

# **STABILIZATION OF LOW PLASTIC AND HIGH PLASTIC SOIL USING BIOPOLYMER**



**By**

**Muhammad Ali Rehman**

**(NUST-2016-MS GEOTECH-00000172758)**

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)**

**National University of Sciences and Technology (NUST)**

**H-12 Sector, Islamabad, Pakistan**

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## **THESIS ACCEPTANCE CERTIFICATE**

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**STABILIZATION OF LOW PLASTIC AND HIGH  
PLASTIC SOIL USING BIOPOLYMER**

Submitted by

**Muhammad Ali Rehman**

has been accepted towards the partial fulfillment

of

the requirements

for

Master of Science in Geotechnical Engineering

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**Dr. Syed Muhammad Jamil**  
**Dean**  
**NUST Institute of Civil Engineering (NICE)**

**DEDICATED**

**TO**

**My Beloved Parents whose continuous support and  
encouragement helped me to achieve this milestone**

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I am extremely thankful to Almighty ALLAH, the most Gracious and Merciful, who gave me knowledge and enlightenment to carry out this research work. Countless salutations upon Holy Prophet (P.B.U.H), the source of knowledge and guidance for mankind in every walk of life. I want to express sincere gratitude towards my research supervisor Dr. Syed Muhammad Jamil who continuously and convincingly conveyed a spirit of hardworking and steadfastness to plot and complete this project. Without his painstaking efforts, support and guidance, completion of this project would not have been possible.

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## **LIST OF ABBREVIATIONS**

ASTM:	American Society for Testing and Materials
USCS:	Unified Soil Classification System
AASHTO:	American Association of State Highway and Transportation Officials
CL:	Low Plastic Clay
CH:	High Plastic Clay
LL:	Liquid Limit
PL:	Plastic Limit
PI:	Plasticity Index
UCS:	Unconfined Compressive Strength
CBR:	California Bearing Ratio
BP:	Biopolymer
GG:	Guar Gum
OMC:	Optimum Moisture Content
MDD:	Maximum Dry Density
BP-1:	1 % Biopolymer by Weight of the Soil
BP-2:	2 % Biopolymer by Weight of the Soil
BP-3:	3 % Biopolymer by Weight of the Soil
BP-4:	4 % Biopolymer by Weight of the Soil

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## **ABSTRACT**

Throughout the evolution of human civilization, soil stabilization has been an important consideration. In geotechnical engineering soil stabilization provides viable and cost-effective solutions associated with problematic soils. Various additives including cement, lime, gypsum, fly ash, and bitumen were being in use as soil stabilizer. With upsurge in the need for environmentally friendly and sustainable materials, researchers have been investigating alternative materials for soil stabilization. Biological approaches have recently been developed for improving the properties of soil. Biopolymers are produced from living organisms and are considered to be environmentally friendly soil stabilizers. An elaborate study on stabilization of soil using guar gum biopolymer was carried out through intensive laboratory experiments. Two soils, low plastic (CL) and high plastic (CH) clays were treated with different percentages of biopolymer (1%, 2%, 3% and 4%) by weight of dry soil. The experimental program mainly focused on compaction characteristics, unconfined compressive strength, California bearing ratio and one-dimensional swell potential tests. All the samples were prepared on dry mix basis. The UCS of cured and soaked samples was tested after 0, 2, 7, 14 and 28 days of curing and soaking. Strengthening effect of guar gum biopolymer was observed with increasing biopolymer content and curing time. A significant improvement in UCS of low plastic and high plastic soil was observed at 2% biopolymer at end of the curing period. The results indicated a substantial improvement in the CBR of both low plastic and high plastic clays under soaked and unsoaked conditions. Evidently, the use of guar gum biopolymer has shown significant improvement in geotechnical properties of low plastic and high plastic soil and can be identified as potentially sustainable alternative material for the stabilization of soil.

# **INTRODUCTION**

## **1.1 GENERAL**

From the prospect of civil engineering, soil is the relatively loose agglomeration of minerals and organic materials found above the bedrock (Holtz & Kovace, 1981). Soil has an important role in construction as it acts as the ultimate load bearing material. The superstructures, such as buildings, roads, bridges etc. transfer the load to the soil. With the increase in population, there has been an increased demand for the use of land for better living and transportation. As a result of urbanization, the availability of suitable soil at construction sites became less, which urges to utilize the land with unfavorable & problematic soil for the construction purposes. Clayey soils are expansive in nature as they tend to undergo volumetric changes upon interaction with water. The swelling and shrinkage behavior, caused by the addition and removal of water respectively, of clayey soils causes the problems like differential settlement, cracking of pavements and building foundations, loss of strength, slope failures and breaking up of sewer lines. Study reveals that the damages caused by the problematic soils costs almost twice the damages caused by natural hazards (Jones Jr & Holtz, 1973).

The options to deal with such problematic soils may include, avoiding the site; changes in superstructure according to the site conditions; removing & replacing of problematic soil; and improvement in soil properties (Hausmann, 1990). Soil Stabilization generally refers to the practice of enhancing the geotechnical properties of problematic soils in order to develop its suitability for the construction purposes. Soil properties can be improved either mechanically, chemically, or biologically. For example, use of compaction techniques; mixing of fibers with the soil; addition of cement, lime and other pozzolanic materials; addition of bio enzymes, bio polymers and bacteria to the soil. Using of admixtures in soil to improve its properties has been



found beneficial since ancient times. The conventional techniques of soil stabilization may include the utilization of cement, lime, gypsum, fly ash etc., which may cause environmental degradation. With an increase in environmental awareness, researchers are tending towards the use of biopolymers as admixtures for improving soil properties, considering biopolymers being environment friendly soil stabilizers (Biju & Arnepalli, 2016).

## **1.2 NEED FOR RESEARCH**

Throughout the evolution of human civilization, soil stabilization has been an important consideration. Stabilization is a process of alteration/modification of soil properties in order to improve the engineering performance and characteristics of soil. In geotechnical engineering soil stabilization provides viable and cost-effective solutions associated with problematic soils. Various materials such as lime, cement, bitumen, fly ash, wood ash, salts and other pozzolanic materials are being used for ages for the improvement of soil characteristics from the aspect both mechanical and chemical stabilization. The stabilizing agents can help improving soil particle cohesion and water proofing (Sanders et. al 2004). Most of the soil stabilization methods are expensive, time consuming and labor insensitive. So, it is of prime importance for engineers and researchers to develop an economic and feasible solution for the improving the soil properties. The best solution is to utilize readily available, cheap, and renewable materials for the soil stabilization.

Recently in geotechnical engineering, biological techniques are being studied and successfully employed for the treatment of unsuitable soils, which includes the use of biopolymers and bio enzymes as an alternative soil stabilizing agent to the traditional soil stabilizers. Biopolymers are produced by the living organisms such as animals and plants. The utilization of biopolymers as suitable soil stabilizing agents is not totally new, as various materials such as straw and sticky rice binders had been in the past (Chang, Jeon, & Cho, 2015). Use of biopolymers can help improving the soil's engineering properties such as compressive

strength, erosion control, reduction in permeability and vegetation suitability (Cole, Ringelberg, & Reynolds, 2012). Biopolymers have shown the capability of being sustainable materials for the improvement of strength and stability of various soils and found to be advantageous over traditional stabilizers in terms of being environment friendly and effective at low concentrations (Cho & Chang, 2018). Soils treated with biopolymers exhibit that small concentration of biopolymers mixed with soils result in higher compressive strength in comparison with large amount of cement used for achieving high strength values (Chang, et al., 2015). A study on Korean residual soils exhibited that glucan biopolymer causes an increase in the compressive strength of residual soil up to 200 percent in 60<sup>0</sup>C curing environment (Chang & Cho, 2012).

In Pakistan, lots of studies have been carried out on stabilization of weak and unsuitable soils but the use of biological approach to improve the properties of soil has been very limited or even not found. The current study is envisioned to satisfy the gap in the field of biological soil stabilization. In this research, low plastic and high plastic clayey soils are considered to investigate the effectiveness of biopolymer as stabilizer. Guar Gum biopolymer is chosen as the soil stabilizing agent for this research. Guar (botanical name: *Cyamopsis Tetra-gonoloba*) plant is the ultimate source of guar gum seeds. It is grown abundantly in the arid and semi-arid regions of Punjab and Sind provinces of Pakistan. Guar seeds are locally processed to obtain powder, which can be used as thickener, strength additive, binder, and stabilizer.

### **1.3 RESEARCH OBJECTIVES**

The main objective of this research study is to investigate the effectiveness of guar gum biopolymer as soil stabilizer. The study mainly focuses on:

- Compaction Characteristics of soil
- Unconfined Compressive Strength of soil
- California Bearing Ratio of soil

- Swell Potential of soil

## **1.4 SCOPE AND METHODOLOGY**

The scope of this research is to establish the optimum percentage of guar gum biopolymer for the improvement of soil properties. Two varieties of soils were used in this study, i.e. low plastic clay (CL) and high plastic clay (CH). Soils were characterized by performing gradation and Atterberg limits tests. The effect of biopolymer addition on the soil properties, such as maximum dry density, optimum moisture content, unconfined compressive strength, California bearing ratio and swell potential have been determined by performing standard laboratory tests including modified proctor test, UCS and CBR tests. Detailed methodology of this research has been covered in Chapter 3; however, the scope and brief methodology is discussed in this section as under:

### **1.4.1 Phase I: Characterization of Untreated Soil**

In first phase, following tests were conducted on low plastic and high plastic clay:

- Grain size distribution
- Atterberg limits
- Compaction Characteristics
- Unconfined Compressive Strength
  - Un-soaked
  - Soaked
- California Bearing Ratio
  - Un-soaked
  - Soaked
- Swell Potential

## 1.4.2 Phase II: Characterization of Treated Soil

In this phase, four percentages of guar gum biopolymer varying from 1 to 4 percent with an increment of 1 % were added to both low plastic (CL) and high plastic (CH) soils. The purpose of this phase is to achieve an optimum percentage of biopolymer at which the laboratory tests will show maximum results against soil properties. The following sequence shows the testing to be conducted with varying percentages of biopolymer:

- Modified Proctor Test at four percentages of biopolymer
  - BP1 = 1 % biopolymer in soil mix
  - BP2 = 2 % biopolymer in soil mix
  - BP3 = 3 % biopolymer in soil mix
  - BP4 = 4 % biopolymer in soil mix
- Unconfined Compressive Strength at four percentages of biopolymer (BP1, BP2, BP3, BP4)
  - Cured at 2, 7, 14 and 28 days
  - Soaked at 2, 7, 14 and 28 days
- California Bearing Ratio
  - Un-soaked at four percentages of biopolymer (BP1, BP2, BP3, BP4)
  - Soaked at four percentages of biopolymer (BP1, BP2, BP3, BP4)
- Swell Potential
  - At optimum percentage of biopolymer

## **REVIEW OF LITERATURE**

### **2.1 GENERAL**

Clay is a substantial material in geotechnical engineering. The behavior of soil is significant in designing and construction of civil engineering structures. Clayey soils have been a major concern to geotechnical engineers as these soils have several problems due to their high compressibility, large volumetric changes, and low strength. Soil having higher content of clay minerals are vulnerable to volumetric changes (swelling and shrinkage) in the presence of moisture. Light engineering structures built on such soils suffer serious damages due to expansion of underlying soil (Fredlund, 1975). The reduction in bearing capacity, high swelling and compressibility and low shear strength of soil triggers numerous damages to infrastructures such as buildings, roads and bridges. Expansive soils undergo large changes in volume with changes occurring in environmental conditions. In presence of moisture, these soils tend to swell and lose shear strength, while on drying they exhibit shrinkage and develop cracks. The problems posed to civil engineering structures founded on these soils may include heaving, cracking, and breaking of pavement, building foundations, channels, and reservoir linings (Akbar & Farooq, 2002). The swelling behavior of clays is generally governed by clay minerals and their percentage present in the soil. Generally, montmorillonite minerals are considered as high swelling minerals and kaolinite minerals are regarded as least swelling clay minerals.

### **2.2 Clayey Soils**

Clay is an aggregate of microscopic and submicroscopic particles obtained from the chemical weathering and decomposition of rock materials (Terzaghi, Peck, & Mesri, 1996). “The term clay refers to a naturally occurring material composed primarily of fine-grained materials, which is generally plastic at appropriate water contents and will harden when dried

or fired” (Guggenheim, 1995) .The term clay is linked with both size of the particles and minerology. The characteristics exhibited by the clay particles may include a net negative charge, plasticity, and the size smaller than 0.002 mm (Firoozi, Firoozi, & Baghini, 2016). The size of clay minerals is so small that they are not influenced by gravitational forces instead the particles are dominated by the electrostatic forces due to the charged surfaces of the particles (Terzaghi, et al., 1996).

### **2.2.1 Clay Minerology**

Clay particles are predominantly composed of minerals known as “clay minerals”. Guggenheim and Martin (1995) defined the clay minerals as “the term clay minerals refer to phyllosilicate minerals and to minerals which impart plasticity to clay, and which harden upon drying or firing”. Clay structure refers to the arrangement of different particles which join together to form a clay crystal. Ions bond with each other to form molecules which further join with other molecules to form a sheet like structure. These sheets then stack upon each other to form layers. The clay minerals are composed of two fundamental structural units which are silicon tetrahedron and aluminum octahedron (Firoozi, et al., 2016). In tetrahedral unit (silicon tetrahedron), four oxygen ions enclose a silicon ion, where in octahedral unit (aluminum octahedron) six oxygen or hydroxyl ions surround aluminum, magnesium, iron, or other ions. The schematic diagram of basic tetrahedron and octahedron units is shown in Figure 2.1 and 2.2, respectively.

The basic building units in the clay minerals are linked together to form silica tetrahedral and aluminum octahedral sheets. The sheets are linked in two ways to establish a layer structure, i.e. 1:1-layer structure and 2:1-layer structure (Al Ani & Sarapaa, 2008). The 1:1-layer silicate structure is constituted such that the apical oxygen of tetrahedral sheet replaces one of the hydroxyl ions from octahedral sheet to constitute the 1:1-layer of clay mineral (e.g. Kaolinite).

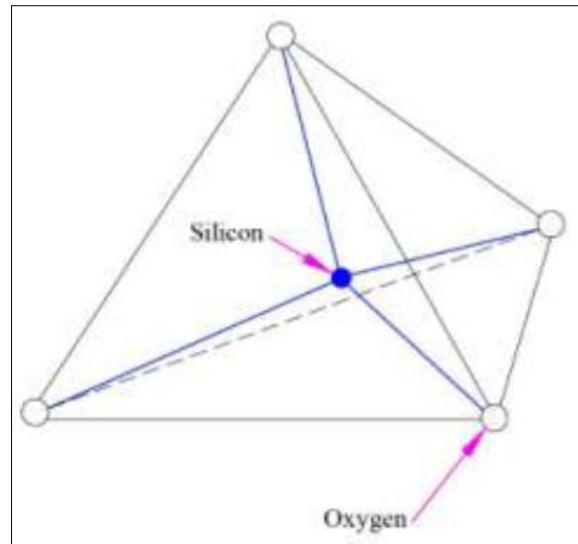


Figure 2.1: Unit of Tetrahedral Mineral

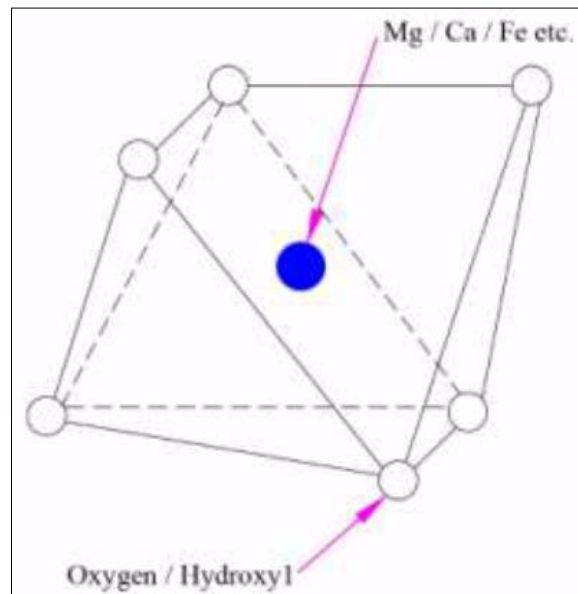


Figure 2.2: Unit of Octahedral Mineral

The 2:1-layer structure is constituted as the octahedral sheet is linked to two tetrahedral sheets such that the hydroxyls in the octahedral sheet are replaced by apical oxygen ions of tetrahedral sheet to develop a 2:1-layer structure of clay mineral (e.g. Illite). The arrangement of octahedral and tetrahedral sheets of 1:1-layer and 2:1-layer structure of clay minerals is shown in Figure 2.3 and 2.4, respectively.

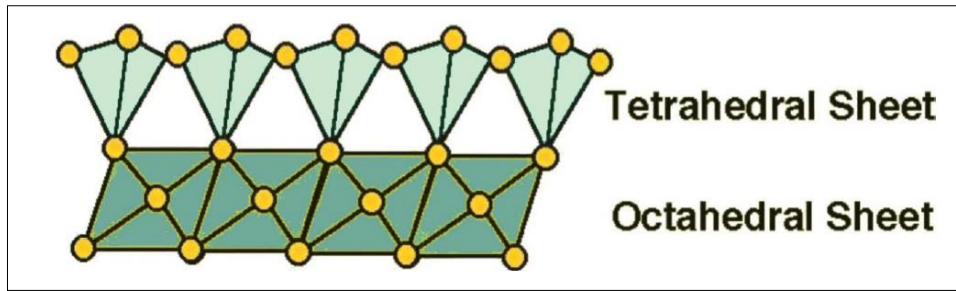


Figure 2.3: Structure of 1:1-layer of Clay Mineral (Kaolinite)

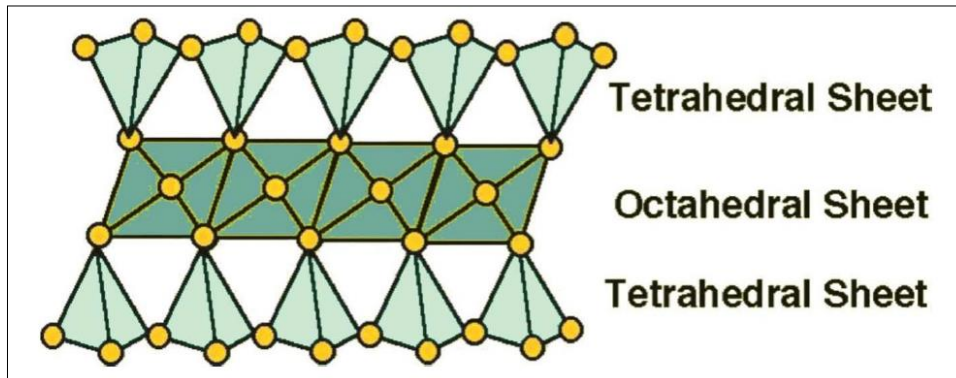


Figure 2.4: Structure of 2:1-layer of Clay Mineral (Illite)

The different combinations of silica tetrahedron and aluminum octahedron sheets, bonding, presence of metallic ions and isomorphous substitution, result in the constitution of different clay minerals. The clay mineral deposits can be constituted either by the weathering of parent minerals to form clay rich residual soils such as kaolinite or by the hydrothermal changes of host rocks, for example Cornish china clay (Al Ani & Sarapaa, 2008). The most common clay minerals that have particular importance in geotechnical engineering are kaolinite, montmorillonite and illite.

### 2.2.1.1 Kaolinite

Kaolin Minerals is a group of minerals which comprises kaolinite, nacrite, dickite and halloysite. The word 'kaolin' comes from Chinese background which resembles 'kauling', a hill in China where it was found a centuries ago. Among kaolin minerals group, Kaolinite is one of the the most abundantly found clay minerals in nature. It has a structure of 1:1-layer comprising of one aluminum octahedral and one silicon tetrahedral sheet. These layers are



linked together by hydrogen bond between the oxygen of tetrahedral sheet and hydroxyl of octahedral sheet, forming a large crystal of kaolinite. The thickness of basic unit sheet of kaolinite is 0.72 nm ( $\text{nm} = 10^{-9}$ ), which stack together to form a hexagonal plate of about 100 nm thickness (Terzaghi, et al., 1996). The schematic diagram of 1:1-layer structure of kaolinite mineral is shown in Figure 2.5. The hydrogen bonding between the octahedral and tetrahedral sheets is illustrated in Figure 2.6. Kaolinite offers a wide range of uses which may include pottery, paper coating, sanitary ware and fillers in paints and rubbers (Al Ani & Sarapaa, 2008).

### 2.2.1.2 Montmorillonite

Montmorillonite is the most common mineral from Smectite group of clay minerals, derived from volcanic ash (Grim, 1953). It has 2:1-layer structure of clay mineral, which is comprised of one central octahedral sheet with two silica tetrahedral sheets. The top of silica sheets is bonded by Van der Waals forces and have a deficiency of net negative charge in octahedral sheet. Therefore, the exchangeable ions and water can enter between the sheets and break the layer. Because of weak interparticle forces, water penetrates into the sheets and causes the layer separation, thus characterizing the swelling behavior of montmorillonite mineral. The schematic diagram of montmorillonite mineral is shown in Figure 2.7.

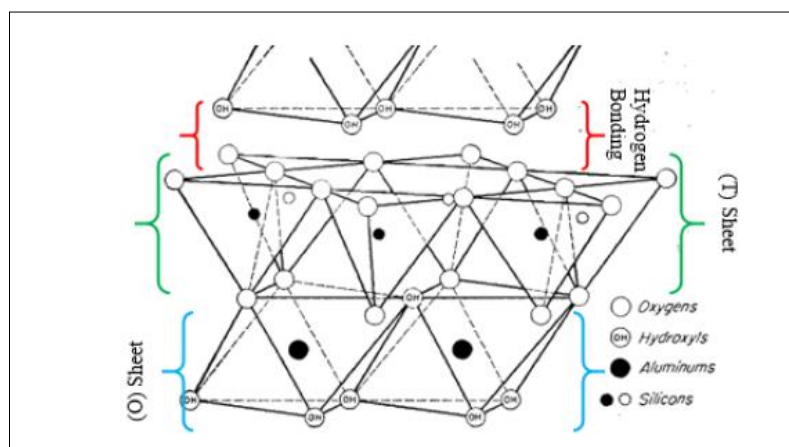


Figure 2.5: 1:1-Layer Structure of Kaolinite Mineral

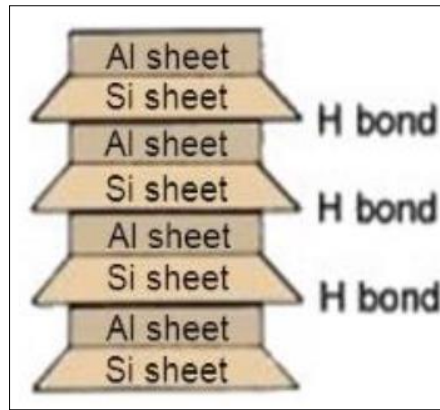


Figure 2.6: Hydrogen Bonding Between Octahedral and Tetrahedral Sheets

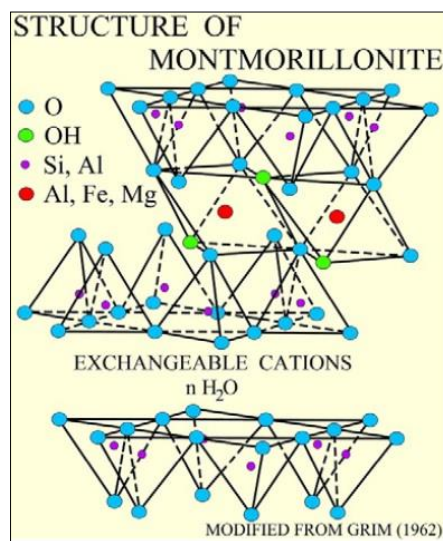


Figure 2.7: Structure of Montmorillonite Mineral

Montmorillonite minerals have wide range of uses which may include, drilling muds, clay liners, oil industries, seepage prevention, lubrication, and prevention of groundwater contamination (Al Ani & Sarapaa, 2008).

### 2.2.1.3 Illite

Illite mineral was discovered and named by Professor Grim from University of Illinois, thus the illite came after Illinois. The mineral structure comprises of two silica tetrahedral sheets and one aluminum octahedral sheet, constituting 2:1-layer structure of clay mineral. The basic structure of illite mineral resembles to montmorillonite, however the basic difference is that the layers are bonded by potassium. The potassium bond is relatively weaker than

hydrogen bond of kaolinite and relatively stronger than Van der Waals forces of montmorillonite (Grim, 1953). Figure 2.8 shows the 2:1-layer structure of illite mineral.

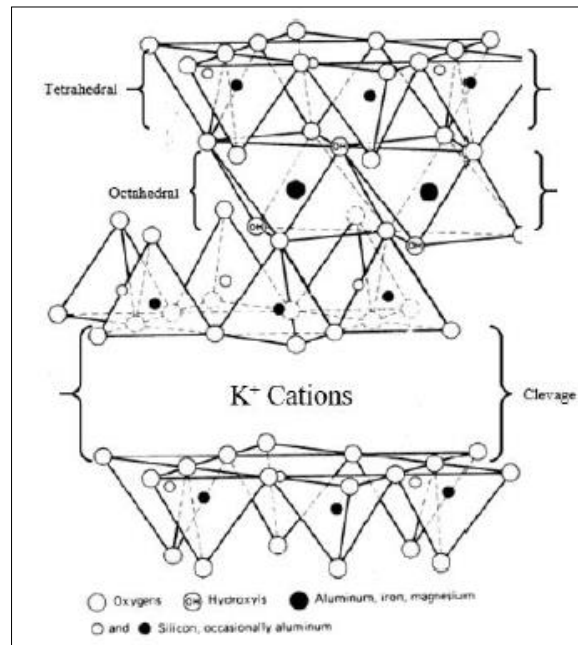


Figure 2.8: Structure of Illite Mineral

## 2.3 SOIL STABILIZATION

Soil has an important role in construction of civil infrastructure for being the ultimate load bearing material. With the evolution of human development and emergence in population, there has been an increased demand of land use for better living and transportation. This needs to exploit the land with undesirable geotechnical conditions for the construction. Very often, soils deal with the problems of low shear strength, low subgrade strength, high swelling potential and compressibility and low permeability. These problems may lead to soil failure which leads to the damage to superstructures. Utilization of land with undesirable geotechnical conditions requires ground improvement. Soil Stabilization is a process of modifying soil properties to improve the engineering performance of soil (Lim, Wijeyesekera, Lim, & Bakar, 2014). Stabilization of soil helps to enhance soil parameters such as bearing capacity, shear strength and swelling characteristics (Kazemian & Huat, 2010). Soil improvement can be

achieved either by densification, dewatering, by chemical additives or by freezing or heating (Wisniewski, Skutink, & Cabalar, 2013).

Most of the ground modification techniques are based on mechanical, chemical, and biological stabilization of soil. The basic purpose of various stabilization methods is to enhance the characteristics of soil (Van Impe, 1989).

Mechanical stabilization of soil is one of the oldest methods that are being employed as stabilization technique. Mechanical stabilization methods physically change the soil properties. It can be achieved through compaction, drainage, dynamic compaction, vibro-floatation, preloading etc. These methods utilize heavy machinery and are intense labor work thus they are not cost-effective techniques for ground improvement.

In chemical stabilization, different chemical additives are mixed with soil to modify its engineering properties. These chemicals additives physically interact with the particles of soil. Majority of these reactions are either cementitious or pozzolanic depending upon type of additive being used.

With the recent developments in ground modification techniques, biological methods of soil stabilization have been carried out effectively. Biological methods of soil stabilization utilize microorganisms, bio-enzymes, and biopolymers for the improvement of soil properties. Polymer stabilization have significant advantages over other traditional stabilization techniques as they are relatively cheap, more effective, and less hazardous for the environment.

Additives which are used to enhance the soil properties are generally known as soil stabilizers. The stabilizers for clayey soil can broadly be divided into two main groups (Tingle, Newman, Larson, Weiss, & Rushing, 2007):

- i. Traditional Stabilizers
- ii. Non-Traditional Stabilizers

### **2.3.1 Traditional Stabilizers**

Traditional stabilizers have been widely used for improvement of problematic soils. These stabilizers may include lime, gypsum, cement, fly ash, slag and bituminous products (Tingle, et al., 2007). Traditional stabilizers improve the strength of wide variety of soils particularly soft soils (Huat, Maail, & Mohamed, 2005).

#### **2.3.1.1 Lime**

Lime is considered to be the oldest soil stabilizer that has been used across the world (Qingquan, Qing, & Zhijing, 2004). Lots of research has been conducted to explore and examine the effectiveness of lime as soil stabilizers. Lime provides effective results in stabilization of low plastic clays (Tingle & Santoni, 2003).

Lime upon reaction with the soil particles produces cementitious products and provides shrinkage resistance, reduces plasticity and helps improving the CBR of the soil (Negi, Faizan, Siddarth, & Singh, 2013).

Lime addition in the soil helps improving the workability and strength, increases the optimum moisture content and decreases the maximum dry density. The improvement in California bearing ratio of soil was observed over a period of 7-day curing (Bell, 1996).

The addition of lime resulted in significant improvement in the compaction and strength characteristics of the Yellowish clay soil. Lime caused a reduction in liquid limit as well as the plasticity index of the soil. Addition of lime also increased the dry density and compressive strength of the Yellowish clay (M M, 2018).

#### **2.3.1.2 Cement**

Cement is the most abundantly used construction material all through the globe. Soils stabilized with cement provide a reliable alternative for satisfactory sustainable infrastructure (Saadeldin & Siddiqua, 2013).

Low plastic clay treated with cement has shown an increase in soaked and unsoaked CBR, reduction in swelling pressure and expansibility and shown better compactable characteristics (Abdelkrim & Mohamed, 2013). It was found that cement stabilization of soil provided strength and durability, caused an increase in the UCS, OMC, and reduction in the dry density of soil (Pandey & Rabbani, 2017).

Cement has also been used in conjunction with other materials for the stabilization of soil. Cement kiln dust (CKD) in combination with cement was reported to raise the unconfined compressive strength and soaked CBR of sabkha soil (Al-Homidy, Dahim, & Abd El Aal, 2017). It was concluded by Al-Homidy et al. that in rigid pavements, 30 % CKD along with 2 % cement can effectively be employed as a sub-base material.

It was observed that cement in combination with rice husk ash (RHA) improved the unconfined compressive strength of lead contaminated soils over a period of 28 days curing (Yin, Mahmud, & Shaaban, 2006).

Significant rise in unconfined compressive strength and a decline in the liquid limit was observed by using cement in combination with glass dust for the stabilization of soft clayey soil (Alam & Rayhan, 2015).

### **2.3.1.3 Gypsum**

Gypsum is hydrated calcium sulphate (chemically known as calcium sulfate dihydrate). It is an abundant naturally occurring material and has been widely used as one of the most common soil stabilizers around the world. The addition of 4 % gypsum to the clayey soil improved the maximum dry density of soil, increased the swelling resistance and CBR value at the optimum percentage of gypsum (Sikarwar & Trivedi, 2017).

It was also reported by Sikarwar and Trivedi that by the incorporation of 1 % calcium chloride to the soil-gypsum mix, an appreciable improvement in soil properties was observed. Soil stabilized with gypsum had shown a considerable rise in CBR value, a raise in the

maximum dry density and reduction in the optimum moisture content (Murthy, Siva Kavya, Venkata Krishna, & Ganesh, 2016).

Treatment of high swelling Bentonite clay with gypsum resulted in a reduction of liquid limit as well as plasticity, enhancement in unconfined compressive strength and a decline in the swell percentage of the soil (I. Yilmaz & Civelekoglu, 2009).

A rise in the unconfined compressive strength and CBR value was witnessed when the low plastic clay was treated with 2 % gypsum with paddy husk ash (Roesyanto, Iskandar, Hastuty, & Dianty, 2018).

#### **2.3.1.4 Blast Furnace Slag**

Blast furnace slag is a by-product of iron industry. It has been successfully used for the stabilization of problematic soils. Soil treated with BFS in the presence of lime activator had shown an improvement in the properties such as compaction characteristics, strength & durability, and swelling resistance (Nidzam & Kinuthia, 2010).

It was found that the treatment of silty clay with ground granulated blastfurnace slag (GGBS) had resulted in a rise in the dry density and increment of 80 percent in the unconfined compressive strength (Al-Khafaji, Jafer, Dulaimi, Atherton, & Jwaida, 2017).

The addition of 15 percent GGBS improved the maximum dry density and soaked CBR of black cotton soil as well as improved the cyclic plate load test results for the flexible pavement (Durga Prasad, Prasad, & Prasada Raju, 2019).

The treatment of highly compressible silt with GGBS in combination with fly-ash was found to increase the unconfined compressive strength by 176 percent after 28 days of curing (Kumar et al., 2015).

#### **2.3.2 Non-Traditional Stabilizers**

With the advancement in geotechnical engineering and ground modification techniques, researchers have been studying different additives for the stabilization purposes.

Non-traditional stabilizers include chlorides, enzymes, polymers, biological binders and potassium compounds (Anjaneyappa & Amarnath, 2011). The composition and interaction of non-traditional stabilizers with soil is very complex (Tingle, et al., 2007).

### **2.3.2.1 Chlorides (Salt Stabilizers)**

Chlorides are generally known as salts. The main chloride salts are calcium chloride ( $\text{CaCl}_2$ ), sodium chloride ( $\text{NaCl}$ ) and magnesium chloride ( $\text{MgCl}_2$ ). These salts are sensitive to change in humidity and are mainly used for the suppression of dust (Kestler, 2009).

The investigation on stabilization of soft soil with chlorides ( $\text{NaCl}$ ,  $\text{MgCl}_2$  and  $\text{CaCl}_2$ ) concluded that the chloride compounds caused a decline in plasticity and the optimum moisture content while an caused a rise in the maximum dry density and unconfined compressive strength increasing chlorides percentage (Jafer, 2013).

It was found that the clay soil stabilized with the chloride compounds (including  $\text{NaCl}$ ,  $\text{CaCl}_2$  and  $\text{MgCl}_2$ ) had resulted in rise of the dry density and drop in the optimum moisture content, swelling index and compression index with increasing percentage of chloride compounds (Afrin, 2017).

The addition of magnesium chloride ( $\text{MgCl}_2$ ) for stabilization of high plastic clay rose the dry density of the soil, while a reduction was observed in plasticity and optimum moisture content (Abood, Kasa, & Chik, 2007).

### **2.3.2.2 Lignosulfonate Stabilizers**

The lignosulfonate products mainly include sodium, calcium and ammonium lignosulfonates and are generally originated from lignin. Primarily, these lignosulfonates are cementing agents and stabilize the soils by cementing effects by bonding the soil particles together (Tingle, et al., 2007).

It was concluded from the study lignosulfonates as soil stabilizers and their effect on the properties of kaolinite clay that they caused a rise in the maximum dry density and shear



strength of the clay while reduced the optimum moisture content and liquid limit of kaolinite clay (G. Vijayan & Sasikumar, 2019).

Stabilization of high plastic clay using lignosulfonate resulted a surge in the unconfined compressive strength and secant modulus (E50) at the optimum percentage of lignosulfonate (Ta'negonbadi & Noorzad, 2017).

It was reported that the soil stabilized with calcium lignosulfonate had shown a significant rise in unconfined compressive strength and CBR value by 25 percent and 400 percent respectively (Ravishankar, Panditharadhya, Reddy, & Amulya, 2017).

Experimental investigations revealed that the soil stabilized with lignosulfonate had shown an improvement in the resistance to repeated wetting and drying cycles up to 77%, an increment in the unconfined compressive strength was noted while the swelling percentage reduced by 23% (Alazigha, Vinod, Indraratna, & Heitor, 2019).

### **2.3.2.3 Polymer Stabilizers**

These stabilizers are more often than not vinyl acetates and acrylic copolymers generally suspended in emulsion. On the evaporation of emulsion water, polymer stabilizers tend to coat the particles of soil and develop physical bonding (Tingle, et al., 2007).

Two polymers, poly vinyl alcohol (PVA) and Butane Tetra Carboxylic Acid (BTCA) were employed for the stabilization the expansive clay. It was noticed from the experimental investigations that these polymers caused an improvement in the unconfined compressive strength of the soil at varying content of PVA and BTCA polymers for 1 to 14 days of curing (Mirzababaei, Arulrajah, & Ouston, 2017).

The effectiveness of liquid acrylic polymer as stabilizing agent for Carbondale soil and commercially available soil was investigated. It was noticed that the polymer addition caused no noticeable change in the liquid limit and plastic limit of both soils. Whereas a drop in the

dry unit weight and considerable rise in the unconfined compressive strength of commercial soil was observed (Kolay, Dhakal, Kumar, & Puri, 2016).

Vinyl acetate polymer was used to stabilize the mechanical and water related properties of soil. It was concluded that with the increase in liquid vinyl acetate concentration, a considerable rise in shear strength, cohesion and unconfined compressive strength was noted. The improvement in erosion resistance of soil was observed when the vinyl acetate diluent was sprayed over the surface of soil (Song et al., 2019).

#### **2.3.2.4 Ionic Stabilizers**

Ionic stabilizers mainly consist of acids and alkaline additives. These stabilizers are used in smaller concentration and result in cation exchange and cause flocculation of clay minerals (Tingle, et al., 2007).

Liquid ionic soil stabilizer (LISS) was utilized to examine its effect on expansive-soils. The LISS consisted of sulfuric acid, phosphoric acid, citric acid, water, and surfactant. The experimental investigation had shown a reduction in plasticity of soil with increasing LISS concentration. LISS was reported to increase the soil strength and reduction of free swell strain of expansive soil (He, Yu, Banerjee, & Puppala, 2018).

A compounded soil stabilizer RBS containing active ingredients of sulfate oil with the magnesium quicklime as an additional stabilizing material was used to stabilize the silt clay soil having low liquid limit. It was concluded that the soil treated with ionic soil stabilizer RBS had resulted a rise in the unconfined compressive strength & stability. The rate of expansion and contraction of soil treated with ionic stabilizer was reported to be reduced (Wang & Liu, 2011).

The study of the effect of ionic soil stabilizer on strength properties of low plastic reddish-brown clay of Jinhua region was conducted. It was concluded that the addition of ionic soil stabilizer reduced the soil's plasticity, thus resulting in the dense structure formation and

improvement in the unconfined compressive strength of low plastic soil. It was noticed that the 20% strength was improved at the optimum dosage of ionic soil stabilizer (Tao, Lin, Luo, Qiu, & Wu, 2015).

#### **2.3.2.5 Enzymatic Stabilizers**

Enzymes are known to be organic (protein) molecules which catalyze only if conditions are favorable for the reaction. The large organic molecules reduce the affinity of clay particles for the moisture by surrounding the clay minerals and neutralize the net charge thus generating a cemented bond which stabilizes the soil (Tingle, et al., 2007).

A study conducted on the stabilization of silty sand (SM) soil using Renolith in combination with cement concluded that the incorporation of Renolith resulted in lowering the percentage of cement to be used in stabilization process. At optimum dosage of 3%, a considerable rise in the California bearing ratio with lesser cement percentage was observed. It was reported that the addition of Renolith caused in 15% to 28% reduction in stabilization cost (Singh & Garg, 2015).

A Bio-Enzyme named TerraZyme was used to stabilize lateritic soil. It was observed that for a dosage of 200 ml/2 m<sup>3</sup> of soil, the CBR value and unconfined compressive strength were increased by 300% and 450% respectively. Using TerraZyme as well reduced the permeability of lateritic soil by 42 percent (Shankar, Rai, & Mithanthaya, 2009).

A laboratory investigation was conducted to examine the effectiveness of liquid enzymes on stabilization of low plasticity and high plasticity soils. It was concluded that swelling percentage and CBR value increased by 5% to 350% and 5% to 70% respectively, based on type of soil and curing period. It was noted that the swell percentage of CH soil increased vividly upon treatment with liquid enzymes (Y. Yilmaz, Avsar, & Gungor, 2009).

A study was carried out to evaluate Eko Soil (ES) enzyme as soil stabilizer for its application in highway embankment construction. The treated expansive soil with ES enzyme

exhibited a drop in plasticity and rise in the soil strength. A noticeable rise in CBR and UCS values up to 347% and 334%, respectively was also noted. It was concluded that ES modified soil can be used as highway embankment, but the strength improvement was not much substantial to be utilized as a potential sub-base or base material (Kushwaha, Kishan, & Dindorkar, 2018).

## **2.4 BIOPOLYMERS**

The term bio-based is generally focused on raw materials and is mainly applied to those polymers which are derived from renewable resources. When a raw material reproduced by the natural processes at a faster rate than its consumption, the material is known to be a renewable material (Ravenstijn, 2010). Biodegradability is a function of polymers in which the polymers degrade under the influence of bacteria, fungi, and molds within a particular time period and environment. The term biodegradable focuses on the functionality of biodegradation. On the basis of biodegradability and raw material sources, biopolymers can be categorized into three types (Niaounakis, 2015).

Type A: It includes biopolymers which are obtained from renewable raw materials and are designated as biodegradable.

Type B: It includes biopolymers which are obtained from renewable raw materials but are not considered biodegradable.

Type C: It includes biopolymers which are obtained from fossil fuels and designated as biodegradable.

Biopolymers that are produced from living organisms such as plants, animals and microorganisms or they may be produced from materials such as sugar, starch and corn etc. can be listed as type A biopolymers. PLA, PHAs, starch or proteins are some of the examples of bio-based biodegradable (type A) biopolymers. Polymers such as polyamides, polyesters-based bio-propanediol, bio-polyethylene, bio-PVC and bio-ethanol are some of the examples

of type B biopolymers. Polymers produced from fossil fuels such as synthetic aliphatic polyesters, poly-butylene succinate (PBS) and aliphatic-aromatic co-polyesters are some of the examples of type C biopolymers. A wide range of biopolymers including deoxyribonucleic acid, ribonucleic acid, proteins, cellulose, and starch etc. are produced by living organisms such as plants, animals, fungi, and bacteria.

Biopolymers can be divided into three main classes: Polynucleotides, Polypeptides and Polysaccharides (Pattanashetti, Heggannavar, & Kariduraganavar, 2016). Amongst three classes of biopolymers, polysaccharides are considered to be most commonly used biopolymers for various applications (Kalia & Avérous, 2011).

Polysaccharides are considered to be the carbohydrate polymers having high molecular weight which may range between  $10^4$  to  $10^7$ . Polysaccharide polymers are generally composed of long chains of monomers (called monosaccharides) which are linked together through glycosidic bonds. Cellulose, starch, glycogen, and chitin are some of the common polysaccharides (Niaounakis, 2015).

Polysaccharides due to their physical and chemical properties including their film forming capacity, water retention, and rheology are used in many industrial applications such as paints, textile, cosmetics, pharmaceutical and in food industry. They exhibit the properties of stabilizing, emulsifying and thickening agents (Moreno, Vargas, Olivares, Rivas, & Guerrero, 1998).

Commercially available natural polysaccharide biopolymers include Guar Gum, Xanthan, Gellan, Agar, Carrageenan, Pectins and alginate. Major part of the available biopolymers is obtained from plants (including guar gum, Arabic gum), algae (including agar, alginate), crustacean (including chitin). The small fraction of the commercially available polysaccharide biopolymers including xanthan, gellan, and welan etc. are obtained from microbes. The application of these commercially available natural polysaccharides

biopolymers is mainly based on their capability to amend the properties of the aqueous system and are being utilized in industries like oil, food, and pharmaceuticals (Niaounakis, 2015).

#### **2.4.1 Biopolymer Stabilization**

Soil stabilization has been an enduring effort for geotechnical and civil engineers. Researchers have been observing various soil stabilization techniques such as compaction, drainage, pre-compression, consolidation, grouting, soil reinforcement, geotextiles, and chemical stabilizers (Delatte, 2001). Mechanical and Chemical soil stabilization processes such as compaction, external loading, consolidation, vibration, hydration or pozzolanic reaction of the soil are some of the main soil improvement techniques (Sherwood & Transport Research, 1993). Cement has been one of the most widely used material for the stabilization of soil after the industrial revolution. It has been dominantly used for construction of superstructures and soil improvement purposes (Basu, Misra, & Puppala, 2015). The excessive production and usage of cement has a great bearing on the environment as it is responsible for greenhouse gas emission.

Keeping the environmental impacts in mind, the demand for environmentally friendly and sustainable materials is increasing. The researchers have been actively studying the alternative materials such as geosynthetics, geopolymers, synthetic polymers, bio-enzymes, biopolymers and microbial injections for the stabilization and improvement of soil properties. Biopolymers are natural organic polymers, produced by living organisms, consist of small monomer units which are bonded together to form longer chains. Biopolymers have been investigated as a sustainable and environmentally friendly renewable materials for the stabilization of soil. Biopolymers are abundantly found in nature and most of the biopolymers are considered to be nontoxic and edible, thus they are believed to be as environmentally friendly alternatives for stabilization of soil.

Generally, biopolymers have electric charges on their high specific surfaces, which facilitates the interaction fine soil particles and biopolymers. This direct interaction of biopolymers with the soil particles form soil-biopolymer matrices having high strength. The strengthening of the soil-biopolymer matrices increases in the presence of clayey particles, which also contain electrical charged surfaces (Chang, Im, & Cho, 2016).

Many researchers have investigated the probability and feasibility of using biopolymers as potential soil stabilizers and obtained satisfactory results. One such experimental study was conducted on expansive soil. Guar gum biopolymer was employed to examine the impact of biopolymer on soil properties. Atterberg Limits, Compaction and Strength Characteristics, and California bearing ratio were part of experimental program. The biopolymer was added in dry form at a percentage of 0.5% to 3.0%. From test results, the optimum dosage of biopolymer came out to be 2% by soil weight. It was concluded that at optimum biopolymer dosage, the dry density, unconfined compressive strength and California bearing ratio of the soil increased significantly, whereas the value of liquid limit and plastic limit reduced by approximately 14% and 23% respectively (Kullayappa & Kumar, 2018).

Xanthan gum biopolymer, which is a microbially induced biopolymer, was added to the low plasticity clay to evaluate the geotechnical attributes of the soil. The biopolymer was mixed with soil at proportions varying from 0.5% - 3.0%. To examine the influence of biopolymer on low plasticity clay, laboratory tests involving UCS, laboratory vane shear, oedometer, permeability, fall cone, swelling and shrinkage tests were performed. The results revealed that the strength of low plasticity clay increased as an effect of biopolymer content as well as the curing of soil-biopolymer mixture. A drop in the unit weight and rise in optimum moisture content of low plasticity clay was noticed. It was suggested that the lower percentages of xanthan gum ranging from 1% to 3% biopolymer should be adopted for improving the properties of low plasticity clay (Cabalar, Awraheem, & Khalaf, 2018).

A commercially available  $\beta$ -1,3/1,6 glucan biopolymer was utilized to evaluate its effectiveness on strength properties of Korean residual soil. The residual soil, named Hwangtoh, mainly comprised of kaolinite and halloysite minerals. The experimental program consisted of tensile strength test, uniaxial compressive test, and microscopic observations. The soil was mixed with different concentrations of biopolymer and curing was performed at various temperatures. It was concluded that the biopolymer increased the compressive strength of residual soil approximately 200% at a concentration of 4.92-g/kg under 60 °C curing temperature (Chang & Cho, 2012).

The engineering properties of Kaolinite clay were evaluated by treating the clay with guar gum biopolymer. The biopolymer was added to the clay at various concentrations ranging from 0.25% to 1.0%. The experimental work included the Atterberg limits, compaction characteristics, UCS and CBR test. From test results, it was concluded optimum content of biopolymer at which maximum values of dry density, unconfined compressive strength and CBR were obtained, was 0.75% (A. Vijayan & Vijayan, 2018).

The evaluation of xanthan gum biopolymer for the treatment of expansive soil was conducted. Xanthan gum was used in the range of 0.2% to 1.2% concentration by weight of dry soil. The experimental study was focused on the UCS and CBR of expansive soil. Xanthan gum biopolymer helps in improving the interparticle relations within the soil, increases the cohesive forces, thereby increasing the soil strength. The optimum percentage of xanthan gum biopolymer in this study came out to be 1% (Naveena & Sreenivasa Reddy, 2015).

Cohesionless fine sand was treated with two biopolymers to examine the impact of biopolymers on soil strengthening. Xanthan gum and Guar gum biopolymers were chosen as stabilizing agents in this work. Dry mixing procedure was implemented to prepare test specimens and biopolymers were mixed by weight of sand at percentages from 0.5% - 1.5% with 0.5 % increment. UCS was performed on biopolymer treated specimen which were air



dried for 3, 7 and 28 days. It was observed that the addition of both biopolymers significantly improved the UCS of fine sand. It was found that the optimum percentage of guar gum was 1.5%, while for xanthan gum it was 1% for the strengthening of cohesionless fine sand. Xanthan gum showed a slightly better strength after 28 days of curing (Patel & Shah, 2016).

The possibility of using biopolymers to improve the mechanical behavior of collapsible soil was investigated by using guar gum and xanthan gum biopolymers. Compaction characteristics, Shear parameters and collapsible potential were main properties of experimental work. The biopolymer solution was used at various concentration of 0.25%, 0.5%, 1.0%, 2.0%, 3.0% and 4.0%. Results indicate that the dry density of collapsible soil reduced by increasing the concentration of both biopolymers, while in contrast the optimum moisture content increased with increasing biopolymers concentration. It was observed that the collapsible potential significantly reduced from 9% to 1% after biopolymer treatment. It was also observed that guar gum had shown better results as compared to xanthan gum and reduced the collapsible potential by 20% as compared to xanthan gum. The optimum biopolymer concentration came out to be two percent for both guar gum and xanthan gum (Ayeledeen, Negm, El-Sawwaf, & Kitazume, 2017).

An effort was made to evaluate the feasibility of using biopolymers to stabilize mine tailings (MTs) for dust control which are extremely prone to wind erosion and pose different environmental concerns. Two natural biopolymers, xanthan, and guar gum were employed for stabilization of mine tailings. The biopolymers were used in the concentration of 0.6%, 1.0% and 1.6% by weight of the soil. Moisture retention and surface strength tests were conducted to evaluate the efficiency of biopolymers. It was observed that MTs treated with biopolymers had shown higher moisture retention capacity and surface strength as compared to untreated specimen. It was also observed that the guar gum had shown better surface strength results as compared with xanthan gum at higher concentrations (Chen, Lee, & Zhang, 2015).

A solution of chitosan biopolymer was used to examine the stabilization of low plastic clay soil traces of sand and finer gravel. The chitosan biopolymer was incorporated at concentrations of 0.02%, 0.04%, 0.08% and 0.16%. It was concluded that the treatment of clay with chitosan biopolymer significantly augmented the interparticle cohesion and overall improved the mechanical properties of soil (Hataf, Ghadir, & Ranjbar, 2018).

An elaborate study was carried out on the engineering behavior of guar gum treated highly compressible silty-clay. By adopting the wet mixing method, the guar gum biopolymer was mixed at various concentrations of 0.5%, 1.0%, 1.5% and 2.0% with water to form a viscous gel. The experimental investigation included consistency limits, compaction characteristics, permeability, UCS and consolidation of the soil. A significant improvement in soil characteristics was observed due to the bonding properties of guar gum. The test results indicated that the optimum concentration of guar gum biopolymer was 2% for which maximum improvement in geotechnical properties was seen. An increment of 45% in the strength of soil without curing was noted. The compressibility of soil reduced with the addition of guar gum biopolymer. There was a percentage reduction in compression index and swelling index by 32% and 85% respectively (Sujatha & Saisree, 2019).

## **MATERIALS AND METHODOLOGY**

### **3.1 GENERAL**

The basic objective of this research is to study the effectiveness and suitability of GG biopolymer as soil stabilizer. Two types of clayey soils, low plasticity clay (CL) and high plasticity clay (CH), were employed in this research work. The low plastic clay (CL) was obtained from Ballewala, near Nandipur district Gujranwala, Pakistan. High plastic clay (CH) was then prepared in laboratory by mixing 25 % of bentonite to low plastic clay of Ballewala. The main reason for selecting the soil for this study is its problematic nature due to high swelling properties. All the necessary laboratory tests were conducted as per ASTM (American Society for Testing Materials) and AASHTO (American Association of State Highway and Transportation Officials) standards. The details of used materials and performed tests will be discussed in this section.

### **3.2 MATERIALS**

The detail about materials used in this research work is given in the following section.

#### **3.2.1 SOIL**

The soil used in this study was collected from Ballewala, near Nandipur district Gujranwala. The soil from Ballewala had grey color with bluish shade and was found to be low plastic in nature. This soil is famously known for preparing the pitches in cricket grounds. The soil sample was obtained from 2 feet beneath the ground surface to prevent impurities in the sample. The procured soil was then oven dried. High plastic clay was artificially prepared in the laboratory by mixing 25 % bentonite to the low plastic clay of Ballewala. Figure 3.1 and 3.2 show the satellite location of Ballewala from where the soil sample has been obtained and oven dried low plastic clay sample, respectively.

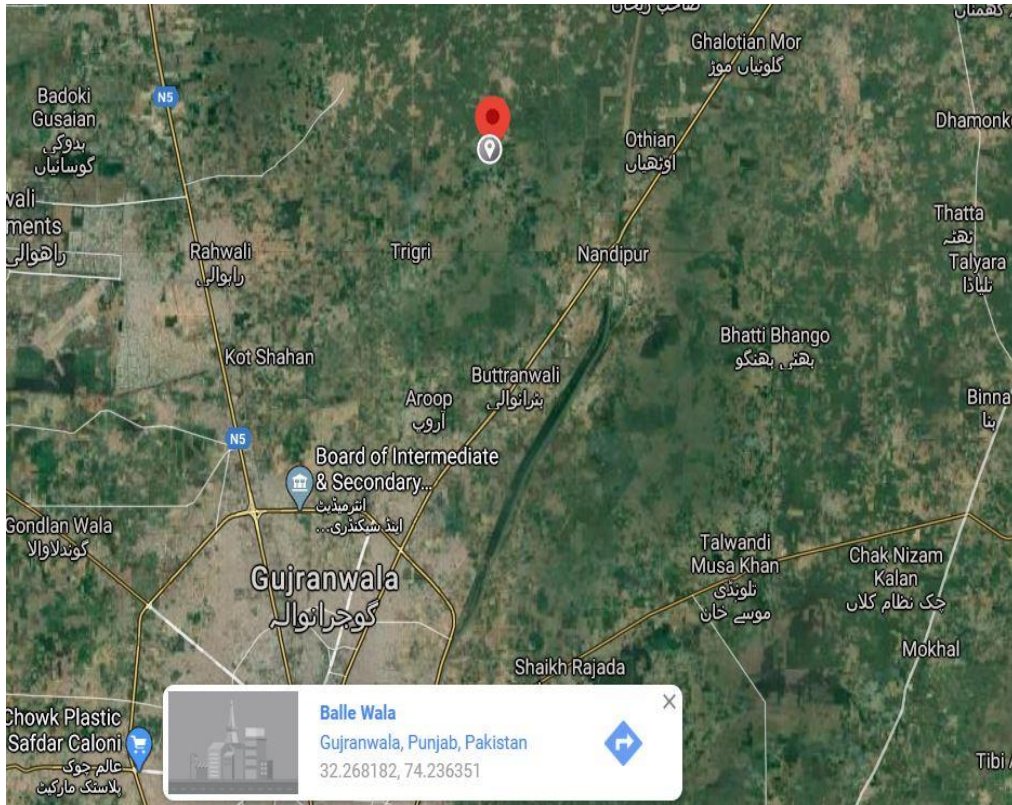


Figure 3.1: Satellite Image of the Source Site of CL Soil, Ballewala



Figure 3.2: Oven dried Ballewala Clay

### 3.2.2 BENTONITE

The bentonite used to prepare the high plastic clay soil specimen was obtained from Ittefaq Clay Tiles Industry, situated in Mughalpura Lahore, Pakistan.

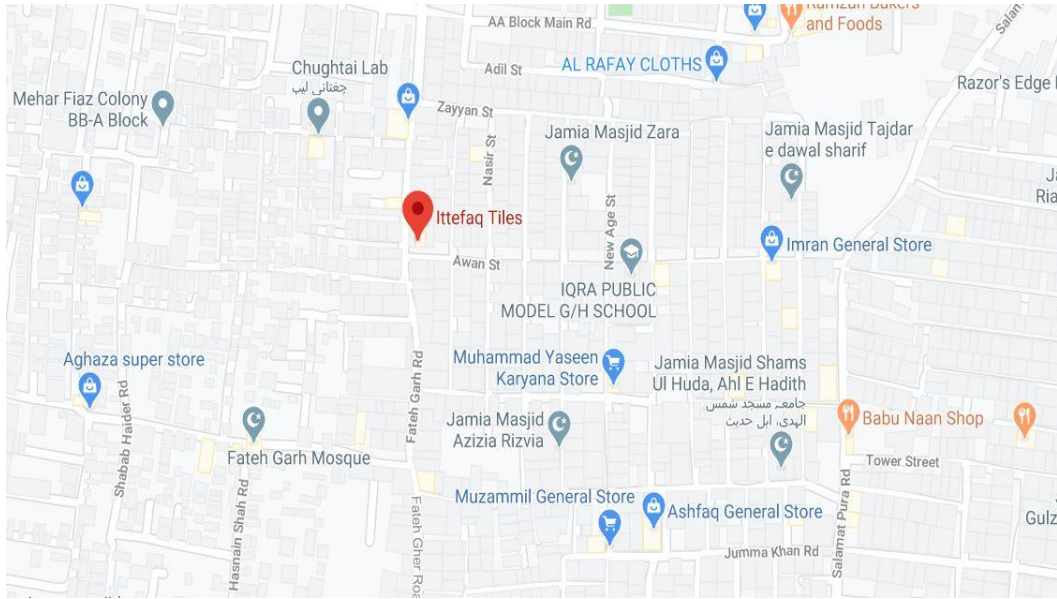


Figure 3.3: Satellite Map for Ittefaq Clay Tile Industry, Lahore



Figure 3.4: Bentonite Clay

The industry manufactures and supplies natural Bentonite powder across Pakistan. Bentonite clay is mostly used as drilling mud, absorbent, groundwater barrier and in slurry walls construction. The Bentonite clay provided by the industry was known as Sodium Bentonite and its approximate chemical composition provided by the supplier is given below in Table 3-1.

Table 3-1: Chemical Composition of Bentonite Clay

Name	Formula	Percentage
Silica	SiO <sub>2</sub>	50.0 to 65.0 %
Alumina	Al <sub>2</sub> O <sub>3</sub>	15.0 to 25.0 %
Ferric Oxide	Fe <sub>3</sub> O <sub>3</sub>	2.0 to 4.0 %
Magnesium Oxide	MgO	3.0 to 6.0 %
Calcium Oxide	CaO	0.50 to 2.0 %
Sodium Oxide	Na <sub>2</sub> O	0.50 to 5.0 %
Potassium Oxide	K <sub>2</sub> O	0.20 to 1.0 %
Titanium Oxide	TiO <sub>2</sub>	0.20 to 0.50 %

### 3.2.3 GUAR GUM

Guar is grown in arid and semi-arid regions of Punjab and Sind provinces of Pakistan and its seeds are locally processed to form guar gum powder. Guar gum used in this research was obtained from United Gums Industries, situated in Korangi Industrial Area, Karachi Pakistan. Guar (botanical name: *Cyamopsis Tetragonoloba*) is the source of guar seeds. Guar gum belongs to polysaccharide family of biopolymers which is mainly comprised of sugars galactose and mannose. The basic structure of guar gum comprises of a linear chain of  $\beta$ -1,4-linked mannose residues to which 1,6-linked galactose residues are linked. The galactose residues are linked with every second mannose in the chain, thus establishing short side branches (Ayeldeen, et al., 2017). Guar gum biopolymer through its hydroxyl groups (-OH) can form frequent hydrogen bonds, which further adds up in the strength of soil-biopolymer matrices (Patel & Shah, 2016). The idealized structure and a sample of gaur gum are shown in Figure 3.5 and Figure 3.6, respectively.

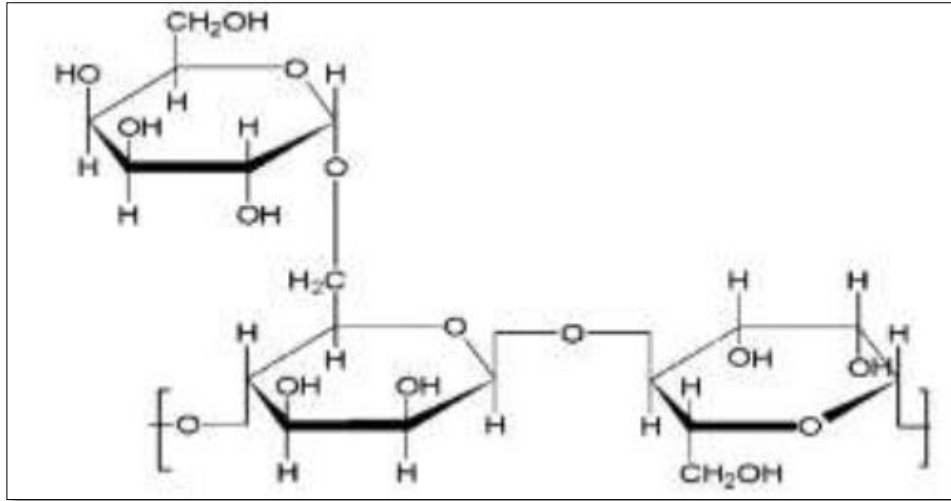


Figure 3.5: Idealized Structure of Guar Gum Biopolymer (Kullayappa, 2018)



Figure 3.6: Guar Gum Powder

### 3.3 METHODOLOGY

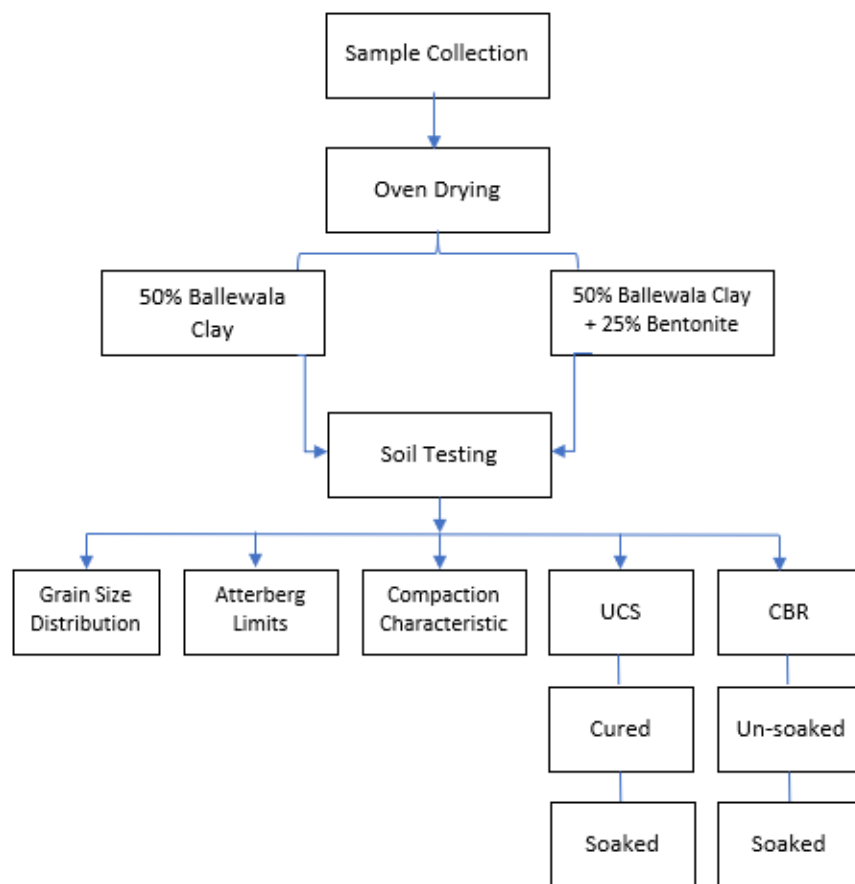
Testing of soil was conducted in two phases:

- Phase I: Characterization of untreated soil
- Phase II: Characterization of treated soil with biopolymer

#### 3.3.1 Phase I: Characterization of Untreated Soil

The first phase of material testing entails the determination of the properties of untreated soil. The untreated soil sample collected from Ballewala was first oven dried for approximately 48 hours at a temperature of  $110 \pm 5$  °C. Half of the oven dried soil was then separated and mixed with 25 % oven dried Sodium Bentonite to prepare high plastic clay. The

properties of the two set of soils, i.e. low plasticity clay and high plasticity clay, such as grain size distribution analysis, Atterberg limits, specific gravity, compaction characteristics, unconfined compressive strength, California bearing ratio and swell potential were then assessed by executing required laboratory tests in comparison with ASTM and AASHTO standards. Figure shows the schematic diagram of phase I.



### 3.3.1.1 Grain Size Distribution Analysis

Grain size distribution was conducted as per ASTM D6913/D6913M-17 standard. As in our soil sample, maximum particle size was less than or equal to sieve # 4 (4.75 mm), method B of the standard was adopted for carrying out grain size distribution. About 500-gram oven dried sample was taken and pulverized for the test.



### **3.3.1.2 Atterberg's Limits**

Atterberg's limits test was carried out in accordance with ASTM D4318-17 test standard. Through this test the liquid limit, plastic limit, and plasticity index (collectively known as Atterberg's Limits) of the soil were determined. A representative soil sample was taken and sieved through sieve # 40 to obtain a 200-g sample for the test. Method A (Multipoint Method) was adapted for the determination of liquid limit of soil. From the prepared specimen of liquid limit test, a 20-g soil was taken for the plastic limit test and hand rolling technique was adapted to find out the plastic limit of the soil.

### **3.3.1.3 Specific Gravity**

Test for the specific gravity of soil was carried out as per ASTM D854-14 standard. The test was conducted on the sample passing through sieve # 4 (4.75 mm) by means of a water pycnometer. About 30-g of oven dried soil sample was taken to perform the test.

### **3.3.1.4 Compaction Characteristics of Soil**

The compaction characteristics of soil were determined in laboratory by using modified effort (Modified Proctor Test). Modified compaction test was performed according to ASTM D1557-12 standard. This modified proctor test is applied to find out the relationship between Optimum Moisture Content (OMC) and Maximum Dry Density (MDD) of soil. As in our soil sample, the retained mass of soil on No. 4 sieve (4.75 mm) was less than 25%, so method A was adapted to perform the test. A 4-inch diameter mold was filled with soil and was compacted in 5 layers with 25 number of blows per layer. Compaction was performed with a 10.0-lbf rammer with a drop height of 18 inches.

### **3.3.1.5 Unconfined Compressive Strength (UCS)**

The unconfined compression test was carried out as per ASTM D2166-13 standard. In this test method, the unconfined compressive strength of cohesive soil is determined by application of axial load on the specimen in unconfined conditions. The test method states that

the specimen to be used in this test must have the height to diameter ratio of 2:1. The mold for preparation of UCS test specimen was 8-cm in length and had a diameter of 4-cm, thus conforming to the standard height to diameter ratio. The samples were prepared in accordance with the maximum dry density (MDD) and optimum moisture content (OMC) of the soil, which were obtained from the results of modified proctor test.



*Figure 3.7: Compaction Test Assembly*

Unconfined compression test was performed under un-soaked (cured) and soaked conditions. For curing, the prepared samples were wrapped individually in airtight plastic sheet and placed in a thermostatically controlled oven at 40°C for desired period of curing. For soaking, the cured samples were first carefully removed from plastic sheets and then wrapped in a cotton gauze bandage (absorbing fabric) and placed in a desiccator for 48 hours. Care was taken to avoid the direct contact of samples with water. The samples were placed above the porous plate in desiccator and the soaking was achieved through the capillary action of water.

Soaking of UCS samples was performed to assess the relative loss in the strength of soil due to water soaking.



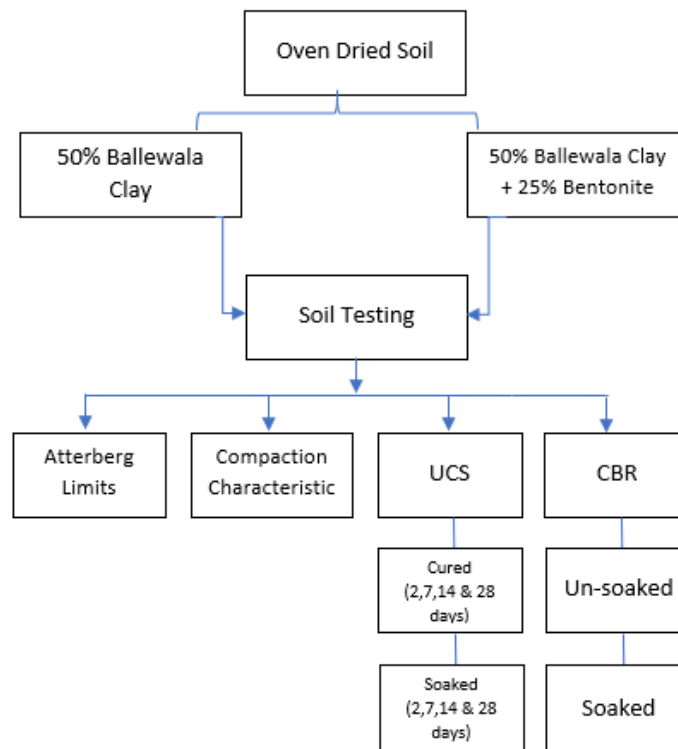
Figure 3.8: UCS Test Sample placed in Compression Testing Machine

### 3.3.1.6 California Bearing Ratio (CBR) and Swell Potential

California bearing ratio test was carried out as per AASHTO T193-13 or ASTM D1883-16 standards. This test method is used to determine the California Bearing Ratio of subgrade soil through laboratory compacted samples. One Point CBR test method was adapted for determining the CBR of subgrade. The test specimens were prepared at OMC obtained from compaction (modified proctor) test. The soil was filled in a 6-inch diameter mold in five layers and compacted with 65 number of blows per layer. A 2.41-inch spaced disk was placed inside the mold before compacting the soil. The samples were prepared for both soaked and un-soaked CBR tests. For soaked CBR test, the prepared samples were placed in a bucket (tub), filled with water, for 96 hours. An additional load of 5-kg was put above the mold during the soaking period for determining the swell potential of the soil.

### 3.3.2 Phase II: Characterization of Treated Soil with Biopolymer

The second phase of material testing involves the determination of soil properties treated with guar gum biopolymer. The influence on the properties of CL and CH soils treated with varying percentages of biopolymer was determined in this phase, such as compaction characteristics, unconfined compressive strength, California bearing ratio and swell potential of soil. Four dosages (percentages) of biopolymer varying from 1 % to 4% with an increment of 1% were added to both low plasticity (CL) and high plasticity (CH) soils. The purpose of this phase is to achieve an optimum percentage of biopolymer to be mixed with soil that would give the maximum results against soil properties.



#### 3.3.2.1 Atterberg's Limit

Atterberg's limits test was conducted as per of the ASTM D4318-17 standard. Atterberg's limits of the CL and CH soil samples were examined by mixing 1%, 2%, 3% and 4% biopolymer to the soil. The trends of Atterberg limits (liquid limit, plastic limit and plasticity index) were than plotted.

### 3.3.2.2 Compaction Characteristics of Soil

Modified proctor test was conducted as per ASTM D1557-12 standard. The CL and CH soil samples were mixed with 1%, 2%, 3% and 4% biopolymer and the effect on compaction characteristics were examined. The samples were prepared by adding a water content of 6% by weight of biopolymer mixed soil and then the water content was gradually increased with an increment of 2%. Compaction curves were plotted for all biopolymer percentages to obtain maximum dry density (MDD) and optimum moisture content (OMC).

### 3.3.2.3 Unconfined Compressive Strength (UCS)

Unconfined compression test was conducted as per ASTM D2166-13 standard. The CL and CH soil samples were mixed with 1%, 2%, 3% and 4% biopolymer and the specimen for unconfined compression test was prepared at OMC obtained from modified proctor test for corresponding biopolymer percentage. The samples were prepared for both curing and soaking conditions. The curing was performed for 2, 7, 14 and 28 days. For soaked test, the samples were cured to desired period prior to soaking and then placed for 48 hours in desiccator. The effect of biopolymer on the cured and soaked UCS of CL and CH soil samples was examined.



*Figure 3.9: Failed UCS Sample*

### 3.3.2.4 California Bearing Ratio (CBR)

CBR test was conducted as per AASHTO T193-13 or ASTM D1883-16 standards. The CL and CH soil samples were mixed with 1%, 2%, 3% and 4% biopolymer. The sample for CBR test was prepared in accordance with OMC obtained from modified proctor test at corresponding biopolymer percentage. Both un-soaked and soaked CBR tests were conducted and the effect of biopolymer on CBR of CL and CH soil samples was examined.

The swell potential of soil was also determined during the soaked CBR by placing a surcharge weight of 5-kg on soil sample.



*Figure 3.10: Soaked CBR Sample Assembly*

## **RESULTS AND DISCUSSIONS**

### **4.1 GENERAL**

The objective of the research was to study the effectiveness of guar gum biopolymer as soil stabilizer. The results of tests conducted in this research study are discussed in this chapter. Two types of soils, Ballewala clay (CL) and the laboratory mixture of Ballewala clay plus bentonite (CH), have been considered in this study. A detailed experimental investigation of untreated and treated soil had been carried out. Laboratory tests, such as Atterberg's limits, modified proctor test, unconfined compression test and CBR tests were performed for both untreated and treated CL and CH soils. The tests were organized in two phases. Phase-I covers the laboratory investigation of untreated CL and CH soil samples. While phase-II covers the laboratory investigation of CL and CH soil samples treated with guar gum biopolymer.

### **4.2 Phase I: Characterization of Untreated Soil**

The laboratory tests were executed to characterize the properties of untreated CL and CH soil samples. These test results were then considered as the benchmark for further soil testing and for the comparison with the results of soil samples treated with biopolymer.

#### **4.2.1 Grain Size Distribution Analysis**

The grain size distribution was carried out as per ASTM standard mentioned previously in chapter 3. The test was conducted for Ballewala clay (CL) as well as for laboratory prepared Ballewala clay plus Sodium Bentonite mix (CH). The results of grain size distribution analysis for both soil samples are given in this section.

#### 4.2.1.1 Low Plastic Clay

It was observed from the results of grain size distribution for low plastic clay sample that 94.42 percent soil passed through 75-micron (No. 200) sieve. Figure 4.1 shows the gradation curve of low plastic clay sample.

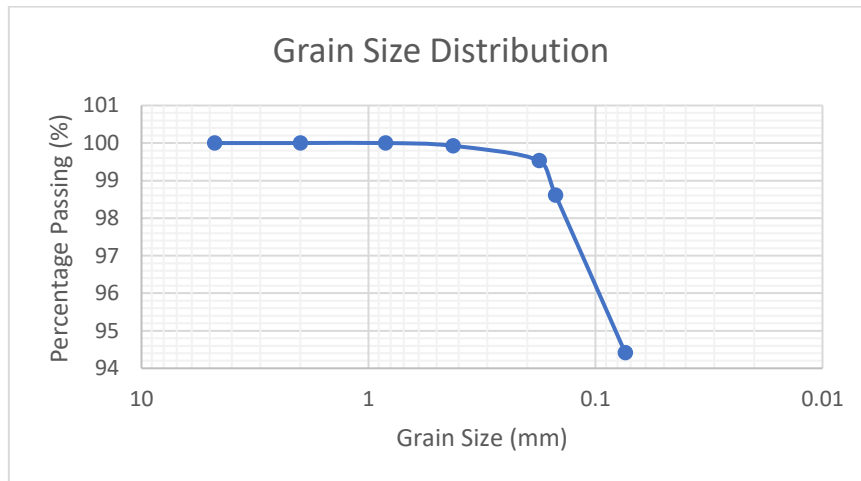


Figure 4.1: Grain Size Distribution Curve of CL

#### 4.2.1.2 High Plastic Clay

It was observed from the results of grain size distribution for high plastic clay sample that 97.09 percent soil passed through 75-micron (No. 200) sieve. Figure 4.2 shows the gradation curve of high plastic clay sample.

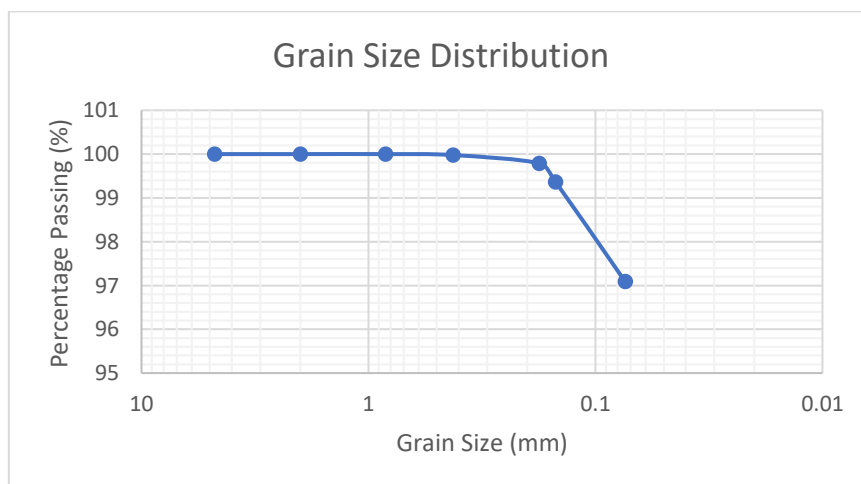


Figure 4.2: Grain Size Distribution Curve for CH



#### 4.2.2 Atterberg's Limits

Atterberg's limits test was performed as per ASTM D4318-17 standard. The liquid limit (LL), plastic limit (PL) and plasticity index (PI) of both soils, Ballewala clay (CL) and laboratory prepared Ballewala clay plus sodium bentonite mix (CH), were determined by using multipoint method. The results of Atterberg's limits test are discussed in this section.

- Results have shown that Ballewala clay (CL) has liquid limit of 48.31% and plastic limit of 21.76%. The plasticity index for Ballewala clay (CL) came out to be 26.55% (which is the numerical difference of liquid limit and plastic limit).
- For Ballewala clay plus sodium bentonite mix (CH), the Atterberg's limits test results have shown that the soil has liquid limit of 59.73%, plastic limit of 28.61% and plasticity index of 31.12%.
- With the addition of Bentonite to the low plastic clay, the liquid limit increased from 48.31% to 59.73% and the rise from 26.55% to 31.12% in plasticity index was also observed. As it is known that the bentonite has a weak crystalline structure and weak bonding between silica and alumina sheets, which permit water to enter into the spaces between the sheets, thus increasing the water holding capacity. This increase in the water holding capacity caused an increase in the liquid limit and plastic limit of the soil.

The results of Atterberg's limits of both soils were then compared to Casagrande Plasticity Chart. Figures 4.3 and 4.4 show that the Ballewala clay lies in the category of low plastic clay, whereas the laboratory prepared Ballewala clay plus sodium bentonite mix sample lies in the category of high plastic clay. The soils, Ballewala clay and laboratory prepared Ballewala clay plus sodium bentonite mix, are therefore denoted as CL and CH respectively throughout the study.

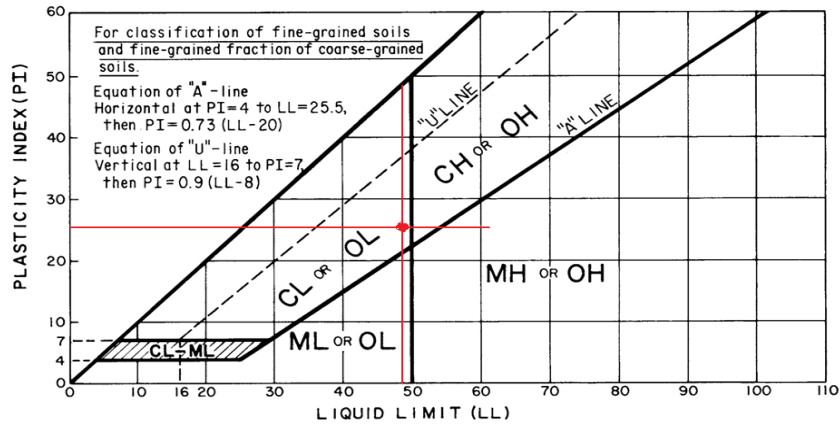


Figure 4.3: Plasticity Chart for Ballewala Clay

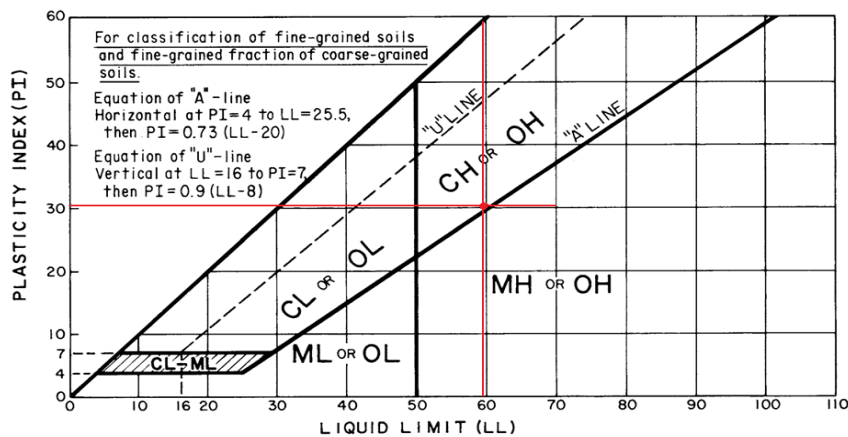


Figure 4.4: Plasticity Chart for Ballewala clay plus Bentonite Mix

### 4.2.3 Specific Gravity

The specific gravity test was conducted as per ASTM D854-14 standard. The test was carried out for both CL and CH soil samples. The results have shown that the CL has specific gravity value of 2.67, whereas CH has specific gravity value of 2.69.

### 4.2.4 Soil Classification

The classification of both soils (CL and CH) was carried out by USCS (Unified Soil Classification System) and AASHTO methods.

#### 4.2.4.1 Unified Soil Classification System (USCS)

Unified soil classification system, developed by Casagrande in 1942, is the most common soil classification system among Geotechnical engineers. The classification of both

soils, CL and CH, were carried out by USCS as per ASTM D2487-11 standard. In USCS, a soil is classified as coarse grained if passing No. 200 sieve is less than 50% and fine grained if passing No. 200 sieve is greater than 50%. The classification system takes into the account the grain size distribution and plasticity of fines passing through 425-micron sieve. By using the results of grain size distribution and Atterberg's limits, the soils were classified by flow chart shown in Figure 4.5.

#### **4.2.4.1.1 Low Plastic Clay**

From the results of grain size distribution and Atterberg's limits, more than 50% passing No. 200 sieve, the soil has liquid limit less than 50% and plasticity index greater than 7 and plots above the "A" line on plasticity chart, so the soil lies in CL region. Hence according to USCS, the soil is Lean Clay.

#### **4.2.4.1.2 High Plastic Clay**

From the results of grain size distribution and Atterberg's limits, more than 50% passing No. 200 sieve, the soil has liquid limit greater than 50%, plasticity index greater than 7 and plots above the "A" line on plasticity chart, so the soil lies in CH region. Hence according to USCS, the soil is Fat Clay.

#### **4.2.4.2 AASHTO Classification of Soil**

AASHTO system of soil classification was developed in 1929 and is standardized by ASTM D3282 and AASHTO M145. AASHTO system classifies the soil into groups, ranging from A-1 (best) to A-8 (worst). AASHTO system of classification uses the results of grain size distribution and plasticity of soil to assign a group classification. Groups are assigned on the basis of whether less than or greater than 35% soil passing through No. 200 sieve. If less than 35% soil passes No. 200 sieve, soil is classified under A-1, A-2, and A-3 groups, these are granular materials. If more than 35% soil passes No. 200 sieve, soil is classified under A-4, A-

5, A-6 and A-7 groups, these silty and clay type materials. Organic soils are placed in A-8 group.

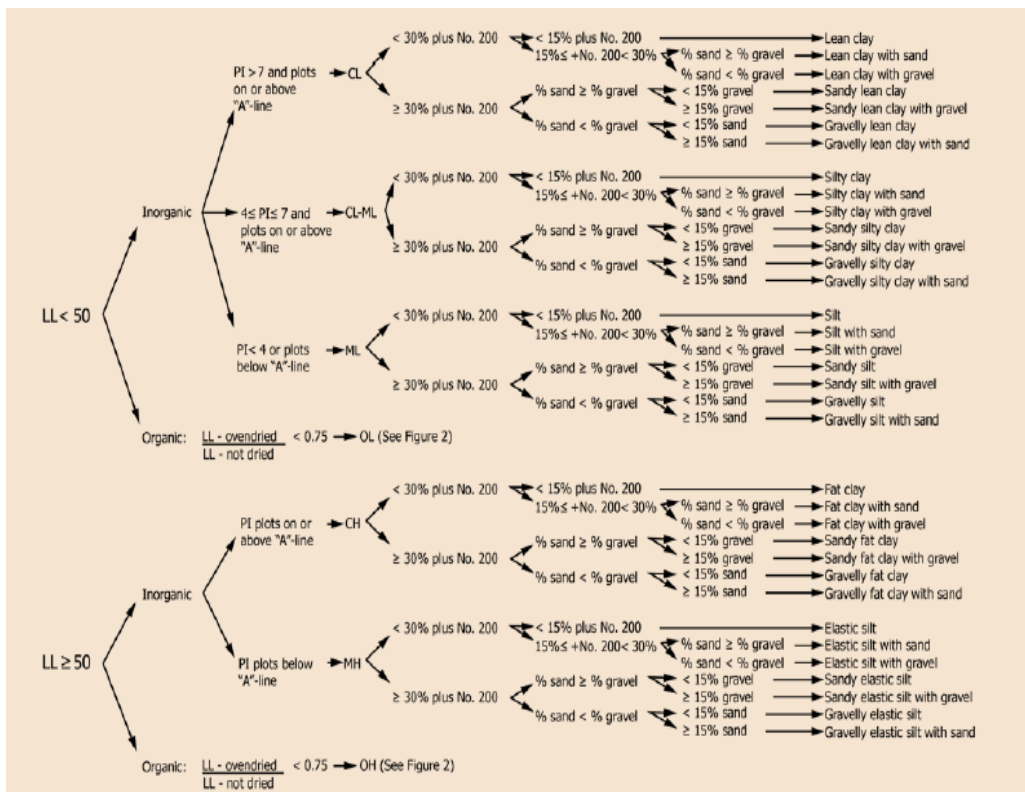


Figure 4.5: Flow Chart for Classifying Fine-Grained Soil (50% Passing No. 200 Sieve)

General classification	Silt-clay materials (more than 35% of total sample passing No. 200)			
	A-4	A-5	A-7 A-7-5 <sup>a</sup> A-6	A-7-6 <sup>b</sup>
Sieve analysis (percentage passing)				
No. 10				
No. 40				
No. 200	36 min.	36 min.	36 min.	36 min.
Characteristics of fraction passing No. 40				
Liquid limit	40 max.	41 min.	40 max.	41 min.
Plasticity index	10 max.	10 max.	11 min.	11 min.
Usual types of significant constituent materials	Silty soils		Clayey soils	
General subgrade rating	Fair to poor			

<sup>a</sup>For A-7-5,  $PI \leq LL - 30$   
<sup>b</sup>For A-7-6,  $PI > LL - 30$

Figure 4.6: AASHTO Classification Table for Silt-Clay Materials (>35% passing No. 200)

From the grain size distribution test, it was observed that both the soil samples (CL and CH) had No. 200 passing percentage greater than 35%, thus the soils under study were

classified under A-4 to A-7 groups. Figure 4.6 shows the AASHTO classification table for silt and clay type materials.

#### **4.2.4.2.1 Low Plastic Clay**

From the results of grain size distribution and Atterberg's limits, it was observed that passing No. 200 was 94.42% greater than 35%, liquid limit was 48.31 and PI was 26.55%. Using the AASHTO classification table, the soil was classified under group A-7-6.

#### **4.2.4.2.2 High Plastic Clay**

From the results of grain size distribution and Atterberg's limits, it was observed that passing No. 200 was 97.09% greater than 35%, liquid limit was 59.73 and PI was 31.12%. Using the AASHTO classification table, the soil was classified under group A-7-6.

### **4.2.5 Compaction Characteristics of Soil (Moisture-Density Relation)**

Compaction characteristics (maximum dry density and optimum moisture content) of both CL and CH soils were determined by modified proctor test. Compaction curves were developed for both soils and MDD and OMC were then determined from compaction curves. For low plastic clay (CL), the MDD came out to be 1.814 g/cm<sup>3</sup> at 12% OMC. For high plastic clay (CH), 1.784 g/cm<sup>3</sup> MDD was obtained at 12.634% OMC. The change in MDD was observed with the addition of bentonite to CL as bentonite particles are lighter than CL particles. Similarly, a slight increase in OMC was also observed because of the water absorption property of bentonite. The compaction curves for both CL and CH are shown in figure 4.7 and 4.8, respectively.

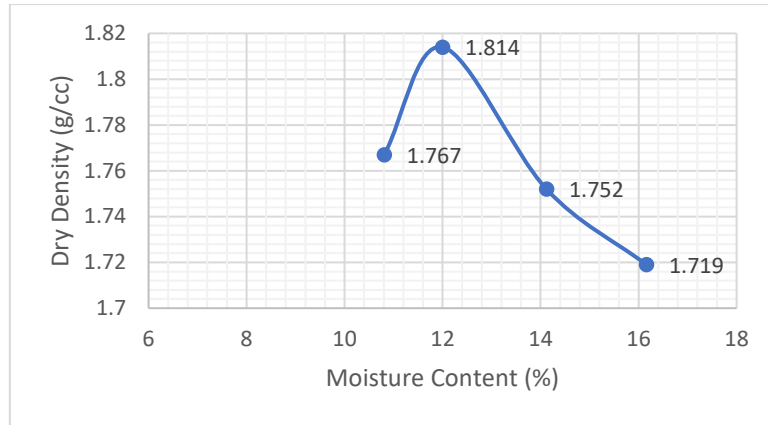


Figure 4.7: Compaction Curve for CL

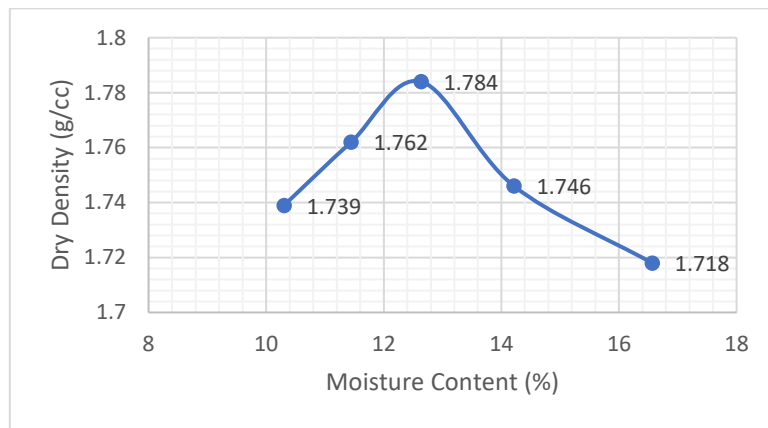


Figure 4.8: Compaction Curve for CH

#### 4.2.6 Unconfined Compressive Strength (UCS)

Unconfined compression test was performed on both CL and CH samples in order to determine the unconfined compressive strength of the soils under study. The UCS for low plastic clay (CL) and high plastic clay (CH) in untreated condition (no biopolymer added) came out to be 24.734 psi and 30.667 psi, respectively. CH sample showed a higher value of UCS because of the extra cohesive nature of bentonite. Figures 4.9 and 4.10 show the stress-strain curve of both CL and CH soils.

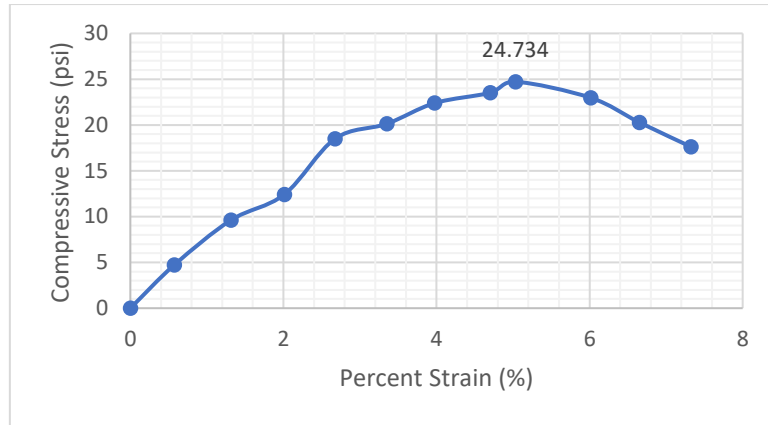


Figure 4.9: Stress-Strain for Untreated CL Sample

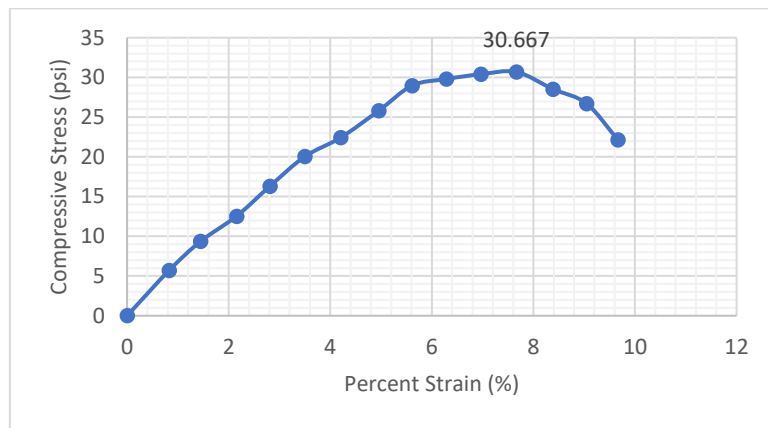


Figure 4.10: Stress-Strain Curve for Untreated CH Sample

#### 4.2.7 California Bearing Ratio (CBR)

CBR test was performed on both soil samples (CL and CH) in soaked and un-soaked conditions. For low plastic clay (CL), values of un-soaked and soaked CBR came out to be 3.69% and 2.12%. For high plastic clay (CH), un-soaked CBR was 2.61% and soaked CBR value came out to be 1.36%. The figures 4.11 and 4.12 show the comparison of soaked and un-soaked CBR values for CL and CH soil samples, respectively.

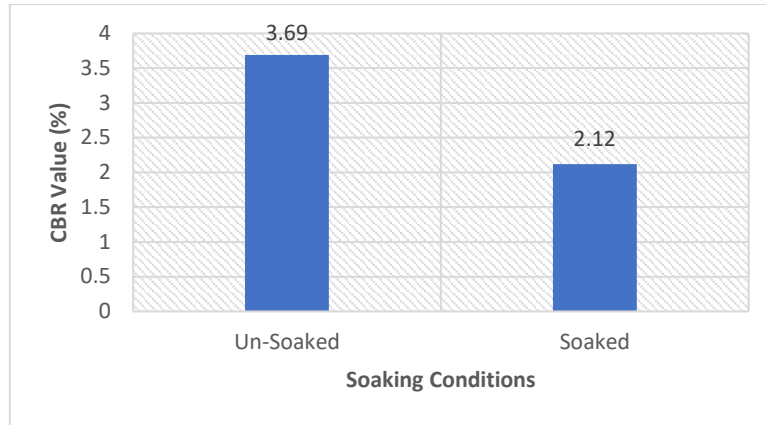


Figure 4.11: Comparison of Un-soaked and Soaked CBR of Untreated CL

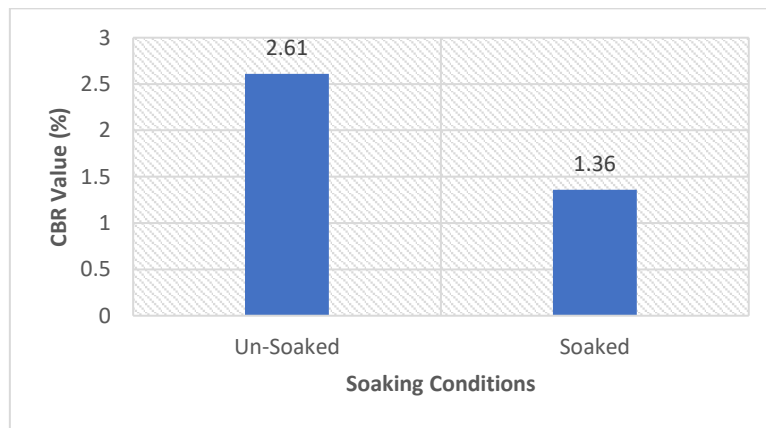


Figure 4.12: Comparison of Un-soaked and Soaked CBR of Untreated CH

#### 4.2.8 Swell Potential

Swell potential of the soils under study was determined from soaked CBR samples. The specimens were placed (soaked) in water bucket for 96 hours and an additional load of 5-kg was also applied on the samples. The original height of soaked sample was recorded. A dial gauge assembly was attached with the molds to evaluate the change in height of the samples. The ratio of the change in height to the original height of the sample gives the swell potential of the soil. The swell potential for CL and CH soil samples were came out to be 5.89% and 7.83% respectively. Figure 4.13 shows the comparison of swell potential values of both soils.



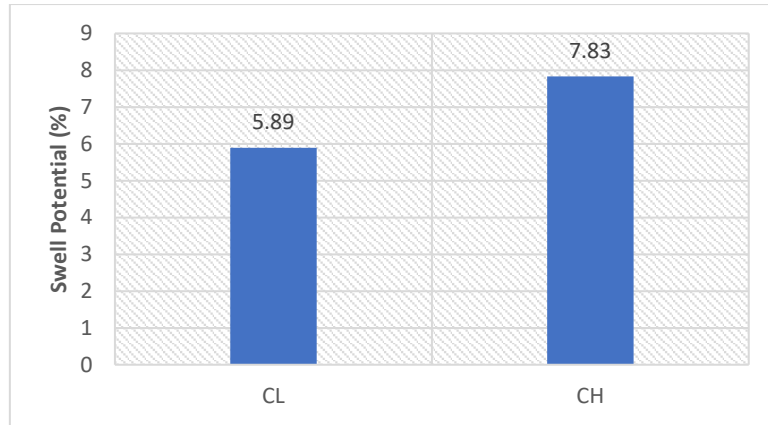


Figure 4.13: Swell Potential of Untreated CL and CH

#### 4.2.9 Summary

The properties of untreated CL and CH soils are condensed in the Table 4-1 given below:

Table 4-1: Summary of Properties of untreated CL & CH soils

Property	Unit	SOIL A – CL	SOIL B – CH
Passing Sieve # 200	Percentage by Mass (%)	94.42	97.09
Liquid Limit (LL)	Percent Moisture (%)	48.31	59.73
Plastic Limit (PL)	Percent Moisture (%)	21.76	28.61
Plasticity Index (PI)	Percent Moisture (%)	26.55	31.12
Specific Gravity (Gs)	Unitless	2.67	2.69
AASHTO Classification	Group	A-7-6	A-7-6
USCS Classification	Nomenclature	CL (Lean Clay)	CH (Fat Clay)
Maximum Dry Density	g/cc	1.814	1.784
Optimum Moisture Content	Percent Moisture (%)	12.00	12.34
Unconfined Compressive Strength	Psi	24.734	30.667
Un-soaked CBR	Percent (%)	3.69	2.61
Soaked CBR	Percent (%)	2.12	1.36
Swell Potential	Percent (%)	5.89	7.83

### 4.3 Phase II: Characterization of Treated Soils with Biopolymer

This phase involves the determination of properties of soil treated with guar gum biopolymer and the optimum percentage of biopolymer for which the soil properties showed maximum results.

#### 4.3.1 Biopolymer Percentage

The biopolymer was added to both soils, CL, and CH, in different percentages varying from 1% to 4% with an increment of 1% per trial. The percentages and their notation used in this research work are given in the Table 4-2 below:

*Table 4-2: Biopolymer Percentages and Their Notation*

<b>Biopolymer Percentage</b>	<b>Notation</b>
No Biopolymer (0%)	BP-0
1% Biopolymer	BP-1
2% Biopolymer	BP-2
3% Biopolymer	BP-3
4% Biopolymer	BP-4

#### 4.3.2 Compaction Characteristics

Compaction is the primary process in soil stabilization, where a soil is compacted to certain density after mixing the stabilizing agent. The achieved density affects other soil properties such as bearing capacity, settlement, and shear strength. It is of prime importance to evaluate the compaction characteristics of soil treated with varying percentages of biopolymer. The modified proctor test was executed on both soils against each biopolymer percentage to evaluate the effect of biopolymer on maximum dry density (MDD) and optimum moisture content (OMC). The results of MDD and OMC of both soils are discussed in this section.

#### 4.3.2.1 Low Plastic Clay (CL)

All four percentages of biopolymer were mixed with low plastic clay to explore the optimum biopolymer percentage and change in the MDD and OMC. It has been observed that the low plastic clay achieved maximum dry density at BP-2. At the optimum biopolymer percentage, the MDD of low plastic clay was increased from 1.814 to 1.874 g/cc, meanwhile, the OMC also increased from 12% to 12.821%. Upon further increasing the biopolymer percentage, a decline in MDD of low plastic soil was seen, however an increase in OMC of the soil had been observed. Following Figures 4.14, 4.15, 4.16 and 4.17 show the comparison and trend of MDD and OMC of low plastic clay at various percentages of biopolymer.

#### 4.3.2.2 High Plastic Clay

All four percentages of biopolymer were added to the high plastic clay and the change in the MDD and OMC was determined. It has been observed that the high plastic clay achieved maximum dry density at BP-2. At the optimum biopolymer percentage, the MDD of low plastic clay was increased from 1.784 to 1.852 g/cc, meanwhile, the OMC also increased from 12.34% to 13.924%.

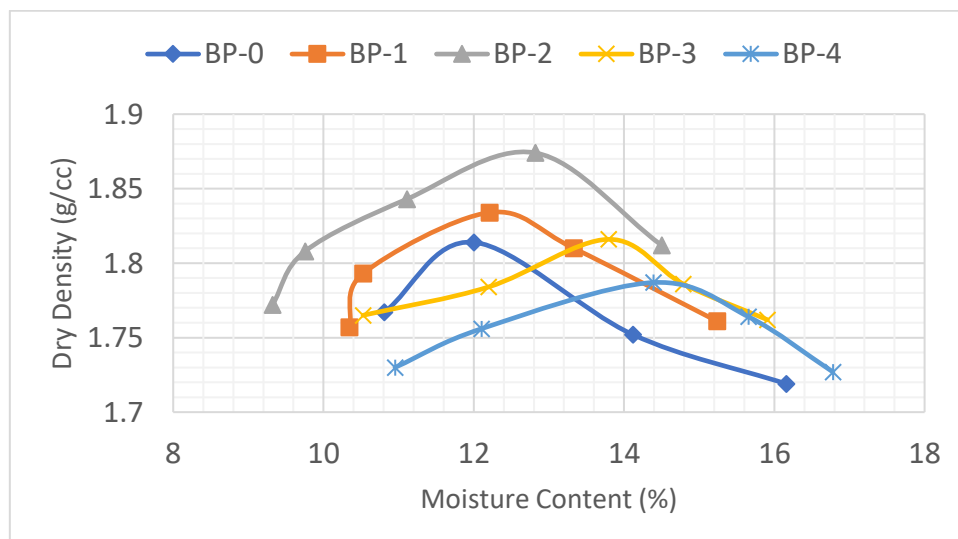


Figure 4.14: Moisture-Density Relation at Different Biopolymer Percentages

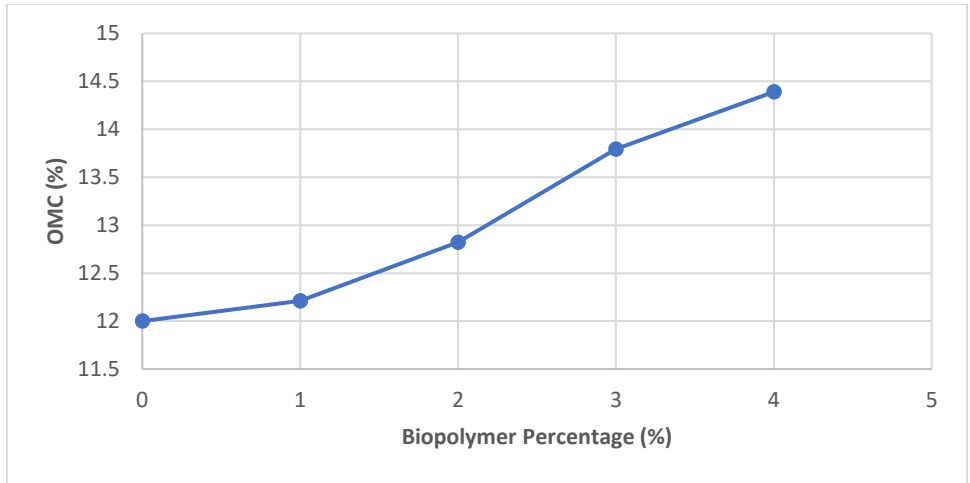


Figure 4.15: Trend of OMC with Different Biopolymer Percentages

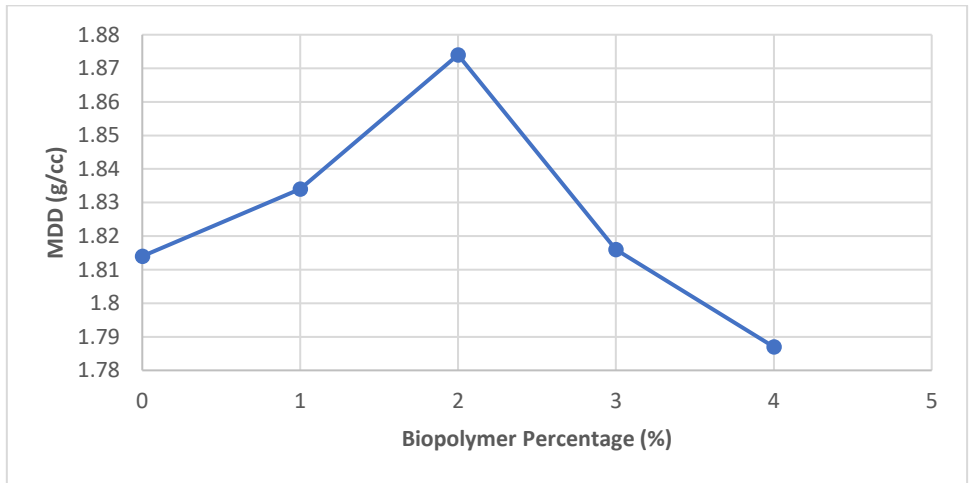


Figure 4.16: Trend of MDD with Different Percentages of Biopolymer

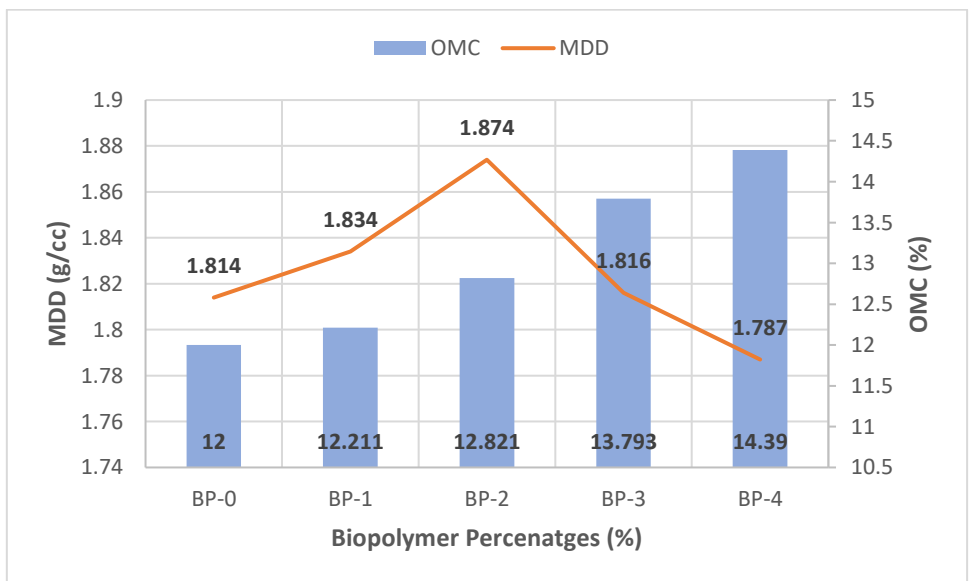


Figure 4.17: Combined Trend of OMC & MDD with Biopolymer Percentages

Upon further increase in the percentage of biopolymer, MDD of high plastic clay was decreased, however an increase in OMC of the soil was observed. Following Figures 4.18, 4.19, 4.20 and 4.21 show the comparison and trend of MDD and OMC of high plastic clay at various percentages of biopolymer.

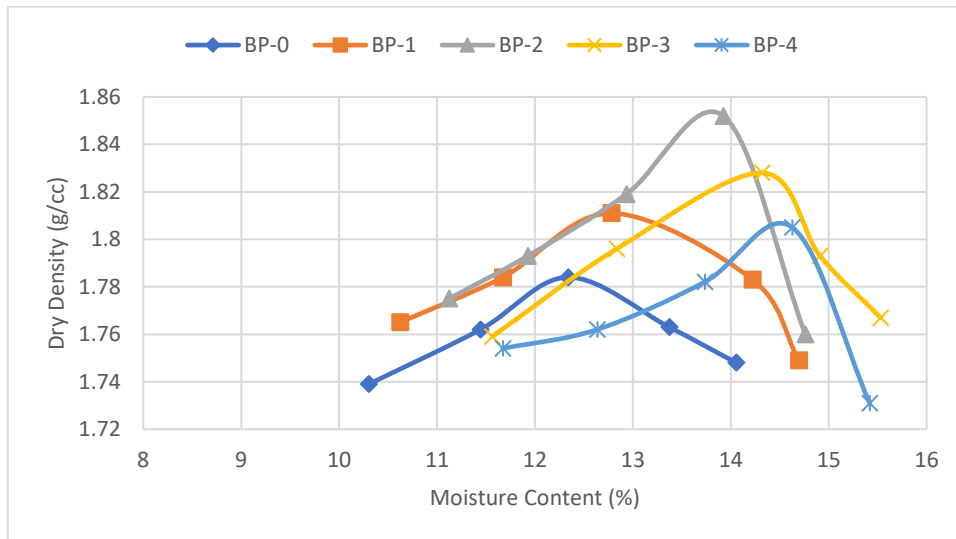


Figure 4.18: Moisture-Density Relation at Different Biopolymer Percentages

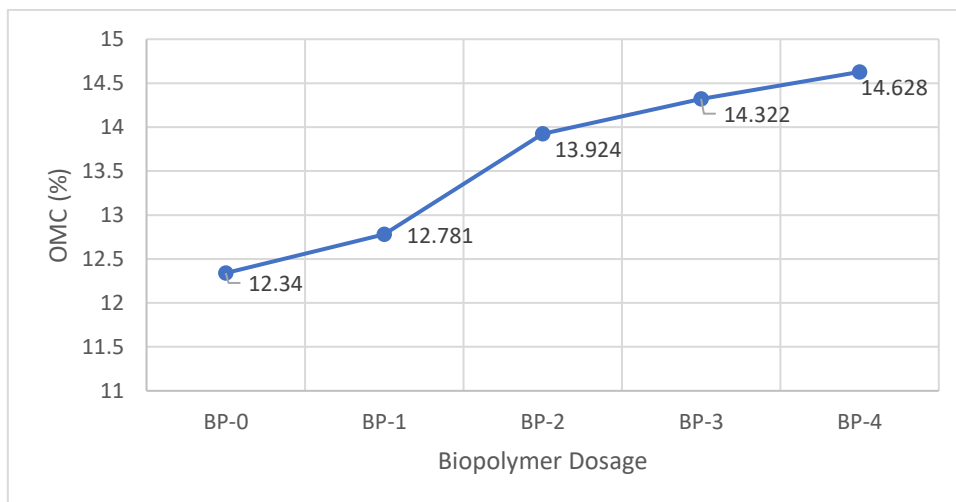


Figure 4.19: Trend of OMC at Different Percentages of Biopolymer

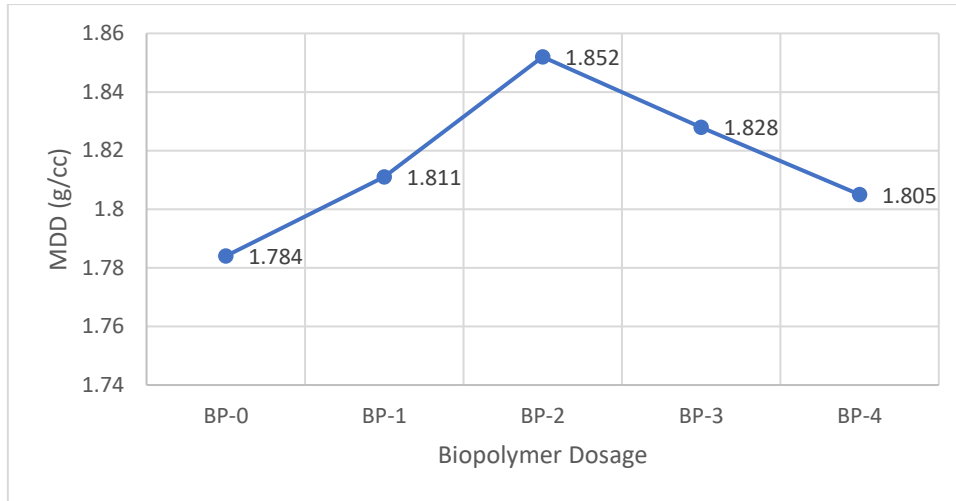


Figure 4.20: Trend of MDD at Different Percentages of Biopolymer

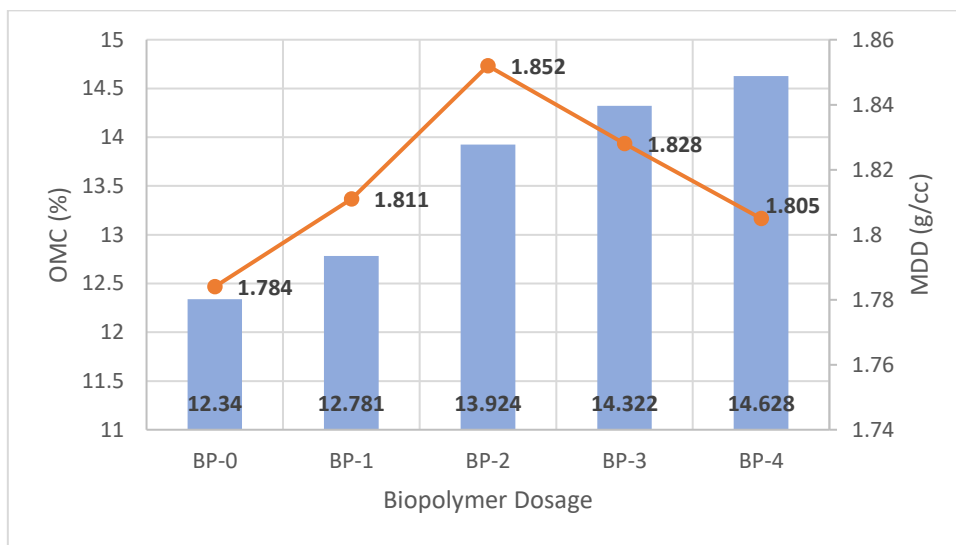


Figure 4.21: Combined Trend of OMC & MDD at Different Percentages of Biopolymer

### 4.3.3 Unconfined Compressive Strength (UCS)

The UCS was evaluated for all the four percentages of biopolymer (BP-1, BP-2, BP-3, and BP-4). The test was performed on both soils (CL and CH) as per ASTM D2166-13 standard. The specimens for the unconfined compression test were prepared at MDD and OMC obtained from modified proctor test for different percentages of biopolymer. The prepared specimens were then wrapped in plastic sheet and left for one day at room temperature (not cured in oven), so the biopolymer could react completely with the available moisture and soil particles. These specimens were then tested, and the results were compared with untreated

uncured CL and CH soil samples. The results of uncured CL and CH soil specimens tested at various percentages of biopolymer are discussed here:

#### 4.3.3.1 Low Plastic Clay (CL)

It has been observed from the results of UCS test that the maximum value of UCS of low plastic clay (CL) was obtained at BP-2. The UCS value climbed to 40.821 psi at the optimum percentage of biopolymer from 24.734 psi. The test results show a pattern that there was a steady increase in the UCS up to BP-2, but upon further increase in the biopolymer percentage, a decrease in the UCS was recorded. Figure 4.22 shows the UCS of uncured CL samples at different percentages of biopolymer.

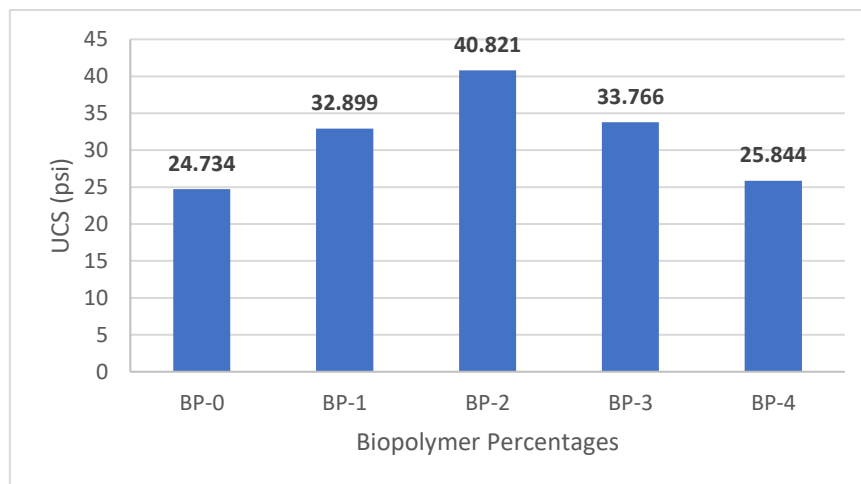


Figure 4.22: UCS of Uncured CL Samples at Different Biopolymer Percentages

#### 4.3.3.2 High Plastic Clay (CH)

From the results of UCS test on CH soil specimens, it has been observed that the maximum value of UCS was obtained at BP-2. The UCS value increased from 30.667 psi to 48.189 psi at optimum percentage of biopolymer. Figure 4.23 demonstrates that the UCS for CH soil increased first with the increase of biopolymer percentage up to BP-2. Upon further increase in biopolymer percentage, a loss in the strength was observed for CH soil.

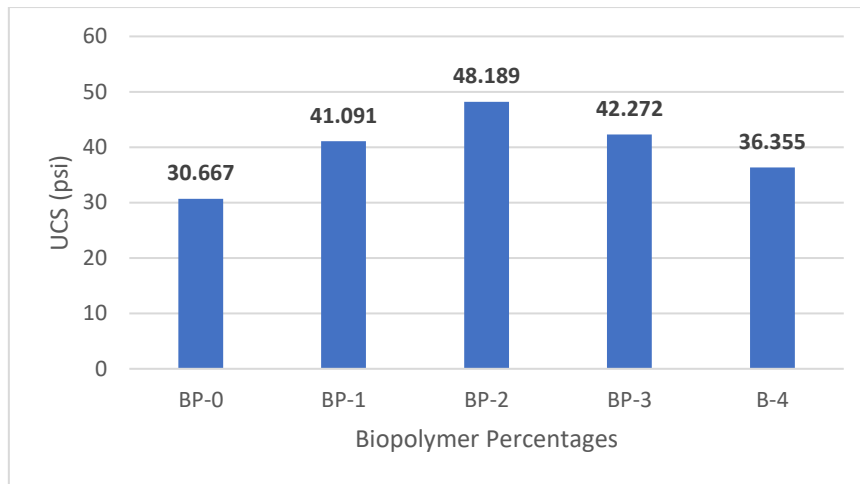


Figure 4.23: UCS of Uncured CH Samples at Different Biopolymer Percentages

#### 4.3.3.3 Gain in Strength with Time

To evaluate the effect of time on the unconfined compressive strength of untreated and treated CL & CH soils, the test specimens were cured for 2, 7, 14 and 28 days. The test was performed under un-soaked and soaked conditions. The curing of samples was done according to ASTM D5102 standard. For curing, the samples were prepared at all the four percentages of biopolymer and then wrapped in plastic sheets. The plastic wrapped test specimens were put in a thermostatically controlled oven at 40 °C temperature for a period of 2, 7, 14 and 28 days. For soaked UCS test, the cured samples were then carefully removed from plastic sheet and were again wrapped in cotton gauze bandage and placed on a porous plate in the desiccator for 48 hours. Curing of UCS samples permits the biopolymer to completely react with the soil particles and available moisture to enhance the stability and strength without moisture loss from the samples. The soaking test signifies the strength of soil subjected to capillary rise of water.

The results of soaked and un-soaked UCS for cured samples of CL and CH prepared at different percentages of biopolymer are discussed here:



#### 4.3.3.3.1 Low Plastic Clay:

- Un-soaked UCS

The un-soaked UCS of untreated and treated CL samples were determined. The treated CL samples were prepared at all four percentages of biopolymer. After the desired period of curing, UCS test was performed on cured samples. Figure 4.24 represents the UCS of untreated and treated CL samples at different curing periods. Figure 4.24 demonstrates that the maximum values of UCS were obtained at BP-2. At optimum percentage of biopolymer, the UCS increased to 44.448 psi at 2 days of curing and continued to increase up to 69.908 psi till 28 days of curing. The outcomes portray that the strength increased significantly up to a curing period of 14 days, afterwards a less noticeable increase rate was observed up to a curing period of 28 days. Figure 4.25 represents the comparison of un-soaked UCS of untreated and treated CL at optimum percentage of biopolymer for curing of 2, 7, 14 and 28 days.

- Soaked UCS

The soaked UCS was determined for both untreated and treated CL samples with optimum biopolymer percentage at a soaking period of 2, 7, 14 and 28 days. In presence of moisture, the soil experiences swelling, reduction in density and loss in the strength. In order to replicate these conditions in lab, the UCS cured samples were placed in desiccator for 48 hours for soaking. The Figure 4.26 shows the comparison of soaked UCS of CL samples under untreated and treated conditions.

From the results of soaked UCS, it has been observed that the untreated CL samples lost almost half of compressive strength due to soaking effect. The soaked UCS for untreated CL samples remained approximately same at different curing periods and no significant changes were observed. At optimum percentage of biopolymer, for 2 days of curing the UCS value obtained was 40.906 psi. As curing period increase, the UCS value increased to 55.933 psi at

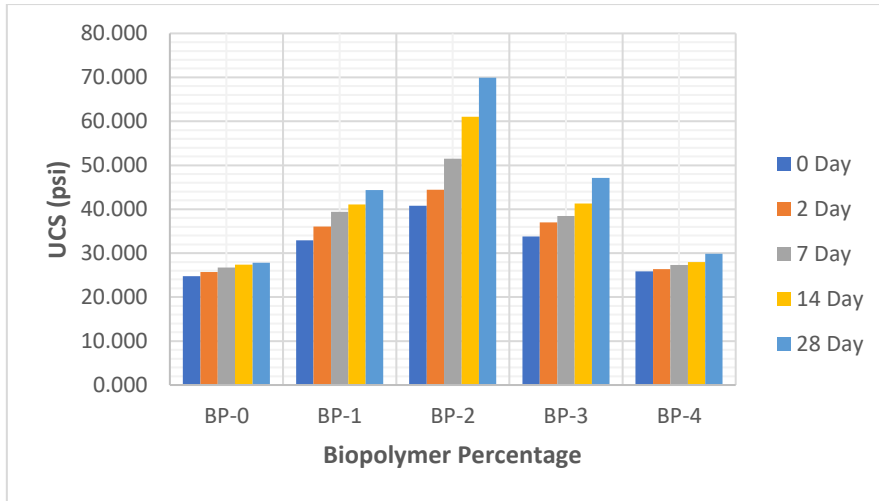


Figure 4.24: UCS of Untreated & Treated CL Samples at Different Curing Periods

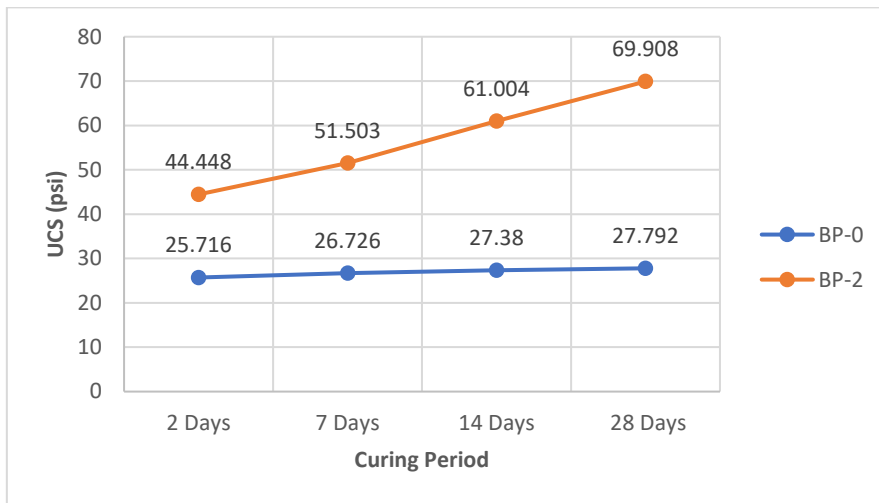


Figure 4.25: Comparison of Un-soaked UCS at Different Curing Periods

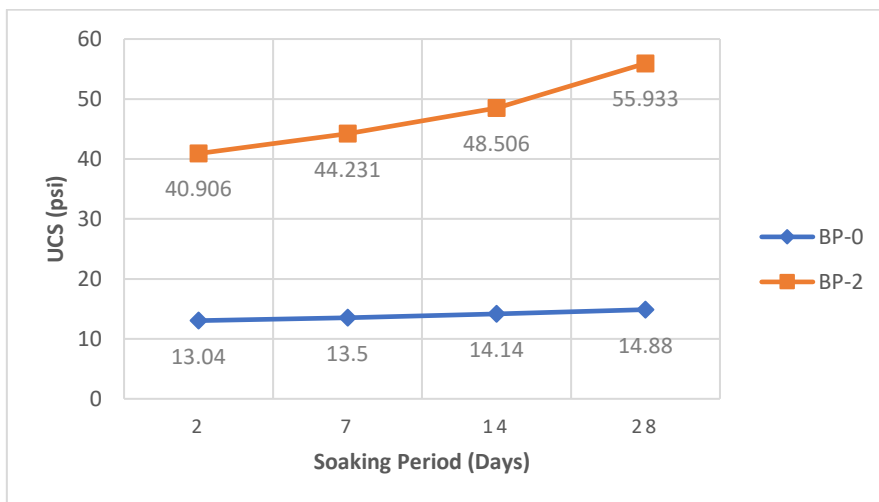


Figure 4.26: Soaked UCS of Untreated and Treated CL Samples

28 days of curing. Comparing with the un-soaked UCS results, the strength decreased from 69.908 psi to 55.933 psi at 28 days of curing.

#### **4.3.3.3.2 High Plastic Clay**

- Un-soaked UCS

The un-soaked UCS of untreated and treated CH samples were determined as per ASTM D2166-13 standard. The treated CH samples were prepared at all four percentages of biopolymer. After the desired period of curing, the UCS test was performed on samples for determining unconfined compressive strength. The figure 4.27 represents the UCS of untreated and treated CH samples at different curing periods. Figure 4.27 demonstrates that the maximum values of UCS were obtained at BP-2. At optimum percentage of biopolymer, the UCS increased to 56.58 psi at 2 days of curing and continued to increase up to 105.28 psi up to a curing period of 28 days. The outcomes exhibit that the strength increased significantly up to a curing period of 14 days, afterwards a less substantial strength increase rate was observed up to a curing period of 28 days. Figure 4.28 compares the un-soaked UCS CH soil samples under untreated and treated conditions at optimum percentage of biopolymer for a curing period of 2, 7, 14 and 28 days.

- Soaked UCS

The soaked UCS was assessed for untreated and treated CH samples with optimum biopolymer percentage at a soaking period of 2, 7, 14 and 28 days. In presence of moisture, the soil experiences swelling, reduction in density and loss in the strength. In order to replicate these conditions in lab, the UCS cured samples were placed in desiccator for 48 hours for soaking. The figure 4.29 illustrates the comparison of soaked UCS of CH samples under untreated and treated conditions. From the results of soaked UCS, it has been observed that the untreated CH samples lost almost half of compressive strength due to soaking effect. The soaked UCS for untreated CH samples remained approximately same at different soaking

periods and no significant changes were observed. At optimum percentage of biopolymer, for 2 days of soaking the UCS value obtained was 52.95 psi. With increase in soaking period, the UCS value increased to 79.86 psi at a curing period of 28 days. In Comparison with the un-soaked UCS, the strength decreased from 105.28 psi to 79.86 psi at 28 days of curing.

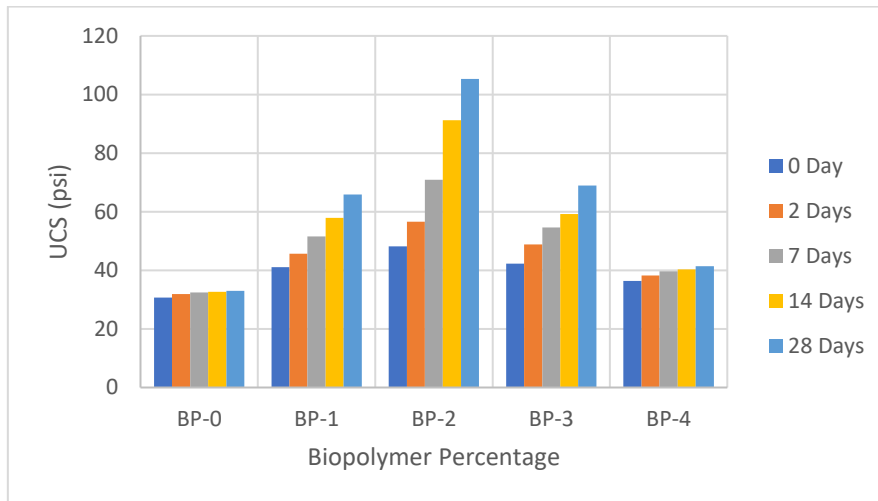


Figure 4.27: UCS of Untreated & Treated CH Samples at Different Curing Periods

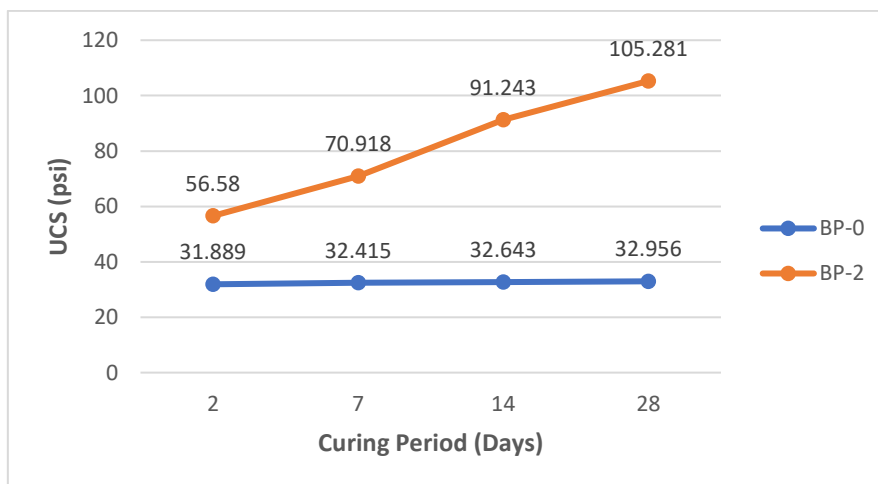


Figure 4.28: Comparison of Un-soaked UCS at Different Curing Periods

#### 4.3.4 California Bearing Ratio

CBR test, established by the California Division of Highways, is a penetration test which is performed to evaluate the subgrade strength of a soil. CBR value of a soil largely depends upon the compaction characteristics of the soil. CBR test was performed for both CL

and CH soil samples which were prepared using the results obtained from the compaction characteristics of the soil.

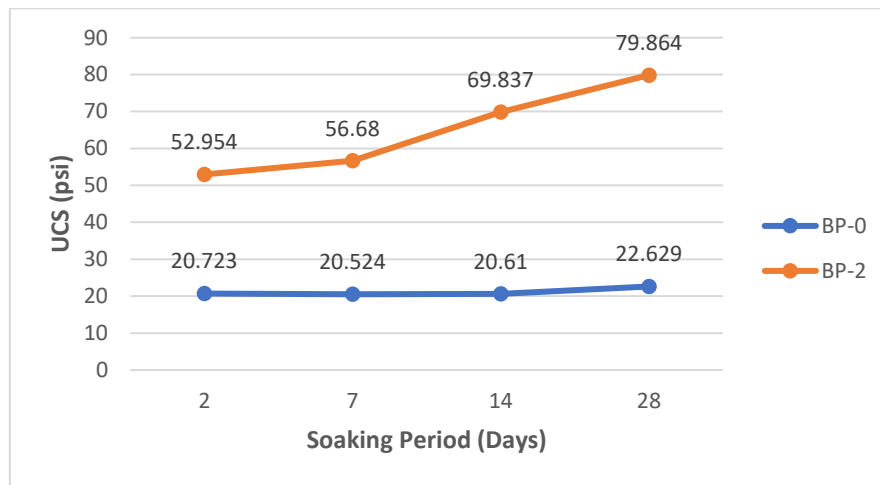


Figure 4.29: Soaked UCS of Untreated and Treated CH Samples

Both CL and CH soil samples were treated at all the four biopolymer percentages to evaluate the influence of biopolymer on subgrade strength of CL and CH soil samples. A significant increase in the value of California Bearing Ratio (CBR) was observed for both CL and CH soils. Owing to increase in the density of CL and CH soils by the addition of biopolymer, the CBR value was also increased for both soils. Both CL and CH soils shown a maximum CBR value at BP-2.

To assess the subgrade strength of the soil under worst moist conditions, the CL and CH samples prepared at optimum biopolymer percentage were soaked as per AASHTO T-193 standard for 96 hours. The samples were submerged in water and an additional load of 5-kg was applied on the molds. Presence of moisture reduced the density of the soil due to the swelling nature of clay, which in turn reduced the CBR value of both CL and CH soils under soaked condition. It was observed that the CBR value of both CL and CH soil samples dropped significantly under soaked condition. Although comparing with CBR test results of untreated soil, a significant improvement in soaked CBR was observed for both soils.

#### 4.3.4.1 Low Plastic Clay (CL)

- Un-soaked CBR

Unsoaked CBR test was performed at all four biopolymer percentages (BP-1, BP-2, BP-3, and BP-4) and the results were compared with untreated soil sample. It was observed that low plastic clay (CL) soil had shown a maximum value of CBR at BP-2. The CBR of CL under unsoaked condition at optimum biopolymer percentage improved from 3.69% to 10.44%. Upon further increase in biopolymer percentage, the CBR value decreased due to decrease in density of the soil. Results of unsoaked CBR test on CL are shown in Figure 4.30.

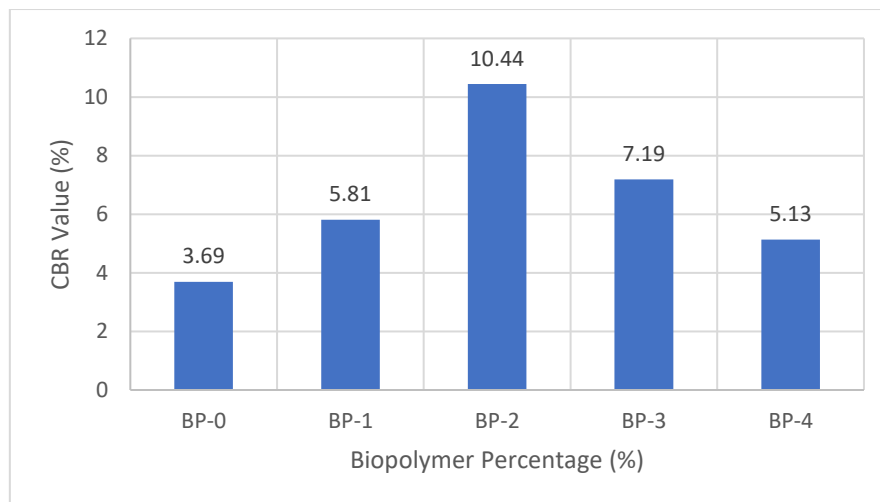


Figure 4.30: Un-soaked CBR of CL Soil at Different Biopolymer Percentages

- Soaked CBR

Soaked CBR test was performed at all four biopolymer percentages (BP-1, BP-2, BP-3, and BP-4) and the results were compared with untreated soil sample. It was observed that low plastic clay (CL) soil had shown a maximum value of CBR at BP-2 under soaked condition. The CBR of CL under soaked condition at optimum biopolymer percentage improved from 2.12 % to 6.41 %. The decrease in CBR value of soaked samples as compared to un-soaked samples was observed due to loss in the density of soil in the presence of moisture and swelling characteristics of soil. Outcomes of soaked-CBR test on CL are shown in Figure 4.31.

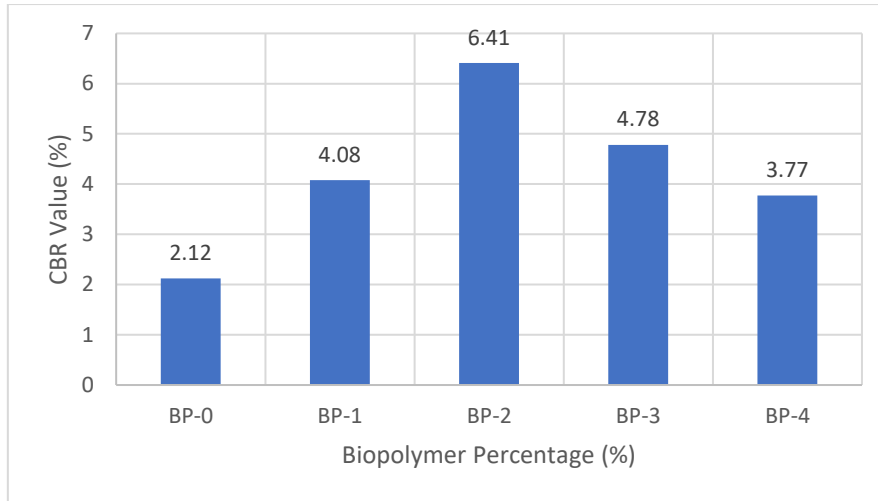


Figure 4.31: Soaked CBR of CL Soil at Different Biopolymer Percentages

#### 4.3.4.2 High Plastic Clay (CH)

- Un-soaked CBR

Unsoaked CBR test was also performed at all four biopolymer percentages (BP-1, BP-2, BP-3, and BP-4) and the results were compared with untreated soil sample. It was observed that high plastic clay (CH) soil had shown a maximum value of un-soaked CBR at BP-2 (optimum percentage). The CBR of CH soil under un-soaked condition at optimum biopolymer percentage improved from 2.61 % to 9.38 %. Further increase in biopolymer percentage, caused the reduction in un-soaked CBR of CH soil due to drop in the density at higher biopolymer percentages. Results of unsoaked CBR test on CH are shown in Figure 4.32.

- Soaked CBR

Soaked CBR test for CH soil was performed at all four biopolymer percentages (BP-1, BP-2, BP-3, and BP-4) and the results were compared with untreated soil sample. From the results, it was observed that high plastic clay (CH) soil had shown a maximum value of CBR at BP-2 under soaked condition. The CBR of CH under soaked condition at optimum biopolymer percentage improved from 1.36 % to 4.97 %.

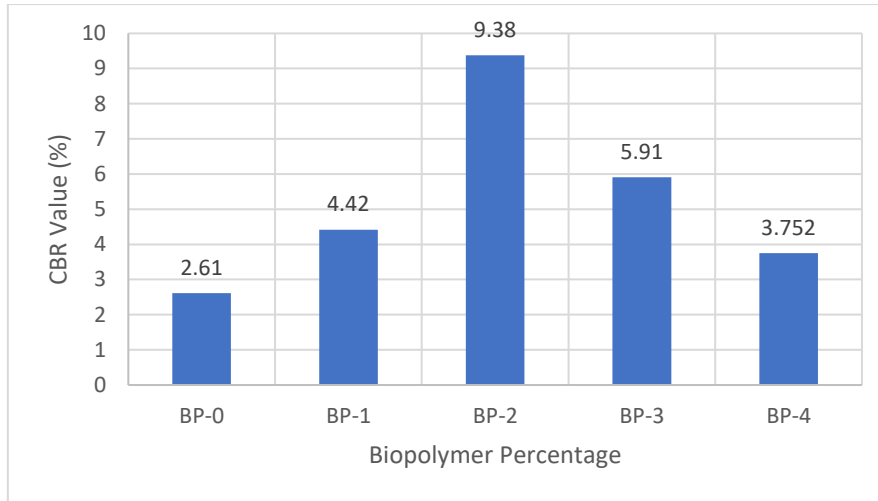


Figure 4.32: Un-soaked CBR of CH Soil at Different Biopolymer Percentages

The decrease in CBR value of soaked samples as compared to un-soaked samples was observed due to loss in the density of soil in the presence of moisture and swelling characteristics of soil. Outcomes of soaked CBR test on CH are shown in Figure 4.33.

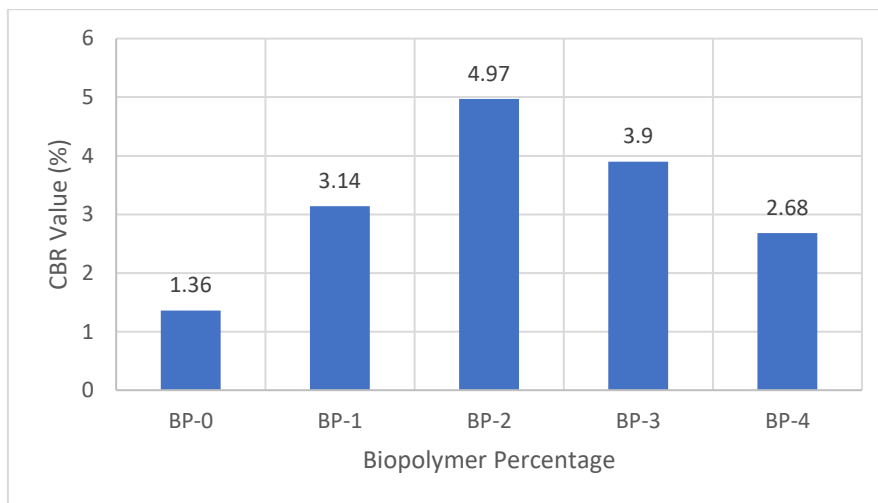


Figure 4.33: Soaked CBR of CH Soil at Different Biopolymer Percentages

#### 4.3.4.3 Comparison of CL and CH

Figure 4.34 shows the comparison of CBR values of low plastic and high plastic clays for both un-soaked and soaked conditions for both untreated and treated soil samples at optimum percentage. It was noticed that CL soil had shown better results with the addition of biopolymer under both un-soaked and soaked conditions. This is due to higher density of the



CL soil at optimum percentage of guar-gum biopolymer. Figure 4.34 shows that the un-soaked CBR value of untreated CL and CH was 3.69 and 2.61 percent, respectively. After treating the soil samples with biopolymer, the un-soaked CBR of CL and CH increased to 10.44 and 9.38 percent, respectively. It was also observed that the biopolymer addition to CL soil had exhibited slightly better results as compared to CH soil. Similarly, the soaked CBR of untreated CL and CH soil samples came out to be 2.53 and 1.36 percent, respectively. After addition of biopolymer, both CL and CH soils had shown a significant improvement of soaked CBR and the value increased to 6.41 and 4.97 percent, respectively. It was also observed that biopolymer treated CL soil had shown a significant improvement in soaked CBR value in comparison with CH soil sample.

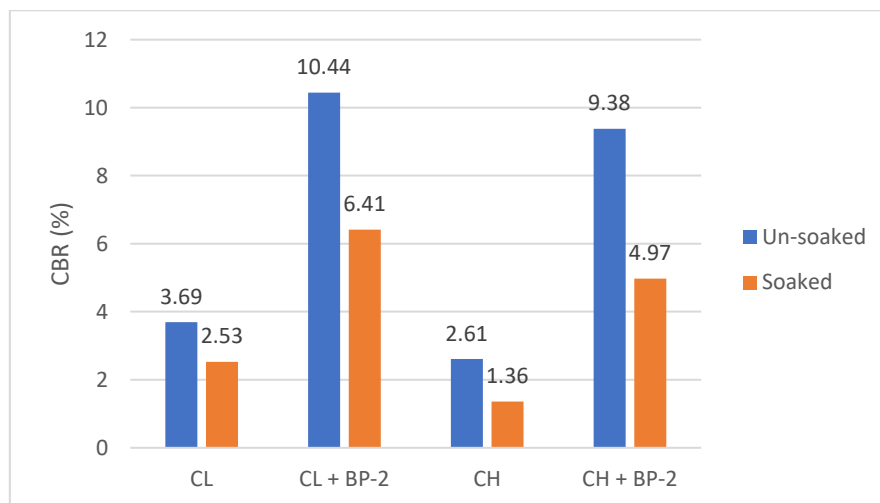


Figure 4.34: Comparison of CBR Values for both CL and CH

#### 4.3.5 Swell Potentials

Swell potential of both untreated and treated low plastic and high plastic soil samples was evaluated during the soaked CBR test. The soaked CBR specimen was subjected to a 5-kg load and a dial gauge was attached to measure the volume change that occurs in the soil specimen. The evaluation of treated soil specimen was carried out at the optimum biopolymer percentage (BP-2) for both CL and CH. Noteworthy drop in the swelling potential of both CL and CH soils has been observed with the addition of optimum percentage of biopolymer.

#### 4.3.5.1 Low Plastic Clay (CL)

The swell potential of low plastic clay with the addition of 2 percent guar gum biopolymer reduced from 5.98% to 2.61%. The overall reduction in swelling potential at the optimum biopolymer percentage was 56.35%. Figure 4.35 illustrates the result of swell potential of untreated and treated low plastic clay.

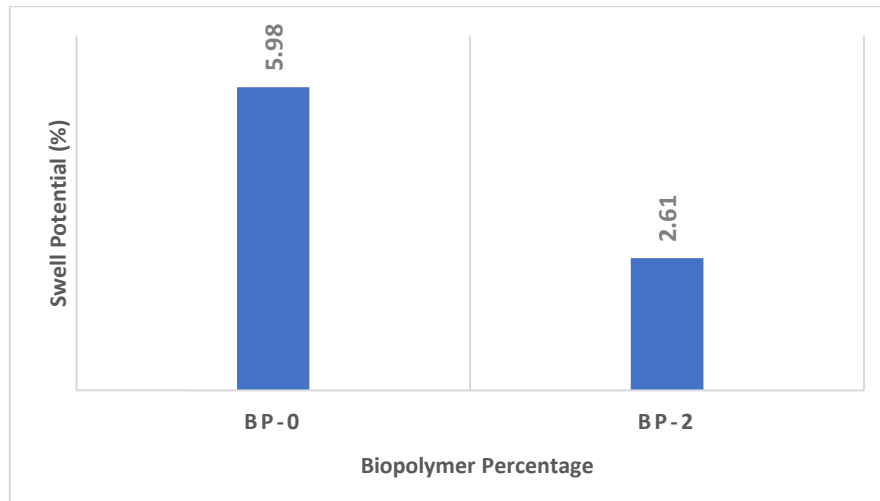


Figure 4.35: Swell Potential of Untreated and Treated CL

#### 4.3.5.2 High Plastic Clay (CH)

For high plastic clay, the swell potential reduced from 7.83% to 4.89% at the optimum guar gum biopolymer percentage. The overall reduction in swelling potential at the optimum biopolymer percentage was 37.55%. Figure 4.36 illustrates the result of swell potential of untreated and treated high plastic clay.

Figure 4.37 indicates the comparison of CL and CH in terms of swell potential in treated and untreated conditions.

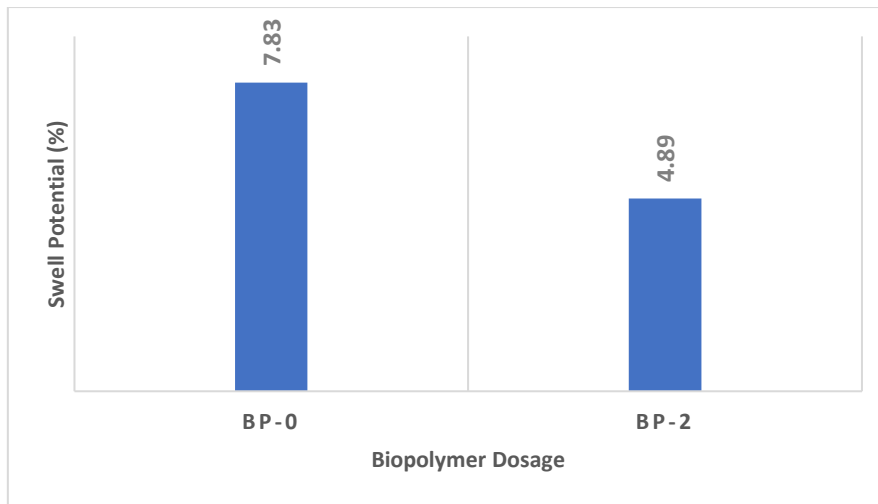


Figure 4.36: Swell Potential of Untreated and Treated CL

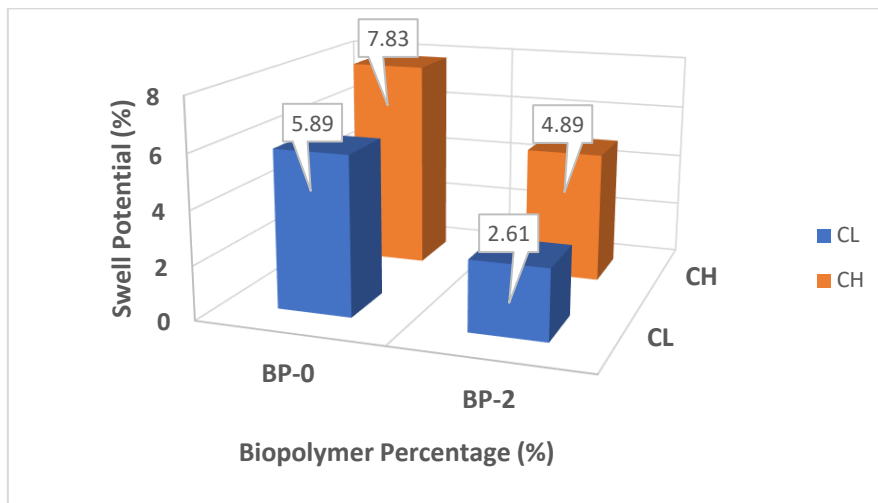


Figure 4.37: Comparison of Swell Potential of Untreated and Treated CL and CH soils

#### 4.3.6 Atterberg Limits

Index properties are one of the basic measures of the nature of fine-grained soils. These properties are widely used to categorize different types of soils and the results are used for classification purposes. Index properties are normally determined from the results of Atterberg Limit's Test. To evaluate the impact of guar gum biopolymer on the Atterberg Limits of both CL and CH, the soils were treated with optimum biopolymer percentage and the Casagrande method was used to perform the test. The reaction of guar gum biopolymer with the wet particles of the soil changes the nature of adsorbed layer by replacing sodium or iodine ions

(Kullayappa & Kumar, 2018). The cation concentration causes a depression in the diffused double-layer around the fine particles of clay. This phenomenon alters the liquid limit and plastic limit of the clayey soil. Thus, overall effects the plasticity index of the clayey soil. The addition of optimum percentage of guar gum biopolymer caused a drop in the liquid limit and plastic limit of both low plastic and high plastic clayey soils. Due to the drop in liquid limit and plastic limit values, a reduction in the plasticity index of the soil was noticed.

#### 4.3.6.1 Low Plastic Clay (CL)

For low plastic clay, it has been observed that the addition of biopolymer at optimum percentage reduced the liquid limit from 48.31% to 41.6%. The plastic limit was reduced from 21.76% to 17.84%. Due to the drop in the liquid limit and plastic limit, the plasticity index also reduced from 26.55% to 23.76%. The percentage reduction in liquid limit, plastic limit and plasticity index at optimum biopolymer percentage was found to be 13.89%, 18.01% and 10.50% respectively. Figure 4.38 illustrates the trend of Atterberg Limits of CL under untreated and treated condition.

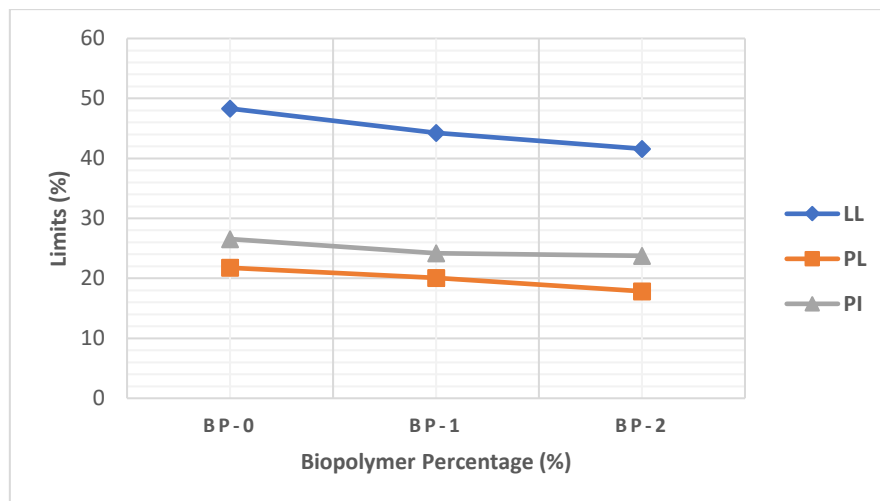


Figure 4.38: Atterberg Limits of Untreated and Treated CL

#### 4.3.6.2 High Plastic Clay (CH)

It has been observed that in case of high plastic clay, the addition of guar gum biopolymer at optimum percentage caused reduction in liquid limit, plastic limit and, plasticity

index. The liquid limit of CH soil reduced from 59.73% to 51.43%. The plastic limit of the CH soil reduced from 28.61% to 23.46%. With the reduction in both LL and PL, the Plasticity Index of CH soil also decreased. The reduction from 31.12% to 27.97% in plasticity index was observed at optimum biopolymer percentage. Figure 4.39 shows the trend of Atterberg Limits of CH under untreated and treated condition.

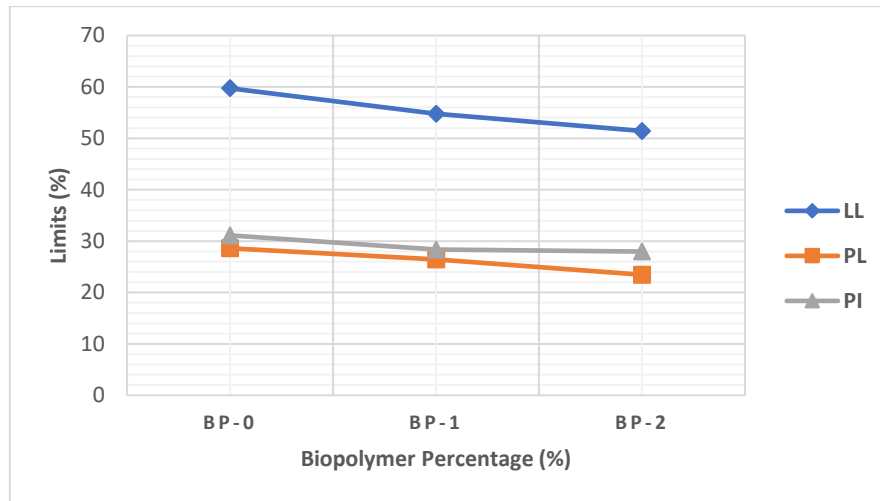


Figure 4.39: Atterberg Limits of Untreated and Treated CH

#### 4.3.7 Summary of Results

Table 4-3: Summary of Results at Optimum Biopolymer Percentage

Property	Unit	SOIL A – CL	SOIL B – CH
Liquid Limit (LL)	Percent Moisture (%)	<b>48.31</b>	<b>59.73</b>
Plastic Limit (PL)	Percent Moisture (%)	<b>21.76</b>	<b>28.61</b>
Plasticity Index (PI)	Percent Moisture (%)	<b>26.55</b>	<b>31.12</b>
Maximum Dry Density	g/cc	<b>1.874</b>	<b>1.852</b>
Optimum Moisture Content	Percent Moisture (%)	<b>12.821</b>	<b>13.924</b>
Unconfined Compressive Strength	Psi	<b>40.821</b> (uncured) <b>69.908</b> (cured @ 28 days)	<b>48.189</b> (uncured) <b>105.28</b> (cured @ 28 days)
Un-soaked CBR	Percent (%)	<b>10.44</b>	<b>9.38</b>
Soaked CBR	Percent (%)	<b>6.41</b>	<b>4.97</b>
Swell Potential	Percent (%)	<b>2.61</b>	<b>4.89</b>

## **CONCLUSION AND RECOMMENDATIONS**

### **5.1 CONCLUSION**

With recent developments, the most vital aspects involved in selection of material to be used as soil stabilizer became the environment friendliness and sustainability. A detailed study was conducted on low plastic clay (Ballewala Clay) and high plastic clay (Ballewala Clay + Bentonite Clay Mix) to inspect the effectiveness of guar gum biopolymer as potential soil stabilizer. The soils were characterized by determining the index properties, such as gradation and Atterberg's limits. The chosen soil parameters to examine the practicality of guar gum biopolymer included the compaction characteristics, unconfined compressive strength, California bearing ratio, one dimensional swell potential, and Atterberg Limits. The experimental program includes the tests on CL and CH soil in both untreated and treated conditions. Test results of untreated and treated soils at optimum biopolymer percentage were then compared. Based on the experiments conducted in laboratory on both clays, following conclusions were drawn:

- A substantial increase in the Dry Density and corresponding OMC of both CL and CH soil was observed at optimum percentage of Guar Gum Biopolymer. At further addition of biopolymer beyond optimum percentage, MDD started decreasing while the OMC kept on increasing due to the high viscous nature and water absorption properties of guar gum biopolymer.
- At optimum biopolymer percentage, the maximum dry density of CL increased from 1.814 g/cc to 1.87 g/cc and of CH from 1.784 g/cc to 1.854 g/cc.

- Due to the large hydroxyl groups of guar gum biopolymer, it forms a network of hydrogels between soil particles and available free water linked with hydrogen bond. These soil-biopolymer matrices contribute to higher compressive strength of soil.
- The strengthening effect of guar gum biopolymer depends on the biopolymer content as well curing time.
- For CL, the UCS value raised from 24.734 psi to 40.821 psi at optimum percentage of biopolymer, which further increased to 69.908 psi after 28 days of curing with a proportion increase of 182.64%.
- For CH, the UCS value climbed from 30.667 psi to 48.189 psi at optimum percentage of biopolymer, which further increased to 105.28 psi after 28 days of curing with a proportion increase of 243.30%.
- Soil in the presence of moisture experiences swelling, reduction in density and loss in strength. In order to replicate these conditions in lab, the samples were placed in desiccator for 48 hours for soaking.
- After soaking, the UCS of CL samples treated with BP decreased from 69.909 psi to 55.933 psi with a proportion decrease of 19.99%.
- Similarly, UCS of CH samples treated with BP decreased from 105.28 psi to 79.864 psi with a proportion decrease of 24.14%.
- An adequate soaked UCS of both soil samples treated with guar gum biopolymer was observed in comparison to the untreated samples.
- Soaked UCS of treated CL samples was improved by 275.89% compared with untreated CL samples.
- Soaked UCS of treated CH samples was improved by 252.93% compared with untreated CH samples.

- The CBR value of both CL and CH specimens was influenced by adding the guar gum biopolymer. The optimum values for both CL and CH in unsoaked and soaked conditions were obtained at 2 percent biopolymer addition.
- The unsoaked and soaked CBR value of CL soil increased with a proportion of 182.93% and 202.36% respectively.
- The unsoaked and soaked CBR value of CH soil increased with a proportion of 259.39% and 265.44% respectively.
- The resistance to Swell Potential of CL and CH soil specimens was improved by 56.35% and 33.74% respectively.

## **5.2 RECOMMENDATIONS**

- In this study, guar gum biopolymer was used as a potential stabilizer for improving geotechnical properties of soil. However, the inter-particle relations and behavior of soil-biopolymer matrices, which contribute to the soil strength, have not been reported extensively and need to be studied.
- The elaborate testing was carried out to examine the effect of guar gum biopolymer on compressive strength. However, the response of soil-biopolymer matrices in tensile strength has not been reported and needs to be studied.
- Soil-biopolymer mix was prepared on dry mix basis throughout the study. A study should be carried out on wet mix based prepared samples side by side and the efficiency of both mixing method and their effect on soil properties should be reported.
- The strengthening effect of guar gum biopolymer maximizes in presence of fine clayey particles. The strengthening effect of guar gum biopolymer on coarse-grained and cohesionless soils should be studied.



- Biopolymers are considered to be sensitive to the presence of moisture. The durability and overall strength of biopolymer treated soil under wet and dry cycles should be studied.
- Cross-linking is technique which is used to improve the material properties by introducing an external agent which facilitates inter-particle interactions and developing stronger soil matrices, thus contributing to the overall strength of problematic soils.
- Cross-linking for biopolymers should be studied to provide more powerful stabilizer for improving geotechnical properties of soil.
- Nature of bonding between soil particles and biopolymers needs to be studied comprehensively.

## REFERENCES

- Abdelkrim, M., & Mohamed, K. (2013). Cement Stabilization of Compacted Expansive Clay. *The Online Journal of Science and Technology*, 3(1).
- Abood, T. T., Kasa, A. B., & Chik, Z. B. (2007). Stabilization of Silty Clay Soil Using Chloride Compounds. *Journal of Engineering Science and Technology*, 2(1), 102-110.
- Afrin, H. (2017). Stabilization of Clayey Soils Using Chloride Components. *American Journal of Civil Engineering*, 5(6), 365. doi: 10.11648/j.ajce.20170506.18
- Akbar, A., & Farooq, K. (2002). Expansive soils in Pakistan – Case Histories. *J. eng. & appl. sci.*, 21(1), 119-129.
- Al-Homidy, A. A., Dahim, M. H., & Abd El Aal, A. K. (2017). Improvement of geotechnical properties of sabkha soil utilizing cement kiln dust. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(4), 749-760. doi: 10.1016/j.jrmge.2016.11.012
- Al-Khafaji, R., Jafer, H. M., Dulaimi, A., Atherton, W., & Jwaida, Z. (2017). *Soft soil stabilisation using ground granulated blast furnace slag*. Paper presented at the The 3rd BUiD Doctoral Research Conference, British University, Dubai.
- Al Ani, T., & Sarapaa, O. (2008). Clay and Clay Minerology. Physical-Chemical Properties and Industrial Uses.: Geological Survey of Finland.
- Alam, M. M. I., & Rayhan, M. A. (2015). *Soil Stabilization by Using the Combination of Cement and Glass Dust*. Paper presented at the International Conference on Recent Innovation in Civil Engineering for Sustainable Development (IICSD-2015).
- Alazigha, D. P., Vinod, J. S., Indraratna, B., & Heitor, A. (2019). Potential use of lignosulfonate for expansive soil stabilisation. *Environmental Geotechnics*, 6(7), 480-488. doi: 10.1680/jenge.17.00051

- Anjaneyappa, & Amarnath, M. S. (2011). Studies on Soils Treated with Non Traditional Stabilizer for Pavements. *Indian Geotechnical Journal*, 41(3), 162-167.
- Ayeldeen, M., Negm, A., El-Sawwaf, M., & Kitazume, M. (2017). Enhancing mechanical behaviors of collapsible soil using two biopolymers. *Journal of Rock Mechanics and Geotechnical Engineering*, 9(2), 329-339. doi: 10.1016/j.jrmge.2016.11.007
- Basu, D., Misra, A., & Puppala, A. J. (2015). Sustainability and geotechnical engineering: perspectives and review. *Canadian Geotechnical Journal*, 52(1), 96-113. doi: 10.1139/cgj-2013-0120
- Bell, F. G. (1996). Lime Stabilization of Clay Minerals and Soils. *Engineering Geology*, 42(4), 223-237.
- Biju, M. S., & Arnepalli, D. N. (2016). *Biopolymer Modified Soil: Prospects of a Promising Green Technology*. Paper presented at the Indian Geotechnical Conference, IIT Madras, Chennai, India.
- Cabalar, A. F., Awraheem, M. H., & Khalaf, M. M. (2018). Geotechnical Properties of a Low-Plasticity Clay with Biopolymer. *Journal of Materials in Civil Engineering*, 30(8), 04018170. doi: 10.1061/(asce)mt.1943-5533.0002380
- Chang, I., & Cho, G.-C. (2012). Strengthening of Korean residual soil with  $\beta$ -1,3/1,6-glucan biopolymer. *Construction and Building Materials*, 30, 30-35. doi: 10.1016/j.conbuildmat.2011.11.030
- Chang, I., Im, J., & Cho, G.-C. (2016). Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering. *Sustainability*, 8(3), 251. doi: 10.3390/su8030251
- Chang, I., Jeon, M., & Cho, G.-C. (2015). Application of Microbial Biopolymers as an Alternative Construction Binder for Earth Buildings in Underdeveloped Countries. *International Journal of Polymer Science*, 2015, 1-9. doi: 10.1155/2015/326745

- Chen, R., Lee, I., & Zhang, L. (2015). Biopolymer Stabilization of Mine Tailings for Dust Control. *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2), 04014100. doi: 10.1061/(asce)gt.1943-5606.0001240
- Cho, G.-C., & Chang, I. (2018). *Cementless Soil Stabilizer - Biopolymer* Paper presented at the Advances in Civil, Environmental, & Material Research (ACEM18), Songdo Convensia, Incheon, Korea.
- Cole, D. M., Ringelberg, D. B., & Reynolds, C. M. (2012). Small-Scale Mechanical Properties of Biopolymers. *Journal of Geotechnical and Geoenvironmental Engineering*, 138(9), 1063-1074. doi: 10.1061/(asce
- Delatte, N. J. (2001). Lessons from Roman Cement and Concrete. *Journal of Professional Issues in Engineering Education and Practice*, 127(3), 109-115.
- Durga Prasad, S., Prasad, D. S. V., & Prasada Raju, G. V. R. (2019). Stabilization of Black Cotton Soil using Ground Granulated Blast Furnace Slag and Plastic Fibers. *International Journal of Recent Technology and Engineering*, 7(6C2).
- Firoozi, A. A., Firoozi, A. A., & Baghini, M. S. (2016). A Review of Clayey Soils. *Asian Journal of Applied Sciences*, 4(6), 1319-1330.
- Fredlund, D. G. (1975). *Engineering Properties of Expansive Clays*. Paper presented at the Seminar on Shallow Foundations on Expansive Clays, Regina, Saskatchewan.
- Grim, R. E. (1953). *Clay Mineralogy*. New York: McGraw-Hill.
- Guggenheim, S. (1995). Definition of Clay and Clay Mineral: Joint Report of the AIPEA Nomenclature and CMS Nomenclature Committees. *Clays and Clay Minerals*, 43(2), 255-256. doi: 10.1346/ccmn.1995.0430213
- Hataf, N., Ghadir, P., & Ranjbar, N. (2018). Investigation of soil stabilization using chitosan biopolymer. *Journal of Cleaner Production*, 170, 1493-1500. doi: 10.1016/j.jclepro.2017.09.256

- Hausmann, M. R. (1990). *Engineering Principles of Ground Modification*. New York: McGraw-Hill.
- He, S., Yu, X., Banerjee, A., & Puppala, A. J. (2018). Expansive Soil Treatment with Liquid Ionic Soil Stabilizer. *Transportation Research Record: Journal of the Transportation Research Board*, 2672(52), 185-194. doi: 10.1177/0361198118792996
- Holtz, D. R., & Kovace, D. W. (1981). *An Introduction to Geotechnical Engineering*. Englewood Cliffs, New Jersey: Prentice-Hall, Inc.
- Huat, B. K. K., Maail, S., & Mohamed, T. A. (2005). Effect of the Chemical in Engineering Properties of Tropical Peat Soil. *American Journal of Applied Sciences*, 2(7), 1113-1120.
- Jafer, H. M. (2013). Stabilization of Soft Soils Using Salts Chloride. *Journal of Babylon University, Engineering Sciences*, 21(5).
- Jones Jr, D. E., & Holtz, W. G. (1973). EXPANSIVE SOILS- THE HIDDEN DISASTER. *American Society of Civil Engineers*, 43(8), 49-51.
- Kalia, S., & Avérous, L. (2011). *Biopolymers: Biomedical and Environmental Applications*: Wiley.
- Kazemian, S., & Huat, B. B. K. (2010). Assessment of stabilization methods for soft soils by admixtures. *2010 International Conference on Science and Social Research (CSSR 2010)*, 118-121.
- Kestler, A. M. (2009). *Stabilization Selection Guide for Aggregate and Native Surfaced Low Volume Roads*: US Department of Agriculture, Forest Service.
- Kolay, P. K., Dhakal, B., Kumar, S., & Puri, V. K. (2016). Effect of Liquid Acrylic Polymer on Geotechnical Properties of Fine-Grained Soils. *International Journal of Geosynthetics and Ground Engineering*, 2(4). doi: 10.1007/s40891-016-0071-5

- Kullayappa, G., & Kumar, S. P. (2018). Experimental Study by of Soil Mixed with Guar Gum a Bio Enzyme-(case study). *International Research Journal of Engineering and Technology*, 5(8).
- Kumar, A., Marathe, S., Vikram, R., Shenoy, N., Bhat, V. L., & Venkatesh, A. (2015). Stabilization of lithomargic soil using alkali activated fly-ash with GGBS. *International Journal of Constructive Research in Civil Engineering*, 1(1), 19-23.
- Kushwaha, S. S., Kishan, D., & Dindorkar, N. (2018). Stabilization of Expansive Soil Using Eko Soil Enzyme For Highway Embankment. *Materials Today: Proceedings*, 5(9), 19667-19679. doi: 10.1016/j.matpr.2018.06.329
- Lim, S. M., Wijeyesekera, D. C., Lim, A. J. M. S., & Bakar, I. B. H. (2014). Critical reviews of innovative soil road stabilization technique. *International Journal of Engineering and Advance Technique*, 3(5).
- M M, S. H. (2018). Soil Stabilisation using Lime. *International Journal for Research in Applied Science and Engineering Technology*, 6, 1096-1100. doi: 10.22214/ijraset.2018.1167
- Mirzababaei, M., Arulrajah, A., & Ouston, M. (2017). Polymers for Stabilization of Soft Clay Soils. *Procedia Engineering*, 189, 25-32. doi: 10.1016/j.proeng.2017.05.005
- Moreno, J., Vargas, M. A., Olivares, H., Rivas, J. n., & Guerrero, M. G. (1998). Exopolysaccharide production by the cyanobacterium *Anabaena* sp. ATCC 33047 in batch and continuous culture. *Journal of Biotechnology*, 60(3), 175-182. doi: 10.1016/s0168-1656(98)00003-0
- Murthy, G., Siva Kavya, K. B. V., Venkata Krishna, A., & Ganesh, B. (2016). Chemical stabilization of subgrade soil with gypsum and NaCl. *International Journal of Advances in Engineering & Technology*, 9(5), 569-581.

- Naveena, S., & Sreenivasa Reddy, G. (2015). Strength Characteristics of Expansive Soils Using Eco-Friendly Xanthan Gum. *International Journal of Science and Research*, 6(6), 2439-2442.
- Negi, A. S., Faizan, M., Siddarth, D. P., & Singh, R. (2013). Soil Stabilization Using Lime. *International Journal of Innovative Research in Science, Engineering and Technology*, 2(2).
- Niaounakis, M. (2015). *Biopolymers: Applications and Trends. Definitions of Terms and Types of Biopolymers*: William Andrew Publishing.
- Nidzam, R. M., & Kinuthia, J. M. (2010). Sustainable soil stabilisation with blastfurnace slag – a review. *Proceedings of the Institution of Civil Engineers - Construction Materials*, 163(3), 157-165. doi: 10.1680/coma.2010.163.3.157
- Pandey, A., & Rabbani, A. (2017). Soil Stabilisation Using Cement. *International Journal of Civil Engineering and Technology*, 8(6), 316-322.
- Patel, K. C., & Shah, A. J. (2016). Effect of Guar and Xanthan Gum Biopolymer on Soil Strengthening. *International Journal for Scientific Research & Development*, 4(3), 280-283.
- Pattanashetti, N. A., Heggannavar, G. B., & Kariduraganavar, M. Y. (2016). *Smart Biopolymers and Their Biomedical Applications*. Paper presented at the Procedia Manufacturing: International Conference on Sustainable and Intelligent Manufacturing, Leiria, Portugal.
- Qingquan, L., Qing, W. D., & Zhijing, G. (2004). *The Applications of Non-Standard Stabilizers to the Base Course of Rural Roads*. Paper presented at the International Conference on Sustainable Construction Waste Management, Singapore.
- Ravenstijn, J. (2010). Bioplastics in consumer electronics. *Industrial Biotechnology*, 6(5), 252-263.

- Ravishankar, A. U., Panditharadhya, B. J., Reddy, K. J. C., & Amulya, S. (2017). *Experimental Investigation of Lateritic Soil treated with Calcium Lignosulfonate*. Paper presented at the Indian Geotechnical Conference 2017 GeoNEst, IIT Guwahati, India.
- Roesyanto, Iskandar, R., Hastuty, I. P., & Dianty, W. O. (2018). Clay stabilization by using gypsum and paddy husk ash with reference to UCT and CBR value. *IOP Conference Series: Materials Science and Engineering*, 309, 012026. doi: 10.1088/1757-899x/309/1/012026
- Saadeldin, R., & Siddiqua, S. (2013). Geotechnical characterization of a clay–cement mix. *Bulletin of Engineering Geology and the Environment*, 72(3-4), 601-608. doi: 10.1007/s10064-013-0531-2
- Shankar, A. U., Rai, H. K., & Mithanthaya, I. (2009). Bio-Enzyme Stabilized Lateritic Soil as a Highway Material. *Journal of Indian Roads Congress*.
- Sherwood, P. T., & Transport Research, L. (1993). *Soil stabilization with cement and lime*. London: HMSO.
- Sikarwar, B. P. S., & Trivedi, M. K. (2017). Stabilization of Clayey Soil by using Gypsum and Calcium Chloride. *International Journal for Research in Applied Science & Engineering Technology*, 5(V).
- Singh, A., & Garg, P. (2015). *EVALUATION OF RENOLITH AS A SUBGRADE STABILIZER*. Paper presented at the 50th Indian Geotechnical Conference, Pune, Maharashtra, India.
- Song, Z., Liu, J., Bai, Y., Wei, J., Li, D., Wang, Q., . . . Qian, W. (2019). Laboratory and Field Experiments on the Effect of Vinyl Acetate Polymer-Reinforced Soil. *Applied Sciences*, 9(1), 208. doi: 10.3390/app9010208
- Sujatha, E. R., & Saisree, S. (2019). Geotechnical behaviour of guar gum-treated soil. *Soils and Foundations*, 59(6), 2155-2166. doi: 10.1016/j.sandf.2019.11.012



- Ta'negonbadi, B., & Noorzad, R. (2017). Stabilization of clayey soil using lignosulfonate. *Transportation Geotechnics*, 12, 45-55. doi: 10.1016/j.trgeo.2017.08.004
- Tao, J. Q., Lin, W. Y., Luo, X. H., Qiu, X., & Wu, J. H. (2015). Compressive Strength Analysis of Ionic Soil Stabilizer Improving Soil. *Key Engineering Materials*, 667, 341-346. doi: 10.4028/[www.scientific.net/KEM.667.341](http://www.scientific.net/KEM.667.341)
- Terzaghi, K., Peck, R. B., & Mesri, G. (1996). *Soil Mechanics in Engineering Practice*. New York: John Wiley & Sons, Inc.
- Tingle, J. S., Newman, J. K., Larson, S. L., Weiss, C. A., & Rushing, J. F. (2007). Stabilization Mechanisms of Nontraditional Additives. *Transportation Research Record: Journal of the Transportation Research Board*, 1989-2(1), 59-67. doi: 10.3141/1989-49
- Tingle, J. S., & Santoni, R. L. (2003). Stabilization of Clay Soil with Nontraditional Additives. *Transportation Research Record: Journal of the Transportation Research Board*, 72-84.
- Van Impe, W. F. (1989). *Soil improvement techniques and their evolution*. Rotterdam, Netherlands; Brookfield, VT: Balkema.
- Vijayan, A., & Vijayan, V. L. (2018). Study on the Strength Characteristics of Biopolymer on Kaolinite Clay. *International Journal of Research and Scientific Innovation*, V(XII).
- Vijayan, G., & Sasikumar, A. (2019). Stabilization of Clayey Soil by using Lignosulfonate. *International Research Journal of Engineering and Technology*, 6(2), 1963-1967.
- Wang, Y., & Liu, X. (2011). *Tests of ionic soil stabilizer reinforcing expansive soil*. Paper presented at the Second International Conference on Mechanics Automation and Control Engineering.
- Wisniewski, M., Skutink, Z., & Cabalar, A. F. (2013). Laboratory Assessment of Permeability of Sand and Biopolymer Mixtures. *Annals of Warsaw University of Life Sciences*, 45(2), 217-226.

- Yilmaz, I., & Civelekoglu, B. (2009). Gypsum: An additive for stabilization of swelling clay soils. *Applied Clay Science*, 44(1-2), 166-172. doi: 10.1016/j.clay.2009.01.020
- Yilmaz, Y., Avsar, C., & Gungor, A. (2009). *Stabilization of clays using liquid enzymes*.
- Yin, C.-Y., Mahmud, H. B., & Shaaban, M. G. (2006). Stabilization/solidification of lead-contaminated soil using cement and rice husk ash. *Journal of Hazardous Materials*, 137(3), 1758-1764. doi: 10.1016/j.jhazmat.2006.05.013