Strength and Durability Study on Enzyme Induced Carbonate Precipitation Stabilized Clayey Soil

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Of

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For

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I confirm that I have reviewed the final version of Munawar Hussain (Registration No. NUST-2019-MS-Geotechnical-318737)'s MS thesis from the NUST Institute of Civil Engineering (NICE), and have found it to be in accordance with all NUST Statutes/Regulations, and free of plagiarism, errors, and mistakes. It satisfies the requirements for partial fulfillment of the MS degree. I also certify that any changes recommended by the GEC members of the scholar have been incorporated into the thesis.

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DECLARATION

I certify that this research work titled "**Strength and Durability Study on Enzyme Induced Carbonate Precipitation Stabilized Clayey Soil**" is my own work. The work has not been presented elsewhere for assessment. The material that has been used from other sources it has been properly acknowledge / referred.

Munawar Hussain

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Dedicated to my wonderful parents

ABSRTACT

A bio-inspired technology called enzyme-induced carbonate precipitation (EICP) aims to improve the geo-mechanical characteristics of soils by causing calcium carbonate to precipitate. The creation of calcium carbonate, a cementitious agent that binds soil particles together at their contact sites and increases the strength and stiffness of treated soils, is catalyzed by enzymes in this process. EICP has various benefits over conventional binders and is used in erosion control, building materials, and ground improvement. While several studies have examined the efficacy of EICP on granular soils, there hasn't been much study on soils with a high fine content (more than 40%). Additionally, the enzyme source in the majority of investigations has been urease powder that is readily available commercially. In order to fill these gaps, this research focuses on testing the efficacy of EICP at different molar concentrations utilizing yellow soybean as the enzyme source in strengthening and maintaining clayey soil. Unconfined compression testing and immersion experiments are carried out to evaluate the effects of EICP. The strength of a cylindrical soil specimen is determined by measuring the highest axial compressive stress that it can sustain before failing in the unconfined compression test. On the other hand, the immersion test measures the mass loss over time while immersing the soil to test its resistance to erosion and determines how durable it is. According to the study's findings, in situations when there is too much water, enzyme-induced carbonate precipitation successfully increases soil strength and prevents erosion. The soil's mechanical qualities are enhanced, resulting in greater strength and stiffness, by stimulating the development of calcium carbonate.Additionally, EICP has been found to be effective in reducing the soil erosion, when soil is exposed to water as evidenced by immersion tests performed on cylindrical samples.

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Chapter 1

1 Introduction

The geotechnical engineering community has moved towards sustainable building methods and materials as a result of climate change and global warming. The geotechnical engineering community has moved towards sustainable building methods and materials as a result of climate change and global warming. Earthen materials, for example, are considered sustainable due to their low embodied and operational energy, fire resistance, and ease of recycling. Unfortunately, because to their susceptibility to water-induced disintegration and poor strength, they have not been widely employed in building. The bulk of traditional soil restoration procedures are costly, energy-intensive, and environmentally hazardous. Biostabilization, on the other hand, has lately emerged as a feasible replacement that can address some of these shortcomings. One of the multiple biostabilization techniques, enzyme-induced carbonate precipitation (EICP), is particularly promising due to its compatibility with various soil types and ease of usage. By functioning as a catalyst for the urease enzyme, which causes calcium carbonate to precipitate in the presence of calcium ions, EICP accelerates the breakdown of urea in pore water. This study investigated how silty clay may be made stronger and more durable using unconfined compression tests, immersion, contact, and drip testing. While the addition of cement and lime has enhanced ground qualities and creates more resilient earthen materials, it has also increased carbon emissions and energy usage.

Recent studies have shown that the use of cement to stabilize earthen materials has had a detrimental effect on the environment. Particularly, it has been discovered that the carbon emissions of cement-stabilized earthen materials are comparable to those of lean concrete and fired brick. As a result, natural soils' initial green credentials have been eroded, which has raised worries. Moreover, the use of cement and lime has reduced the material's ability to absorb moisture and be recycled, which can result in earthen structures requiring more energy to operate and less environmentally friendly waste management techniques.

More energy consumption may be needed to maintain a suitable interior atmosphere in clay structures as a result of the material's decreased capacity to absorb and release moisture (hygroscopic capacity). In addition, the material's diminished ability to be recycled results in landfill disposal after its useful life is through. The necessity for alternate stabilizing techniques that may deliver the required technical performance without compromising the material's hygroscopic and recycling qualities is therefore apparent.

The use of biostabilization techniques has become a cutting-edge way to enhance ground characteristics without harming the ecosystem. (It could be achieved in two ways explain both EICP and MICP) UICP, or ureolytic-induced carbonate precipitation, is a promising technique for improving weak soils with the least degree of negative environmental impact. The urease enzyme is utilized in this technique to catalyse the hydrolysis of urea (also known as ureolysis), which results in the precipitation of calcium carbonate, which assists in binding soil particles together, increasing strength, and decreasing void sizes. UICP has the ability to significantly improve the mechanical properties of poor soils without negatively impacting the environment. EICP, on the other hand, has lately gained popularity, leaving lots of room for more research and improvement.

In this study the improvement in the properties of silty clay soil was investigated using EICP technique. The results show modification in the plastic behavior of the soil,appreciable increase in the strength of the soil and resistance to erosion as a result of stabilization with Enzyme induced carbonate precipitation (EICP).

1.1 Background of Enzyme Induced Carbonate Precipitation (EICP):

The idea of creating bio-cemented soil columns utilizing regulated EICP injection for the goal of ground improvement was first presented by Kavazanjian and Hamdan[1] and Kavazanjian[2]. . In order to increase bearing capacity, reduce settlement, and stabilize slopes, columnar soil strengthening techniques are frequently used[3] . EICP has an advantage over other columnar ground improvement technologies in that it may be put beneath and around existing structures and infrastructure without causing disruptions [2]. EICP also offers a low viscosity treatment alternative, and it has the benefit of not creating trash. This characteristic permits the use of lower injection pressures, which reduces energy usage and equipment size. Additionally, a larger variety of grain sizes that are appropriate for the method may be used with EICP. According to the TA Instruments DHR-3 Rheometer at 50 Hz sample frequency, the basic EICP solution, which is an aqueous solution with soluble components, has a viscosity during injection that is just 1.75 times bigger than water. EPIC-stabilized soil and similar carbonate precipitation-based approaches have both been questioned as to their long-term sustainability. The durability of

EPIC-treated soils in the presence of acid rain, which may dissolve carbonate precipitates, has been a source of concern for Gowthaman[4]. Alcite is the most stable mineral phase, however different mineral phases have different susceptibilities to CaCO3 dissolution. Geological data indicates that calcite-cementated sands are quite durable in terrestrial settings.

Ureaolytic calcification needs the urease enzyme as a catalyst to convert urea (CH4N2O) into ammonium (NH4+) and carbonate ions (CO32). This procedure helps to stabilise the earth. Carbonate ions react with calcium ions (Ca+2) to form calcium carbonate (CaCO3), which precipitates in the earth. When urease is used as a catalyst, urea hydrolysis occurs quickly in water, according to Hausinger, R. P., & Hausinger, R. P. [5]. Urease can be added directly to the reaction media or urea-producing bacteria (like those in MICP) can speed up the ureolytic process (as in EICP). Figure 1 illustrates how the phases of these two techniques are similar, but as will be discussed later, there may be significant variances in the requirements for effective implementation.

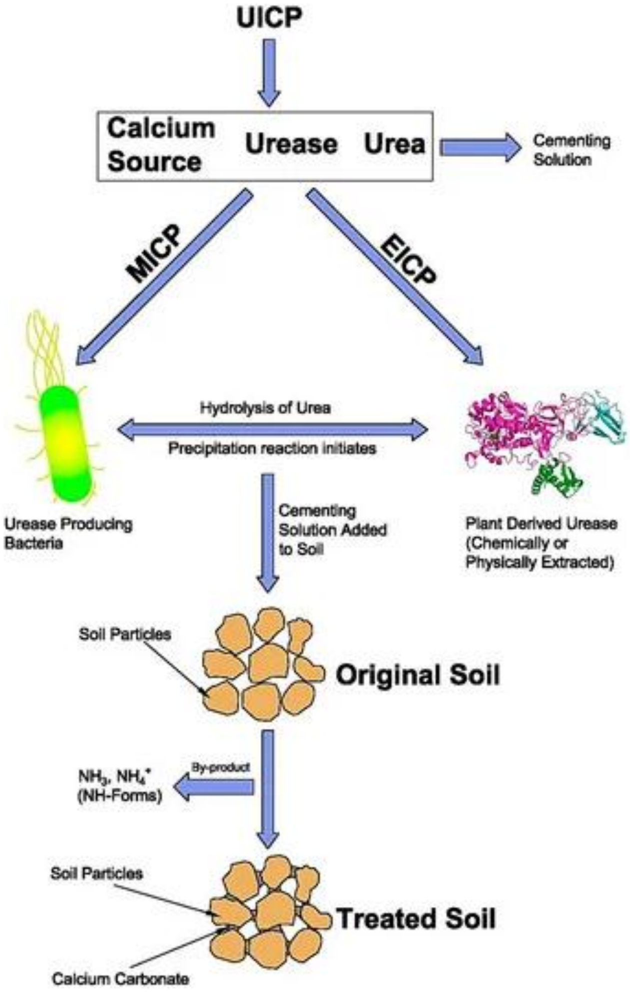

Figure 1.1: Schematic representation of UICP[6].

In Equations (1) through (6), the chemistry involved in UICP stabilisation is discussed. The first equation illustrates how the digestion of urea results in the production of ammonia and carbamic acid, which raises pH. Equation (2) illustrates the hydrolysis of carbamic acid into ammonia and carbonic acid. The creation of hydroxide, ammonium, carbonate, and ammonium ions—all of which raise the pH of the reaction medium—is shown in equations (3) and (4). One mole of urea hydrolysis results in the release of two moles of ammonium and one mole of carbonate ions, as shown by equation (5), which summarises the four processes before it. Equation (6) shows how the precipitation of calcium carbonate results from the interaction of calcium and carbonate ions after super saturation.

$$CO\left(NH_2\right)_2 + H_2O \rightarrow NH_2\,COOH + NH_3 \tag{1}$$

$$NH_2\,COOH + H_2O \rightarrow NH_3 + H_2\,CO_3 \tag{2}$$

$$2\,NH_3 + 2H_2O \rightarrow 2NH_4^+ + 2OH^- \tag{3}$$

$$2OH^- + H_2\,CO_3 \rightarrow CO_3^{-2} + 2H_2O \tag{4}$$

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{-2} \tag{5}$$

$$Ca^{+2} + CO_3^{-2} \rightarrow CaCO_3 \tag{6}$$

The urease enzyme catalyses urea hydrolysis, resulting in the formation of calcium carbonate. This chemical reaction elevates the pH of the reaction medium and causes calcium carbonate to precipitate. The ability of calcium carbonate to bind soil particles together and fill gaps between the particles improves soil qualities by increasing strength and stiffness while decreasing permeability. UICP has a variety of applications, including limestone monument preservation, selective filling of oil reservoir voids, pollutant removal from soils and groundwater systems, concrete crack repair, ground swelling reduction, and soil liquefaction mitigation. The carbonate precipitate is similarly long-lasting and dissolves very slowly over geological time scales.

1.2 Research Objectives:

- To investigate the effect of EICP using yellow soybean as a soil stabilization method.
- To examine the effectiveness of EICP technique for the improvement of clay soils including the improvement in the mechanical strength and durability of the soil.

1.3 Organization of Thesis:

In Chapter 1, this thesis outlines its objectives, offers a concise explanation of EICP, and presents the organizational structure of the thesis.

Chapter 2 consists of a comprehensive literature review that delves into the chemistry of EICP, explores pertinent details regarding the impacts of bio-cementation, and examines potential applications for bio-cementation.

Chapter 3 provides a detailed account of the experimental procedures conducted to gather the necessary data for analysis in this thesis.

Chapter 4 focuses on the laboratory testing conducted on both unstabilized and stabilized clay soil.

Chapter 5 presents the final conclusions drawn from the thesis and offers recommendations for future studies centered around the utilization of EICP in soils containing a substantial amount of fines.

Chapter 2

2 Review of the Literature:

2.1 Introduction:

Enzyme Induced Carbonate Precipitation (EICP) is a very efficient and environmentally responsible method of ground stabilization that can get around some of the drawbacks of MICP. EICP is applied directly to the soil together with urea and calcium ions as reactants in place of relying on bacterial metabolic activity to produce urease enzyme. By doing away with the need for bacterial fixation and culture, this technique reduces the difficulties associated with on-site bioreactor maintenance. Additionally, it avoids problems like low oxygen levels at very deep levels and the presence of native bacteria in the soil.

Bacteria, higher order plants, and certain animals frequently produce hexameric proteins, such as the urease enzyme [7]. The urease molecule is substantially smaller at 12 nm when compared to bacteria, which often exceed 300 nm and vary from 500 to 5000 nm . For instance, S. pasteurii cells have an average size of 2800 nm, making them more than 200 times larger than urease molecules [8]. EICP, as contrast to MICP, which is only effective on coarse materials, can be used to stabilize fine-grained and highly compacted soils because of the urease molecule's relatively small size and ability to fit into microscopic holes. The urease enzyme also degrades spontaneously in soil without harming the local environment and has a limited shelf life.

By using synthetic techniques, which are frequently employed by chemical manufacturers, purified urease is separated from plants. Jack beans, soybeans, watermelon seeds, and members of the pine family are just a few of the plants that are particularly abundant sources of the urease enzyme[9] . Although a number from a commercial seller from 2021 estimates a price of roughly EUR 20 per gramme, buying pure urease can be expensive. Due to the high cost, large-scale applications are not economically feasible. Because unrefined plant extracts are more cost-effective than refined urease, several researchers have advised utilizing them in place of the latter. Unprocessed extracts from jack beans, watermelon seeds, and soybeans are used in this procedure.

2.2 Development of Enzyme Induced Carbonate Precipitation (EICP) Technique:

For geotechnical considerations, Nemati and Voordouw originally suggested in 2003 using free urease enzyme generated from plant sources as a catalyst in carbonate biomineralization. The ability of the enzymatic response to reduce soil permeability and prevent soil pore clogging was the focus of their investigation, which may be helpful for applications requiring oil recovery. The concept of employing enzymatic activities to enhance the mechanical properties of sandy soil was first put out by Yasuhara et al and they expanded on it in 2005. Their study revealed that soil's unconfined compressive strength (UCS) was dramatically boosted after being subjected to many cycles of enzymatic solutions.

Kavazanjian and Hamdan coined the name "EICP" (enzyme-induced carbonate precipitation) in 2015 to describe the biomineralization process that involves employing urease enzyme produced from plants for urea hydrolysis. In order to enhance the mechanical properties of the soil in their study, EICP solutions were injected into sand columns. Since its inception, EICP has been applied in a variety of disciplines, such as the control of wind erosion through the use of dust suppressants [10, 11]. It has also been utilized to produce bio-bricks, stop surface water erosion, minimize sand liquefaction, and promote the healing of concrete fractures. Figure 1 shows a pie chart representing the distribution of research publications in this area. The graph demonstrates that the majority of studies, largely conducted in laboratories, have focused on determining how effectively EICP works to enhance the mechanical properties of sandy soils. However, recent research has focused on the actual use of EICP as a grout for ground improvement in field applications [12]. The environmental impact of enzyme induced carbonate precipitation (EICP) as a dust suppressant for reducing wind erosion and as a grout for soil improvement has also been addressed in a number of recent research studies[12].

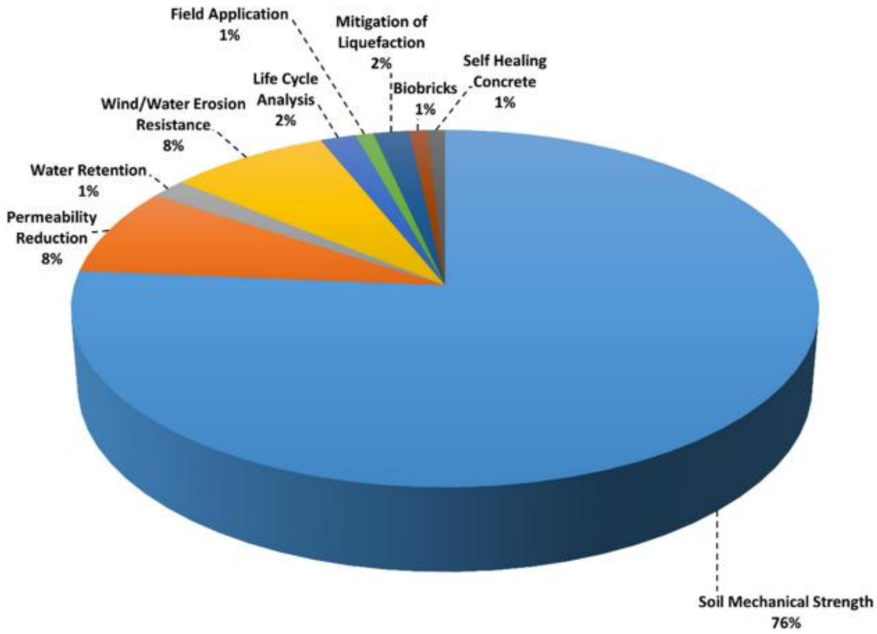

Figure 2.1: A pie Chart showing the number of studies that have applied EICP to construction and building material applications as well as geotechnical engineering applications[13].

2.3 Effect of Enzyme Induced Carbonate Precipitation (EICP) on Strength:

The mechanical characteristics of soils stabilized by EICP have shown notable improvements in several investigations [14, 15]. Figure 12 displays published data illustrating the unconfined strength values measured on several types of treated soils, with varying amounts of calcium carbonate provided as a percentage of the total soil mass. The graph demonstrates that, on average, carbonate contents between 4% and 8% consistently provide values of strength between 300 kPa and 2000 kPa. With a low carbonate concentration of less than 1%, Almajed et al.[2] attained the greatest strength value of 1745 kPa. This surprising outcome may have been caused by the addition of powdered milk in the cementing solution, which promoted the formation of bigger crystals at advantageous nucleation locations. In comparison, despite using a significantly greater carbonate concentration.

The largest strength enhancement is caused by carbonate precipitation at interparticle contacts, whereas precipitation on the particle surface or in the pore space has minimal impact on the material's mechanical characteristics. Simatupang and Okamura [16] investigated the liquefaction resistance of EICP-treated sand samples cured at two different relative humidity levels of 30% and 97% using saturated undrained cyclic triaxial testing. SEM investigations revealed that samples dried at lower relative humidity exhibited calcium carbonate crystallization at interparticle contacts, as the little moisture present in the soil tended to collect there. Higher humidity samples, on the other hand, had more water that completely filled the pores. As a result of the carbonate precipitation, a specific topology developed that coated the whole particle surface..Under cyclic loading, Simatupang and Okamura [16] discovered that samples with a curing humidity of 30% outperformed those with a curing humidity of 97%. Furthermore, the strength of the interparticle carbonate bindings was a critical determinant of liquefaction resistance, and after these connections were disrupted, the liquefaction resistance became nearly similar for both treated and untreated sand. According to their findings, a volumetric strain of 1% considerably broke carbonate bonds, whereas a volumetric strain of 1.7% completely destroyed them. According to several research, Figure 13 demonstrates the link between urea-CaCl2 concentration and matching unconfined compressive strength. Figure 13 shows that higher urea-CaCl2 ratios do not always result in stronger materials. As increased urea concentrations lower the pH of the cementing solution, the reaction rate slows. As a result, when the concentration of the reactant surpasses a certain threshold, the strength of the treated samples is likely to decrease. The specific value of this optimal level is controlled by parameters such as curing time and urease concentration.

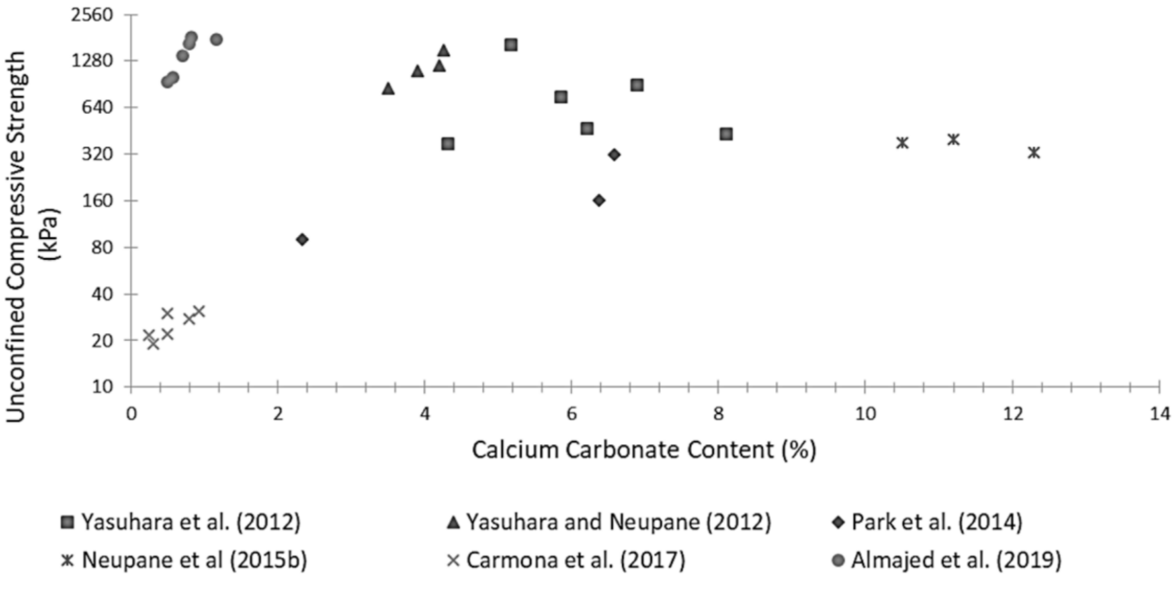

Figure 2-3: Data from literature of UCS testing on soil specimen stabilized with EICP[6].

In general, higher urease concentrations are more likely to cause carbonate precipitation. However, when the urease concentration crosses a certain threshold, several studies have found a decrease in strength. This unexpected result was caused by the urease enzyme clinging to the surface of the calcium carbonate precipitate, preventing crystal formation.

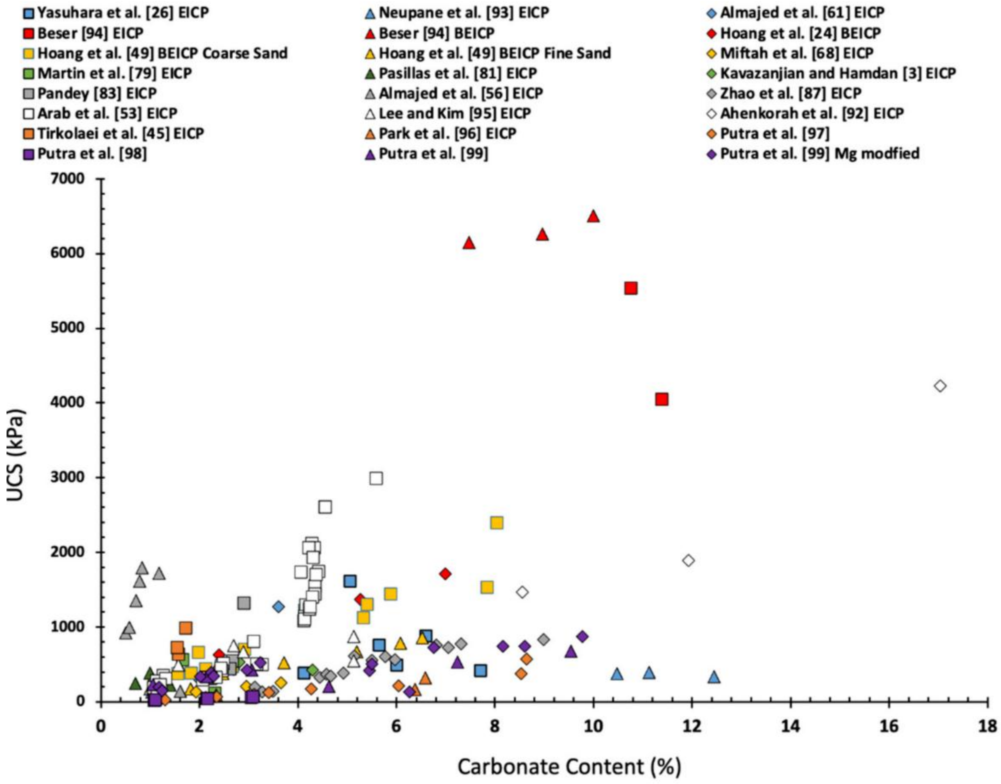

Figure 2-4: Data gathered from literature of the maximum strength obtained for soil specimen stabilized with EICP[13].

2.4 Impact of EICP on Hydraulic Conductivity:

The enhanced hydraulic conductivity of the soils is a key sign of how effective soil management practises are. The soil particles are bound by the EICP treatment, which causes treated soils to have a somewhat decreased hydraulic conductivity. The cementing solution employed and the number of treatment cycles, however, may have an impact on the size of the drop. Because the behaviour of the soil mass depends on macroscale particle-particle interactions, the soil packing density and resulting porosity are connected to the soil hydraulic conductivity.[17].

2.5 Impact on the Shear Strength of the Soil:

Aishwarya & Christy[18] used a direct shear test to examine how EICP treatment influenced the shear strength of sandy soils. At a typical stress of 50 kPa, they discovered that EICP soil treatment had increased the shear strength of untreated soil by a factor of two. It's crucial to keep in mind that shear strength decreases when carbonate precipitation increases past a certain point. This was explained by the inability of the unstable carbonate in soil pores to serve as a mortar between soil particles.[19].

Additionally, Putra [19] used a direct shear test to analyse soil that has undergone modified EICP using magnesium sulphate. 4.1% precipitation had no effect on the friction angle but produced a cohesiveness of 53 kPa. Compared to untreated sand, treated sand had an observed friction angle of about 19° instead of 20°.

Chapter 3

3 Experimental Testing on Unstabilized Soil:

This chapter discusses the laboratory testing performed on unstabilized soil according to relevant ASTM standards. Furthermore, different graphs and bar charts of different tests are discussed

3.1 Particle size distribution

Sieve analysis and hydrometer analysis was performed according to ASTM Standard **(**D422–63**)** on unstabilized soil. Sieve analysis revealed that 64.5% of the soil sample consists of fines for which hydrometer analysis was performed.

Table 3-1: Sieve Analysis of Unstabilized Soil.

Sieve Sizes	Sieve Number	Sieve weight	Sieve weight plus soil	weight of soil retained	Cumulative retained	Percent Passing
0.59	30	406	406	0	0	100
0.42	40	400	420	20	20	96
0.3	50	381	401	20	40	92
0.177	80	380	406	26	66	86.8
0.149	100	380	395	15	81	83.8
0.074	200	367	455	88	169	66.2
	Pan	276	429	330	499	
Total soil Weight			500			

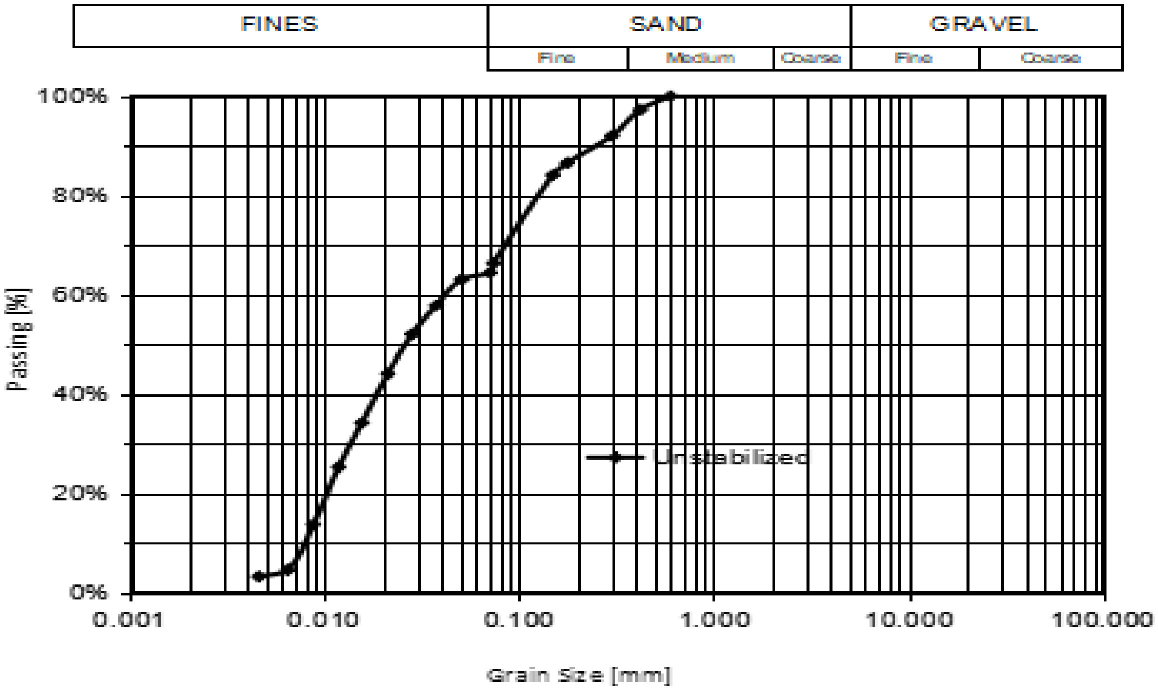

Figure 3-1: Grain size distriubtion curve for unstabilized soil.

3.2 Plasticity:

The plasticity of the unstabilized soil was evaluated using ASTM-D4318. The unstabilized soil sample's liquid limit was found to be 29. The liquid limit shows the moisture level at which the soil changes from a liquid to a plastic state. The plastic limit of the unstabilized soil was found to be 15 percent moisture content, which stands for the moisture level at which the soil experiences a considerable shift in plastic behaviour. This indicator measures the range of soil moisture content where plastic behaviour occurs. A greater plasticity index means that the soil may remain plastic over a larger range of moisture contents.

3.2.1 Liquid Limit:

The plasticity of the unstabilized soil was evaluated using ASTM-D4318. The unstabilized soil sample's liquid limit was found to be 29. The liquid limit shows the moisture level at which the soil changes from a liquid to a plastic state. The plastic limit of the unstabilized soil was found to be 15 percent moisture content, which stands for the moisture level at which the soil experiences a considerable shift in plastic behaviour. This indicator measures the range of soil moisture content where plastic behaviour occurs. A greater plasticity index means that the soil may remain plastic over a larger range of moisture contents.

Table 3-2: Data for determination of liquid limit for unstabilized soil.

Test		**Liquid Limit**		
Shocks Limit		15-25	20-30	25-35
No. of Shocks		16	28	33
Container Number		A	B	C
Weight of Wet Soil + Container	gm	52.3	53.1	42.3
Weight of Dry Soil + Container	gm	47	50.1	39
Weight of Container	gm	30.7	38.6	25
Water's Weight	gm	5.3	3	3.3
Dry Soil Weight	gm	16.3	11.5	14
Moisture Content	%	32.52	26.09	23.57

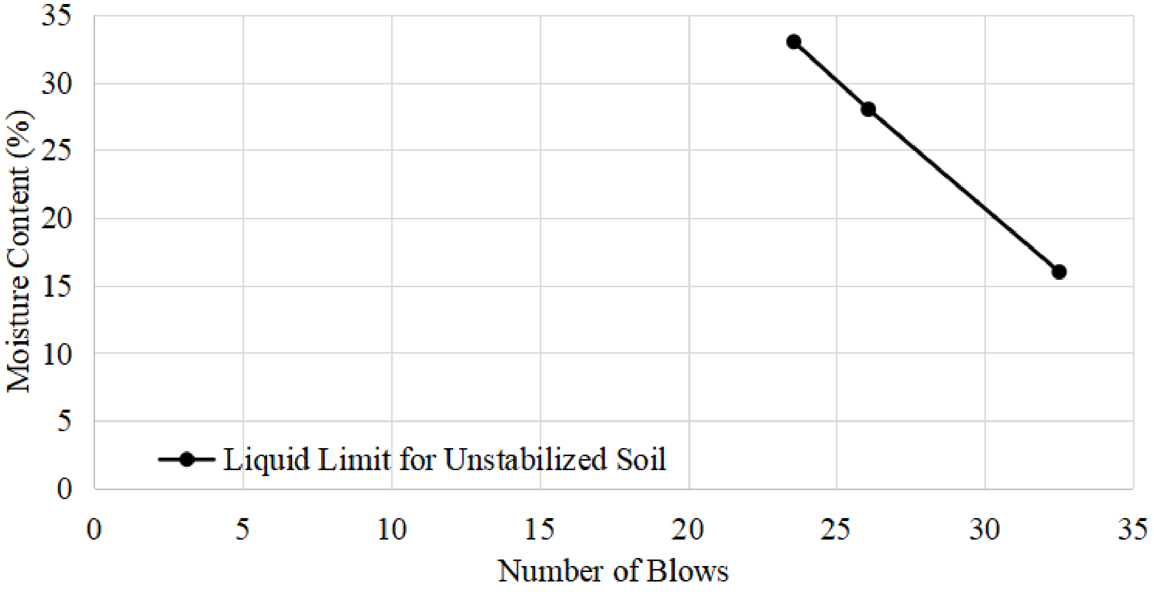

Figure 3-2 : Liquid Limit of Unstabilized Soil.

3.2.2 Plastic Limit:

Hydrometer analysis and Sieve analysis tests on soil sample as per their ASTM standards. Percentage of materials of soil has shown in table 4.3

Table 3-3: Data for determination of plastic limit of unstabilized soil.

Test		Plastic Limit	
Container Number		A	B
Wet Soil + Container Weight	gm	35.5	37.8
Dry Soil + Container Weight	gm	34.8	37.2
Weight of Container	gm	29.9	33.4
Weight of Water	gm	0.7	0.6
Weight of Dry Soil	gm	4.9	3.8
Moisture Content	%	14.29	15.79
		Avg. P L	**15.04**

3.3 Specific Gravity

According to ASTM D854-14 standard, the specific gravity of the unstabilized soil was evaluated using water pyrometer. The information for calculating the soil's specific gravity is provided in Table A, and it shows that the soil has a specific gravity of 2.71.

Table 3-4: Data for the determination of specific gravity of soil.

Flask Weight	105.22
Dry Soil + Flask Mass	142.37
Mass of Flask + Soil + Water	379.12
Mass of Flask + Water	355.02
Specific Gravity	2.71

3.4 Proctor Test:

The Proctor test was carried out in accordance with ASTM-D 698. The purpose of the test was to establish the ideal moisture level for the soil sample. The test results indicated that the optimal moisture content for the soil was found to be 14%. At this moisture content, the maximum dry density achieved was 1.96 g/cm3. The data obtained from the test has been presented in Table 6, and a graphical representation of the data can be found in Figure 6. The data in Table 6 likely includes various moisture contents tested during the Proctor test, along with their corresponding dry unit weights. These values are used to construct a compaction curve, which is then analyzed to determine the moisture content that yields the maximum dry density. The maximum dry density in this instance was attained with a moisture content of 14%. The relationship between the moisture content and dry unit weight is depicted graphically in Figure 6. The graph's curve peaks at 14%, the ideal moisture level, showing the maximum dry unit weight obtained throughout the test.

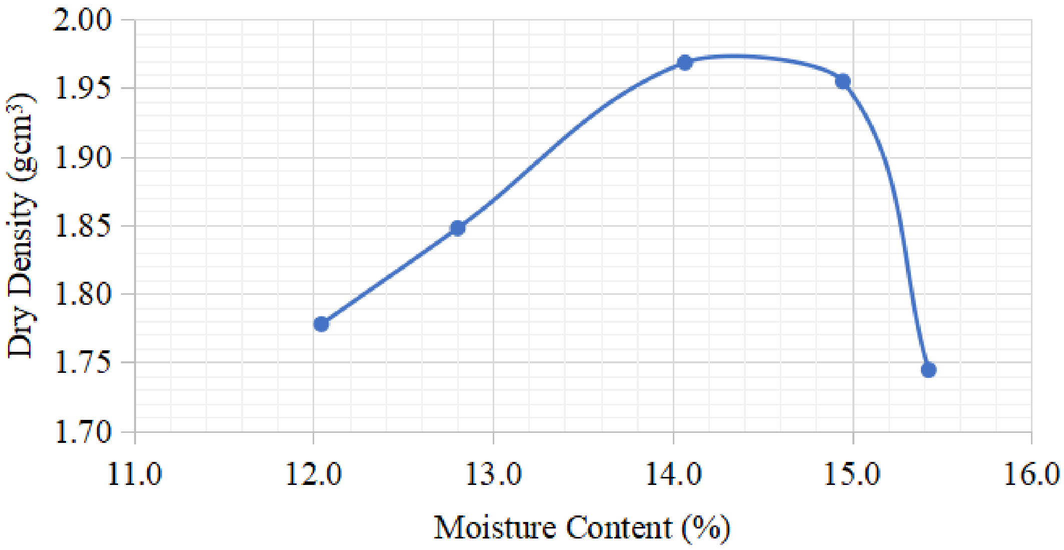

Figure 3 : Curve for maximum dry density of the soil by proctor test.

3.5 Immersion Test Results

To assess the soil's resistance to access water, DIN 18945 immersion tests were carried out. Circular samples having diameter of 140 mm and a length of 70 mm were submerged in water for 10 minutes in accordance with the standard.The following equation was used to calculate the mass loss.

$$\%\Delta m = \frac{(m_i - m_f)}{m_i} \times 100$$

According to table below, which contains the results of immersion experiments on unstabilized soil, the average mass loss for unstabilized samples was 21.57%.

Table 3-5 : Data for the immersion test for unstabilized soil.

Unstabilized Samples	Sample Weight at Oven Dry Conditions(g)	Prior to immersion, sample weight (g)	Sample Weight Following Immersion (g)	Following immersion, Sample Weight at Oven Dried Conditions (g)	Mass Loss %
Sample 1	944	1011	750	737	21.93%
Sample 2	934	985	795	745	20.24%
Sample 3	958	1025	760	742	22.55%

3.6 Soil Classification

The unstabilized soil has a liquid limit of 28% and Plastic limit of 15% and plasticity index of 13% with this knowledge about the soil it is possible to classify it according to USCS system. The chart shown in Figure A is used to classify the soil according to which this soil falls into the category of clayey Soil (CL).

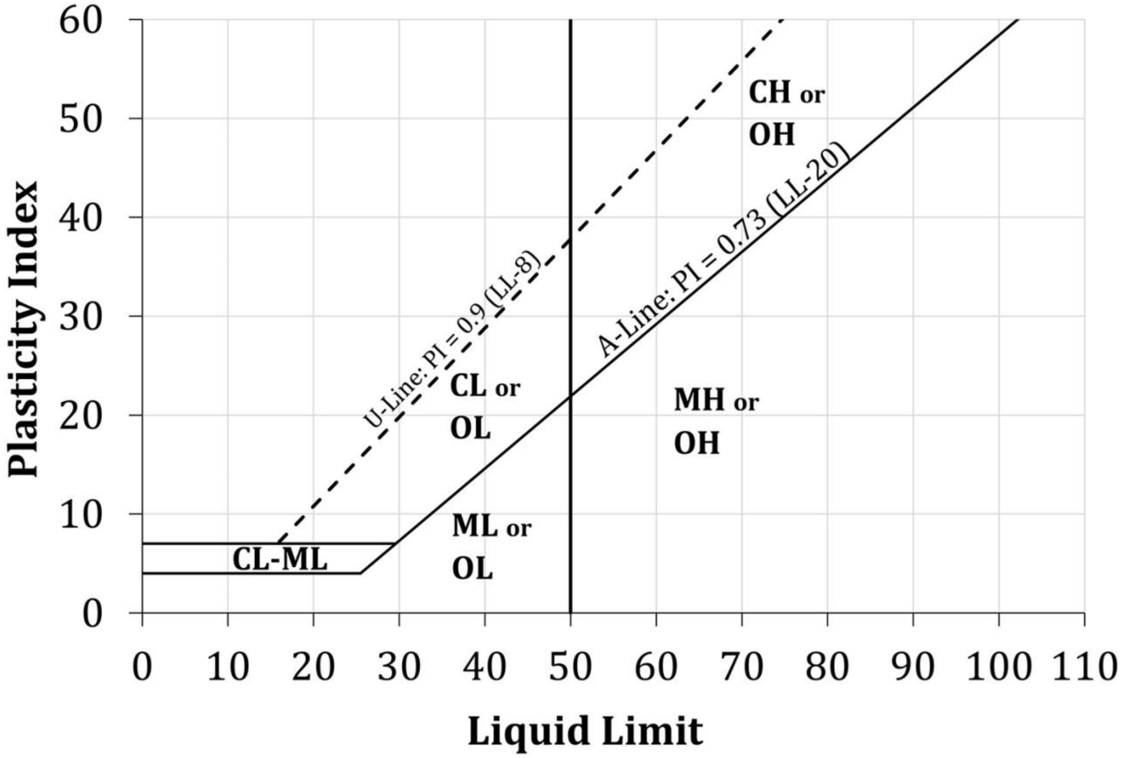

Figure 3-4: USCS fine grained soil categorization chart based on ASTM D2487-17 (2017) standard.

Chapter 4

4 Experimental Testing on Stabilized Clay

4.1 Solution Preparation

100 grams of soybeans were used to create the cementing solution after soaking it in water for 24 hours. Following centrifugation, the resultant slurry was run through a fine mesh to extract the juice. In this study, three distinct cementing solutions were made by adding urea and calcium chloride in varying amount of 0.5, 1, and 2.5 moles, respectively.

1.100g of soybean was taken

2.Soybean was soaked for 24 hours

3.Blender centrifugation.

4. Urease solution

5.Urea

6.Clacium Chloride

Figure 4-1 : Process of solution making.

4.2 Test Tube Experiments:

The test tube experiment's goal was to use a crude urease extract to demonstrate the process of urea hydrolysis. The results of the experiment were then investigated to determine the best electrolytic induced calcium carbonate precipitation (EICP) solutions based on various calcium chloride and urea concentrations. In the experiment, urea and calcium chloride were added to a urease solution in test tubes, and then calcium carbonate precipitated on filter paper. For different urea and calcium chloride concentrations during predetermined time periods, the amount of precipitation was measured.

The results of the experiment showed a positive association between the quantity of precipitation and the urea and calcium chloride concentrations. In particular, the 1 mole concentration fell in the middle, with the 2.5 mole concentration showing the maximum degree of precipitation and the 0.5 mole concentration showing the lowest. The variable rates of precipitation recorded were probably impacted by the length of the precipitation measurement, which ranged from 1 hour to 72 hours. The rate of precipitation may be sped up by elements like increased concentrations of urea and calcium chloride.

Table 4-1: Mass of calcium carbonate precipitated at various time duration for 0.5,1.0 and 2.5 moles.

Test Tube Experiments	1 (hr)	4 (hr)	6 (hr)	12 (hr)	24 (hr)	72 (hr)
0.5 Mole	0.87 (g)	1.52 (g)	1.96 (g)	2.35 (g)	2.95 (g)	3.38 (g)
1 Mole	1.77 (g)	2.61 (g)	3.22 (g)	3.88 (g)	4.1 (g)	4.7 (g)
2.5 Mole	2.2(g)	3.3 (g)	4.1 (g)	5.2(g)	6.2 (g)	8.2 (g)

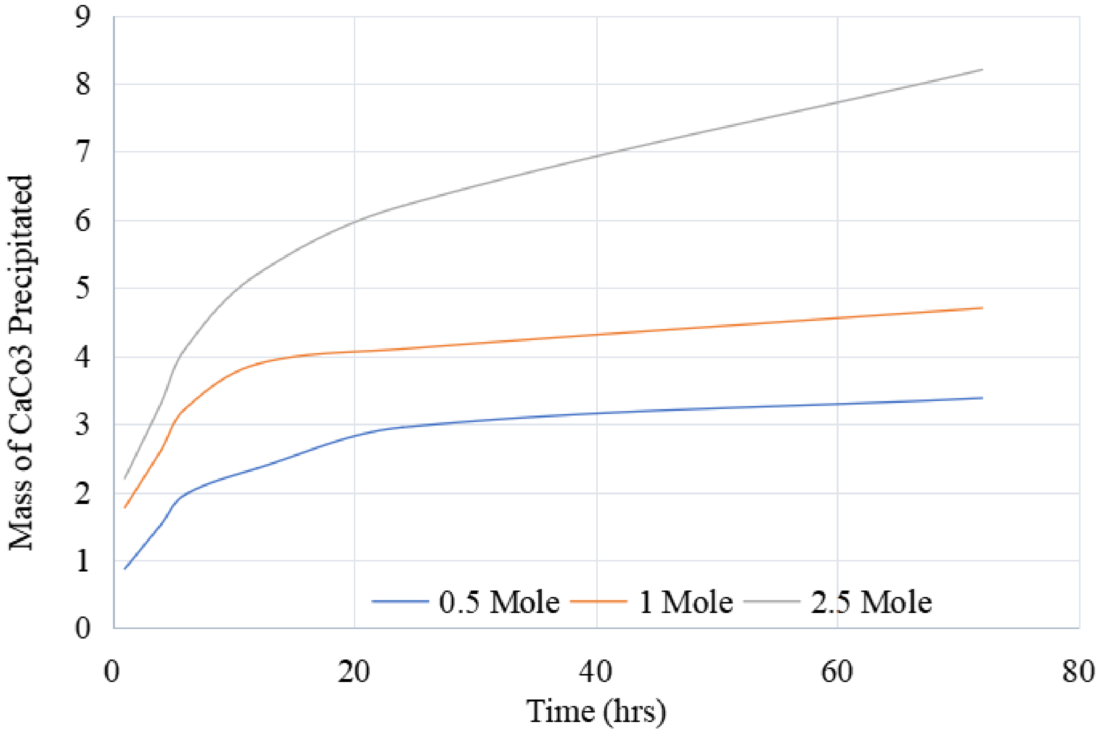

Figure 4-2: Relationship of amount of calcium carbonate precipitated at various times.

Figure 4-3 : The precipitated Calcium Carbonate on filter paper.

4.3 Soil Stabililzed with 0.5 Mole:

In order to make soil samples for 0.5 moles appropriate amount of Calcium Chloride and Urea was taken and mixed with the solution of centrifuged soybean and mixed with dry soil according to OMC which was then compacted in the mold at maximum dry density to prepare samples.

4.3.1 Particle Size Distribution:

Particle size distribution of the soil was performed according to ASTM ASTM D6913, the results for which are shown in the table below, the particle size distribution is shown below in figure 4-2.

Table 4-2 : Sieve Analysis data for soil stabilized with 0.5 Moles of solution

Sieve Sizes	Sieve Number	Sieve weight	Sieve weight plus soil	weight of soil retained	Cumulative retained	Percent Passing
0.59	30	406	406	0	0	100
0.42	40	400	415	15	15	97
0.3	50	381	412	31	46	90.8
0.177	80	380	400	20	66	86.8
0.149	100	380	395	15	81	83.8
0.074	200	367	460	93	174	65.2
	Pan	276	429	324	498	
Total soil Weight			500			

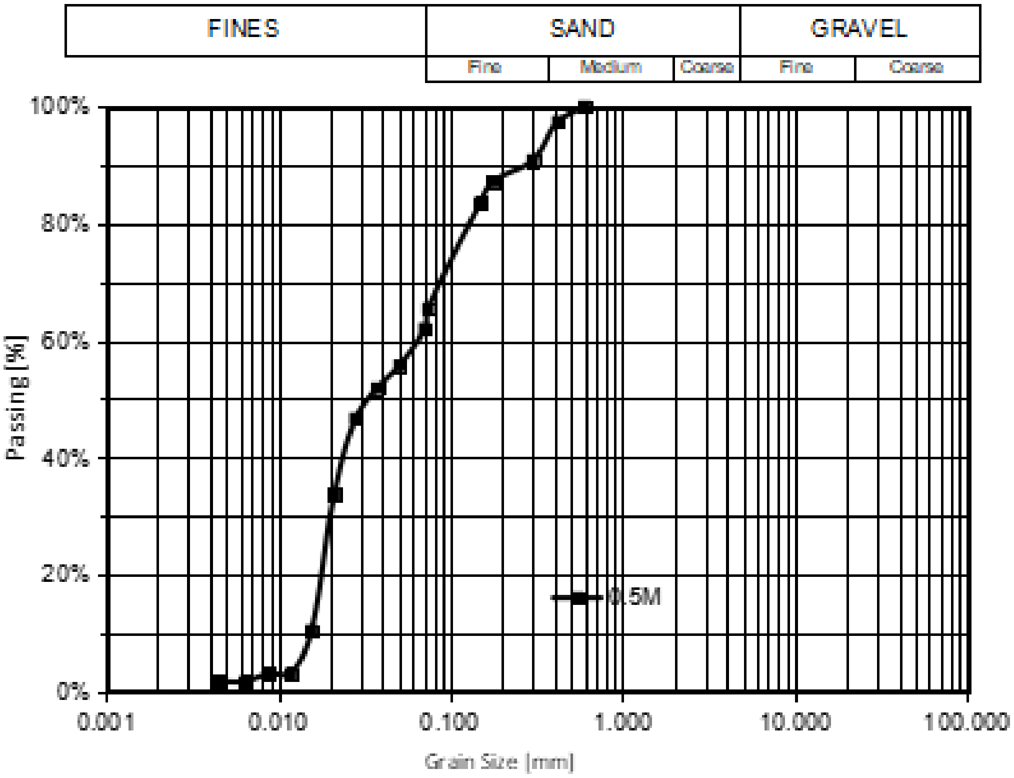

Figure 4: curve for soil stabilized with 0.5 moles of solution.

4.3.2 Liquid Limit:

ASTM Standard (D4318) was followed to determine the liquid limit of the soil. The liquid limit of the soil was determined to be 25%. The data for the test performed is given in table 4-3 and graphically shown in the figure 4-5.

Table 4-3: Data for determination of liquid limit for soil stabilized with 0.5 Mole solution.

Test		Liquid Limit		
Shocks Limit		15-25	20-30	25-35
No. of blows		16	23	33
Container Number		A	B	C
Wt. of Wet Soil + Container	gm	55.1	53.2	55.5
Wt. of Dry Soil + Container	gm	48.9	50	50.7
Wt. of Container	gm	30.7	38.6	25

Wt. of Water	gm	6.2	3.2	4.8
Wt. of Dry Soil	gm	18.2	11.4	25.7
Moisture Content	%	34	28	19

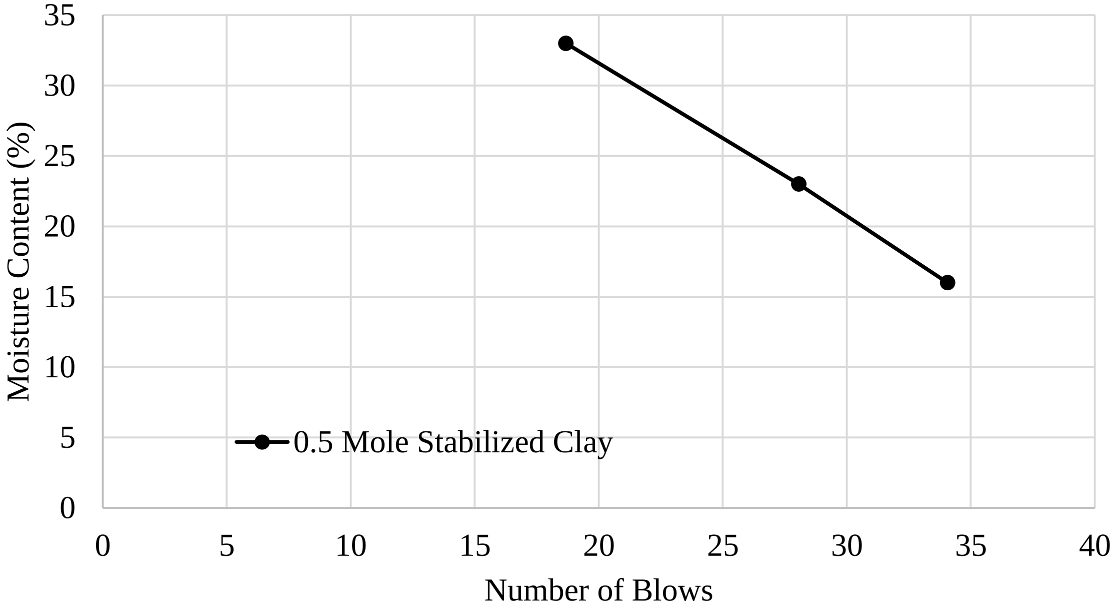

Figure 4-5: Relationship between number of blows and moisture content for soil stabilized with 0.5 mole of solution to find liquid limit.

4.3.3 Plastic Limit

ASTM Standard (D4318) was followed for finding the plastic limit of the soil which was determined to be 15% as shown in the table below.

Table 4-4: Plastic limit for soil stabilized with 0.5 Mole of solution.

Plastic limit Test		**PL of the soil**	
		Trial 1	Trial 2
Containers		A	B
Weight of the Container with Wet Soil	grams	39.6	40.5
Weight of the Container with Dry Soil	grams	38.3	39.6
Weight of empty container	grams	29.9	33.4
Weight of water	grams	1.3	0.9

Weight of dry soil	grams	8.4	6.2
Moisture Content of the samples	%	15.48	14.52

4.4 Soil Stabilized with 1 Mole

In order to make soil samples for 1 mole appropriate amount of Calcium Chloride and Urea was taken and mixed with the solution of centrifuged soybean and mixed with dry soil OMC which was then compacted in the mold at maximum dry density to prepare samples.

4.4.1 Partical Size Distribution:

Particle size distribution of the soil was performed according to ASTM ASTM D6913, the results for which are shown in the table below, the particle size distribution is shown below in figure 4-5.

Table 4-5: Grain size distribution data for soil stabilized with 1 mole of solution.

Sieve Sizes	Sieve Number	weight of the sieve (g)	Weight of soil plus sieve (g)	Retained Soil Weight (g)	Weight of Cumulative Soil retained (g)	Percent Passing (g)
0.59	30	406	406	0	0	100
0.42	40	400	415	15	15	97
0.3	50	381	412	31	46	90.8
0.177	80	380	398	18	64	87.2
0.149	100	380	399	19	83	83.4
0.074	200	367	460	93	176	64.8
	Pan	276	429	324	500	
Total soil Weight				500 (g)		

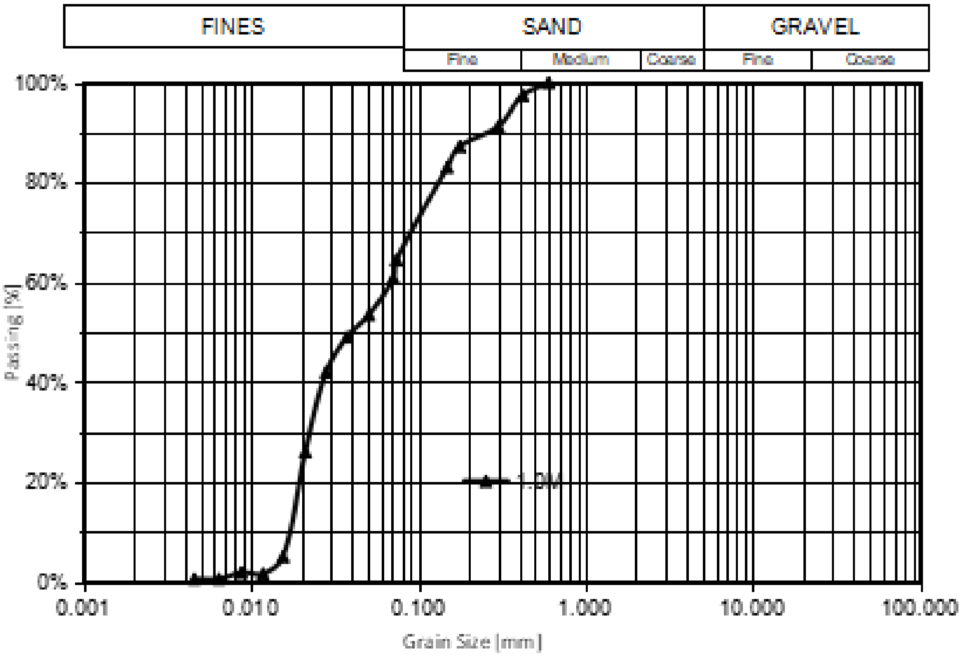

Figure 4-6 : Grain size distribution of soil stabilized with 1 mole of solution.

4.4.2 Liquid Limit:

ASTM Standard (D4318) was followed to determine the liquid limit (LL) of the soil which was determined to be 19.8% as shown in table below.

Table 4-6 : Data for determination of liquid limit of soil stabilized with 1 mole of solution.

Test		Liquid Limit		
Shocks Limit		15-25	20-30	25-35
No. of blows		18	24	29
Container Number		A	B	C
Weight of Wet Soil + Container	Grams	45.3	53.5	44
Weight of Dry Soil + Container	Grams	42	51	41.5
Weight of Container	Grams	30.7	38.6	25
Weight of Water	Grams	3.3	2.5	2.5
Weight of Dry Soil	grams	11.3	12.4	16.5

Moisture Content	%	29	20	15

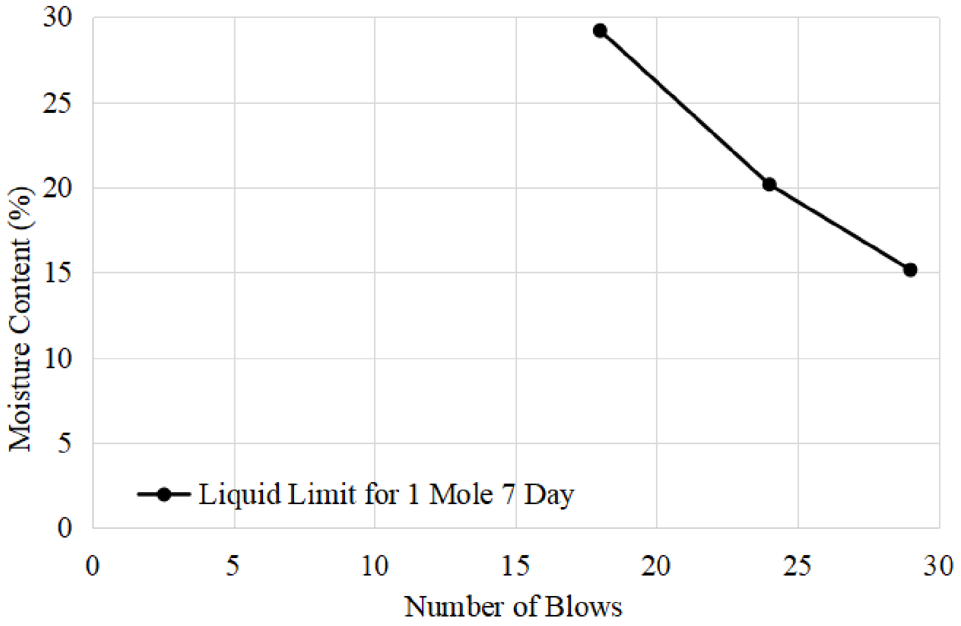

Figure 4-7 : Relationship between number of blows and moisture content for the determination of liquid limit for soil stabilized with 1 mole of solution.

4.4.3 Plastic Limit:

ASTM Standard (D4318) was followed to determine the liquid limit which is 11.5%. The data for the test performed is given in table 4-7.

Table 4-7 : Data for the determination of plastic limit for soil stabilized with 1 mole solution.

Test		**Plastic Limit**	
Shocks Limit		1	2
Number of blows			
Containers		A	B
Wet Soil Weight plus Container Weight	grams	37	41
Dry Soil Weight plus Container Weight	grams	36.3	40.2
Weight of Container	grams	29.9	33.4
Weight of Water	grams	0.7	0.8

Weight of Dry Soil	grams	6.4	6.8
Moisture Content	%	10.94	11.76
		Avg. P L	**11.35**

4.5 Soil Stabilized with 2.5 Mole:

In order to make soil samples for 2.5 moles appropriate amount of Calcium Chloride and Urea was taken and mixed with the solution of centrifuged soybean and mixed with dry soil according to OMC which was then compacted in the mold at maximum dry density to prepare samples.

4.5.1 Particle Size Distribution:

Partical size distribution of the soil was performed according to ASTM ASTM D6913, the results for which are shown in the table below, the partical size distribution is shown below in figure 4-8.

Table 4-8 : Sieve analysis data for soil stabilized with 2.5 mole of solution.

Sieve Sizes	Sieve #	Sieve Weight (g)	Sieve Weight plus soil (g)	Weight of retained soil on each sieve (g)	Cumulative retained (g)	Percent Passing (%)
0.59	30	406	406	0	0	100
0.42	40	400	412	12	12	97.6
0.3	50	381	414	33	45	91
0.177	80	380	400	20	65	87
0.149	100	380	402	22	87	82.6
0.074	200	367	460	93	180	64
	Pan	276	429	318	498	
Total soil Weight (g)			500			

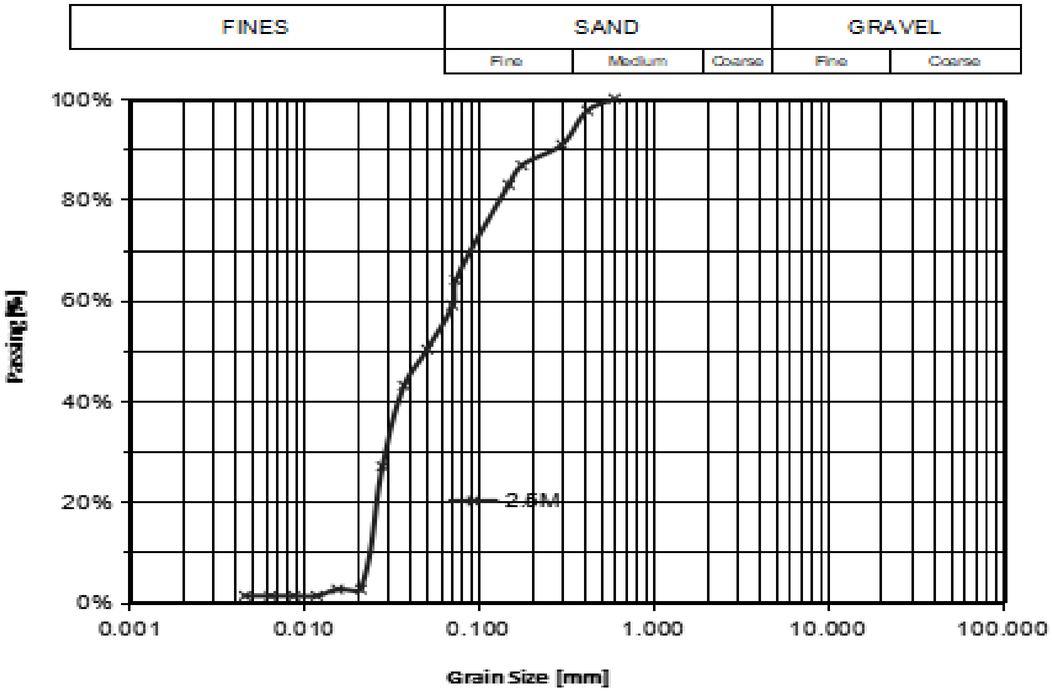

Figure 8 : Gradation Curve curve for soil stabilized with 2.5 Mole of solution.

4.5.2 Liquid Limit:

ASTM Standard (D4318) was followed to find the liquid limit . The liquid limit of the soil was determined to be 19%. The data for the test performed is given in table given below.

Table 4-9 : Data for determination of liquid limit of soil stabilized with 2.5 mole of solution.

Test		**Liquid Limit**		
Shocks Limit		15-25	20-30	25-35
No. of blows		19	24	33
Container Number		A	B	C
Weight of Wet Soil + Container	grams	49.8	58.3	46.2
Weight of Dry Soil + Container	grams	45.9	55.1	43.8
Weight of Container	grams	30.7	38.6	25
Weight of Water	grams	3.9	3.2	2.4

Weight of Dry Soil	grams	15.2	16.5	18.8
Moisture Content	%	26	19	13

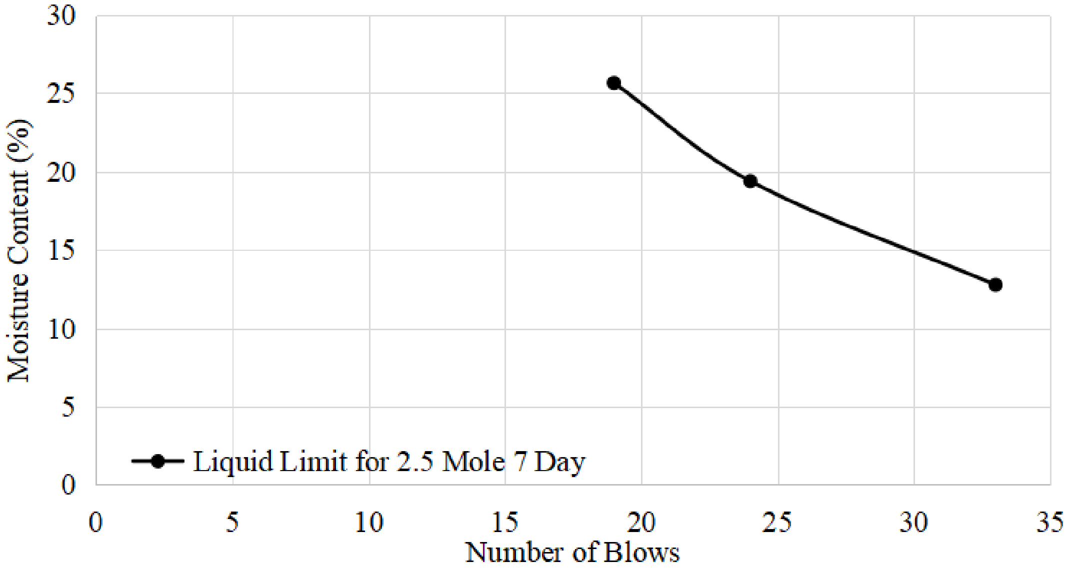

Figure 4-9: Relationship between number of blows and liquid limit for soil stabilized with 2.5 mole solution.

4.5.3 Plastic Limit:

ASTM Standard (D4318) was followed to find the plastic limit which is 11.5%. The data for the test performed is given in table 4-10.

Table 4-10 : Data for determination of plastic limit for soil stabilized with 2.5 moles of solution.

Test		**Plastic Limit**	
Shocks Limit		Trial 1	Trial 2
Blow Counts			
Containers		A	B
Weight of Wet soil weight and Container	grams	36	40.8
Dry Soil weight plus Container	grams	35.4	40
Weight of Container	grams	29.9	33.4
Weight of Water	grams	0.6	0.8

Weight of Dry Soil	grams	5.5	6.6
Moisture Content	%	10.91	12.12
		Avg P L	**11.52**

4.6 Preparation of Stabilized Samples for UCS Testing

Mix and compact method was sued to prepare stabilized samples for which oven dried soil passing through sieve #30 was taken, solution prepared by the above mentioned method was added to the soil according to the OMC of the soil, the samples were compacted in UCS mould and kept for saturation for 7 days. Upon the completion of curing period the samples were tested at two different humanities, 1) at laboratory humidity and oven dried conditions, for testing samples at oven dried conditions, the samples were kept in oven for 24 hours upon the completion of curing period.

Figure 4-10: Stabilized samples prepared with various molar concentration of EICP solution.

4.7 UCS Testing Soil Specimen:

UCS testing was conducted in according with ASTM D4918 on samples of 70mm diameter and 140mm length. The stabilized samples were prepared according to mix and compact method. Prior to performing the UCS test, the top and bottom surface of each sample was leveled.

The EICP solutions were made at varied urea-calcium chloride concentrations (0.5, 1 and 2.5 M) and soil samples for UCS tests were moulded in UCS mould.The cementing solution was prepared by first soaking 100 grams of soybean in water for 24 hours then the water and soybean was centrifuged, the slurry was passed throug a thin cloth to extract the juice which was added to the dry soil passed through #30 sieve soil was mixed thoroughly to get a uniform distribution of urease throughout the soil. The soil was compacted in ucs mould in 3 layers. After the compaction the samples were left to cure for seven days and then tested in UCS machine. Sampels were tested at two relative humidities at laboratory humidity and at oven dried conditions.

Figure 4-11 :Failure of the Sample in Unconfined Compression Testing.

UCS (Unconfined Compressive Strength) testing was conducted on samples under two different conditions: laboratory humidity and oven dried conditions. The samples were prepared and allowed to cure for seven days before testing.In the case of laboratory humidity testing, the samples were tested at the humidity level at which they were initially cured. This means that the samples were kept in an environment with the same humidity as during the curing process.For the oven dried conditions, the samples were first cured for seven days and then placed for drying in oven for twenty four hours. After the oven drying process, the samples were allowed to cool down for a short period of time and were immediately subjected to testing.

The results obtained from the UCS testing were then analyzed. It was observed that, for each concentration of the EICP solution, the UCS values for the oven dried conditions were consistently higher than those for the laboratory humidity conditions. In other words, the samples tested under oven dried conditions exhibited greater strength compared to the samples tested under laboratory humidity conditions.The figure provided below depicts the results of the UCS testing, illustrating the variation in strength for different concentrations of the EICP solution under the two testing conditions.

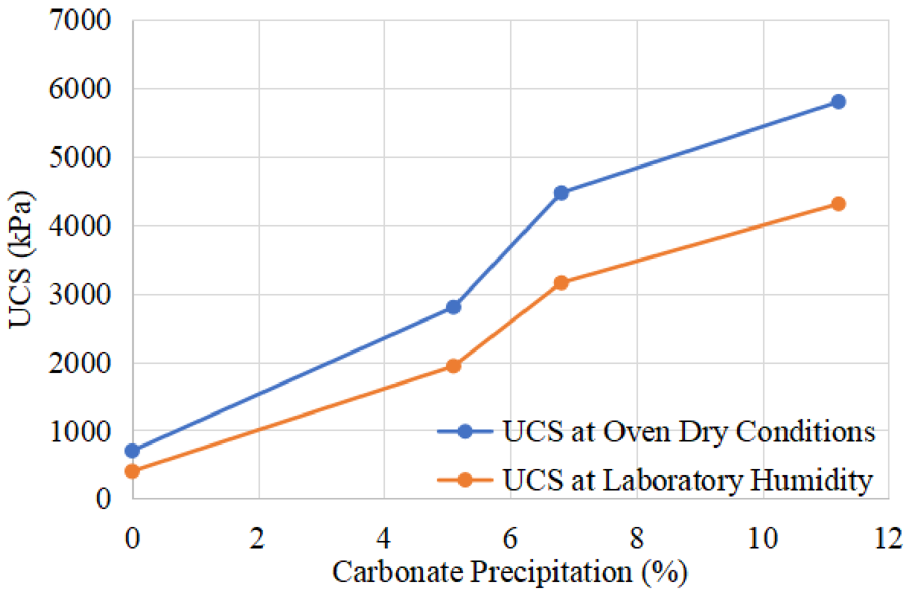

Figure 4-12: Relationship between carbonate content and unconfined compression stress.

4.8 Immersion Tests

Calcium chloride and urea were mixed in freshly centrifuged soybean extract to create the cementing solution. The calcium chloride and urea were added after the cementing solution had been completely mixed into the dry soil. To prevent the formation of calcite crystals, the solution was quickly compressed by hand into a sample that measured 70 mm in diameter and 140 mm in height. Similar to this, distilled water rather as the cementing solution was used to create a new series of samples.All samples were kept in reach the relative humidity and temperature of laboratory. Each sample's initial mass (mi) was noted, and an immersion test was used to gauge how well the samples stood up to water erosion. During the process of immersion the soil sample had to be submerged for ten minutes.The percentage of mass loss after immersion was then calculated using the following equation in combination with the beginning mass (mi) after recording the final sample mass (mf).

$$\%\Delta m = \frac{(m_i - m_f)}{m_i} \times 100$$

Immersion tests are frequently performed to determine how durable soil samples are, especially when exposed to water. In this study, immersion tests were carried out on soil samples that had been stabilised and those that had not. The results showed that the stabilised samples had less mass loss than the unstabilized ones.The disparity in mass loss can be attributed to the EICP (Electrolytic Induced Calcium Carbonate Precipitation) stabilization process facilitating the cohesion between soil particles and enhancing the overall stability and durability of the soil.

During the immersion test, the soil samples were immersed in water and allowed to soak for a specified duration. Over time, water infiltration causes the breakdown and erosion of soil particles, resulting in mass loss. However, the presence of EICP stabilization in the samples imparts a higher resistance to mass loss due to the interlocking of soil particles mediated by the calcium carbonate precipitation. This interlocking creates bonds between the particles, making them more resistant to erosion. Conversely, unstabilized samples lack such interlocking mechanisms, rendering them more susceptible to mass loss.

The obtained results from the immersion tests are consistent with the anticipated effects of EICP stabilization on soil durability. These findings hold practical implications for soil stabilization and erosion control practices. Further investigation and experimentation can be pursued to validate and expand upon these findings, thus contributing to the advancement of knowledge in this field.

Table 4-11 : Data for immersion tests on soil stabilized with 0.5 Moles of solution.

0.5 Mol/Liter	Sample Weight at Oven Dry Conditions	Prior to immersion, sample weight	Sample Weight following Submersion	Sample Weight at Oven dried conditions after immersion	Mass Loss %
Sample 01	941 (g)	951 (g)	780 (g)	779 (g)	17.22
Sample 02	933 (g)	946 (g)	802 (g)	788 (g)	15.54
Sample 03	951 (g)	962 (g)	780 (g)	765 (g)	19.56

Table 4-12 : Data for immersion tests on soil stabilized with 1 mole of solution.

1 Mol/Liter	Sample Weight at Oven Dry Conditions	Prior to immersion, sample weight	Sample Weight following Submersion	Sample Weight at Oven dried conditions after immersion	% Mass Loss
Sample 01	954 (g)	964 (g)	850 (g)	838 (g)	12.16
Sample 02	961 (g)	971 (g)	875 (g)	852 (g)	11.34
Sample 03	963 (g)	974 (g)	880 (g)	854 (g)	11.32

Table 4-13 : Data for immersion tests on soil stabilized with 2.5 Moles of solution.

2.5 Mol/Liter	Sample Weight at Oven Dry Conditions (g)	Prior to immersion, sample weight (g)	Sample Weight following Submersion (g)	Sample Weight at Oven dried conditions after immersion	% Mass Loss
Sample 01	983	1007	976	938	4.58
Sample 02	976	1003	968	930	4.72
Sample 03	981	1006	783	929	5.3

4.9 Acid Digestion Test:

20g of oven-dried soil samples were taken from each sample that had undergone EICP treatment in order to determine the calcium carbonate concentration. Using the gravimetric acid wash method, the calcium carbonate concentration was ascertained. The dry components were dissolved in the 4M HCl acid after being filtered using paper. Calculating the amount of calcium carbonate included comparing the mass of the dried samples before and after acid digestion. The leftover debris on the sieve was weighed after oven drying. The following equation provides the formula for determining calcium carbonate content:

$$\mathrm{CCC} = 100 - \left(\frac{B}{A}\right) \times 100$$

Where A represents the majority of the oven-dried treated soil before to washing, B represents the mass of oven dried soil after washing, and CCC represents the calcium carbonate content (%). Using acid digestion tests, the thesis investigated the carbonate content of soil samples. The samples were obtained from specimens that had undergone Unconfined Compressive Strength tests at molar concentrations of 0.5, 1, and 2.5. The average mass of each sample was 15g. During the acid digestion testing, the samples were soaked in hydrochloric acid (HCl) for 24 hours. The mass loss of the samples after the acid digestion process was recorded, which directly corresponded to the carbonate content present in the soil.

The findings revealed that the carbonate content varied based on the molar concentration. For the 0.5 mole concentration, a carbonate content of 5.1% was recorded. This indicates that the soil sample with a 0.5 mole concentration had a relatively lower carbonate content.In contrast, for the 1 mole concentration, the carbonate content was measured at 6.81%. This suggests an increase in carbonate content compared to the 0.5 mole concentration, indicating a higher concentration of carbonates in the soil sample.For the highest molar concentration of 2.5 mole, the recorded carbonate content was 11.2%. This indicates a significant increase in carbonate content compared to the lower molar concentrations, implying a higher concentration of carbonates present in the soil sample.

The results show that the carbonate content increased as the molar concentration increased, indicating a larger presence of carbonates in the soil. This suggests that the molar concentration has an influence on the carbonate content of the soil, which can be valuable information for assessing soil properties and potential stabilization techniques.Overall, these findings provide insights into the relationship between molar concentration and carbonate content, emphasizing the importance of considering the chemical composition of soil for various engineering and stabilization applications.

Table 4-14 : Data for Acid Digestion tests conducted on soil stabilized with 0.5,1 and 2.5 moles of EICP solution.

	Moles	weight before digestion	After digestion	% of Calcium Carbonate precipitation
7 Day	0.5	16.65 (g)	15.81 (g)	5.15%

	1	11.35 (g)	10.58 (g)	6.81 %
	2.5	15.23 (g)	13.52 (g)	11.22 %

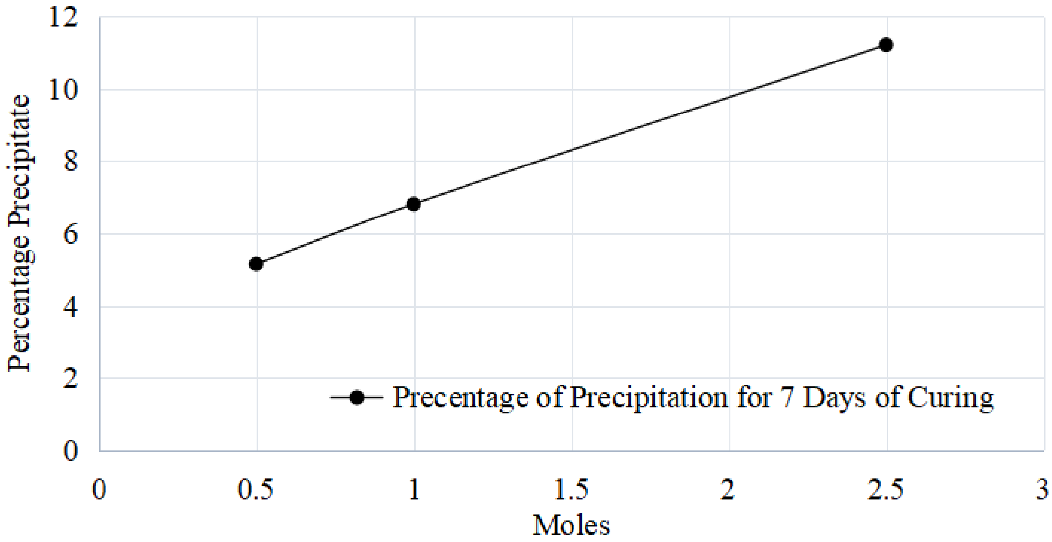

Figure 4-13 : The relationship between carbonate precipitation and moles of EICP solution.

4.10 Scanning Electron Microscopy for Stabilized Samples (SEM)

Scanning electron microscope (SEM) analysis was done to study stabilized soil samples and confirm the presence of carbonate crystals. The images captured during the analysis, shown in the figure below, clearly indicate that these crystals are spread throughout the sample. In other words, it was discovered that the carbonate crystals are evenly distributed in the soil.

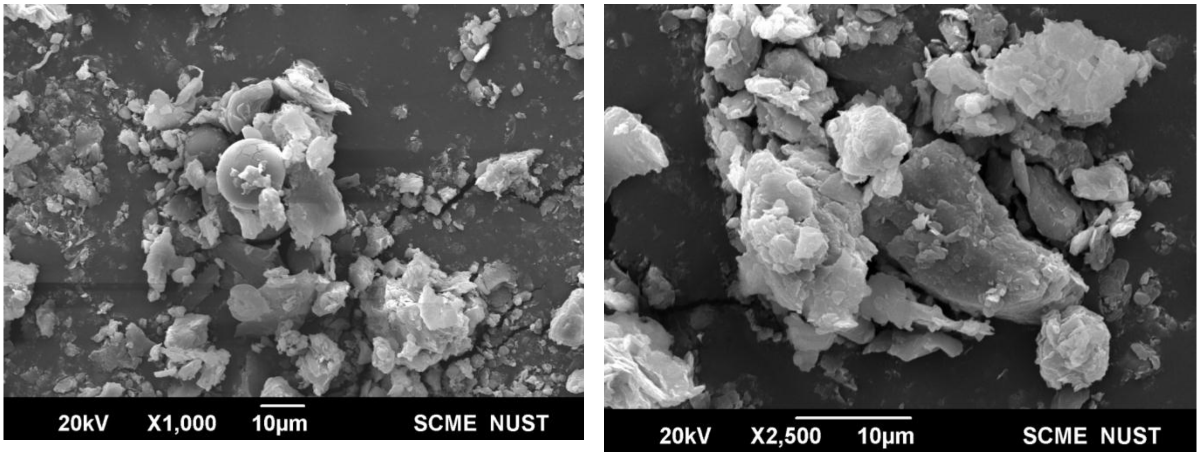

Figure 4-14: Images obtained from Scanning electron microscopy (SEM).

4.11 Energy Dispersive X-ray Analysis for Stabilized Samples (EDX)

On materials stabilized with EIC P, energy dispersive X-ray analysis was done. This technique enables the identification and quantification of components in a sample. The findings of the examination revealed the presence of calcium and carbon elements in the samples, indicating that calcium carbonate was formed.The material is bombarded with high-energy X-rays during the energy dispersive X-ray examination. The interaction of the X-rays with the atoms in the sample results in the emission of distinctive X-rays. These unique X-rays have distinct energy signatures that relate to specific components. The elemental composition of the sample can be established by detecting and measuring the energy of the emitted X-rays.The presence of calcium and carbon atoms in the samples implies the development of calcium carbonate in this scenario. Calcium carbonate is a common chemical formed by the reaction of calcium ions (Ca2+) and carbonate ions (CO_3 $^{2-}$) come together. The presence of calcium and carbon in the energy dispersive X-ray examination clearly suggests that calcium carbonate precipitated in the samples stabilised with EICP.

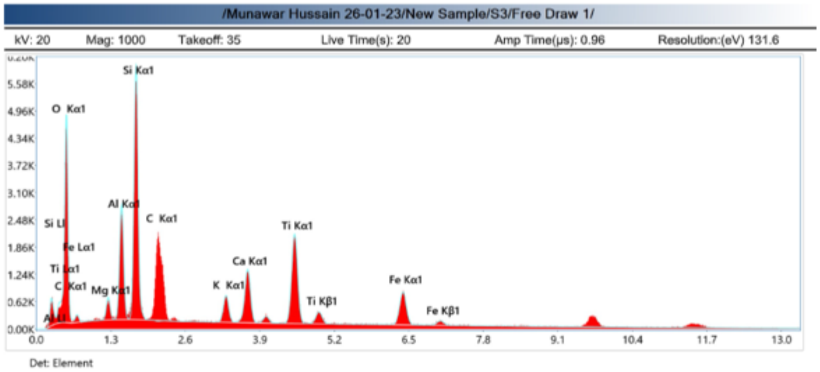

Figure 4-15: The elemental composition of the sample obtained as a result of energy dispersive x-ray analysis.

Chapter 5

5 Conclusions:

This chapter give the conclusions of this study. Furthermore it compares the improvement in the plasticity of the soil,in the uniaxial compressive strength of the soil and its resistance to immersion as a result of stabilization with Enzyme induced carbonate precipitation (EICP) technique.

5.1 Impact of EICP on Grain size distribution:

The study aimed to compare grain size using two different methods: sieve analysis and hydrometer analysis. The samples included unstabilized soil and soil stabilized with EICP. The results indicated that there was not a substantial difference in grain sizes when analyzed using sieve analysis. However, significant differences were observed when utilizing hydrometer analysis. In this method, it was found that the particle size increased with an increase in carbonate content as a result of EICP stabilization.

Sieve analysis is a technique that measures the grain size distribution of soil particles using a series of sieves with different mesh sizes. The results from this analysis suggested that the unstabilized soil and soil stabilized with EICP had relatively similar grain sizes, indicating minimal impact on particle size distribution due to the stabilization process.On the other hand, hydrometer analysis is a method that measures the particle size distribution of fine-grained soils by determining the settling velocity of soil particles in water. The results from hydrometer analysis revealed a noticeable difference in particle size between the unstabilized soil and soil stabilized with EICP. Specifically, as the carbonate content increased as a result of EICP stabilization, the particle size also increased.

These findings suggest that EICP stabilization, through an increase in carbonate content, had a more significant influence on the finer particles of the soil. This result may indicate that the stabilization process affected the cohesive and fine-grained components of the soil, leading to a change in particle size distribution. It highlights the importance of considering both sieve analysis and hydrometer analysis to comprehensively assess the impact of EICP stabilization on grain size characteristics in soil.

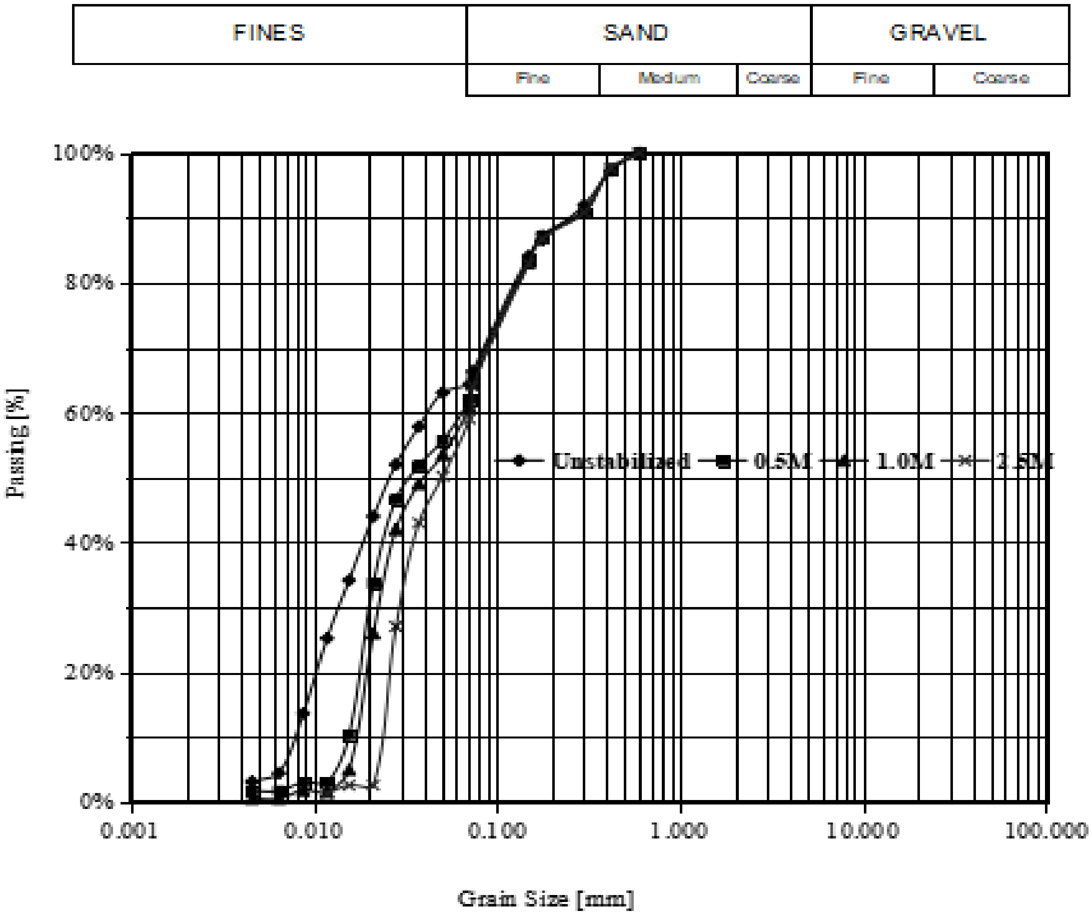

Figure 5-1: comparison of grain size distribution of unstabilized soil with soil stabilized with 0.5,1 and 2.5 moles of EICP solution.

5.2 Impact of EICP on Plasticity of Soil:

The study examined the influence of EICP (Electrolytic Induced Calcium Carbonate Precipitation) stabilization on the plasticity of soil. The liquid limit of the unstabilized soil was initially measured at 28. However, as the carbonate content increased due to EICP stabilization, the liquid limit progressively decreased.At a carbonate content of 5.1%, the liquid limit reduced to 26, indicating a slight reduction in the soil's plasticity compared to the unstabilized soil. This suggests that EICP stabilization had a minor effect on decreasing the soil's ability to undergo plastic deformation.With a higher carbonate content of 6.81%, the liquid limit further decreased to 21. This significant reduction indicates that EICP stabilization led to a notable decrease in the soil's plasticity. The soil became less prone to undergoing plastic deformation and exhibited improved stability.

Finally, at an even higher carbonate content of 11.2%, the liquid limit reached its lowest value of 19. This demonstrates that EICP stabilization at this level resulted in a substantial reduction in the soil's plasticity, indicating a highly stable soil with limited potential for plastic deformation.Overall, the results suggest that EICP stabilization has a considerable impact on the plasticity of soil.it results in reducing the plasticity of the soil. As the carbonate content increases, the soil's ability to undergo plastic deformation decreases, leading to improved stability and reduced potential for soil failure.

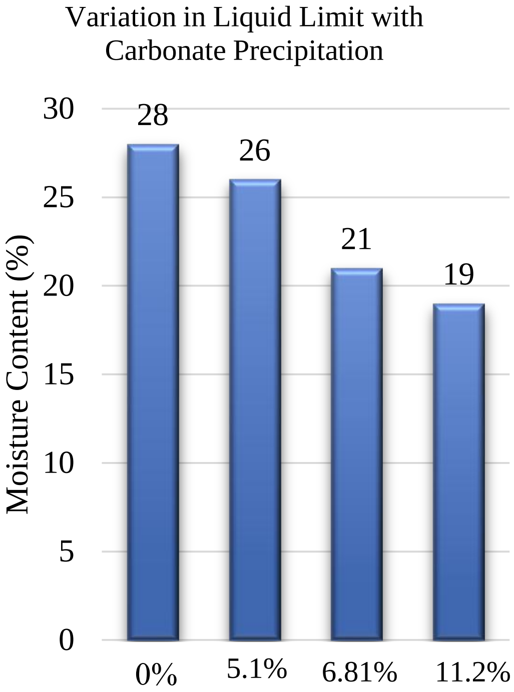

Figure 5-2 : Comparison of Liquid limit of unstabilized soil with soil stabilized with 0.5,1 and 2.5 mole of EICP solution.

The study focused on examining the effect of Enzyme Induced Calcium Carbonate Precipitation (EICP) stabilization on the plastic limit of soil. Initially, the unstabilized soil had a plastic limit of 15%. However, as the carbonate content increased due to EICP stabilization, the plastic limit of the soil decreased. At a carbonate content of 5.1%, the plastic limit reduced to 14%, indicating a slight decrease in the soil's ability to undergo plastic deformation. With a higher carbonate content of 6.81%, the plastic limit further decreased to 12%, suggesting a significant reduction in plasticity and improved soil stability. Finally, at 11.2% carbonate content, the plastic limit reached its lowest value of 11%, indicating a highly stable soil with a limited potential for plastic deformation. These findings demonstrate that EICP stabilization effectively reduces the plastic limit of soil, enhancing its stability and reducing the risk of soil failure.

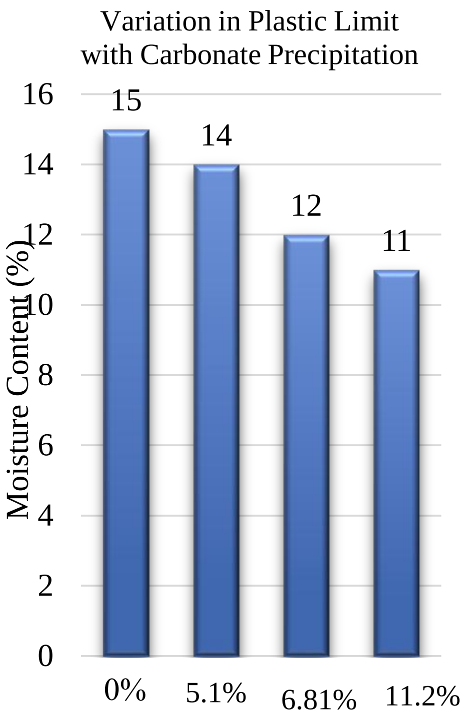

Figure 5-3: Comparison of Plastic limit of unstabilized soil with soil stabilized with 0.5,1 and 2.5 mole of EICP solution.

The thesis focused on investigating the relationship between carbonate content and the plasticity index of soil. The study examined unstabilized soil and compared it to soil samples stabilized with increasing levels of carbonate content through Enzyme Induced carbonate Precipitation (EICP).The results revealed that the unstabilized soil had a plasticity index of 13. However, as the carbonate content increased, the plasticity index consistently decreased. At 5.1% carbonate content, the plasticity index reduced to 12, indicating a slight decrease in the soil's plastic range. With a further increase in carbonate content to 6.81%, the plasticity index decreased to 9, signifying a significant reduction in the soil's plastic range.

At the highest carbonate content of 11.2%, the plasticity index reached its lowest value of 8. This indicates a considerable decrease in the soil's plastic range, suggesting that EICP stabilization and higher carbonate content lead to improved soil stability and reduced plasticity.These findings demonstrate that increasing the carbonate content through EICP stabilization effectively reduces the plasticity index of the soil. A lower plasticity index implies a narrower range of moisture content in which the soil exhibits plastic behavior. This reduced plasticity enhances soil stability, reduces potential deformations, and improves its overall engineering properties.Overall, the study highlights the beneficial effect of EICP stabilization and increased carbonate content on mitigating the plasticity of soil, making it more suitable for construction applications and reducing the risks associated with soil failure.

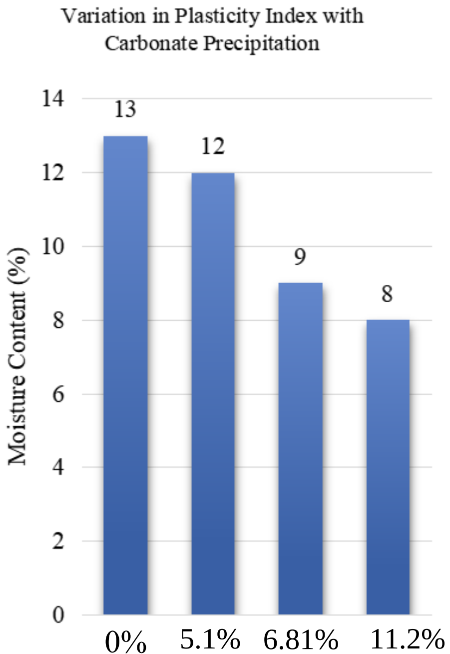

Figure 5-4: Comparison of plastic limit of unstabilized soil with soil stabilized with 0.5,1 and 2.5 mole of EICP solution.

5.3 Impact of EICP on UCS Strength of the soil:

The unconfined compression tests tests were conducted according ASTM D2166-06 standard. These tests were performed under two different conditions: laboratory humidity and oven dried conditions. The samples used in the tests included both unstabilized samples and samples stabilized with different amounts of EICP solution (0.5, 1, and 2.5 moles).The figure below illustrates the graphs depicting the UCS strengths at various carbonate content levels. The graphs illustrate that as the carbonate concentration increases, so does the unconfined compression strength. Additionally, it is observed that the strengths achieved at specific carbonate content levels are higher for the samples that were subjected to oven drying conditions compared to those tested under laboratory humidity.

This finding suggests that the samples that were dry and had lower moisture content exhibited greater strength. The reduced moisture content likely contributed to enhanced bonding between the particles, resulting in improved UCS strength. On the other hand, the samples tested under laboratory humidity conditions had higher moisture content, which might have led to weaker inter-particle bonding and consequently lower UCS strength.In conclusion, the figures demonstrate a favourable correlation between UCS strength and carbonate content. The study illustrates how oven drying may lower moisture levels and increase strength in the tested materials, underscoring the significance of moisture content even more.

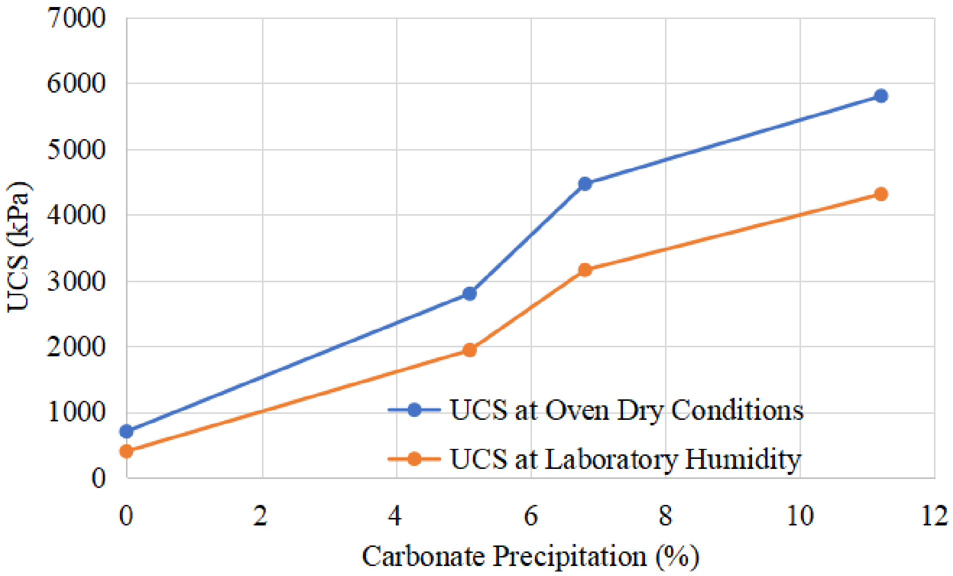

Figure 5-5 : Relationship between carbonate content and unconfined compression stress.

5.4 Impact of EICP on Erosion of the Soil:

The study investigated the impact of Electrolytic Induced Calcium Carbonate Precipitation (EICP) stabilization on soil erosion. Soil samples were immersed in water for 10 minutes, and the resulting mass loss was measured. The findings revealed that unstabilized soil experienced a mass loss of 21%. However, when the soil had a carbonate content of 5.1%, the mass loss decreased to 17.4%. With a higher carbonate content of 6.81%, the mass loss further decreased to 11.6%. The soil sample with the highest carbonate content of 11.2% exhibited the lowest mass loss of 4.86%. These results indicate that EICP stabilization, along with increased carbonate content, contributed to a significant reduction in soil erosion. The presence of carbonate in the soil strengthened its structure, mitigating the erosion process when exposed to water. These findings emphasize the importance of EICP stabilization and highlight the beneficial role of carbonate content in preventing soil erosion.

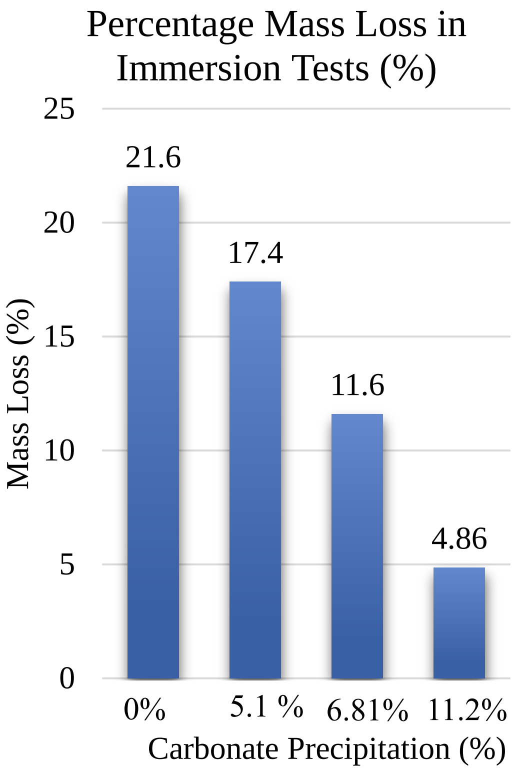

Figure 5-6: Comparison of Mass loss with carbonate content for unstabilized soil with soils of carbonate content of 5.1%.6.81% and 11.2%.

6 References:

1. Kavazanjian, E. and N. Hamdan, *Enzyme induced carbonate precipitation (EICP) columns for ground improvement*, in *IFCEE 2015*. 2015. p. 2252-2261.
2. Kavazanjian Jr, E., A. Almajed, and N. Hamdan, *Bio-inspired soil improvement using EICP soil columns and soil nails*, in *Grouting 2017*. 2017. p. 13-22.
3. Lin, P., R.J. Bathurst, and J. Liu, *Statistical evaluation of the FHWA simplified method and modifications for predicting soil nail loads.* Journal of Geotechnical and Geoenvironmental Engineering, 2017. **143**(3): p. 04016107.
4. Gowthaman, S., K. Nakashima, and S. Kawasaki, *Durability analysis of bio-cemented slope soil under the exposure of acid rain.* Journal of Soils and Sediments, 2021. **21**: p. 2831-2844.
5. Lee, M.H., et al., *Purification and characterization of Klebsiella aerogenes UreE protein: a nickel‐ binding protein that functions in urease metallocenter assembly.* Protein science, 1993. **2**(6): p. 1042-1052.
6. Saif, A., et al., *Advances in enzyme induced carbonate precipitation and application to soil improvement: A review.* Materials, 2022. **15**(3): p. 950.
7. Hamdan, N., E. Kavazanjian Jr, and S. O'donnell. *Carbonate cementation via plant derived urease*. in *Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering*. 2013.
8. Tobler, D.J., M.O. Cuthbert, and V.R. Phoenix, *Transport of Sporosarcina pasteurii in sandstone and its significance for subsurface engineering technologies.* Applied geochemistry, 2014. **42**: p. 38-44.
9. Das, N., A.M. Kayastha, and P.K. Srivastava, *Purification and characterization of urease from dehusked pigeonpea (Cajanus cajan L.) seeds.* Phytochemistry, 2002. **61**(5): p. 513-521.
10. Hamdan, N. and E. Kavazanjian Jr, *Enzyme-induced carbonate mineral precipitation for fugitive dust control.* Géotechnique, 2016. **66**(7): p. 546-555.
11. Bang, S.S., et al., *Application of novel biological technique in dust suppression*. 2009.

12. Andrus, R.D. and R.M. Chung, *Ground improvement techniques for liquefaction remediation near existing lifelines*. 1995: US National Institute of Standards and Technology Gaithersburg, MD, USA.
13. Arab, M.G., et al., *State-of-the-art review of enzyme-induced calcite precipitation (EICP) for ground improvement: Applications and prospects.* Geosciences, 2021. **11**(12): p. 492.
14. Park, S.-S., S.-G. Choi, and I.-H. Nam, *Effect of plant-induced calcite precipitation on the strength of sand.* Journal of Materials in Civil Engineering, 2014. **26**(8): p. 06014017.
15. Yasuhara, H., et al., *Experiments and predictions of physical properties of sand cemented by enzymatically-induced carbonate precipitation.* Soils and Foundations, 2012. **52**(3): p. 539-549.
16. Simatupang, M. and M. Okamura, *Liquefaction resistance of sand remediated with carbonate precipitation at different degrees of saturation during curing.* Soils and foundations, 2017. **57**(4): p. 619-631.
17. Cho, G.-C., J. Dodds, and J.C. Santamarina, *Closure to "particle shape effects on packing density, stiffness, and strength: natural and crushed sands" by Gye-Chun Cho, Jake Dodds, and J. Carlos Santamarina.* Journal of geotechnical and geoenvironmental engineering, 2007. **133**(11): p. 1474-1474.
18. Juneja, A., et al., *Bio cemented Sands.*
19. Putra, H., et al., *Improving shear strength parameters of sandy soil using enzyme-mediated calcite precipitation technique.* Civil Engineering Dimension, 2018. **20**(2): p. 91-95.