic clay from medium plastic clay. Medium plastic clay will be denoted as CL and high plastic clay as CH in later stages.

3.2.2 Gypsum

Gypsum used in the research was obtained from DFB Gypsum Industries, Karachi. Its product ID was GypPlaster®, and it had purity level of 98%. Gypsum will be denoted as G in the later stages.

Table 3.1: Properties of Gypsum (DFB Gypsum Industries)

Chemical Composition	Calcium Sulphate Hemihydrates $CaSO_4 \cdot \frac{1}{2} H_2O$
Fineness	4 to 6% only remaining on sieve 200
Initial Setting Time	From 3 minutes for Speedo plaster to 10 Minutes as per requirement
Final Setting Time	From 12 Minutes for Speedo Plaster to 30 Minutes as per requirement
Compressive strength	Greater than 10.5 MN/m^2 or 1525 psi (pure plaster).
Density	1100 kg/m^3
Thermal conductivity	0.22W/m.K (i. e. gypsum plaster's insulation is about five times better than cement - sand plaster).

3.2.3 Bagasse Ash

Bagasse ash was obtained from Baba Fareed Sugar Mills Pvt Ltd, Okara (Figure 3.2). Chemical analysis of bagasse ash was performed in lab of IESE Department of National University of Science & Technology (NUST), Islamabad. Bagasse ash will be denoted as BA in the later stages.

3.2.4 Bentonite

Bentonite was added to soil sample to make it high plastic clay. Bentonite used in this research was obtained from Ahmed Saeed & Company Lahore. Product ID of the material used was “Bentobest”. It is high swelling sodium bentonite. Some properties of this bentonite are given below provided by the manufacturer Table 3.2.

Figure 3.2: Baba Fareed Sugar Mill Ltd, Okara (Bagasse Ash Sample Collection)

Table 3.2: Properties of Bentobest (Ahmed Saeed & Company)

SiO_2	50 – 60 %
Al_2O_3	15 – 20 %
Fe_2O_3	2 – 4 %
MgO	4 – 6 %
CaO	0.5 – 1 %
Na_2O	0.9 – 1.9 %.
K_2O	0.2 – 0.5 %
TiO_2	0.2 – 0.5 %
Others	0.5 – 1 %
Moisture	5 – 10 %
Loss on Ignition	10 – 15 %
Swelling	Above 12 times
Suspension	Above 12 times
Water absorption	5 times
Fineness	3 to 5% only remaining on sieve 200

3.3 METHODOLOGY

Material testing was carried out in four phases: -

- Phase I: Properties of untreated / natural soil
- Phase II: Optimization of gypsum content

- Phase III: Optimization of bagasse ash content
- Phase IV: Properties of treated soil

3.3.1 Phase I: Properties of Untreated/Natural Soil

The first step in my research was aimed at determining the properties of natural or untreated soil or without any admixtures. Both medium and high plastic soils were used and their properties were determined in an untreated condition.

3.3.1.1 Sample collection

The soil sample was collected from Ballewale village near Nandipur, Gujranwala. The region is famous for exporting clayey soil for cricket pitches all around the world. The sample was collected from one of these locations (see Figure 3.1). The excavation was in progress and sample was collected from 2 feet depth to reduce the chances of organic matter, roots, etc.

3.3.1.2 In-Situ density and moisture content of soil

The in-situ density of soil was determined by core cutter method. The test was carried out in accordance with ASTM D 2937.

In-situ moisture content of the soil was determined by oven drying method performed in accordance with ASTM D 2216-98.

3.3.1.3 Grain size distribution

Sieve analysis was carried out in accordance with ASTM D 422-63. A 300 gm of soil sample was taken, pulverized and washed over sieve no 200.

For particle gradation of fine fraction (passing #200 sieve) hydrometer analysis was performed in accordance with ASTM D 7928-16.

3.3.1.4 Atterberg’s limits of soil

ASTM D 4318 was followed for the determination of Liquid Limit and Plastic Limit of Soil. Soil passing #40 sieve was used in the test. Both AASHTO and USCS (unified soil classification system) were used for the classification purpose.

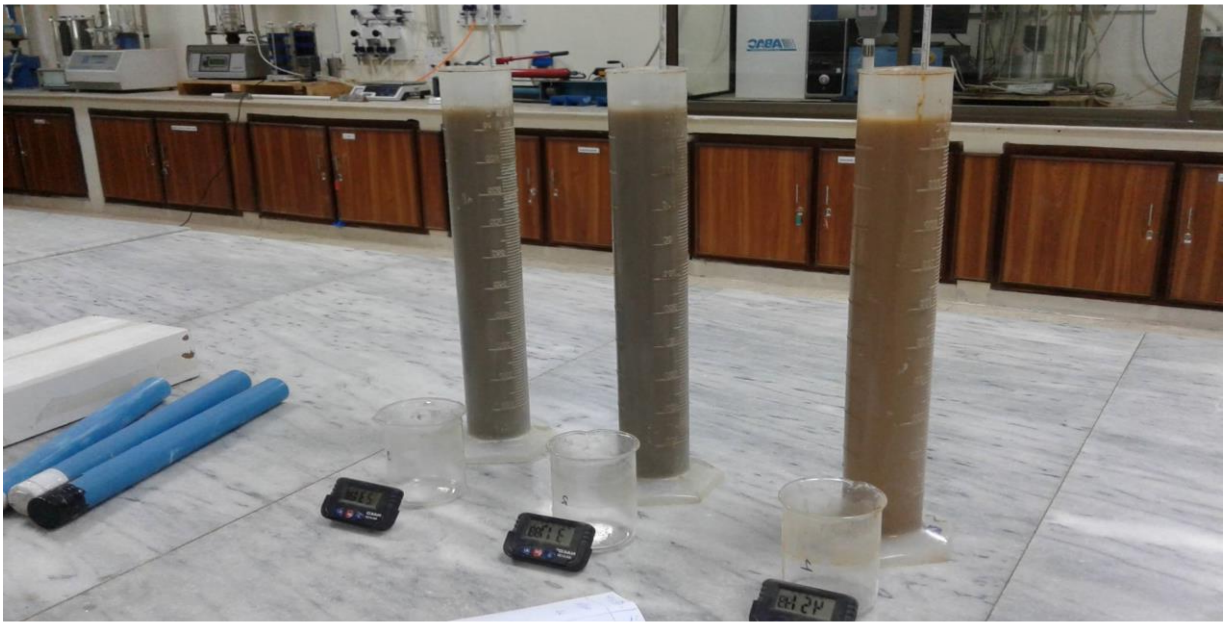

Figure 3.3: Testing Arrangements for Hydrometer Analysis

3.3.1.5 Specific gravity of soil

The specific gravity of the soil was determined in accordance with ASTM D 854-14. Hotplate was used for the removal of air voids and specific gravity was calculated accordingly.

3.3.1.6 Compaction characteristics of soil

Standard Proctor Test method was used to establish the moisture-density relationship of untreated soil. Compaction test in accordance with ASTM D 698 was performed for determination of compaction characteristics of soil.

Figure 3.4: Standard Proctor Test on Soil

3.3.1.7 Unconfined compressive strength of soil

ASTM D 2166 was followed for the determination of unconfined compressive strength(UCS) of the soil samples. This standard requires that the height to diameter ratio of the mold must be 2:1. Mold with 4 cm diameter and 8 cm height were used. The unconfined compressive test was performed in both soaked and unsoaked conditions and relative loss in strength due to the soaking was noted. The sample was fabricated according to the optimum moisture content (OMC) and maximum dry density (MDD) of the soil already obtained from Standard Proctor test. Two samples were prepared for each test and their average strength was reported.

For soaked testing, samples were subjected to capillary soak for 48 hours prior to testing. For the soaking purpose, ASTM 5102 procedure B was followed. Samples were removed from airtight plastic bags, wrapped up in absorption fabric and placed on a porous stone inside a container (Figure 3.6). Direct contact of water and sample was avoided. Tests were carried out after samples have been subjected to capillary soak for 48 hours. Two specimens were tested for each condition and their average strength was reported.

Figure 3.5: Soaking Arrangements for Samples

3.3.1.8 California Bearing Ratio (CBR) and swell potential of soil

One point CBR test was performed in accordance with ASTM D 1883-99. CBR samples were prepared at OMC and compacted in five layers with 76 blows applied for the compaction of each layer. Apparatus used include a mold with an internal diameter of 6-inches and height of 7 inches, 2 inches' thick spacer disk and a surcharge weight of 5 kg.

Samples were soaked for 96 hours and CBR test was performed for the soaked condition. Maximum dry density determined from a 4-inch diameter mold is normally greater than that determined in 6-inch diameter mold. So a relatively higher compaction effort is required to achieve equal or greater dry density.

One dimensional swell of the soil was determined in accordance with ASTM D 4546-96. CBR and swell potential of both medium plastic "S" and high plastic "BS" soils were determined. Preparation, soaking, and testing assembly are shown in Figure 3.6.

3.3.2 Phase II: Optimization of Gypsum Content

Second phase of this research was intended for the determination of optimum gypsum content for soil under study. Optimum gypsum content was determined for both soils by applying methodology given in following paragraphs.

3.3.2.1 Moisture-Density Relationship at various gypsum contents

Different samples were prepared by adding 9%, 12%, 15% and 18% Gypsum. OMC and MDD were found for each specimen using standard proctor tests. All tests were performed in accordance with ASTM D 698.

3.3.2.2 Unconfined Compressive Strength at various gypsum contents

Unconfined compressive strength test samples were prepared at for 9%, 12%, 15% and 18% Gypsum content. The samples were prepared at OMC and MDD already determined by Standard proctor test. Two test specimens were prepared for each percentage and their average strength value was reported. All tests were performed in accordance with ASTM D 2166. Maximum change due to addition of gypsum is observed after 7 days of curing. All test samples were wrapped up in airtight plastic bags to prevent moisture loss and cured at $30^{o}C$ for 7 days. After 7 days of curing, samples were tested and the gypsum percentage resulting in the highest improvement in UCS was selected as optimum gypsum content.

Figure 3.6 (a): Preparation of CBR Samples

Figure 3.6 (b): Soaking Arrangement for CBR Sample

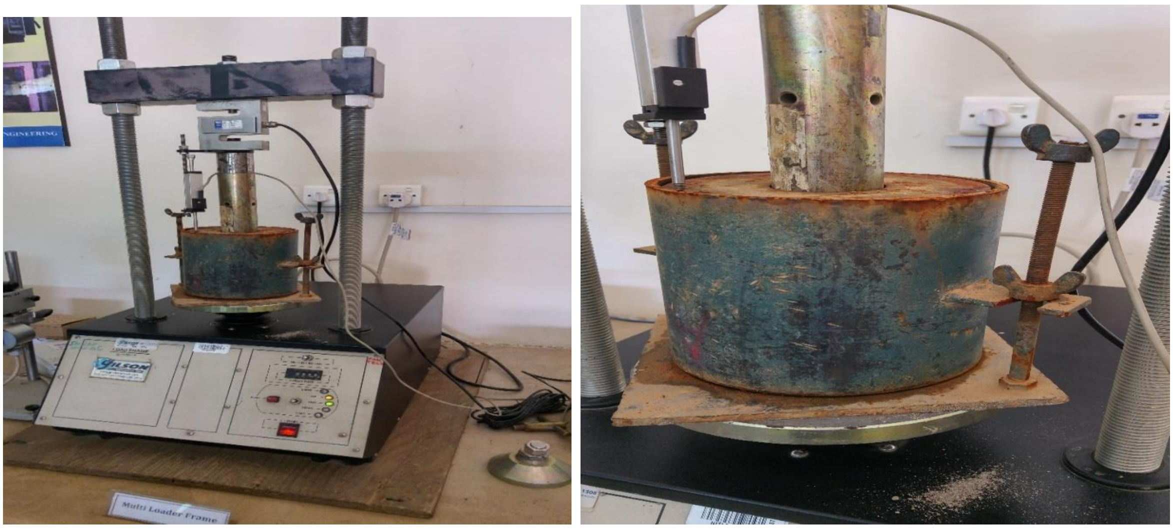

Figure 3.6 (c): Testing Arrangement for CBR Samples

3.3.2.3 Optimization of excess moisture

Excess moisture is required for hydration process and the reaction between gypsum and soil to progress. So a need was felt to check the amount of excess moisture required for the optimum results. Samples were prepared with, Optimum gypsum content determined in previous stage, and 1%, 2% and 3% excess moisture than that of OMC of the sample. Two specimens were prepared and tested for each condition. Samples were cured for 7 days at 30^{o}C and tested. Samples with highest UCS value were selected as optimum value for excess moisture. All samples were prepared and tested in accordance with ASTM D 2166.

3.3.3 Phase III: Optimization of Bagasse Ash Content

Third phase of this research was intended for the determination of optimum Bagasse ash content for soil under study. Optimum bagasse ash content was determined for both soils by applying the methodology given in following paragraphs.

3.3.3.1 Chemical composition of bagasse ash

Before using bagasse ash as stabilizing agent for soil, it was important to verify the suitability of the material as per ASTM requirements for Pozzolanic material. Chemical composition of bagasse ash was determined with the help of X-Ray fluorescence test. Then it was compared with ASTM C618 requirements for a pozzolanic material. Test was performed in IESE department of NUST, Islamabad. Testing apparatus for X-Ray Fluorescence test is shown in Figure 3.7.

Figure 3.7: Testing Apparatus for X-Ray Fluorescence

3.3.3.2 Moisture-Density Relationship at various bagasse ash contents

Once it was verified that the bagasse ash under study meets ASTM requirements for a pozzolanic material, Different soil samples were prepared by adding optimum gypsum content determined in Phase II and 2%, 4%, 6% and 8% bagasse ash. Optimum moisture content (OMC) and maximum dry density (MDD) were found for each specimen using standard proctor tests. Soil is compacted in three layers with 25 blows applied to each layer with a 5.5lb hammer with drop height of 12 inches. All tests were performed in accordance with ASTM D 698.

3.3.3.2 Unconfined Compressive Strength at various bagasse ash contents

Unconfined compressive strength test samples were prepared at optimum gypsum and 2%, 4%, 6% and 8% Bagasse Ash content. The samples were prepared at optimum moisture content (OMC) and maximum dry density (MDD) already determined by Standard proctor test. Two test specimens were prepared for each percentage and their average strength value was reported. All tests were performed in accordance with ASTM D 2166. Maximum change due to addition of Bagasse Ash is observed after 7 days of curing. All test samples were wrapped up in airtight plastic bags to prevent moisture loss and cured at 30^{o}C for 7 days. After 7 days of curing, samples were tested and the bagasse ash percentage resulting in the highest improvement in UCS was selected as optimum gypsum content.

3.3.3.3 Optimization of excess moisture

Excess moisture is required for hydration process and the reaction between gypsum, bagasse ash and soil to progress. So a need was felt to check the amount of excess moisture required for the optimum results. Samples were prepared with, optimum gypsum content and optimum bagasse ash content determined in previous stage, and 1%, 2% and 3% excess moisture than that of OMC of the sample. Two specimens were prepared and tested for each condition. Samples were cured for 7 days at 30^{o}C and tested. Samples with highest UCS value were selected as optimum value for excess moisture. All samples were prepared and tested in accordance with ASTM D 2166.

3.3.4 Phase IV: Properties of Treated Soil

Once the optimum content for both gypsum and bagasse ash were established, Atterberg's limits, moisture-density relationship, UCS at 2,7,14 and 28 days curing, CBR and swell potential of soil were determined for gypsum and for both gypsum and bagasse ash.

3.3.4.1 Atterberg's Limits of treated soil

Liquid limit and plastic limit of soil were determined for untreated as well as treated form with gypsum and bagasse ash. All tests were performed in accordance with ASTM D 4318.

3.3.4.2 Moisture Density Relationship for treated soil

ASTM D 698 was used to establish the moisture-density relationship for treated soil. Standard proctor test method was used to determine the optimum moisture content and maximum dry density for each soil sample.

3.3.4.3 Unconfined Compressive Strength of treated soil

Unconfined compressive strength tests were carried out on samples with optimum gypsum content and samples with optimum gypsum and bagasse ash content after 2, 7, 14 and 28 days of curing. Samples were prepared at maximum dry density and 1% and 2% excess moisture for medium and high plastic clays, respectively. Excess moisture content was optimized in phase II for gypsum and phase III for gypsum and bagasse ash. Two test specimen were prepared for each test and their average value was reported. Samples were wrapped up in air tight plastic bags for the preservation of moisture and cured at 30^{o}C for the respected curing period. Both soaked and unsoaked strengths were determined. For soaked strength, samples were subjected to capillary soak for 48 hours prior to testing. Soaking of the samples was carried out by wrapping up the samples in fabric material and placing it in a water container in a way that there is no direct contact between soil and water and soaking is done due to capillary rise of water through fabric. Direct contact between the soil and sample was avoided.

3.3.4.4 California Bearing Ratio (CBR) and swell potential of treated soil

California bearing ratio (CBR) and swell potential of the soil were determined for untreated and soils treated with gypsum and bagasse ash. ASTM D 1883-99 was followed throughout the test procedure. CBR samples were prepared at Optimum moisture content already determined from moisture density relationship and compacted in five layers with 76 blows applied for the compaction of each layer. Apparatus used include a mold with internal diameter of 6-inches and height of 7 inches, 2 inches' thick spacer disk and a surcharge weight of 5 kg. Samples were soaked for 96 hours and CBR test was performed for soaked condition. One dimensional swell of the soil was determined in accordance with ASTM D 4546-96.

Chapter 4

RESULTS AND DISCUSSION

4.1 GENERAL

This research was intended to study the suitability of gypsum and bagasse ash as a soil stabilizer for medium plastic and high plastic clay.

4.2 PHASE I: PROPERTIES OF NATURAL/UNTREATED SOIL

4.2.1 In-Situ Density and Moisture Content of Soil

In-Situ density for the medium plastic clay was determined as 1.61g/cm^3 and natural moisture content for medium plastic soil was determined as 15.5%. Since high plastic clay was prepared artificially, it was not possible to determine natural moisture content and in-situ density for high plastic clay.

4.2.2 Grain Size Distribution

Grain size distribution of natural or medium plastic soil was carried out using wash method to determine percentage passing no 200 sieves while silt and clay percentages were determined by hydrometer analysis of soil. 89% of soil was passing no 200 sieves while hydrometer analysis showed that soil contained 54 percent of silt particles and 35 percent of clay particles. While high plastic clay had 95 percent passing of sieve no 200 with 46 percent silt and 49 percent clay particles.

4.2.3 Atterberg’s Limits of Soil

Casagrande apparatus was used for the determination of liquid limit of soil while plastic limit was determined by making threads 1/8” thickness as per ASTM requirements.

Liquid limit of medium plastic soil was determined by 48 percent and plastic limit as 24 percent. Plasticity index of medium plastic clay was 24. It is classified as CL as per USCS system and A-6-7 as per AASHTO classification system.

By adding 25 percent of bentonite to the medium plastic soil, its liquid limit increased from 48 to 65 percent while plasticity index increased from 24 to 42 percent. This increase in liquid limit and plasticity index is due to the fact that water-holding capacity of the soil is increased. Bentonite (sodium montmorillonite) have a weak crystalline structure and weak bonding between silica and alumina sheets permit water and other chemical solutions to enter in the spaces between these sheets. As a result, an increase in liquid limit and plasticity index is observed.

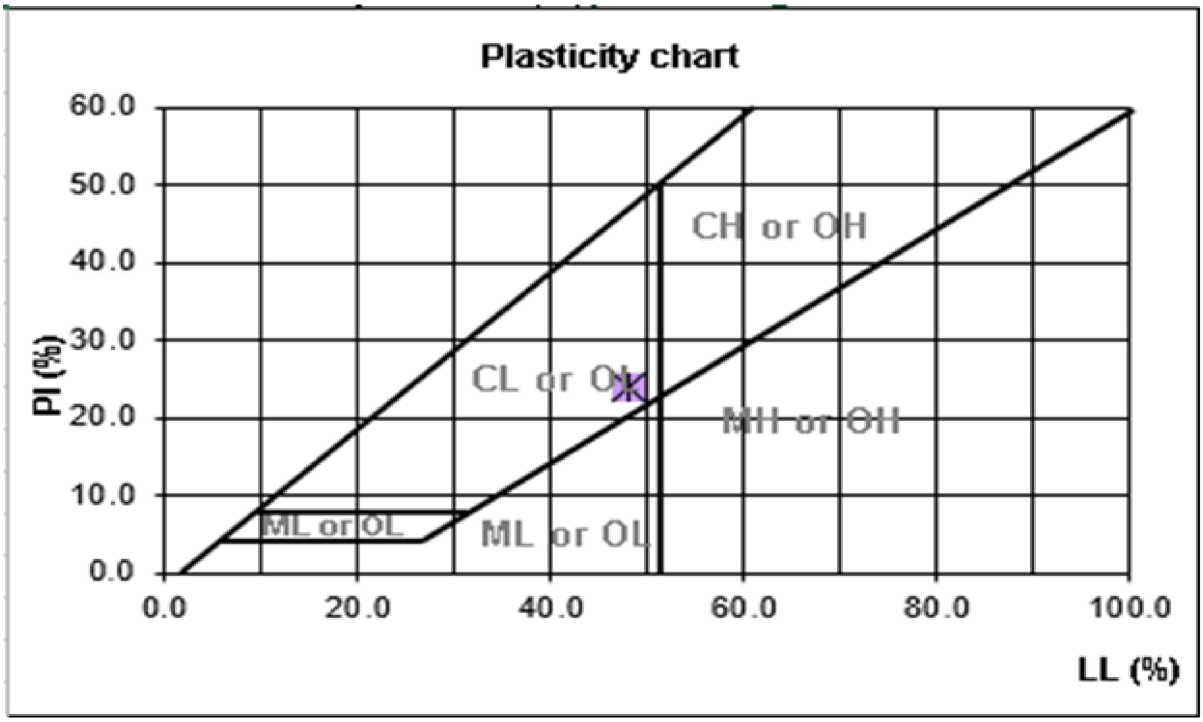

Figure 4.1 (a): USCS Classification of CL

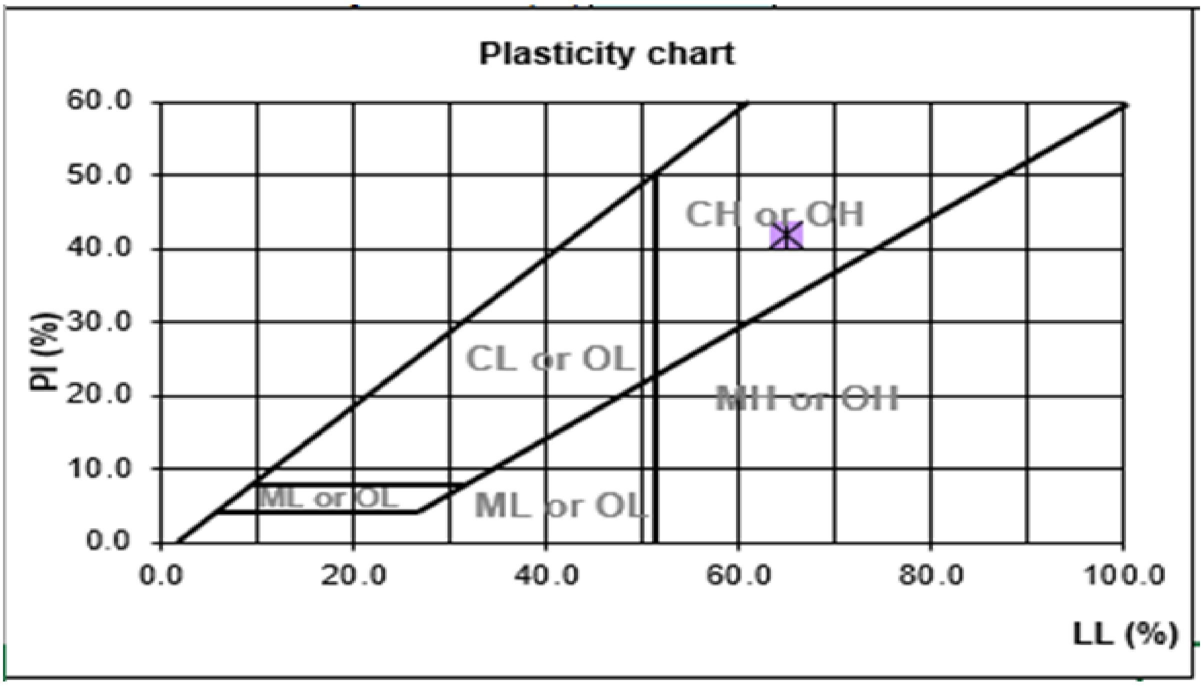

Figure 4.1 (b): USCS Classification of CH

4.2.4 Specific Gravity Gs of Soil

The specific gravity of both CL and CH were determined as per ASTM D 854-98 standard. Specific gravity for CL was determined to be 2.67 while that for CH was 2.7. Both of these values fall within the range described by ASTM for clayey soils.

4.2.5 Compaction Characteristics of Soil

MDD and OMC for CL were 1.73 g/cm3 and 19.67% respectively and that for CH was 1.68 g/cm3 and 21.81%. Compaction curve for both soils is shown below in figure 4.2

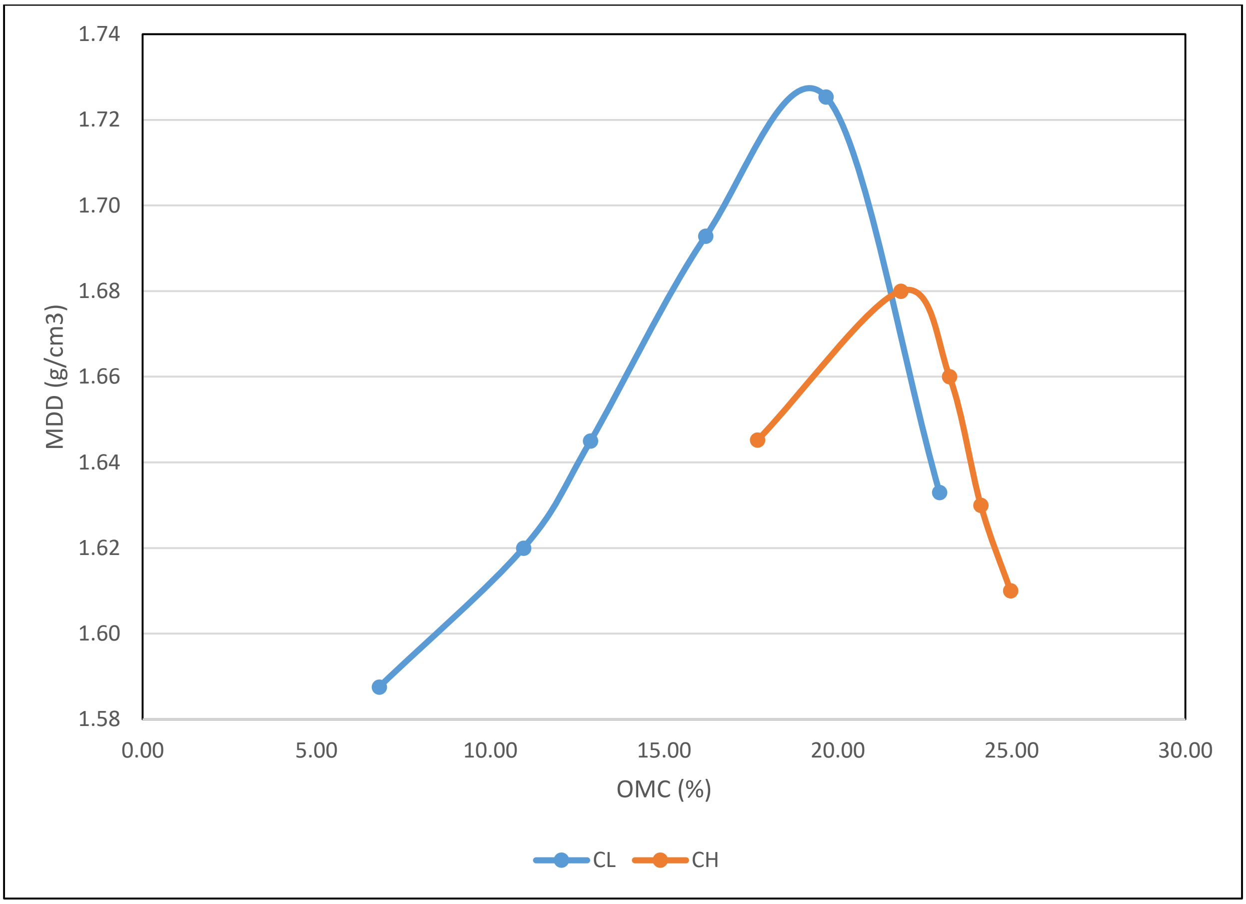

Figure 4.2: Compaction Curve for CL and CH

4.2.6 Unconfined Compressive Strength of Untreated Soil

Unconfined compressive strength test samples were prepared and testing was carried out for both soils.

CL, had an unconfined compressive strength of 125.4 KPa. Unconfined compressive strength was reduced to 25 KPa in soaked condition. Almost 80 % of strength was lost when soil was subjected to capillary soak for 48 hours.

Similarly, CH, had an unconfined compressive strength of 153.17 KPa. Unconfined compressive strength was reduced to 18.2 KPa in soaked condition. Almost 88 % of strength was lost when soil was subjected to capillary soak for 48 hours. Effect of soaking was more severe in high plastic clay as compared to medium plastic clay.

4.2.7 California Bearing Ratio (CBR) And Swell Potential of Soil

Samples were soaked for 96 hours, CBR and one-dimensional swell potential was determined for both soils as per ASTM standard. CL had a CBR value of 3.1% and one dimensional swell potential of 6.3%. While CH had CBR value as 1.5% and one dimensional swell potential as 9.45%. Based on CBR value, both materials are classified as poor materials.

A brief summary of the properties of natural/untreated soil is given in Table 4.1, detailed discussion of the test results is given in subsequent paragraphs.

Table 4.1: Summary of Properties of Untreated Soils

	CL		CH	
Liquid Limit (%)	48		65	
Plastic Limit (%)	24		23	
Plasticity Index (%)	24		42	
% age Passing #200	89		95	
Silt (%)	54		46	
Clay (%)	35		49	
Soil Type	USCS	CL	USCS	CH
	AASHTO	A-7-6	AASHTO	A-7-6
In-Situ Dry Density (g/cm^3)	1.61			
Natural Moisture Content (%)	15.5			
Specific Gravity Of Soil	2.67		2.7	
Maximum Dry Density (g/cm^3)	1.73		1.68	
Optimum Moisture Content (%)	19.67		21.81	
Unconfined Compressive Strength UCS (KPa)	Unsoaked	125.4	Unsoaked	153.17
	Soaked	25	Soaked	18.2
California Bearing Ratio(CBR) (%)	3.1		1.5	
One dimensional Swell Potential (%)	6.3		9.45	

4.3 PHASE II: OPTIMIZATION OF GYPSUM CONTENT

Optimum content for gypsum is which gives the best results for the soil under study. The main criteria are that the gypsum content which gives the highest value for unconfined compressive strength is the optimum gypsum content.

4.3.1 Moisture Density Relationship at Various Gypsum Contents

Moisture density relationship is established for various gypsum contents. Samples are prepared by adding 9 %, 12 %, 15 % and 18% gypsum and standard proctor test is used to determine optimum moisture content OMC and maximum dry density MDD for each sample**.**

Following graphs show the moisture-density relationship for CL. From graphs, it is clear that 12 % gypsum has the maximum effect on compaction characteristics of soil. Figure 4.3(a, b, c). Maximum change in moisture content and dry density of soil is observed at 12 % gypsum level.

Similarly, compaction test results for soil-bentonite mix BS are shown in Figure 4.4 (a, b, c). Maximum change in moisture content and dry density of soil is observed at 15 % gypsum level.

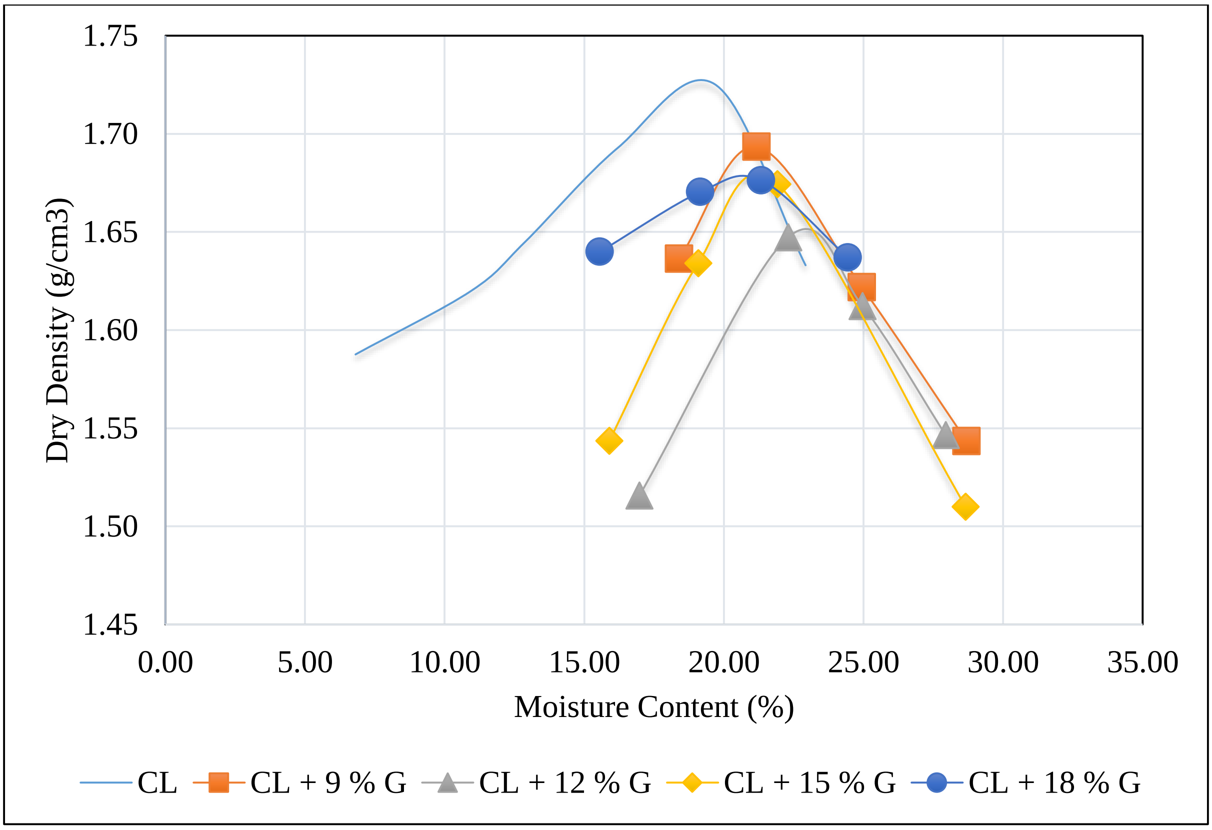

Figure 4.3 (a): Moisture Density Relationship for CL at Various Gypsum Contents

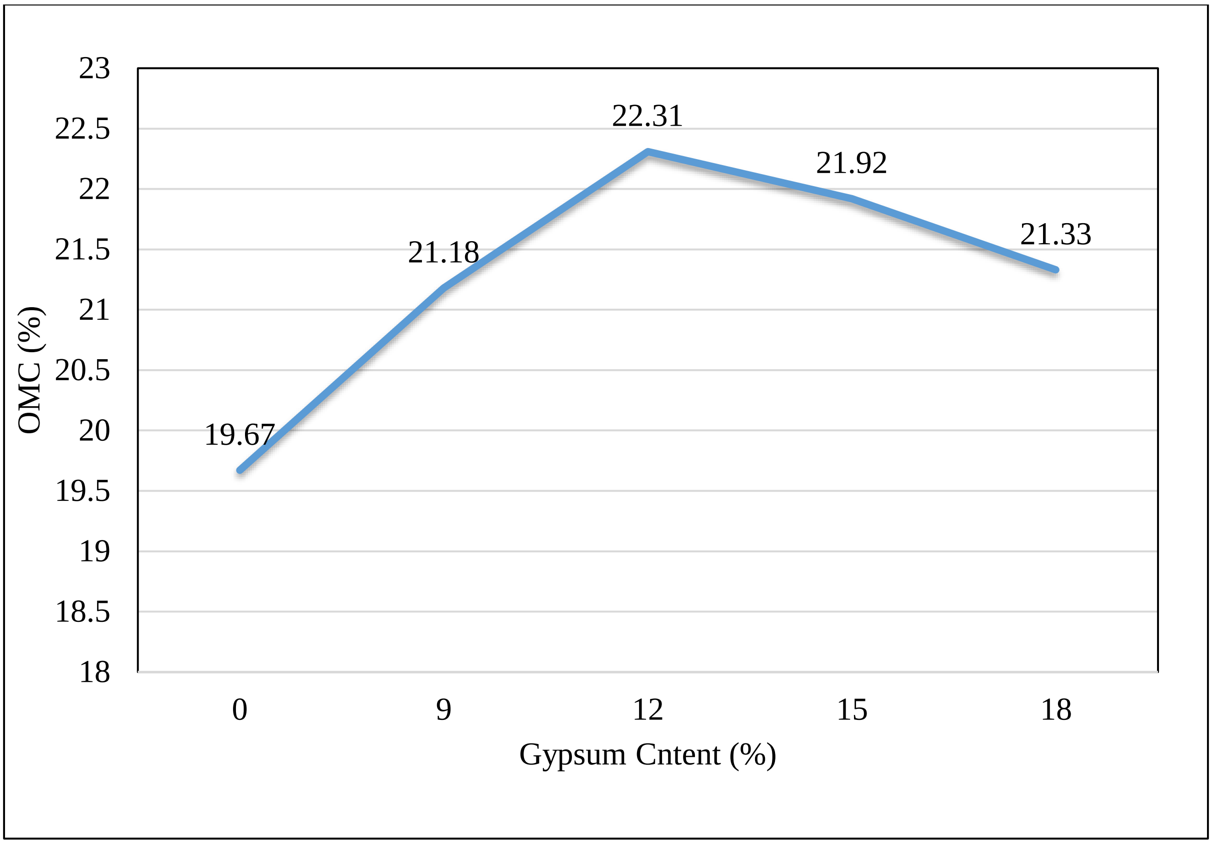

Figure 4.3 (b): Variation of OMC with Various Gypsum Contents for CL

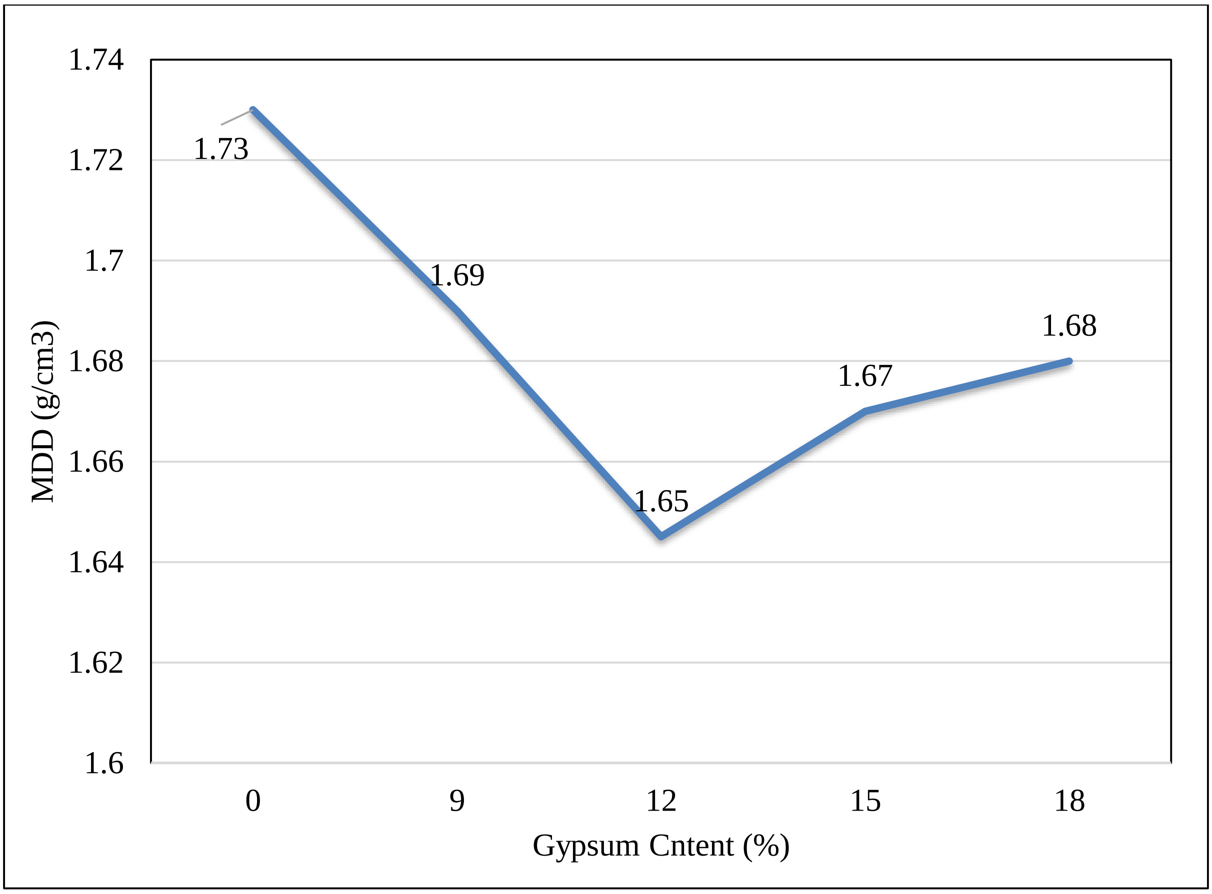

Figure 4.3 (c): Variation of MDD with Various Gypsum Contents for CL

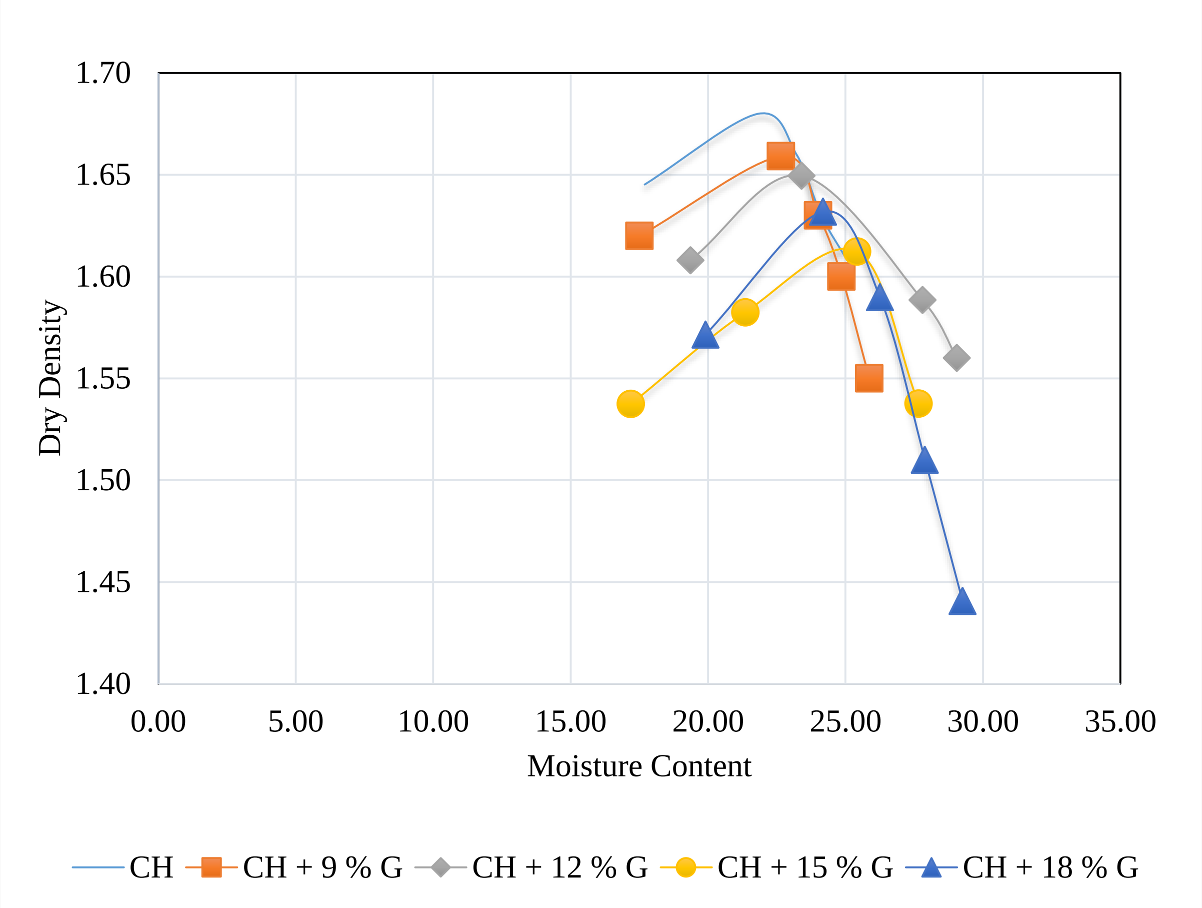

Figure 4.4 (a): Moisture Density Relationship for CH at Various Gypsum Contents

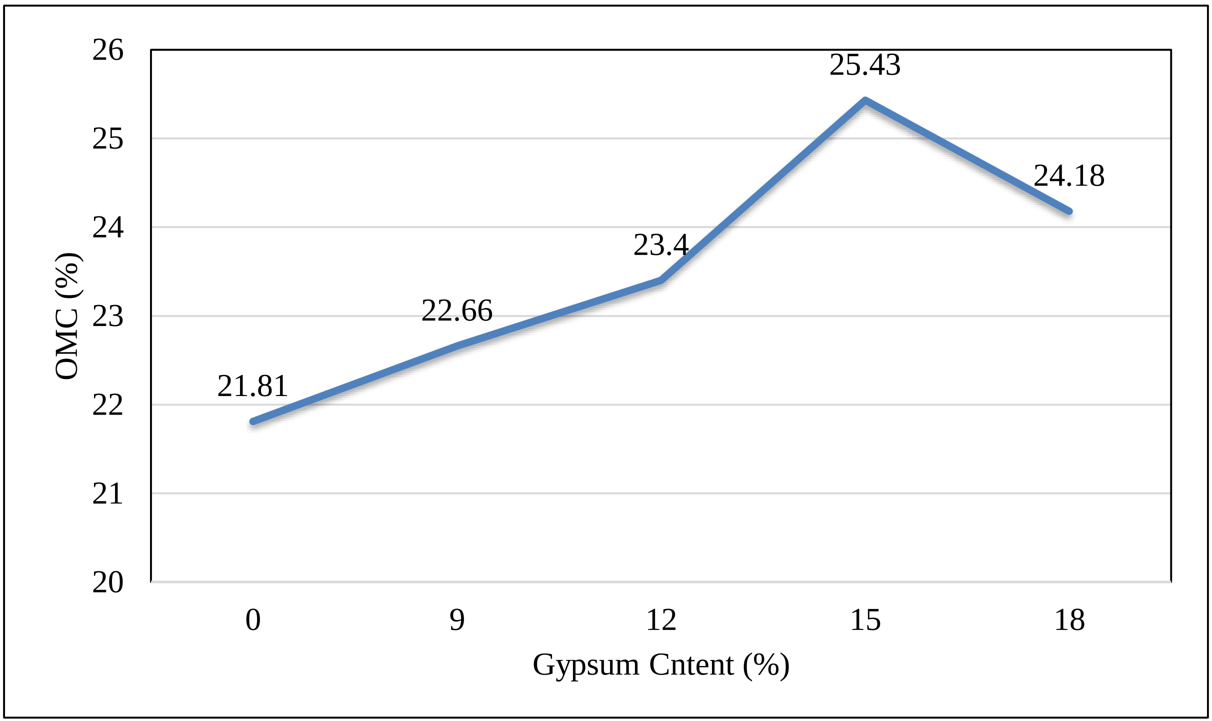

Figure 4.4 (b): Variation of OMC with Various Gypsum Contents for CH

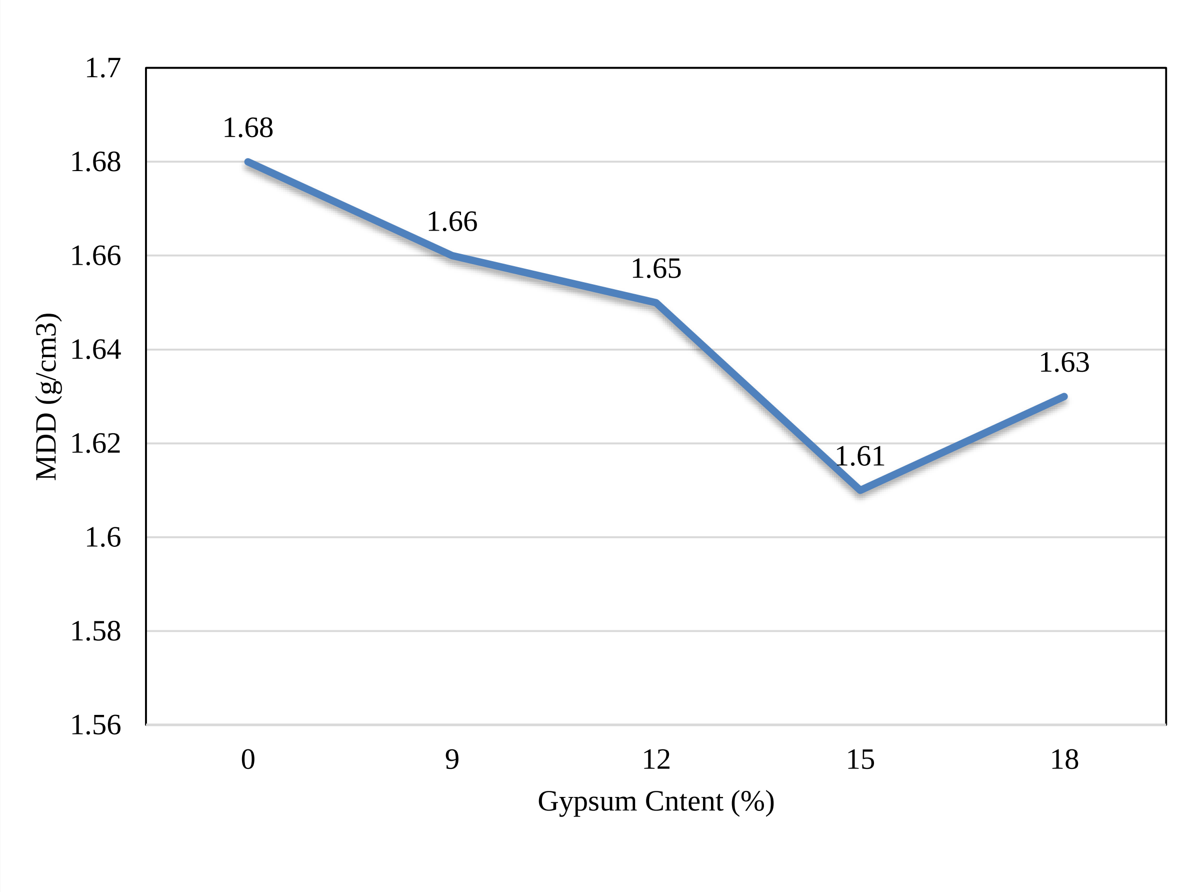

Figure 4.4 (c): Variation of MDD with Various Gypsum Contents for CH

The variation of OMC and MDD for CL and CH is shown in Figure 4.3 and Figure 4.4. Compaction test results on these soils indicate a gradual decrease and then increase in maximum dry density of soil. This reduction in maximum dry density is due to the flocculation and agglomeration of fine-grained soil particles. These flocculated particles occupy larger spaces which reduce the dry density of soil. It is also due to the development of coating of soil particles by gypsum which forms large sized particles. On the other hand, the optimum moisture content of soil increases with increase in gypsum content. This is due to the reason that gypsum is finer than soil. The finer the material is, larger will be its surface area and more water will be required for the lubrication of these particles. Moreover, gypsum also reduces the amount of free silt and clay fraction forming coarser materials which occupy larger spaces for retaining water. The increase in water content is also attributed to the pozzolanic activity between gypsum and soil particles.

4.3.2 Unconfined Compressive Strength at Various Gypsum Contents

Unconfined compressive strength UCS samples were prepared for various gypsum contents at their OMC and MDD as determined by compaction test. Samples were cured for 7 days and then tested. Gypsum percentage giving maximum unconfined compressive strength was selected as optimum gypsum content.

Test results show that maximum unconfined compressive strength is obtained for 12 % gypsum for CL and for 15% gypsum for CH.

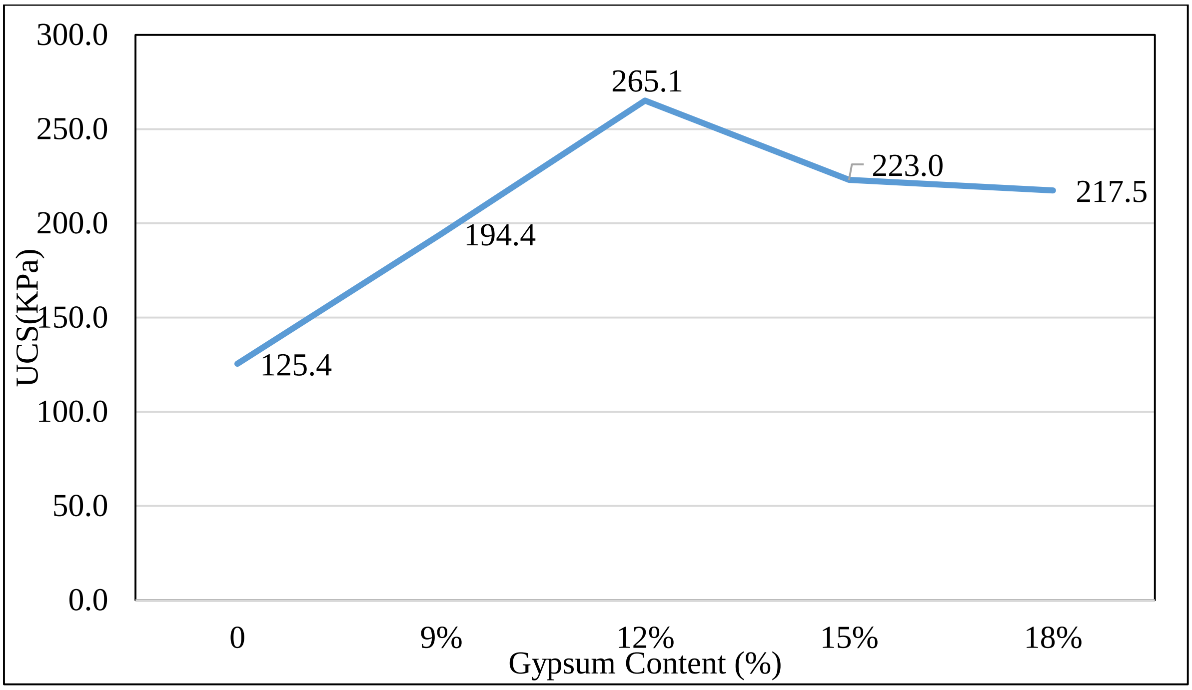

Figure 4.5 (a): Variation of UCS at Various Gypsum Contents for CL

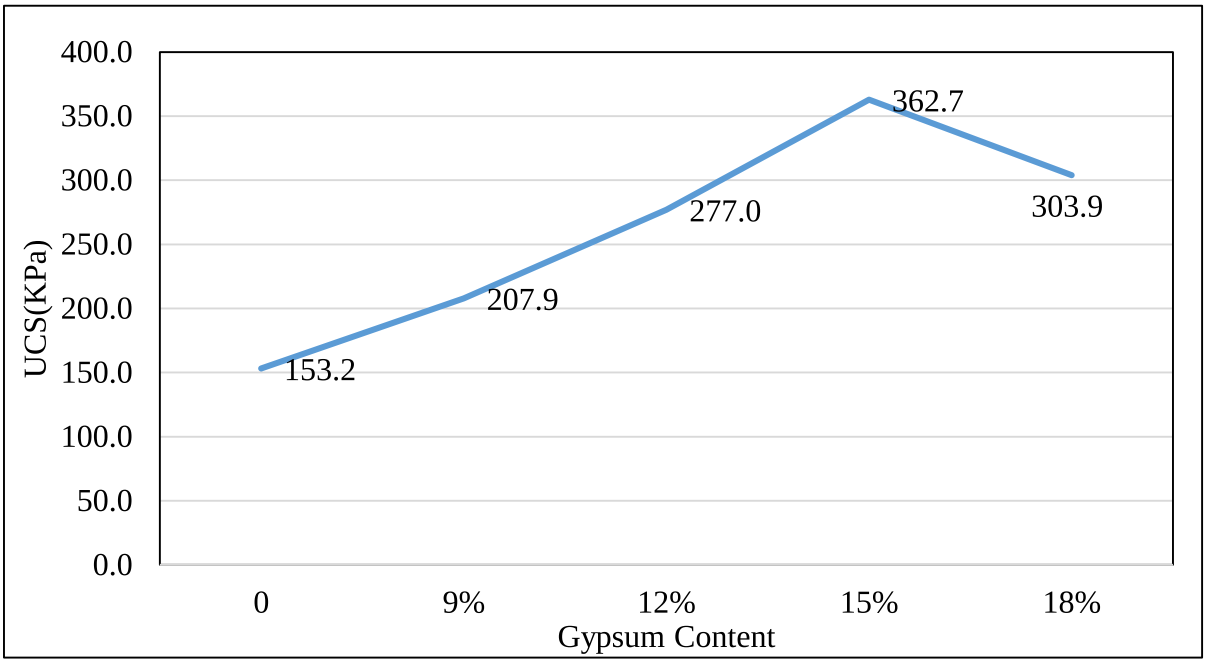

Figure 4.5 (b): Variation of UCS at Various Gypsum Contents for CH

4. 3. 3: Optimization of Excess Moisture

Excess moisture is required for hydration process as well as the reaction between soil and gypsum to proceed. So, some additional water is required for the above-mentioned purpose. But if water is added more than what is needed, it can reduce the unconfined compressive strength of soil. So it is important to determine the optimum excess moisture for best results.

Soil samples are prepared for optimum gypsum content at 1%, 2 % and 3% moisture above OMC. Test results show that highest UCS is obtained at 1% excess moisture for CL and 2% excess moisture for CH Figure 4.6 & 4.7.

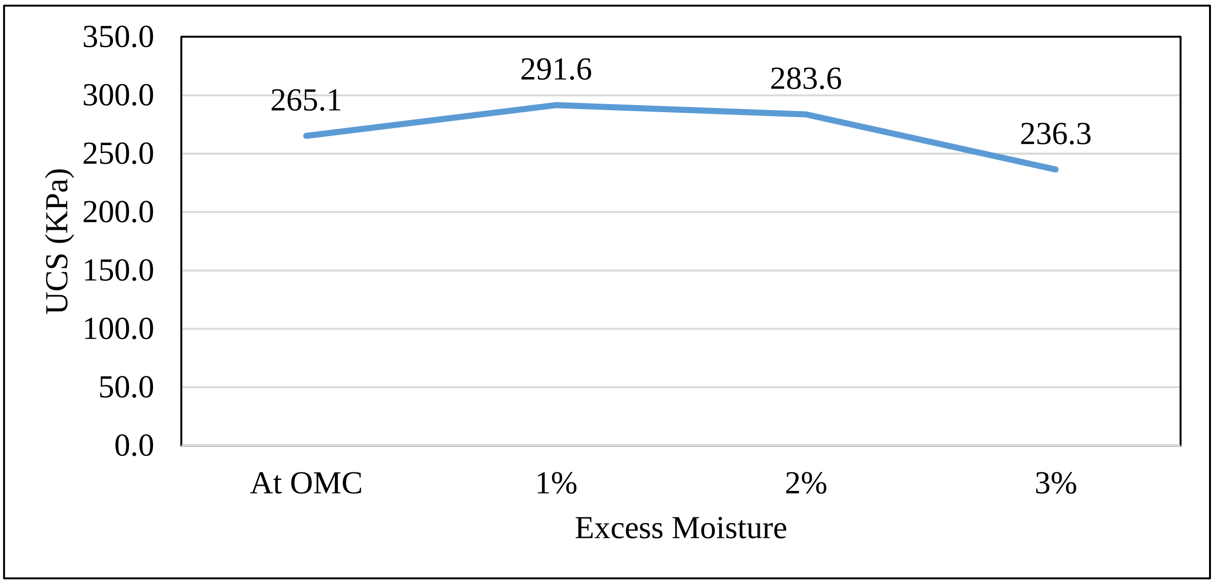

Figure 4.6: UCS at Various Excess Moisture Contents for CL + 12 % G

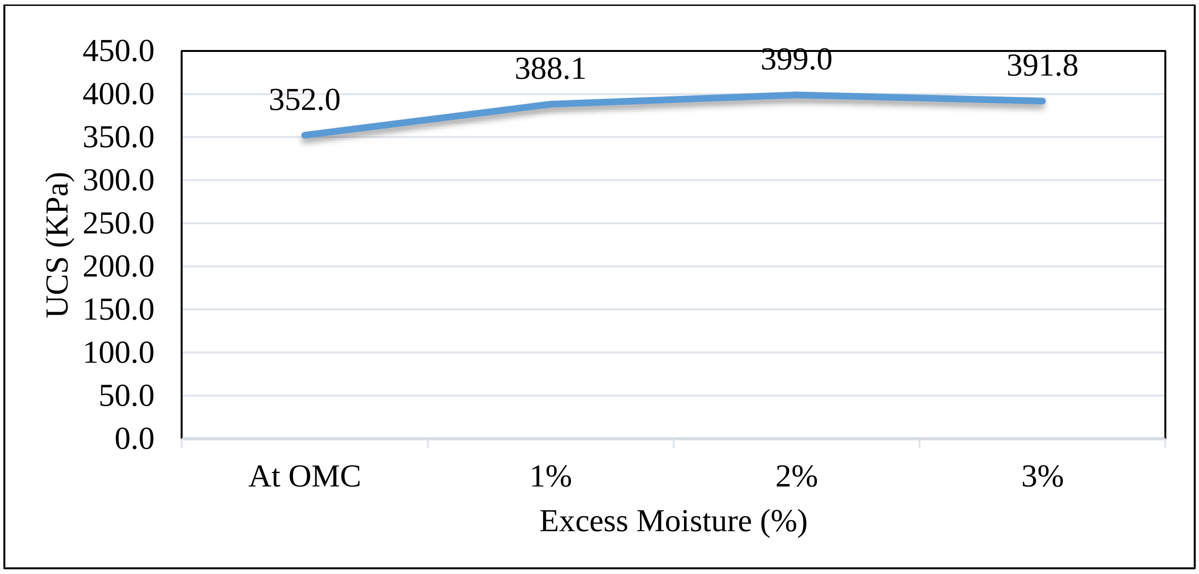

Figure 4.7: UCS at Various Excess Moisture Contents for CH + 15 % G

4.4: PHASE III: OPTIMIZATION OF BAGASSE ASH CONTENT

The main criteria for determination of optimum bagasse ash content is same as for optimum gypsum content determination, i.e., bagasse ash percentage which gives the highest unconfined compressive strength is selected as optimum bagasse ash content.

Table 4.2: Chemical Composition of Bagasse Ash

Constitute	Percentage	ASTM C-618 Requirement
Silicon Dioxide, (SiO_2)	60.58	Minimum 70%
Aluminum Oxide, (Al_2O_3)	25.4	
Ferric Oxide, (Fe_2O_3)	2.91	
Calcium Oxide, (CaO)	1.42	4% maximum
Magnesium Oxide, (MgO)	3.21	4% maximum
Sulfur Trioxide, (SO_3)	0.95	4% maximum
Potassium Oxide, (K_2O)	3.5	4% maximum
Moisture Content	2.58	3% maximum
Loss on Ignition	2.81	10% maximum

4.4.1 Moisture density relationship at Various Bagasse Ash Contents:

Moisture density relationship is established at various bagasse ash contents. Samples are prepared at optimum gypsum content determined in phase II and different bagasse ash contents. 2 %,4 %,6 % and 8 % bagasse ash is added and standard proctor test is used to determine optimum moisture content OMC and maximum dry density MDD for each soil sample. Following graphs show the moisture-density relationship for CL. From graphs, it is clear that 4% bagasse ash has the maximum effect on compaction characteristics of soil. Figure 4.8 (a, b, c). Maximum change in moisture content and dry density of soil is observed at 4% bagasse ash level. Similarly, Figure 4.9 (a, b, c) shows the moisture-density relationship for CH. It is clear from compaction test results that maximum change in compaction characteristics for CH are observed at 6% bagasse ash level. The phenomenon associated with a decrease in maximum dry density and increase in optimum moisture content is similar to as that in case of gypsum.

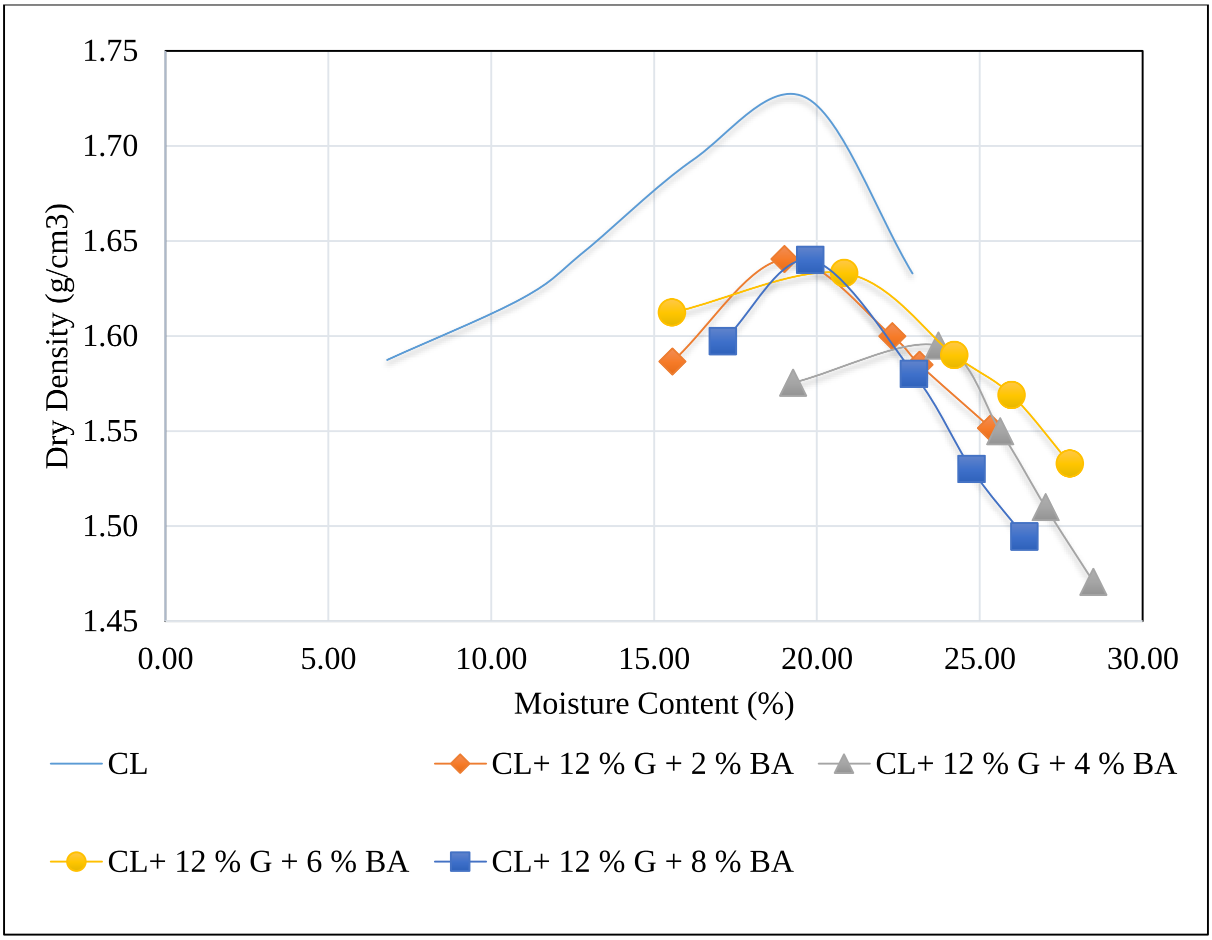

Figure 4.8 (a): Moisture Density Relationship for CL at Various Bagasse Ash Contents

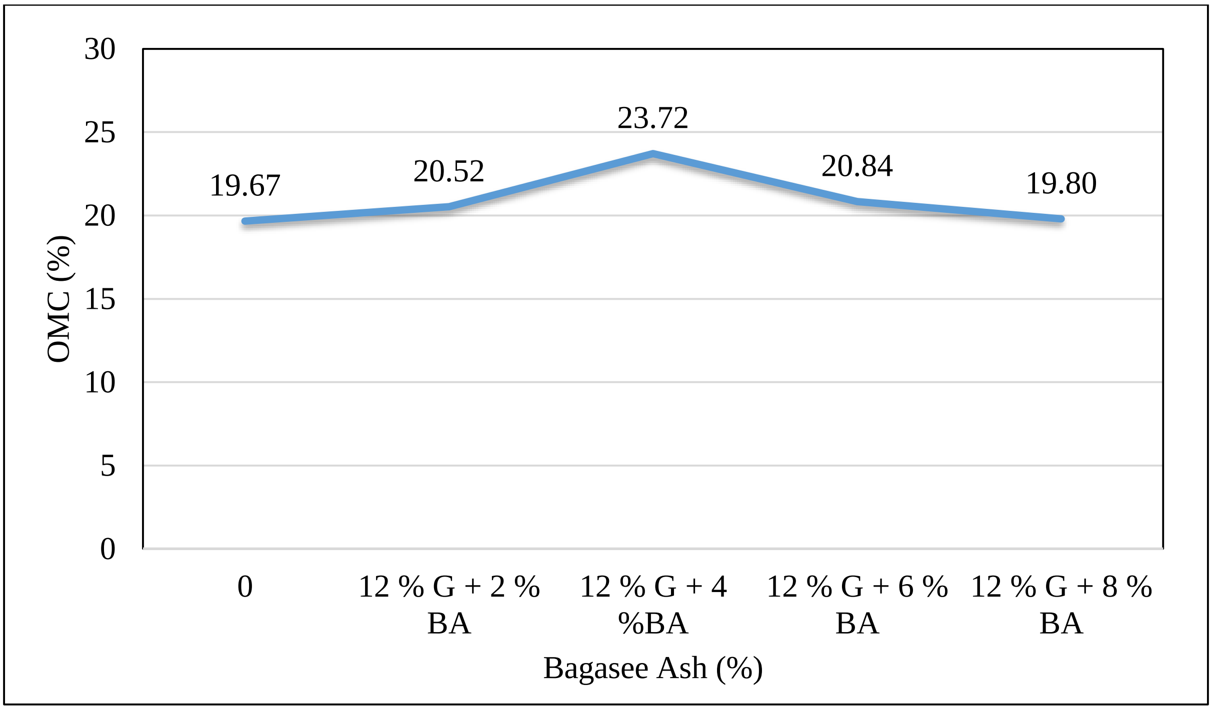

Figure 4.8 (b): Variation of OMC with Different Bagasse Ash Contents for CL

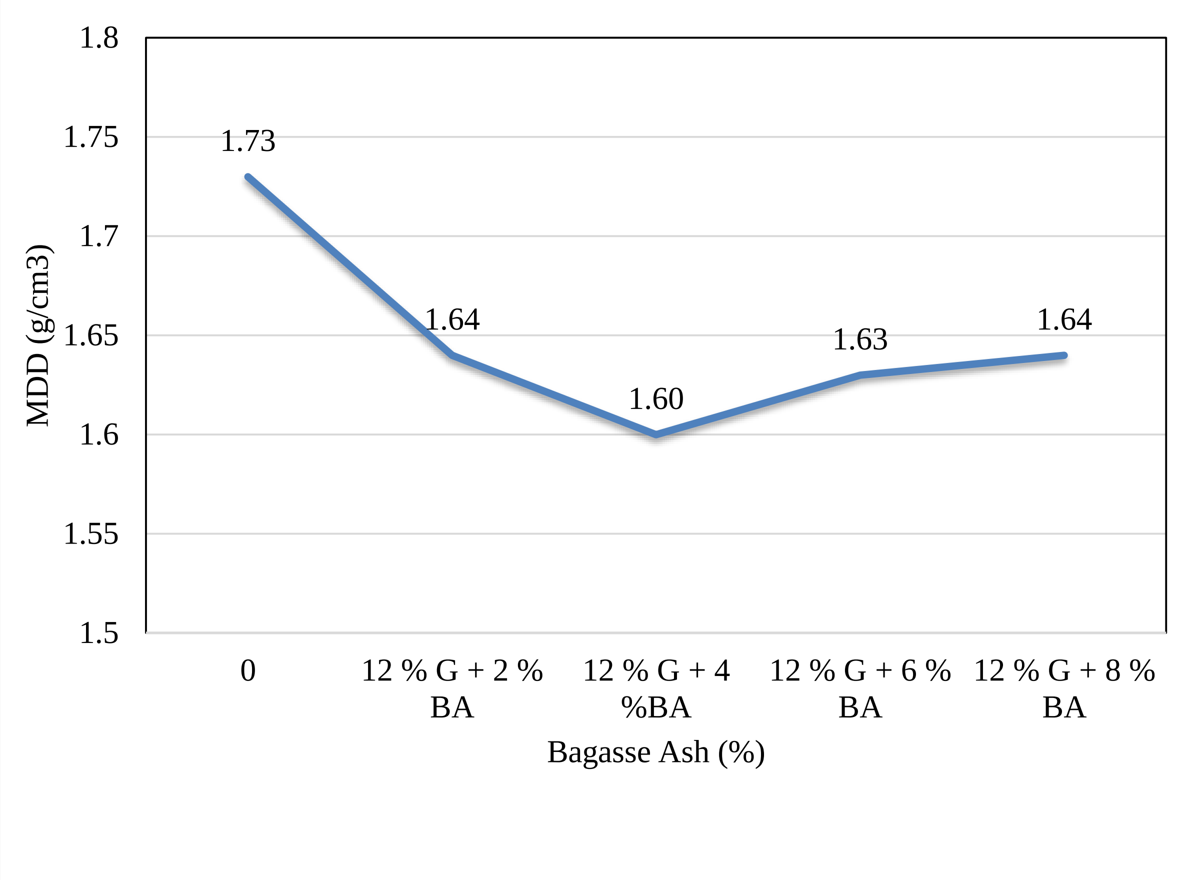

Figure 4.8 (c): Variation of MDD with Different Bagasse Ash Contents for CL

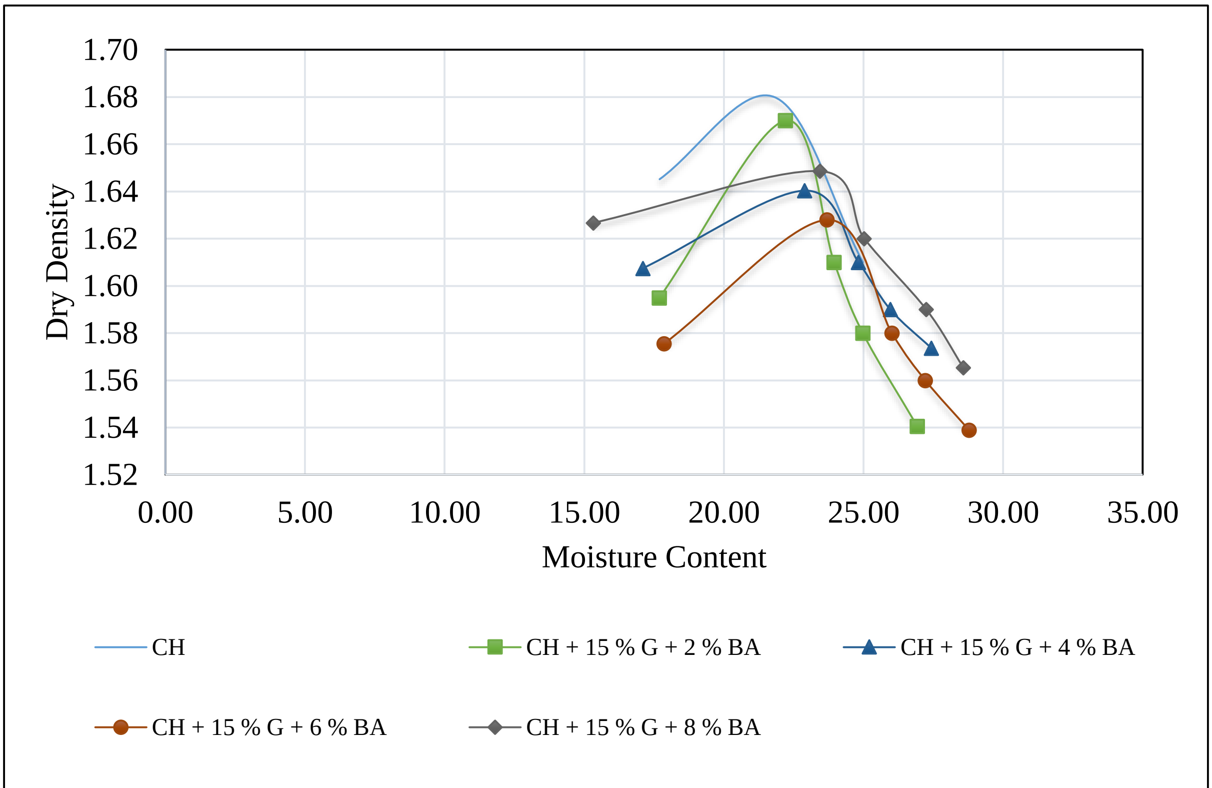

Figure 4.9 (a): Moisture Density Relationship for CH at Various Bagasse Ash Contents

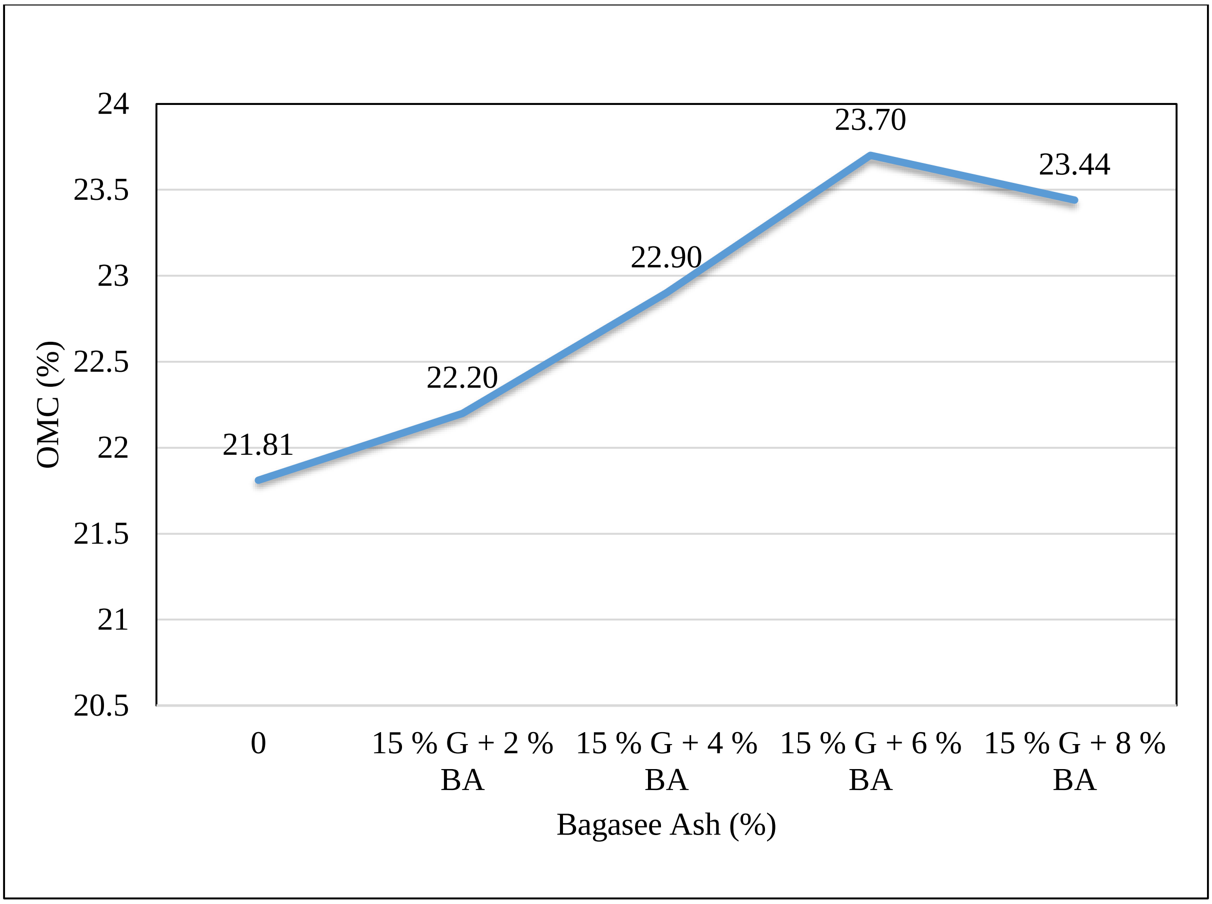

Figure 4.9 (b): Variation of OMC with different bagasse ash contents for CH

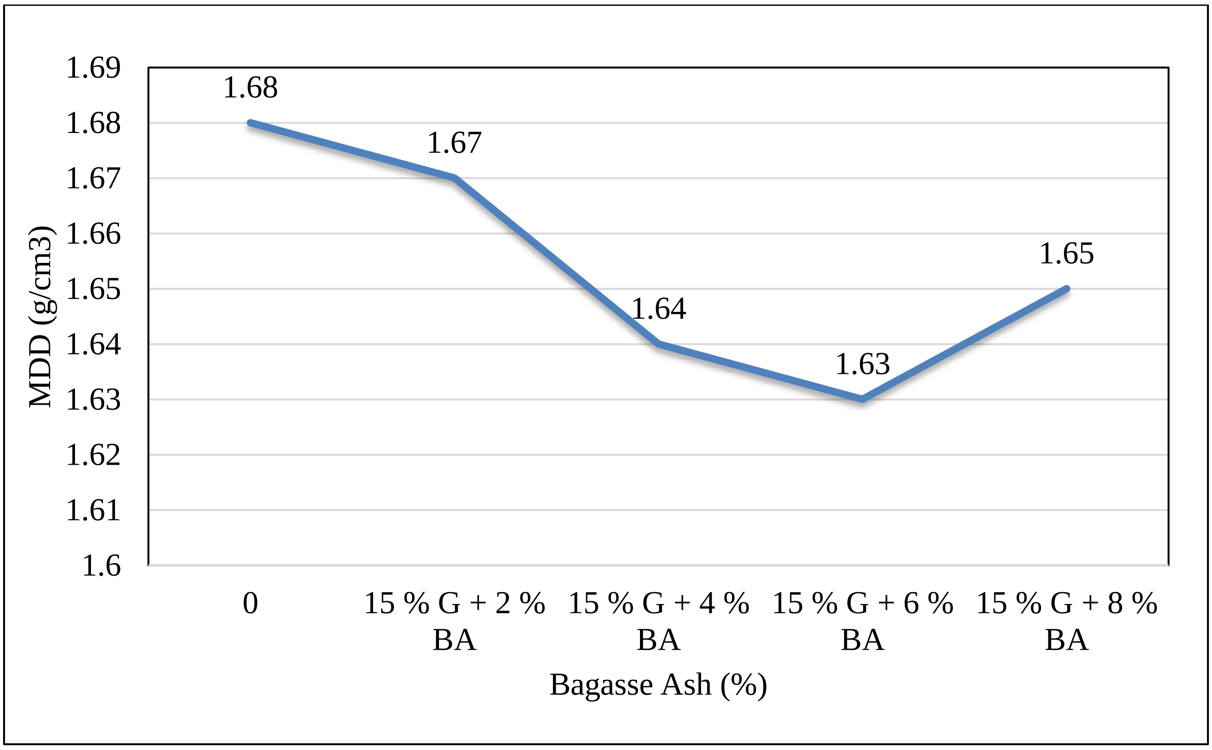

Figure 4.9 (c): Variation of MDD with Different Bagasse Ash Contents for CH

Compaction test results on these soils indicate a gradual decrease in maximum dry density of soil. This reduction in maximum dry density is due to the flocculation and agglomeration of fine-grained soil particles. These flocculated particles occupy larger spaces which reduce the dry density of soil. It is also due to the development of coating of soil particles by gypsum which forms large sized particles. An increase in optimum moisture content is observed with increase in bagasse ash content. This is due to the reason that gypsum and bagasse ash are finer than soil. The finer the material is, larger will be its surface area and more water will be required for the lubrication of these particles. Moreover, gypsum and bagasse ash also reduces the amount of free silt and clay fraction forming coarser materials which occupy larger spaces for retaining water. The increase in water content is also attributed to the pozzolanic activity between gypsum, bagasse ash, and soil particles

4.4.2 Unconfined Compressive Strength at Various Bagasse Ash Contents

Unconfined compressive strength UCS samples were prepared for optimum gypsum and various bagasse ash contents at their OMC and MDD as determined by compaction test. Samples were cured for 7 days and then tested. Bagasse Ash percentage giving maximum unconfined compressive strength was selected as optimum Bagasse Ash content.

Test results show that maximum unconfined compressive strength is obtained for 4 % bagasse Ash for CL and for 6% Bagasse Ash for CH.

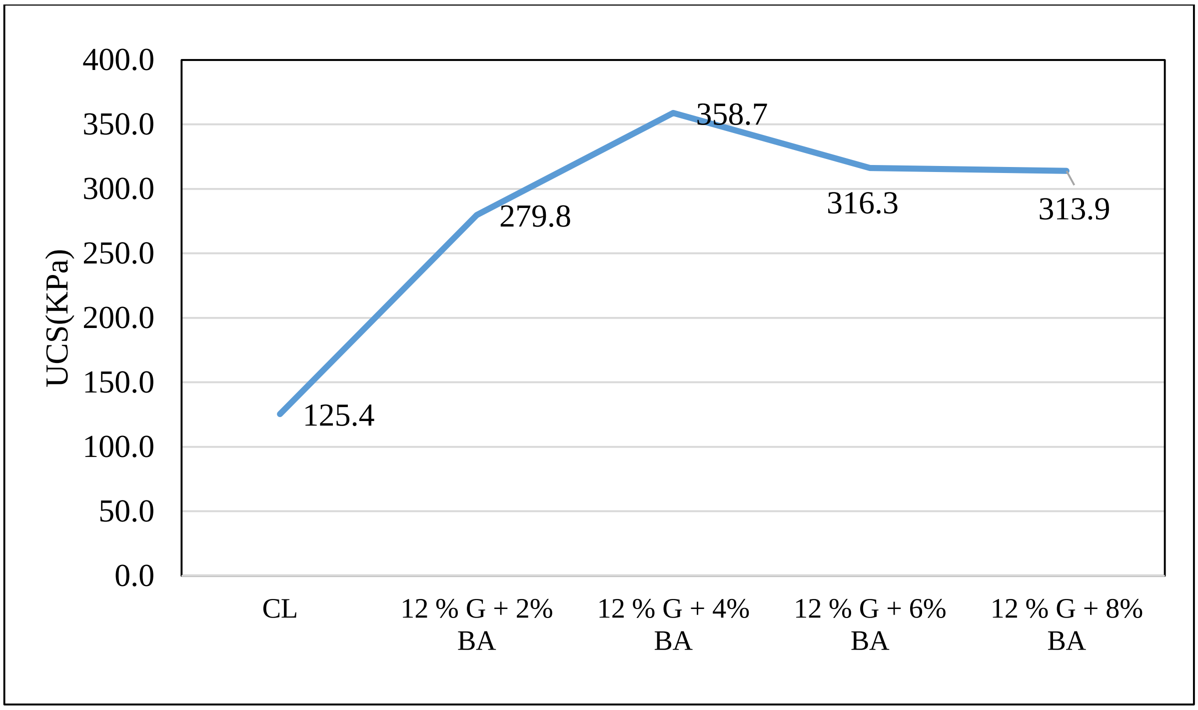

Figure 4.10: UCS at Various Gypsum Contents for CL

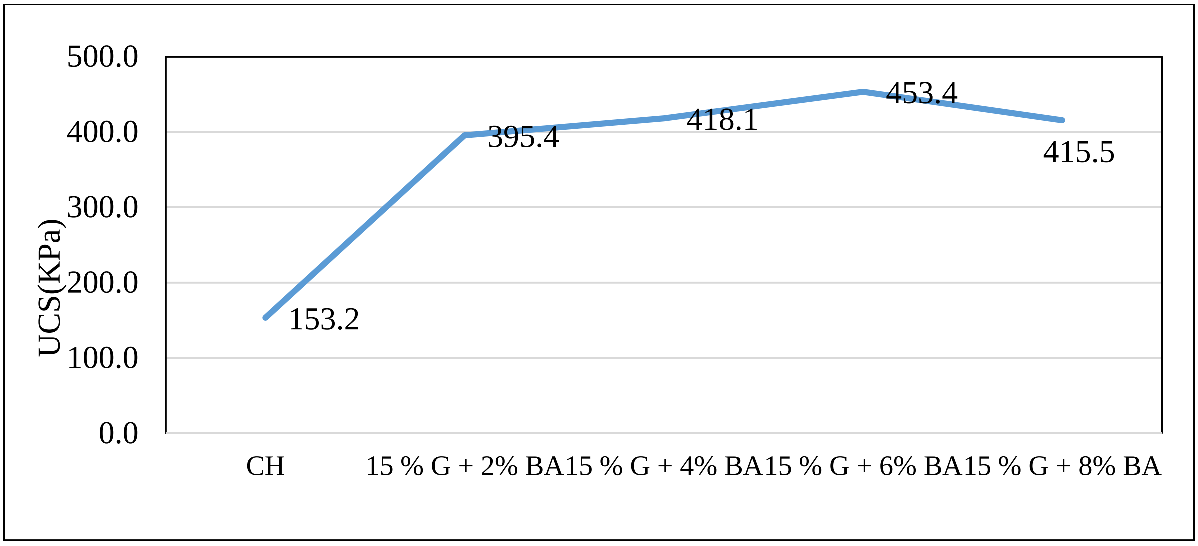

Figure 4.11: UCS at Various Gypsum Contents for CH

4. 4. 3: Optimization of Excess Moisture

Excess moisture is required for hydration process as well as the reaction between soil and gypsum to proceed. So, some additional water is required for the above-mentioned purpose. But if water is added more than what is needed, it can reduce the unconfined compressive strength of soil. So it is important to determine the optimum excess moisture for best results.

Soil samples are prepared for optimum gypsum and optimum bagasse ash content at 1%, 2 % and 3% moisture above OMC. Test results show that highest unconfined compressive strength is obtained at 1% excess moisture for CL and 2% excess moisture for CH (Figure 4.12 & 4.13).

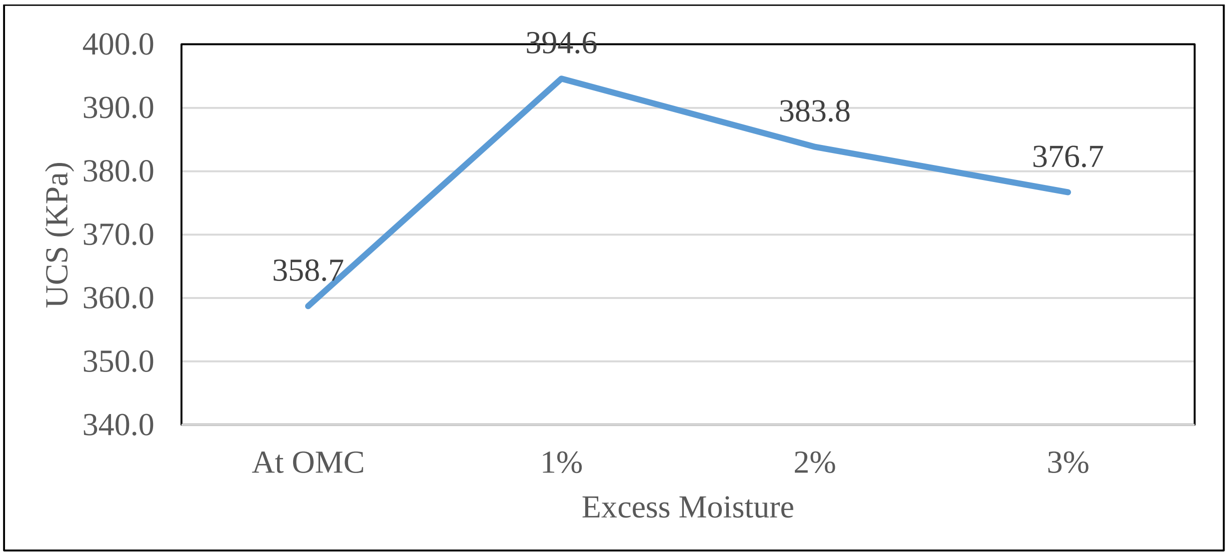

Figure 4.12: UCS at Various Excess Moisture Contents for CL + 12 % G + 4 % BA

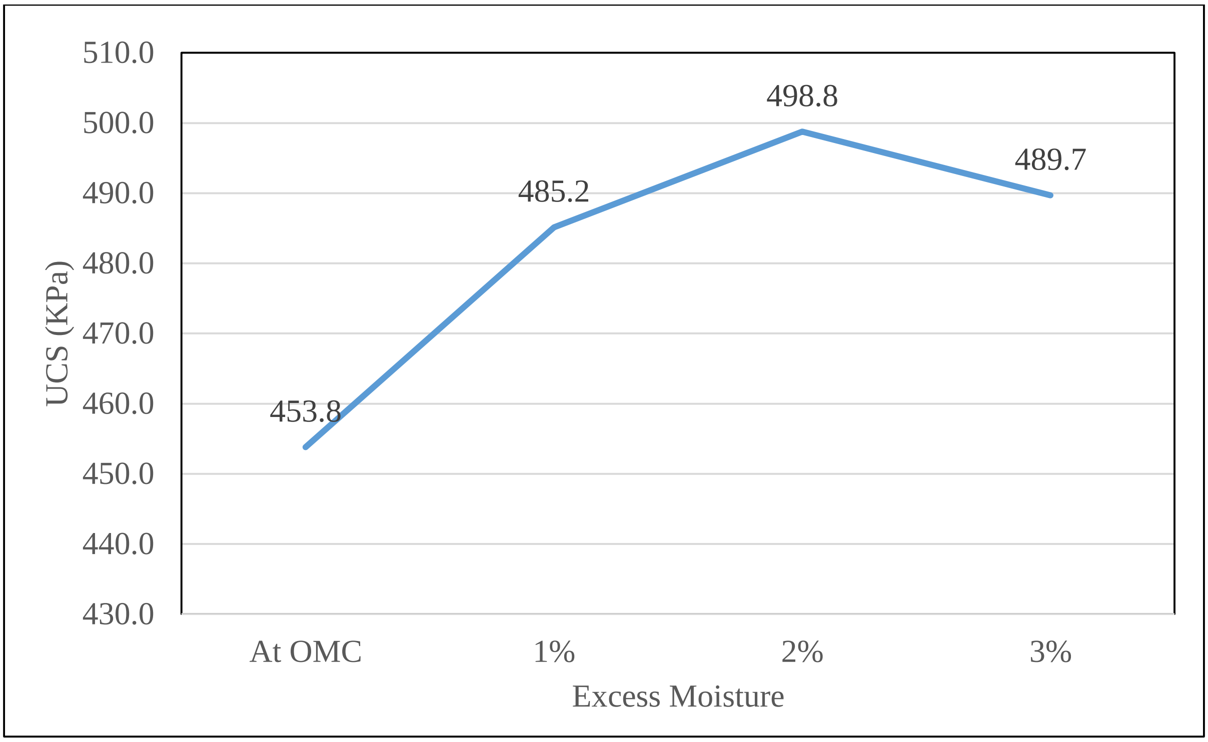

Figure 4.13: UCS at Various Excess Moisture Contents for CH + 15 % G + 6 % BA

4.5: PHASE IV: PROPERTIES OF TREATED SOIL

Once, optimum content of gypsum and bagasse ash are known, different soil properties i.e. Atterberg's limits, unconfined compressive strength and durability, California bearing ratio and one dimensional swell potential of soil are determined and the potential of gypsum and bagasse ash as soil stabilizers is assessed.

4.5.1 Atterberg's Limits of Treated Soil

Index properties are a basic measure of nature of the fine grained soil. Index properties are extensively used to differentiate between different types of soils and to classify them into broad categories. Index properties are normally determined from Atterberg's limits tests to result. The results of Atterberg's limits using Casagrande method for CL and CH are shown in figure 4.14 and 4.15. Liquid limit of CL reduced from 48 % to 40 % when gypsum was added to the soil. It further dropped to 35.5 % with the addition of bagasse ash. Plastic limit remained around 24 % for all cases. But there was an overall decrease in plasticity index from 24 % to 16% and 12.25 % with gypsum and gypsum plus bagasse ash respectively Figure 4.12 & 4.13 and Table 4.2 & 4.3.

Liquid limit of CH reduced from 65 % to 60 % when gypsum was added to the soil. It further drops to 50 % with the addition of bagasse ash. Plastic limit increased from 23 % to 24 % with the addition of gypsum and bagasse ash. There was an overall decrease in plasticity index from 42 % to 36% and 26 % with gypsum and bagasse ash, respectively.

Table 4.3: Atterberg's Limits Test Results for CL

Sample	LL	PL	PI	CEC*	Swell**
CL	48	24	24	36	5.04
CL + 12 % G	40	24	16	31	1.87
CL + 12 % G + 4 % BA	35.25	23	12.25	28	0.98

Note 1: * CEC is determined by using empirical correlation of Yilmaz (2004)

Note 2: ** Swell is determined by using empirical correlation of Seed et al. (1962)

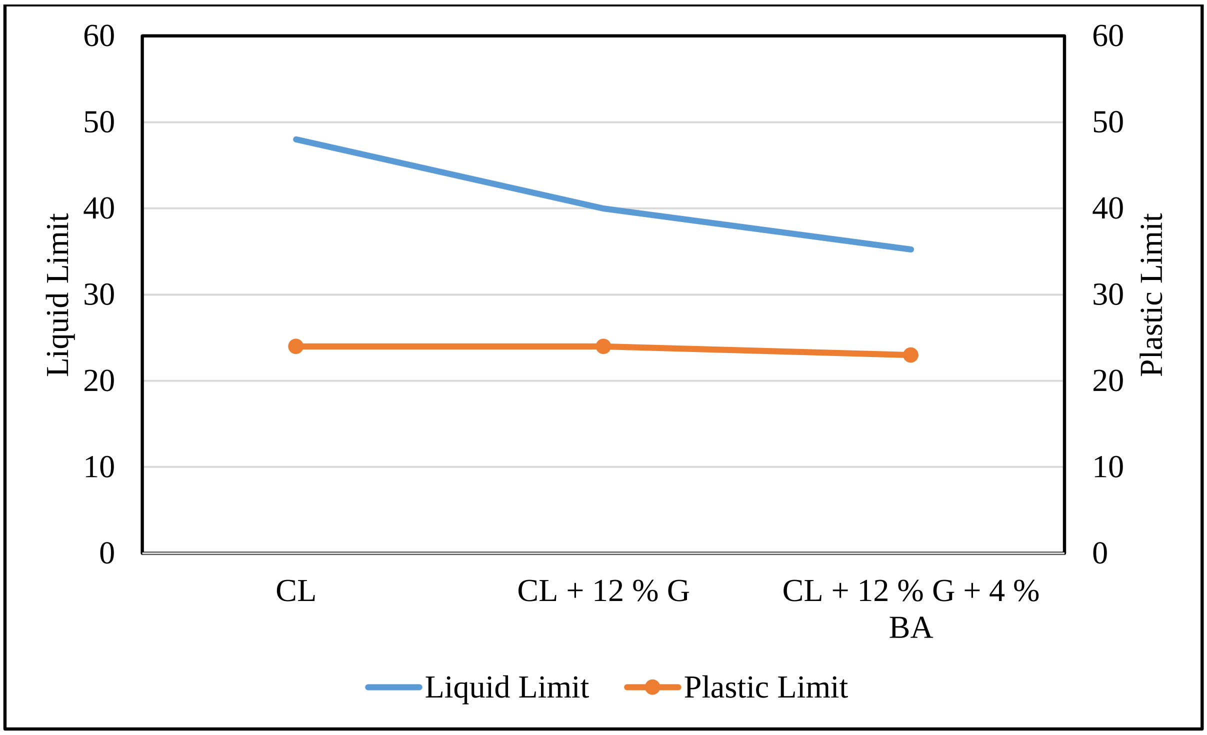

Figure 4.14: Variation of LL and PL Gypsum and Bagasse Ash of CL

Table 4.4: Atterberg's Limits Test Results for CH

Sample	LL	PL	PI	CEC*	Swell**
CH	65	23	42	51	19.7
CH + 15 % G	60	24	36	46	13.5
CH + 15 % G + 6 % BA	50	24	26	38	6.1

Note 1: * CEC is determined by using empirical correlation of Yilmaz (2004)

Note 2: ** Swell is determined by using empirical correlation of Seed et al. (1962)

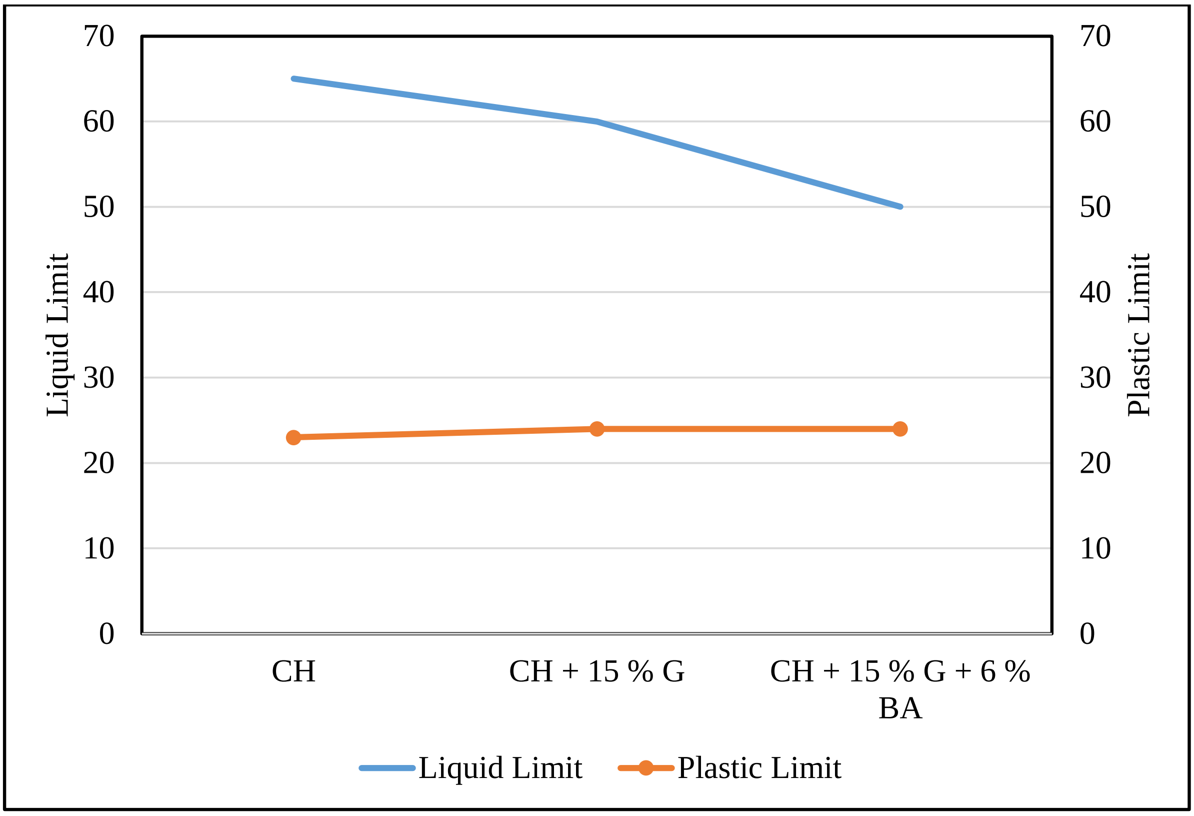

Figure 4.15: Variation of LL and PL Gypsum and Bagasse Ash of CH

A significant decrease in the liquid limit of soil was observed when gypsum and bagasse ash were added to the soil. Plastic limit of soil remained almost constant but the reduction in plasticity index of soil was observed due to decreased liquid limit. The reduction in plasticity index is due to the flocculation and agglomeration of soil particles, the particle size of soil is increased, the soil becomes more friable, the soil tends to be more silt like and plasticity of soil is reduced. Empirical correlation provided by Yilmaz (2004) and seed et al. (1962) were used to determine cation and exchange capacity and free swell potential of soil.

4.5.2 Moisture-Density Relationship for Treated Soil

The variation of OMC and MDD for CL and CH with varying gypsum content is shown in figure 4.3 and figure 4.4 and with varying bagasse ash content is shown in Figure 4.7 and Figure 4.8. Compaction test results on these soils indicate a gradual decrease in maximum dry density of soil. This reduction in maximum dry density is due to the flocculation and agglomeration of fine-grained soil particles. These flocculated particles occupy larger spaces which reduce the dry density of soil. It is also due to the development of coating of soil particles by admixtures which forms large sized particles. On the other hand, the optimum moisture content of soil increases with increase in gypsum content. This is due to the reason that admixture used (gypsum and bagasse ash) are finer than soil. The finer the material is, larger will be its surface area and more water will be required for the lubrication of these particles. Moreover, gypsum and bagasse ash also reduces the amount of free silt and clay fraction forming coarser materials which occupy larger spaces for retaining water. The increase in water content is also attributed to the pozzolanic activity between gypsum, bagasse ash, and soil particles

4.5.3 Unconfined Compressive Strength of Treated Soil

Unconfined compressive strength tests in both soaked and unsoaked condition were performed on soil samples after 2,7,14 and 28 Days curing. Soaked testing was done to assess the relative behavior of these soils to the moist condition.

Unconfined compressive strength tests result for CL, CL + 12 % G, CL + 12 % G + 4 % BA are shown in below. Figure 4.16, Figure 4.17 and Figure 4.18 represent unconfined compressive strength in unsoaked condition, soaked condition and ratio of the soaked to unsoaked strength. These results indicate that there is a gradual increase in UCS of soil in treated form as the curing period increases. Figure 4.17 shows that the UCS of natural soil increased to 529.8 KPa after 28 days of curing when treated with 12 % gypsum as compared to 127.4 KPa of untreated soil. Improvement observed was even more when 4 % bagasse ash was also used in conjunction with 12 % gypsum. There was almost 6 times increase in unsoaked UCS of CL when treated with gypsum and bagasse ash. Improvement was even more significant when comparison was made between soaked UCS in treated and untreated form (Figure 4.18). UCS of treated soil increased to almost 18 times with 12 % gypsum and 27 times when bagasse ash was also used. A significant improvement in ratio of soaked to unsoaked UCS was also observed for treated soil which indicates the improvement of resistance of soil to moist conditions. Ratio of Unsoaked to Soaked strength improved to 0.9 from 0.2.

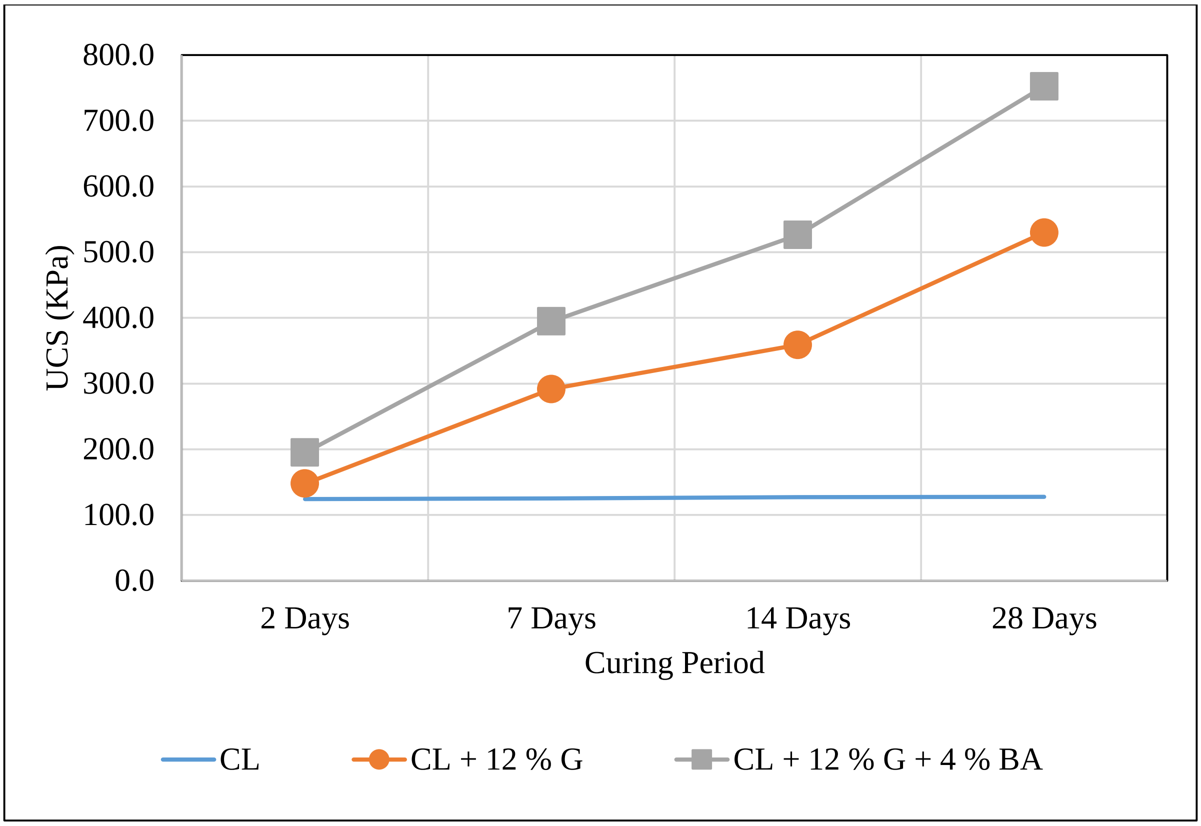

Figure 4.16: UCS (Unsoaked) Comparison at Various Curing Periods for CL

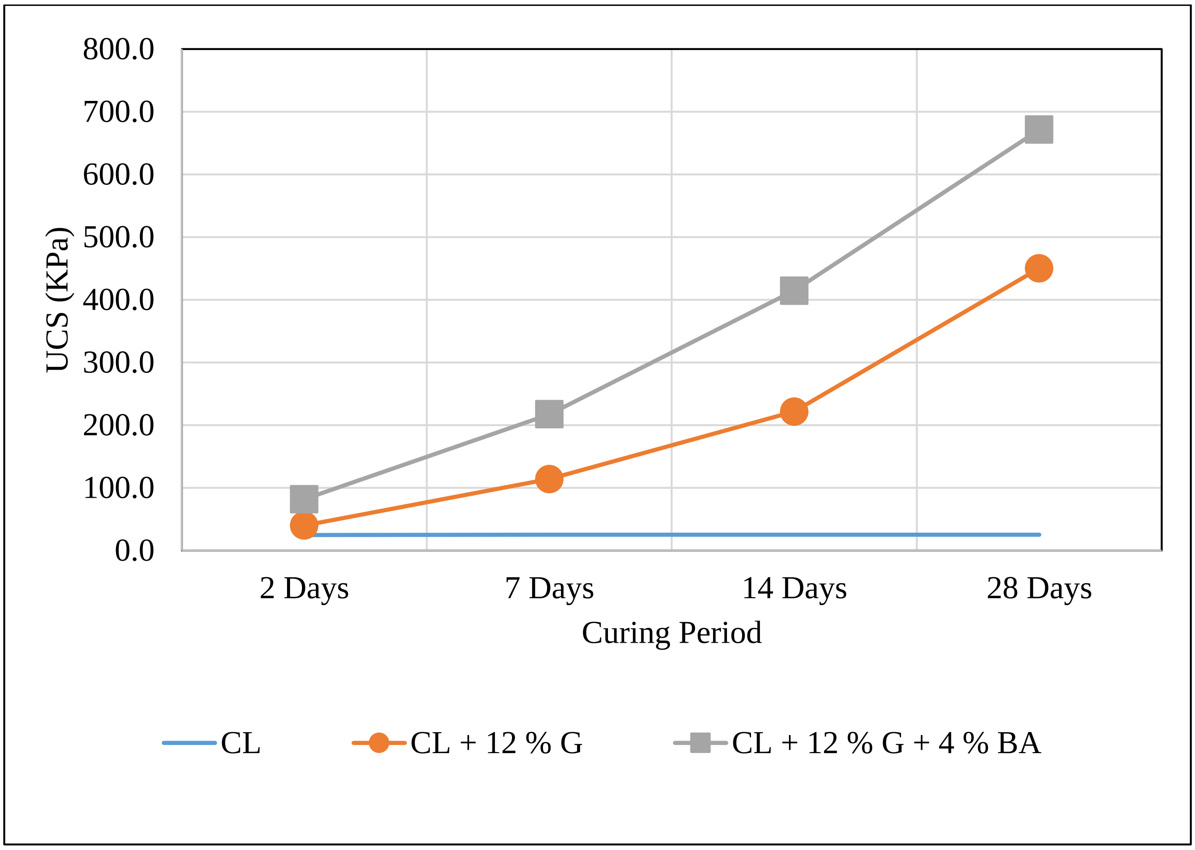

Figure 4.17: UCS (Soaked) Comparison at Various Curing Periods for CL

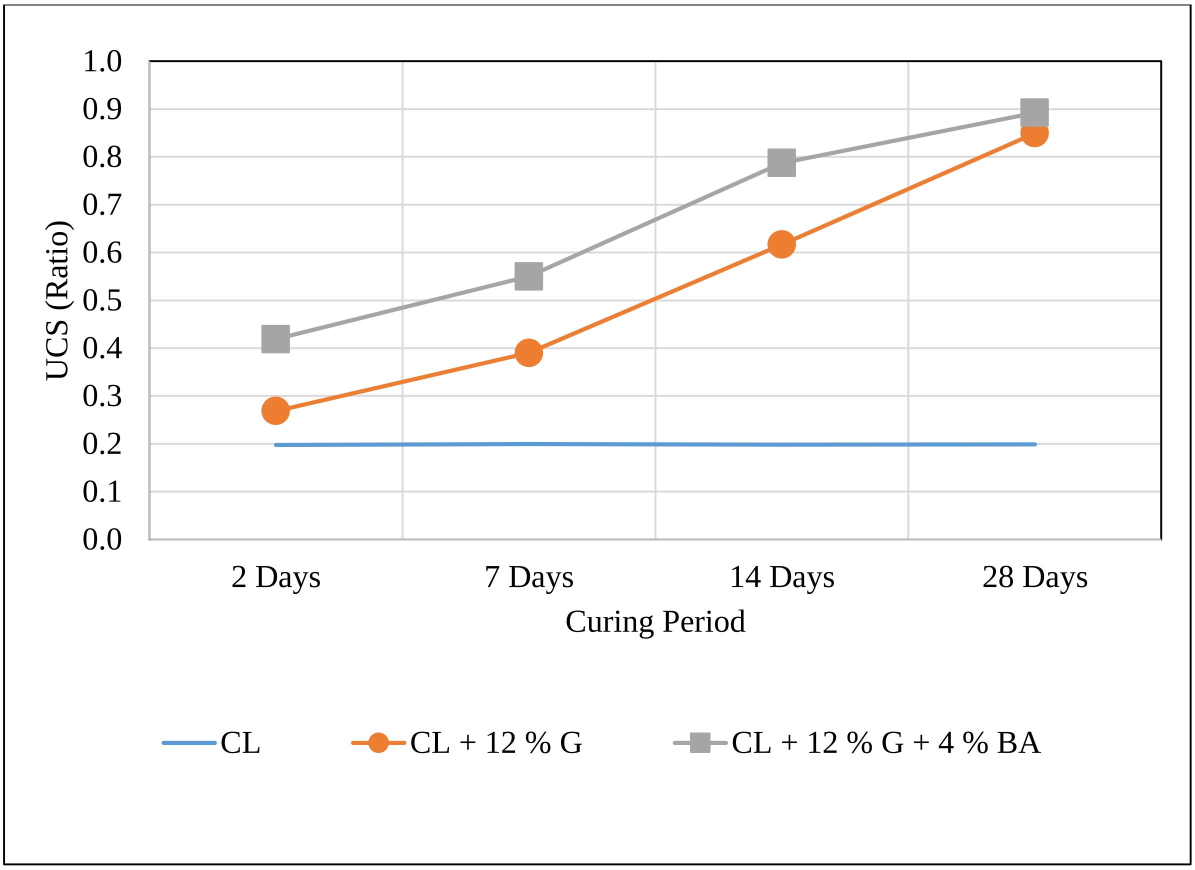

Figure 4.18: UCS (Soaked/Unsoaked) at Various Curing Periods for CL

Similar trend was observed for CH as well when treated with gypsum and bagasse ash. Unconfined compressive strength tests result for CH, CH + 15 % G, CH + 15 % G + 6 % BA are shown in Figure 4.19, Figure 4.20 and Figure 4.21. These results indicate that there is a gradual increase in UCS of soil in treated form as the curing period increases. Figure 4.20 shows that the UCS of CH increased to 584.52 KPa after 28 days of curing when treated with 15 % gypsum as compared to 154.21 KPa of untreated soil. Improvement observed was even more when 6 % bagasse ash was also used in conjunction with 15 % gypsum. Soil had a UCS of 682.54 KPa when treated with gypsum and bagasse ash. There was an overall 5.5 times increase in unsoaked UCS of CH when treated with gypsum and bagasse ash. Improvement was even more significant when comparison was made between soaked UCS in treated and untreated form (Figure 4.20). UCS of treated soil increased to almost 23 times with 15 % gypsum and 30 times when bagasse ash was also used. A significant improvement in ratio of soaked to unsoaked UCS was also observed for treated soil which indicates the improvement of resistance of soil to moist conditions. Ratio of Unsoaked to Soaked strength improved to 0.87 from 0.12.

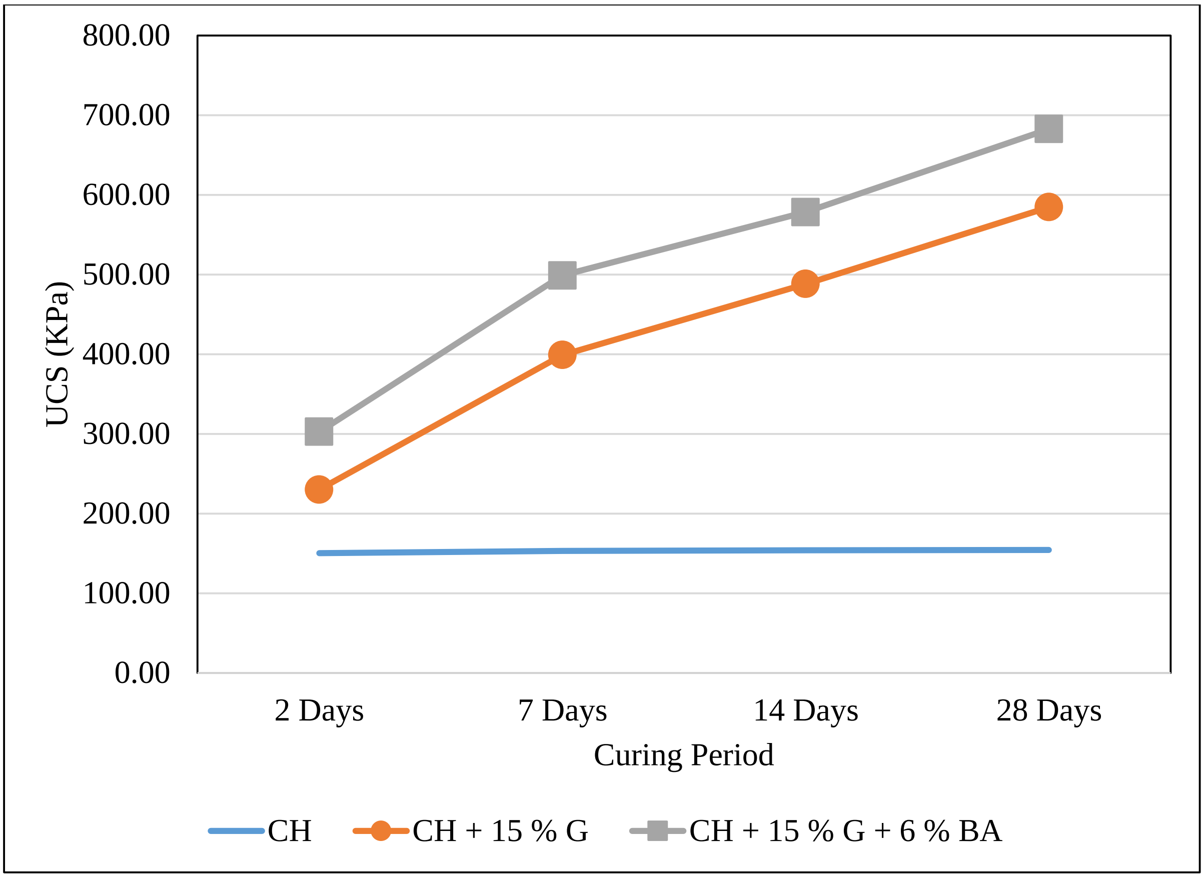

Figure 4.19: UCS (Unsoaked) Comparison at Various Curing Periods for CH

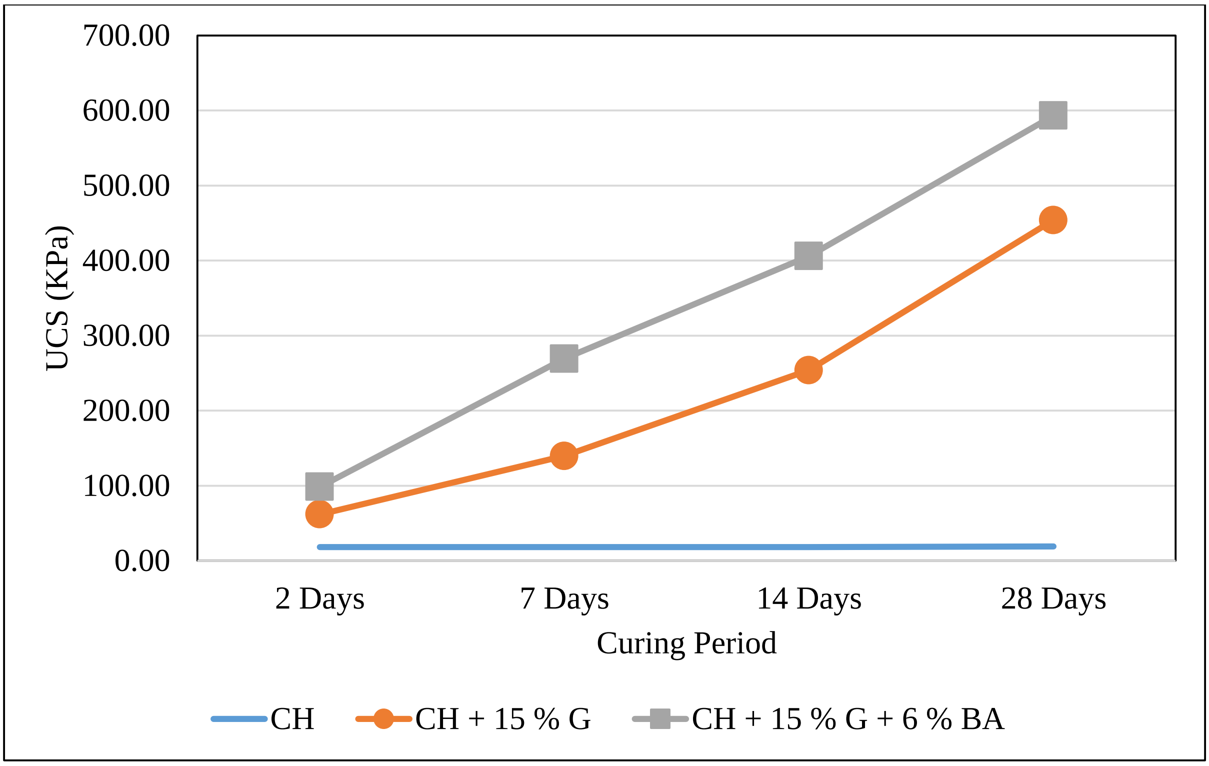

Figure 4.20: UCS (Soaked) Comparison at Various Curing Periods for CH

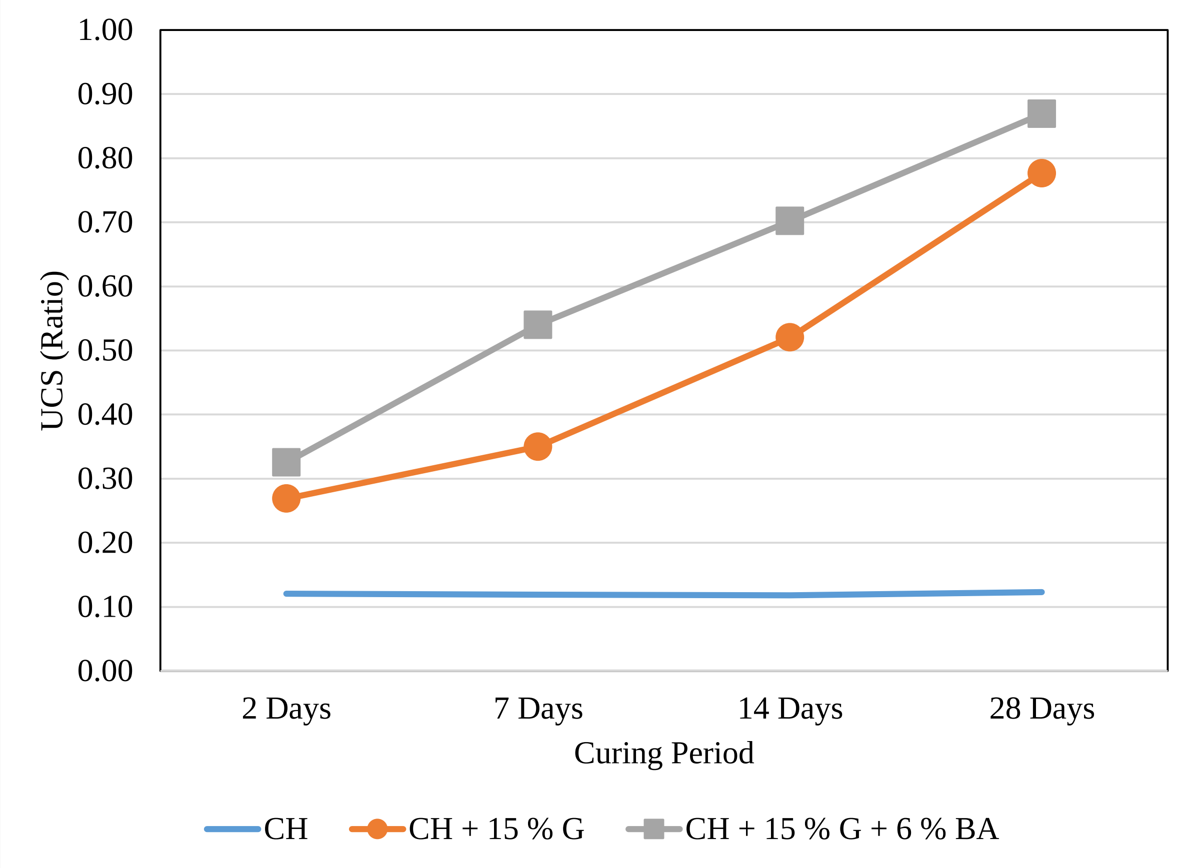

Figure 4.21: UCS (Soaked/Unsoaked) Comparison at Various Curing Periods for CH

4.5.4 California Bearing Ratio and Swell Potential

California Bearing Ratio and one dimensional swell potential of treated and untreated soils are determined. CBR and swell potential values for CL and CH are shown in Table 4.5 and Table 4.6 respectively, while a comparison between tests results is various conditions is made in Figure 22 and Figure 23. Test results indicate that significant improvement is observed in CBR and one-dimensional swell of both CL and CH when these soils are treated with gypsum and bagasse ash as compared to untreated soil. This improvement is associated with cation exchange and pozzolanic reaction between soil, gypsum and bagasse ash particles.

Table 4.5: CBR and Swell of CL in Treated Form

	CBR (%)	Swell (%)
CL	3.1	6.30
CL + 12 % G	6.6	2.05
CL + 12 % G +4 % BA	9.1	0.95

Table 4.6: CBR and Swell of CH in Treated Form

	CBR	Swell
CH	1.5	9.45
CH+ 15 % G	2.4	0.98
CH + 15% G +6 % BA	4.7	0.16

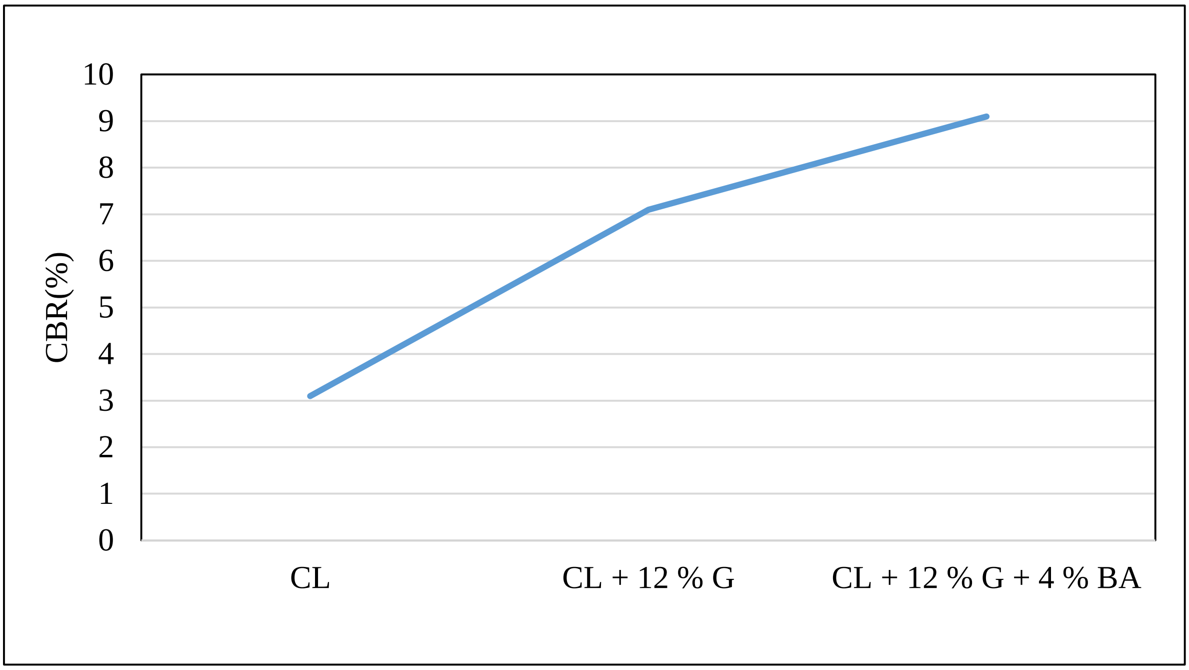

Figure 4.22: Variation of CBR for CL in Treated Form

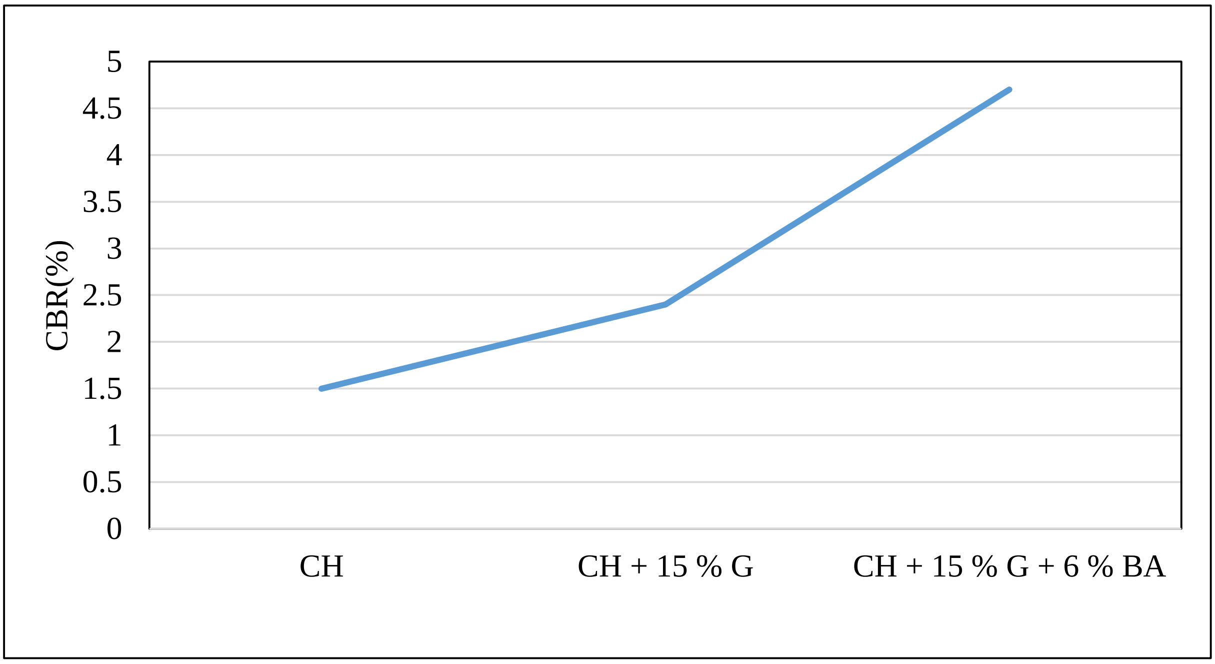

Figure 4.23: Variation of CBR for CH in Treated Form

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

This study has been conducted to check the efficiency of gypsum and bagasse ash mix as a stabilizing agent for medium plastic and high plastic clayey soils. Optimization of admixtures was carried out. 12 percent gypsum and 4 percent bagasse ash were selected as optimum content for medium plastic clay while it was 15 percent gypsum and 6 percent bagasse ash for high plastic clay. Some fundamental geotechnical properties, i.e., index properties, compaction characteristics, the unconfined compressive strength of soil, CBR and one dimensional swell potential of soil were determined in both untreated and treated form. Based on the experimental activity performed, following conclusions are drawn:

- A series of liquid limit and plastic limit tests were performed for both treated and untreated soils. Results show a significant decrease in liquid limit and plasticity index of soil with the addition of gypsum alone as well as for the combination of gypsum and bagasse ash. The improvement in Atterberg's Limits was more significant when a combination of gypsum and bagasse ash was used as compared to gypsum individual effect of gypsum. Cation exchange capacity and swell potential of soil were also reduced. Nature of soil change from High to Low swelling for medium plastic clay and High swelling to medium swelling for high plastic clay. This change is associated with the flocculation and agglomeration of soil particles due to the addition of gypsum and bagasse ash. This improvement causes the soil behavior to change from clay to silt.
- Maximum dry density is decreased by the addition of gypsum and bagasse ash while an increase in optimum moisture content of soil is observed. Decrease in dry density is due to flocculation of soil particles. Soil becomes more friable and difficult to compact. While the increase in optimum moisture content is due to the increased surface area of soil particles due to the addition of gypsum and bagasse ash which are finer particles. Higher the surface area, more water is required for wetting of soil particles.
- There is a significant improvement of unconfined compressive strength of soil in soaked and unsoaked condition with the addition of gypsum and bagasse ash for both medium plastic and high plastic. There was almost 6 times increase in unsoaked and 27 times increase in soaked UCS of medium plastic clay. While the improvement was 5.5

times for unsoaked and 30 times for soaked samples for high plastic clay. The loss in strength due to soaking for treated soil was significantly low as compared to untreated soil. Ratio of soaked to unsoaked strength improved from 0.2 to 0.9 for medium plastic and 0.12 to 0.87 for high plastic clay. This improvement in unconfined compressive strength is associated with the pozzolanic reaction between soil, gypsum and bagasse ash, which result in the formation of cementitious products.

- California Bearing Ratio of the soil was improved almost 3 times for treated soil as compared to untreated soil. Soil quality improved from fair to moderate for medium plastic and poor to fair for high plastic clay. Whereas one-dimensional swell potential was reduced to less than 1% for treated soil. So a sufficient improvement in California bearing ratio and one-dimensional swell potential was observed with the addition of gypsum and bagasse ash.

In the light of the results obtained, it can be concluded that gypsum and bagasse ash can be efficiently used for the stabilization and improvement of medium plastic and high plastic clay soils. The improvement is more prominent when a combination of gypsum and bagasse ash is used as compared to the gypsum alone.

5.2 RECOMMENDATIONS

- High plastic clay used in this research was artificially prepared by mixing bentonite with medium plastic clay. It is recommended to use naturally available high plastic clay.
- California Bearing Ratio was determined using one point CBR test by preparing samples at optimum moisture content and maximum dry density as determined in standard proctor test. The recommendation is to determine CBR value for a range of moisture contents and dry densities.
- One dimensional swell was taken into consideration for this research. The overall free swell of soil should also be determined.
- The composition of agro-based waste products varies with soil (due to the silica available in soil). Effort should be made to compare the bagasse ash from various sources all over the country to standardize its use as a pozzolan in soil stabilization.

5.3 Recommendations for Future Research

- The present study was focused on some basic geotechnical properties of soil i.e. index properties, compaction characteristics, UCS, CBR and swell potential of the soil. It is recommended for future research to study the effect of gypsum and bagasse ash on shear strength parameters of soil as well.

- The efficiency of a combination of gypsum with other pozzolanic materials, e.g., rice husk ash, can also be checked to measure its suitability for the soil stabilization.
- Since the combination of gypsum and bagasse ash produces cementitious products, so it can also help improve the properties of granular soil especially those rich in silt content. Future study can also be done to check the suitability of gypsum and bagasse ash for improvement of granular soils.

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Appendix A

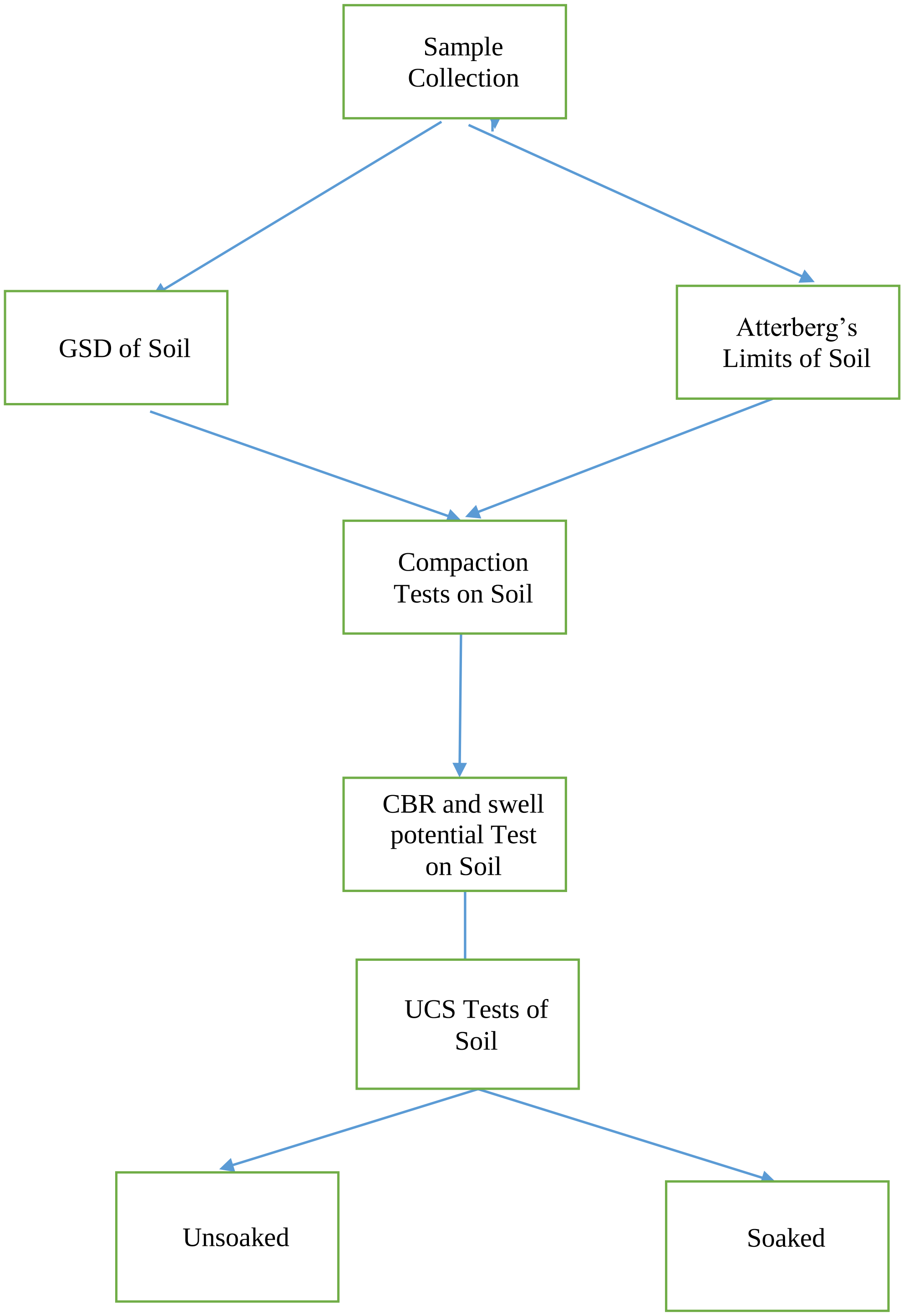
Trial testing for the selection of optimum percentage of bentonite was carried out. Atterberg's Limits at various bentonite content were determined and 25 percent bentonite was selected as suitable percentage as it produced quite a significant change in liquid limit and plasticity index of natural soil.

Table A-1: Atterberg's Limits of natural soil at various bentonite contents

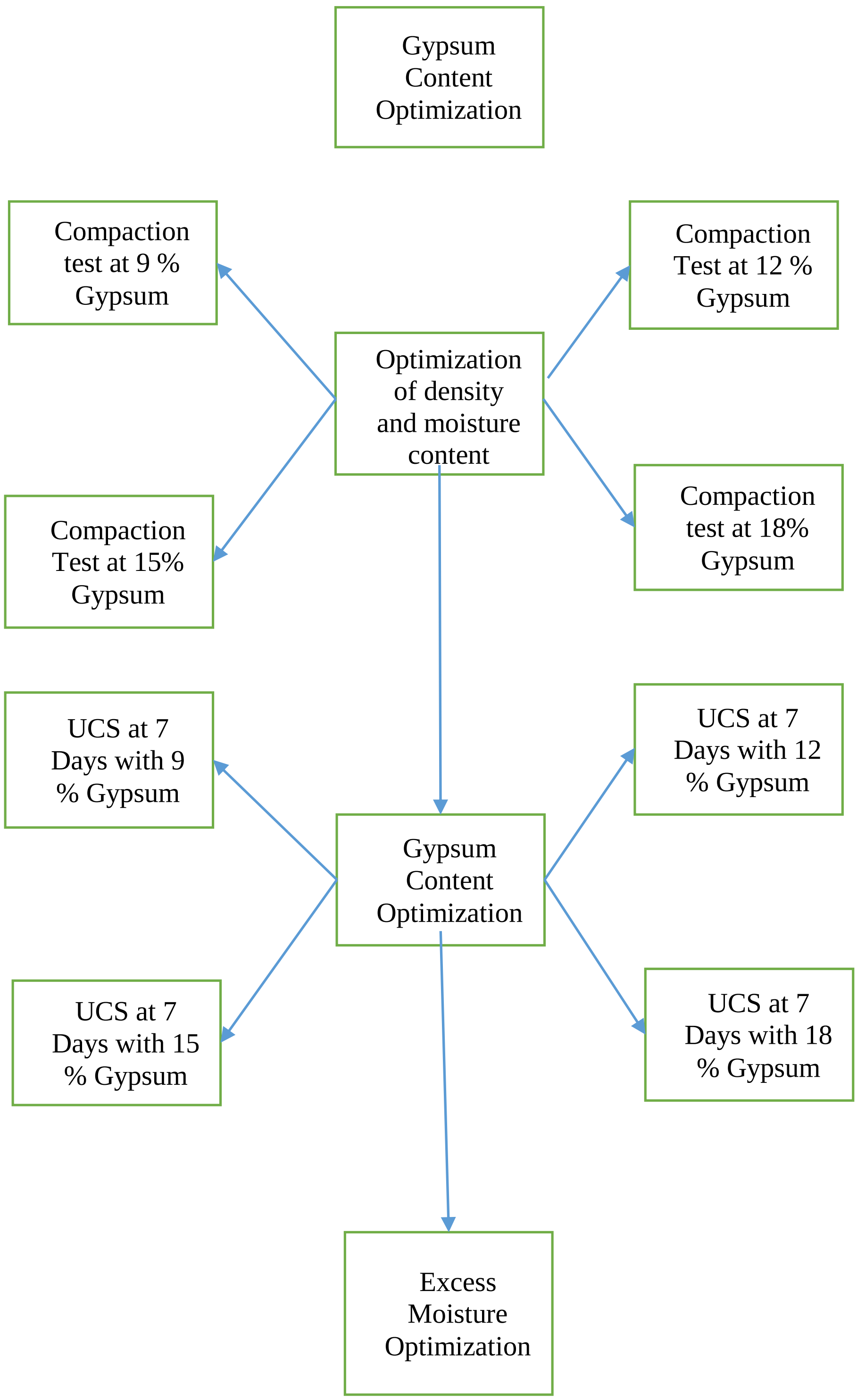
	Natural Soil	10 % Bentonite	15 % Bentonite	25 % Bentonite
LL	48	52	56	65
PL	24	24	22	23
PI	24	28	34	42

Appendix B

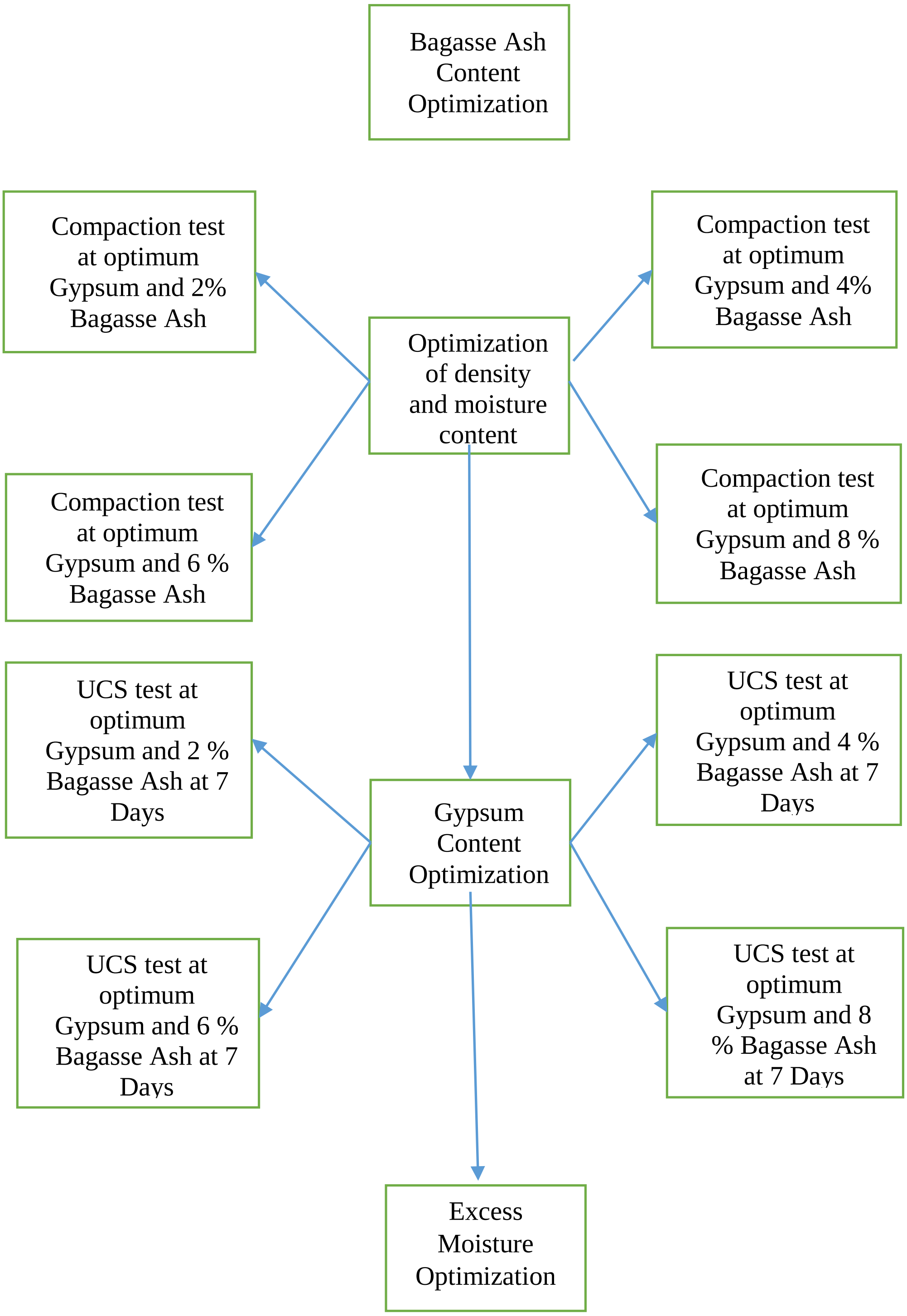
Experimental Program
Properties of Natural Soil (Phase I)



Optimization of Gypsum Content (Phase II)



Optimization of Bagasse Ash (Phase III)



Properties of treated Soil (Phase IV)