EFFECT OF CONFINING PRESSURE ON THE CEMENT TREATED SOIL

A Thesis

by

PRASHANT MADHUKAR PATIL

Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Chair of Committee,	Jean-Louis Briaud
Committee Members,	Marcelo Sanchez
	Terry Creasy
Head of Department,	Robin Autenrieth

May 2019

Major Subject: Civil Engineering

ABSTRACT

Low workability and high water content in soil cause many problems in construction industry. The best way to deal with this is to replace the existing soil by good quality soil which may not be feasible every time due to scarcity of good quality soil. This issue forces engineers to work on soil stabilization. Out of those many methods of soil stabilization, mixing an admixture like cement, fly ash etc., with soil is the most common method. These additives affect chemical and mechanical properties like bearing capacity, elastic behavior of treated soil, so an additive should be chosen depending upon the soil properties and purpose of stabilization. Unconfined compressive strength is also one of those important parameters which are taken into consideration during soil stabilization but in real life, soil has confining pressure because of the soil present around the specimen under consideration. To follow this actual field situation in analysis and design program, it's necessary to check the effect of the confinement on the strength of the soil.

This study mainly deals with finding out the effect of level of confinement on confined compressive strength of the cement treated soil at different cement to soil weight ratio and different curing periods. To have an idea about the strength of the soil without confinement, specimen for all proportions and curing periods are tested for unconfined compression strength and split tensile strength also.

CONTRIBUTORS AND FUNDING SOURCES

Contributors

The research work mentioned in this thesis is supervised by a thesis committee comprising of Dr. Jean-Louis Briaud [Advisor] and Dr. Marcelo Sanchez of the Zachry Department of Civil Engineering and Dr. Terry Creasy of the Department of Material Science and Engineering at Texas A&M University.

Material required for the study has been provided by Mr. Dennis Boehm, senior vice president at Hayward baker and Dr. Brian Freilich, Mr. Dean Sudderth, Engineers at Hayward Baker.

All work for the thesis is done by the student independently.

Funding Sources

University has provided all the equipment required for the thesis.

TABLE OF CONTENTS

LIST OF FIGURES

Page

LIST OF TABLES

CHAPTER I

INTRODUCTION

Depending upon the water content and other properties like plasticity index, flow index etc., a soil can be classified as workable and non-workable. The higher the water content and plasticity index, the lower the workability is. Low workability and high water content in a soil leads to many problems in construction processes [1] including differential settlement and lateral movement etc., while working on such soils. The most used conventional alternative for such situations is to replace the soil with good quality material. Replacing a soil may not be an economical solution depending upon availability and location. To avoid this problem and to make the existing soil more workable, soil stabilization and modification are taken into consideration.

Soil stabilization can be done by adding some chemicals into soil, some naturally available material like jute fiber or providing some synthetic reinforcing material like polypropylene fiber. Every additive possesses different physical and chemical properties which play an important role in deciding the behavior of soil after treatment. Unconfined compressive strength is one of those important properties of soil which impact the suitability of soils for construction use. It represents the vertical load carried by the isolated soil matrix without any confining pressure around it. In real life situation and almost all cases, soil will not be in an unconfined state so considering unconfined strength as a parameter to decide the type and dosage of the additive may not be the best decision although probably a conservative one. Confinement provides increased vertical load capacity which is overlooked in considering unconfined strength only. As the depth increases, the overburden pressure increases and does the confining pressure. To maintain a real-life situation in analyzing the treated soil, it’s always better to consider the confinement around the soil matrix.

The soil used in this study is from a construction site in New Orleans, handled by the Hayward Baker company. This study deals with finding out basic properties of soil to decide the best suitable additive, measuring the effect of different proportions of cement on soil, determining the influence of curing period and confinement pressure on compressive strength of the soil. The effect of cement treatment and confining pressure on the modulus of elasticity and shear parameters is also studied. The split tensile strength is also measured for all proportions and curing periods.

CHAPTER II

LITERATURE REVIEW

Selecting a suitable stabilizing agent or an additive is an important step in soil stabilization. Many factors such as water content, organic matter present in soil, pH of the soil affect this selection process. Out of those many methods for selecting an appropriate additive, Currin et al and US army method are most commonly used. Figure 1 reprinted from [8] shows Currin et al. criteria to be followed to select the best suitable additive for soil stabilization.

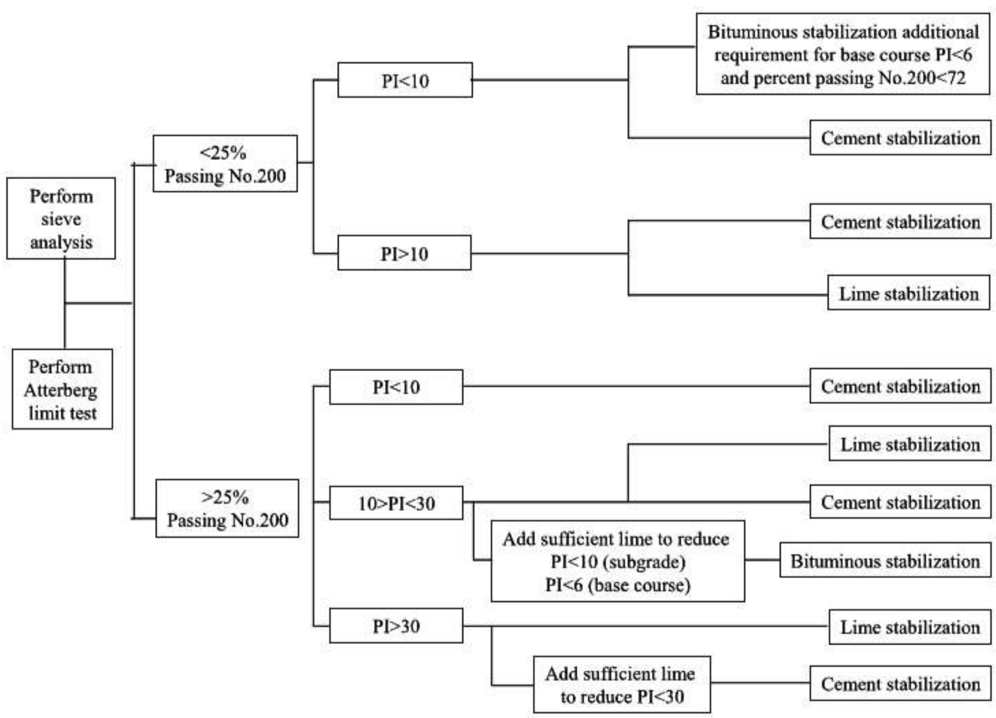

Figure 1 Selection Criteria for an Additive Reprinted From [8]

US army method depends on the gradation properties of the soil as shown in Table 1 adapted from [18]. Soil is basically classified by following United States Classification System and depending upon plasticity index the additive is selected.

Table 1 Additive Selection Criteria Adapted From [18]

Soil Classification	Type of Stabilizing Additive Recommended	Restriction on Liquid Limit and Plasticity Index	Restriction on Percent Passing Sieve #200	Remarks
SW or SP	Bituminous			
	Portland Cement			
	Lime-Cement-Fly Ash	PI≤25		
SW-SM or SP-SM or SW-SC or SP-SC	Bituminous	PI≤10		
	Portland Cement	PI≤30		
	Lime	PI≤12		
	Lime-Cement-Fly Ash	PI≤25		
SM or SC or SM-SC	Bituminous	PI≤10	Not to exceed 30% by Weight	

Table 1. Continued

Soil Classification	**Type of Stabilizing Additive Recommended**	**Restriction on Liquid Limit and Plasticity Index**	**Restriction on Percent Passing Sieve #200**	**Remarks**
SM or SC or SM-SC	Portland Cement	B**		
	Lime	PI≤12		
SM or SC or SM-SC	Lime-Cement-Fly Ash	PI≤25		
GW or GP	Bituminous			Well graded material only
	Portland Cement			Material should contain at least 45% by weight of material passing sieve #4
	Lime-Cement-Fly Ash	PI≤25		
GW-GM or GP-GM	Bituminous	PI≤10		Well graded material only

Table 1. Continued

Soil Classification	**Type of Stabilizing Additive Recommended**	**Restriction on Liquid Limit and Plasticity Index**	**Restriction on Percent Passing Sieve #200**	**Remarks**
GW-GM or GP-GM or GW-GC or GP-GC	Portland Cement	PI≤30		Material should contain at least 45% by weight of material passing sieve #4
	Lime	PI≤12		
	Lime-Cement-Fly Ash	PI≤25		
GM or GC or GM-GC	Bituminous	PI≤10	Not to exceed 30% by Weight	Well graded material only
GM or GC or GM-GC	Portland Cement	B**		Material should contain at least 45% by weight of material passing sieve #4

Table 1. Continued

Soil Classification	**Type of Stabilizing Additive Recommended**	**Restriction on Liquid Limit and Plasticity Index**	**Restriction on Percent Passing Sieve #200**	**Remarks**
GM or GC or GM-GC	Lime	PI≤12		
	Lime-Cement-Fly Ash	PI≤25		
CH or CL or MH or ML or OH or OL or ML-CL	Portland Cement	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
	Lime	PI≥12		

Using cement for stabilizing the soil is a common method in Geotechnical engineering since last many years[2]. In case of a plastic silt, lime and cement is used to modify the soil strength. Soil can be treated with cement only if the organic matter is less than 2% or Ph more than 5.3. Cement reduces the Maximum dry density and increases the

OMC. Also, it increases plastic limit but reduces liquid limit resulting in low plasticity index. Cement increases the strength of soil, reduces shrinkage and swelling. Soils having PI value more than 30% are not workable for cement stabilization so Lime can be added prior to cement to make the soil more workable[3]. Addition of cement and lime in soil increases hydromechanical properties and workability of the silt. Sometimes due to high water content, silt may not be workable so to dewater it, lime can be added at first. Lime addition causes agglomeration of the clay and cement increases the mechanical properties of the soil.[4] Though lime has more potential to reduce the swell index but at the same time it increases the pH of soil and also proved to be expensive [5]. Also, unconfined compressive strength of cement treated soil is always more than the lime treated soil. Due to pozzolanic reaction, the gelatinous material is formed which cements and increases the binding strength. Higher dosage of lime does not guarantee increase in the strength of soil which is not always true in case of cement. Still there is a need to decide the optimum dosage of the binder as lower dosage changes the index properties of the soil but strength parameters may not be affected[6]. Depending upon moisture content and plasticity index, lime could have been used in this study but absence of aluminates and silicates in silts, makes lime unsuitable [17]. Also, the cement addition in soil in previous studies has shown that the liquid limit of the soil decreases upon increase in the cement dosage while plastic limit increases accordingly which converts the medium plasticity soil to low plasticity soil[7]. According to Currin et al., for granular soils and clays with low plasticity index, cement is the best additive [8]. Cement addition increases the unconfined compressive strength, preconsolidation pressure and at the same time it has least environmental issues[9].

Basically, soil behavior is affected by the confining pressure in real so there is no logic in considering unconfined compression strength to determine the effectiveness of the soil stabilization [17]. Strength and deformation properties of the treated soil may be affected by the confining stress present at deep ground. Young's modulus, stiffness, peak strength and bulk modulus increase with curing time regardless of confining pressure, but soil samples sheared under high confining pressure resulted in higher values of mentioned parameters. It has been observed that with the increase in the confining pressure during shearing, the dilatancy decreases irrespective of curing period[10]. Also, the modulus of elasticity of the specimen is affected by confining pressure but the relation is non-linear and depends on the stress field too[11]. Other properties of soil like Poisson's ratio are also affected by the confining pressure. Poisson's ratio decreases with the increase in the confining pressure and the percentage reduction is higher for higher confining pressure and higher shear strain[12]. To check the effect of confining pressure, specimen with same amount of cementation should be tested at different confining pressure. It will give a clear idea about change in compressive strength with change in the confining pressure. If the confining pressure is kept constant, then treated soil showed higher strength than untreated soil. For specimen with same cement dosage, specimen with low confinement show gradual softening after peak while specimen with high confinement show brittleness after reaching peak. Even for cemented sand, the stress-strain behavior is judged by confinement level [13]. For microbial induced calcite precipitated sand, low cementation or high confinement showed reduction in strain softening. Also, increase in confining pressure or decrease in cement content decreases the peak and residual friction angle [14].

Generally, it has been observed that strength envelope levels off with increasing confining pressure and the effect of confining pressure is observed to be weakened with increase in the moisture content[15]. For these reasons, it will be interesting to know the effect of cementation on strength parameters of silt and variation in those parameters on the application of different confining pressures.

CHAPTER III

MATERIALS AND METHODOLOGY

3.1 Materials

The two main materials in this study are soil and cement. Soil at the construction site at New Orleans is used for the experimentation purpose. This soil has high water content of 76%. The basic properties of the soil are found out to check the suitability of the specific additive to the soil. ASTM standards are used without deviation for finding out these properties. Observed basic properties of soil through experimentations are listed below.

1) Natural Water Content = 76%
2) Specific Gravity of soil = 2.21
3) Liquid Limit of soil =54.8%
4) Plastic Limit of soil = 33.26%
5) Plasticity Index of soil = 21.54%
6) Soil Classification as per plasticity chart = MH
7) Organic Content = 2.27%
8) pH of soil = 8.3
9) Shear Strength by mini vane shear test = 6.48 KPa

Plasticity Index of the soil is observed to be less than 30 and pH is 8.3 so it is advisable to use cement as an additive.

Another important material is cement which is mixed with the soil in the form of a grout. Type I/II ordinary Portland cement is used for preparing grout.

3.2 Methodology

1)Soil samples taken from different depths should be combined into a composite sample. Testing shall include:

- Soil Classification - ASTM D2487
- Water Content - ASTM D2216
- Atterberg Limits - ASTM D4318
- Grain Size Analysis - ASTM D422 (sieve and hydrometer)
- Organic Content – ASTM D2974
- pH

2) Composite soil samples should be mixed with different amounts of ordinary Portland cement slurry.

3) Specimens are to be prepared using 3 binder dosages (7.5% (Type A), 11.5% (Type B), and 15.5% (Type C) by weight). The cement content is expressed as (weight of the dry cement)/(total weight of soil including soil solids, water from soil and grout). Table 2 shows the measurements for the grout and soil proportions.

4) Hobart Model A200 mixer or an equivalent mixer can be used to mix the soil with a grout as shown in figure 2.

The mixing process is done in 4 steps lasting for a minute. The soil is mixed in a mixer alone for first 15 seconds on lowest speed setting or on first gear. Mixer needs to be stopped and any material sticking to it is scrapped off to ensure well mixing. Half of the grout is added to the soil and mixed well for 15 second on same setting. Scrapping is done again, and remaining grout is added to be mixed for next 15 seconds. At last stage, sides of the mixer and hook is scrapped off and soil is mixed for last 15 seconds.

Table 2 Grout and Soil Mix Proportions

	Grout for mix type A		Grout for mix type B		Grout for mix type C	
	Pounds	Kilograms	Pounds	Kilograms	Pounds	Kilograms
Total Weight of soil*	17.51	7.94	16.07	7.28	14.63	6.63
Weight of water in soil (70%)	12.25	5.56	11.24	5.09	10.24	4.65
Total weight of soil solids at 70% water content	5.25	2.38	4.821	2.18	4.389	1.98
Cement Weight (dry)	1.43	0.640	2.10	0.950	2.70	1.223
Weight of water added in grout	1.57	0.712	2.19	0.996	2.82	1.281
Cement Content ** (%)	7.5		11.50		15.5	

Total Weight of soil* = Weight of solids and water

Cement Content ** = weight of dry cement / Weight of solids and total water from soil and grout

5) After blending, the grout-soil mixture was filled in greased 2" by 4" plastic cylindrical molds and tamped into the mold to form a uniform mass with minimal voids and cured in the plastic cylinder molds with tightly fitted plastic caps. Figure 3 represents the prepared soil samples which are to be cured.

Figure 2 Soil and Grout Mixing in a Mixer

Specimen were stored in a curing environment meeting the requirements of ASTM C 511 Specification for Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes.

6) Specimen were cured for 7, 28 and 56 days and tested for unconfined compressive strength, confined compressive strength and split tensile strength. Strain rate for compression testing was maintained to be 0.02 inch/minute or 18% per hour for a 4-inch tall specimen. Specimen failed in unconfined and confined compression are shown in figure 4 while figure 5 shows specimen failed in split tensile test.

7) Stress-strain diagrams are to be plotted to find out the modulus of deformation of soil specimen after stabilization.

Figure 3 Prepared Soil Samples

Figure 4 Specimen Failed in Unconfined and Confined Compression Test

8) The effect of cement treatment on the shear parameters of the soil is needed to be checked and Mohr circle method is to be followed to find out those parameters.

Figure 5 Specimen Failed in Split Tensile Test

CHAPTER IV

RESULTS AND DISCUSSION

As discussed in chapter II, soil behavior is influenced by the confinement pressure present around it. In literature it is found that soils with different additives have shown change in the behavior after providing confinement. Few soils have shown softening while few showed brittle failure after reaching peak strength depending upon the amount of confining pressure. Also, shear parameters like the peak and residual friction angle, cohesion are affected by the magnitude of confinement so it's necessary to know the effect of different magnitudes of confinement on soil strength parameters. This study is to find out the effect of confinement on cement treated silt. Magnitude of the confinement provided is 34 KPa or 5 PSI and 103 KPa or 15 PSI. Table 3 gives summary of the main test program and ASTM standards followed during this study. The detailed test pattern is as mentioned in the Table 4.

Table 3 Summary of Tests Performed During Study

Test	**ASTM Followed**
Moisture content of soil	ASTM D2216
Specific Gravity of soil	ASTM D854
Liquid limit of soil	ASTM D4318
Plastic limit of soil	ASTM D4318
Soil classification	ASTM D2487
Organic Content	ASTM D2974

Table 3. Continued

Test	ASTM Followed
pH of soil	ASTM D4972
Shear strength of soil by mini vane shear test	ASTM D4648
Split Tensile Test	ASTM C496
Unconfined compression Test	ASTM D4767
Confined Compression test with 34 KPa confinement	ASTM D4767
Confined Compression test with 103 KPa confinement	ASTM D4767

Table 4 Detailed Test Pattern

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-1	Moisture content of soil	1	Natural	-	-	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-2	Specific Gravity of soil	1	Natural	-	-	-
T-3	Liquid limit of soil	1	Natural	-	-	-
T-4	Plastic limit of soil	1	Natural	-	-	-
T-5	Soil classification	1	Natural	-	-	-
T-6	Organic Content	1	Natural	-	-	-
T-7	pH of soil	1	Natural	-	-	-
T-8	Shear strength by mini vane shear test	1	Natural	-	-	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-9	Split Tensile Test	1	Treated	7.5	7	-
T-10	Split Tensile Test	2	Treated	7.5	7	-
T-11	Split Tensile Test	1	Treated	7.5	28	-
T-12	Split Tensile Test	2	Treated	7.5	28	-
T-13	Split Tensile Test	1	Treated	7.5	56	-
T-14	Split Tensile Test	2	Treated	7.5	56	-
T-15	Split Tensile Test	1	Treated	11.5	7	-
T-16	Split Tensile Test	2	Treated	11.5	7	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-17	Split Tensile Test	1	Treated	11.5	28	-
T-18	Split Tensile Test	2	Treated	11.5	28	-
T-19	Split Tensile Test	1	Treated	11.5	56	-
T-20	Split Tensile Test	2	Treated	11.5	56	-
T-21	Split Tensile Test	1	Treated	15.5	7	-
T-22	Split Tensile Test	2	Treated	15.5	7	-
T-23	Split Tensile Test	1	Treated	15.5	28	-
T-24	Split Tensile Test	2	Treated	15.5	28	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-25	Split Tensile Test	1	Treated	15.5	56	-
T-26	Split Tensile Test	2	Treated	15.5	56	-
T-27	Unconfined Compression Test	1	Treated	7.5	7	-
T-28	Unconfined Compression Test	2	Treated	7.5	7	-
T-29	Unconfined Compression Test	1	Treated	7.5	28	-
T-30	Unconfined Compression Test	2	Treated	7.5	28	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-31	Unconfined Compression Test	1	Treated	7.5	56	-
T-32	Unconfined Compression Test	2	Treated	7.5	56	-
T-33	Unconfined Compression Test	1	Treated	11.5	7	-
T-34	Unconfined Compression Test	2	Treated	11.5	7	-
T-35	Unconfined Compression Test	1	Treated	11.5	28	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-36	Unconfined Compression Test	2	Treated	11.5	28	-
T-37	Unconfined Compression Test	1	Treated	11.5	56	-
T-38	Unconfined Compression Test	2	Treated	11.5	56	-
T-39	Unconfined Compression Test	1	Treated	15.5	7	-
T-40	Unconfined Compression Test	2	Treated	15.5	7	-

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-41	Unconfined Compression Test	1	Treated	15.5	28	-
T-42	Unconfined Compression Test	2	Treated	15.5	28	-
T-43	Unconfined Compression Test	1	Treated	15.5	56	-
T-44	Unconfined Compression Test	2	Treated	15.5	56	-
T-45	Confined Compression Test	1	Treated	7.5	7	34

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-46	Confined Compression Test	2	Treated	7.5	7	34
T-47	Confined Compression Test	1	Treated	7.5	28	34
T-48	Confined Compression Test	2	Treated	7.5	28	34
T-49	Confined Compression Test	1	Treated	7.5	56	34
T-50	Confined Compression Test	2	Treated	7.5	56	34

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-51	Confined Compression Test	1	Treated	11.5	7	34
T-52	Confined Compression Test	2	Treated	11.5	7	34
T-53	Confined Compression Test	1	Treated	11.5	28	34
T-54	Confined Compression Test	2	Treated	11.5	28	34
T-55	Confined Compression Test	1	Treated	11.5	56	34

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-56	Confined Compression Test	2	Treated	11.5	56	34
T-57	Confined Compression Test	1	Treated	15.5	7	34
T-58	Confined Compression Test	2	Treated	15.5	7	34
T-59	Confined Compression Test	1	Treated	15.5	28	34
T-60	Confined Compression Test	2	Treated	15.5	28	34

Table 4. Continued

Sr. No.	**Test Name**	**Sample No.**	**Soil Type**	**Cement Content (%)**	**Curing Period (Days)**	**Confinement Pressure (kPa)**
T-61	Confined Compression Test	1	Treated	15.5	56	34
T-62	Confined Compression Test	2	Treated	15.5	56	34
T-63	Confined Compression Test	1	Treated	7.5	7	103
T-64	Confined Compression Test	2	Treated	7.5	7	103
T-65	Confined Compression Test	1	Treated	7.5	28	103

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-66	Confined Compression Test	2	Treated	7.5	28	103
T-67	Confined Compression Test	1	Treated	7.5	56	103
T-68	Confined Compression Test	2	Treated	7.5	56	103
T-69	Confined Compression Test	1	Treated	11.5	7	103
T-70	Confined Compression Test	2	Treated	11.5	7	103

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-71	Confined Compression Test	1	Treated	11.5	28	103
T-72	Confined Compression Test	2	Treated	11.5	28	103
T-73	Confined Compression Test	1	Treated	11.5	56	103
T-74	Confined Compression Test	2	Treated	11.5	56	103
T-75	Confined Compression Test	1	Treated	15.5	7	103

Table 4. Continued

Sr. No.	Test Name	Sample No.	Soil Type	Cement Content (%)	Curing Period (Days)	Confinement Pressure (kPa)
T-76	Confined Compression Test	2	Treated	15.5	7	103
T-77	Confined Compression Test	1	Treated	15.5	28	103
T-78	Confined Compression Test	2	Treated	15.5	28	103
T-79	Confined Compression Test	1	Treated	15.5	56	103
T-80	Confined Compression Test	2	Treated	15.5	56	103

4.1 Effect of Cement Mixing on The Unconfined Compression Strength

The unconfined compression strength of the soil in natural condition was measured to be 6.48 KPa which was expected to be increased with the addition of cement. During this study, unconfined compression strength is observed to be increasing with increase in cement content and curing period too. Table 5 gives an idea about different values of unconfined compressive strength for type A samples over varying curing period.

Table 5 Unconfined Compression Strength (kPa) of Type A samples

Curing Period in Days	**Strength of Sample 1 (kPa)**	**Strength of Sample 2 (kPa)**	**Average Strength**
7	102.46 (T-27)	119.23 (T-28)	110.85 (Average of T-27 and T-28)
28	183.03 (T-29)	153.82 (T-30)	168.42 (Average of T-29 and T-30)
56	239.17 (T-31)	217.31 (T-32)	228.24 (Average of T-31 and T-32)

Even with low binder content of 7.5% by weight, the unconfined compression strength of the soil has been increased to 110.85 KPa over 7 days curing period and while it is measured to be 228 KPa after 56 days. For same amount of binder dose, samples after 28 days curing have shown maximum stiffness than samples tested after 7 and 56 days. Main binding force generated by chemical reaction is affected by the amount of water present in the soil cement mixture over the curing period. The heat generated because of this chemical reaction might have evaporated the water, leaving some internals cracks in the sample which decreased the stiffness of the treated soil after 28 days. Figure 6, 7 and 8 show the stress Vs strain patterns for Type A samples which are cured for 7, 28 and 56 days respectively.

The preciseness of the mixing process can be determined by plotting the error bar for the samples prepared and tested with same characteristics. The error bar for unconfined compression strength of type A samples over different curing periods is plotted in Figure 9. If the deviation of the stress values from the average stress is more then reason might be the inadequate mixing. To get more precise results, soil samples should be prepared with utmost care.

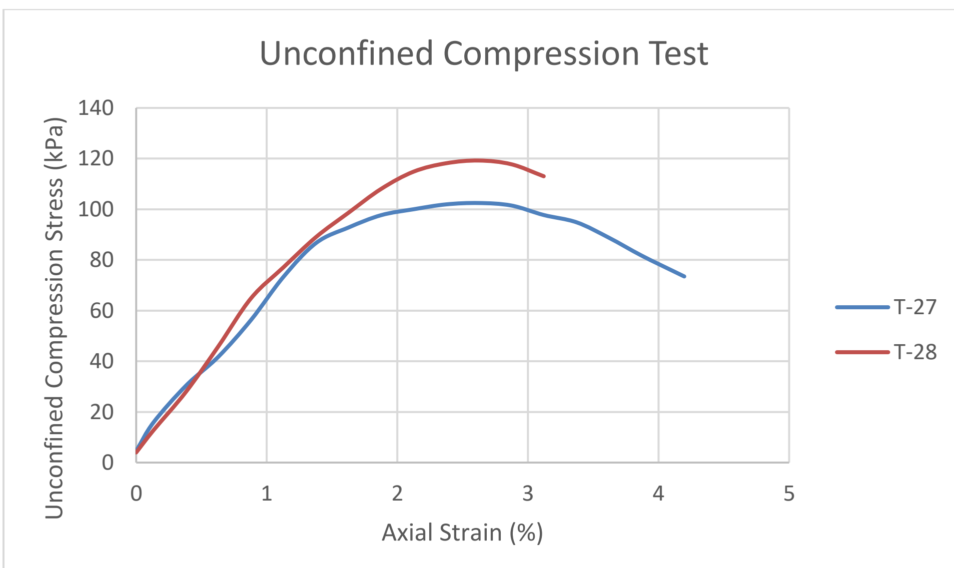

Figure 6 Stress Vs Strain Graph for Unconfined Compression test for Type A sample over 7 Days Curing Period

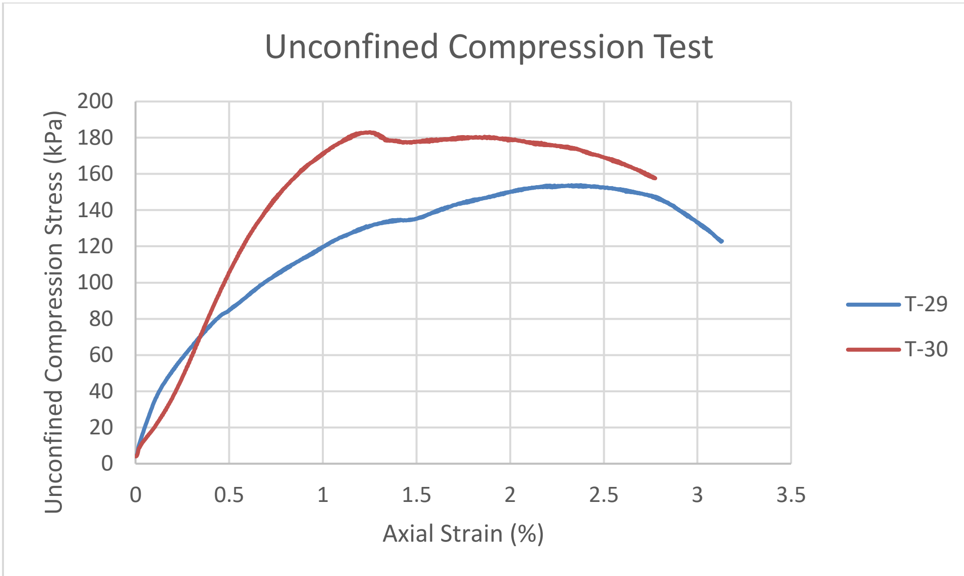

Figure 7 Stress Vs Strain Graph for Unconfined Compression test for Type A sample over 28 Days Curing Period

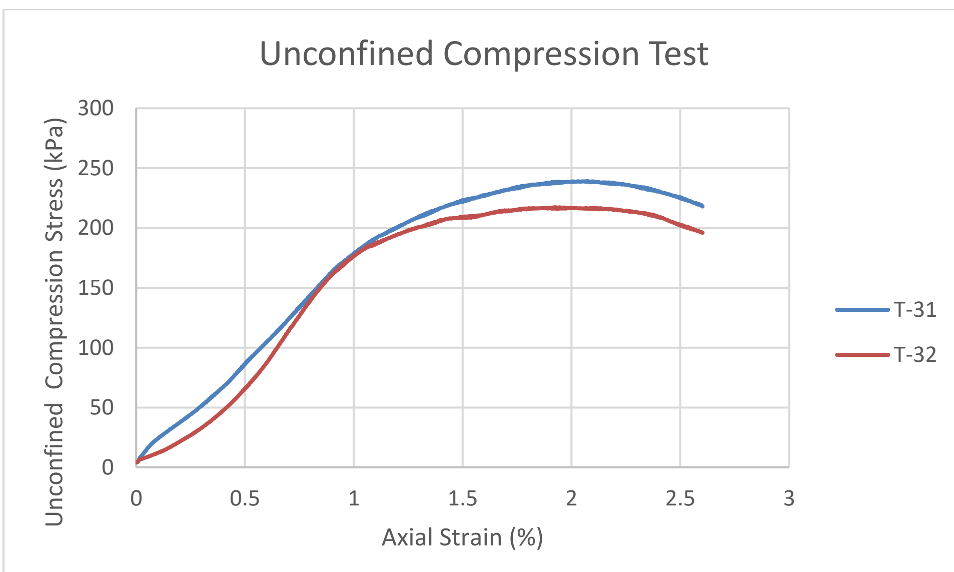

Figure 8 Stress Vs Strain Graph for Unconfined Compression test for Type A sample over 56 Days Curing Period

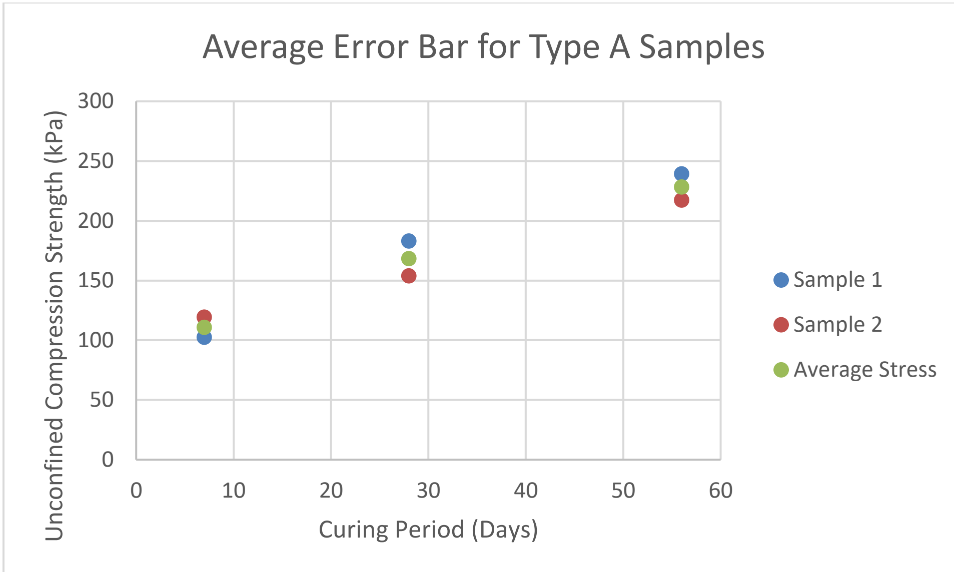

Figure 9 Average Error Bar for Unconfined Compression Strength of Type A Samples

For moderate binder content of 11.5% by weight, the unconfined compression strength of the soil has been increased to 132.73 KPa over 7 days curing period which is higher than that for type A samples. As discussed for type A samples, stiffness is observed to be maximum for samples which are cured for 28 days. Table 6 shows unconfined compressive strength for type B samples over different curing periods.

The error bar for unconfined compression strength of type B samples over different curing periods is plotted in Figure 13. To get more precise results, soil samples should be prepared with utmost care. Samples tested at 7 and 56 days have less deviation from average value as compared to those tested at 28 days.

Figure 10, 11 and 12 show the stress Vs strain patterns for Type B samples which are cured for 7, 28 and 56 days respectively.

Table 6 Unconfined Compression Strength of Type B samples

Curing Period in Days	Strength of Sample 1 (kPa)	Strength of Sample 2 (kPa)	Average Strength (kPa)
7	137.24 (T-33)	128.21 (T-34)	132.73 (Average of T-33 and T-34)
28	238.29 (T-35)	216.43 (T-36)	227.36 (Average of T-35 and T-36)
56	237.26 (T-37)	258.20 (T-38)	247.74 (Average of T-37 and T-38)

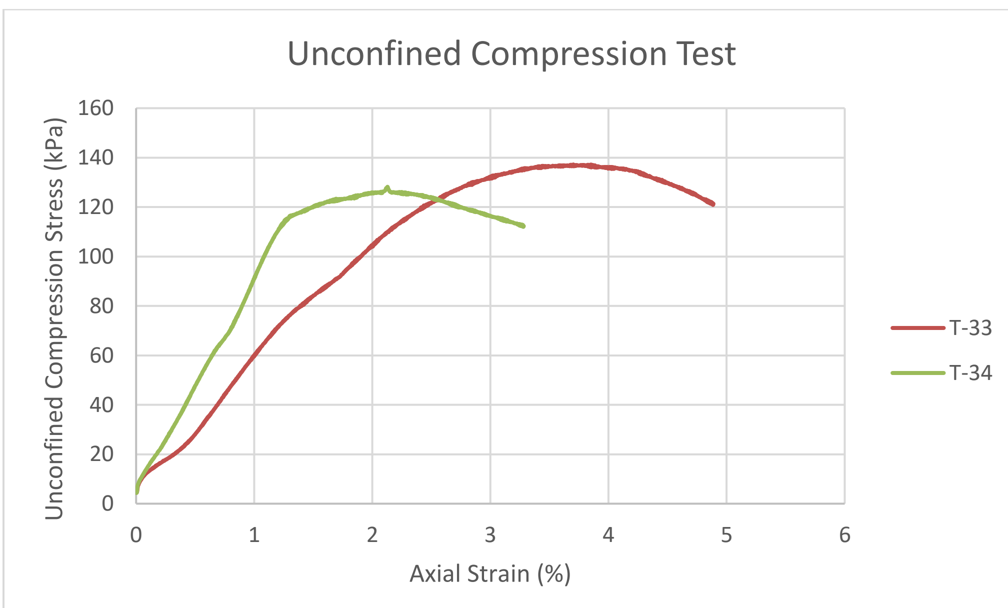

Figure 10 Stress Vs Strain Graph for Unconfined Compression test for Type B sample over 7 Days Curing Period

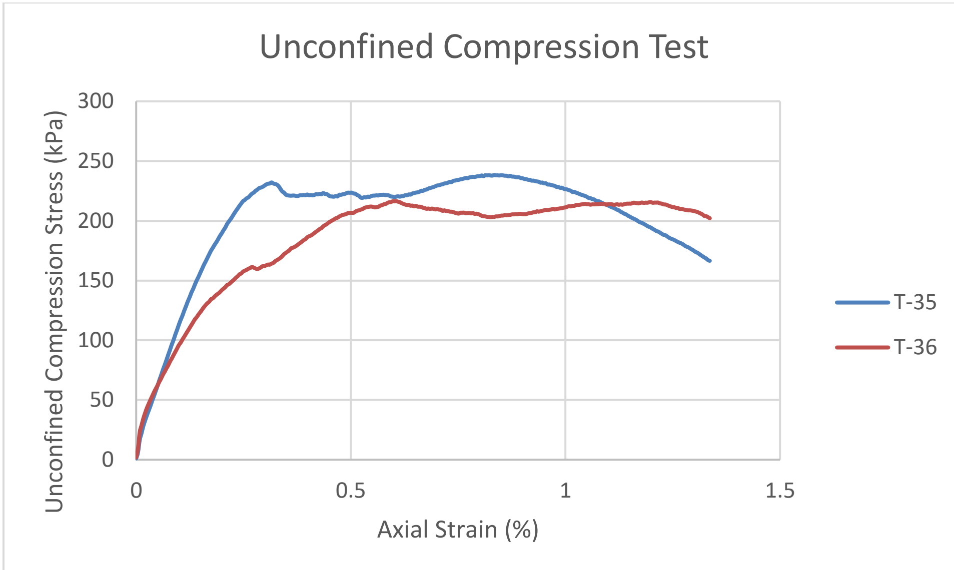

Figure 11 Stress Vs Strain Graph for Unconfined Compression test for Type B sample over 28 Days Curing Period

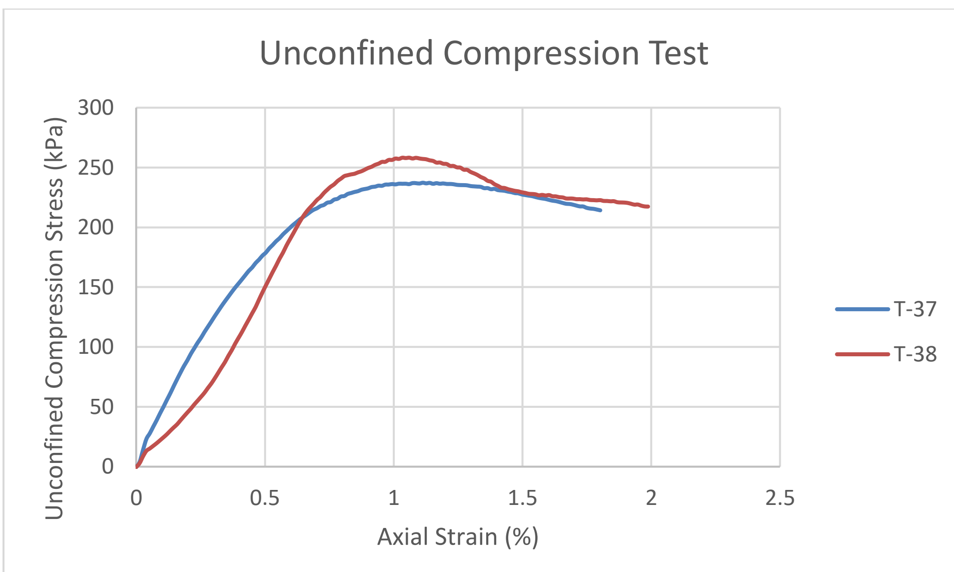

Figure 12 Stress Vs Strain Graph for Unconfined Compression test for Type B sample over 56 Days Curing Period

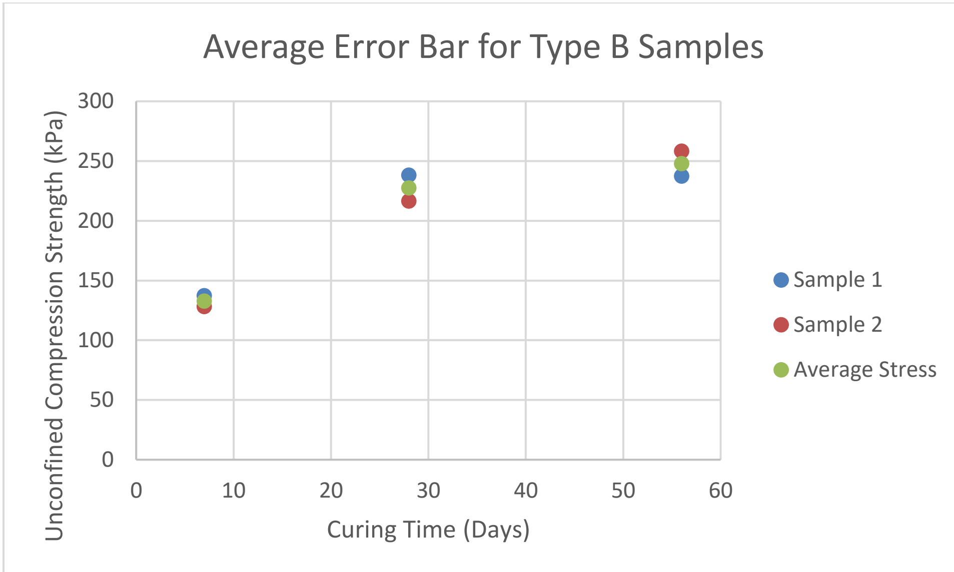

Figure 13 Average Error Bar for Unconfined Compression Strength of Type B Samples

For comparatively higher binder content of 15.5% by weight, the unconfined compression strength of the soil has been increased to 273.61 KPa over 7 days curing period which is highest among all types of samples cured for 7 days. Same pattern of having highest stiffness at 28 days and low at 7 and 56 days is followed for type C samples also. Table 7 shows unconfined compressive strength for type C samples over different curing periods.

Stress Vs strain patterns for Type B samples which are cured for 7, 28 and 56 days are showed in Figure 14, 15 and 16 respectively.

Table 7 Unconfined Compression Strength of Type C samples

Curing Period in Days	**Strength of Sample 1 (kPa)**	**Strength of Sample 2 (kPa)**	**Average Strength (kPa)**
7	286.16 (T-39)	261.07 (T-40)	273.61 (Average of T-39 and T-40)
28	320.02 (T-41)	292.28 (T-42)	306.15 (Average of T-41 and T-42)
56	289.39 (T-43)	392.97 (T-44)	341.18 (Average of T-43 and T-44)

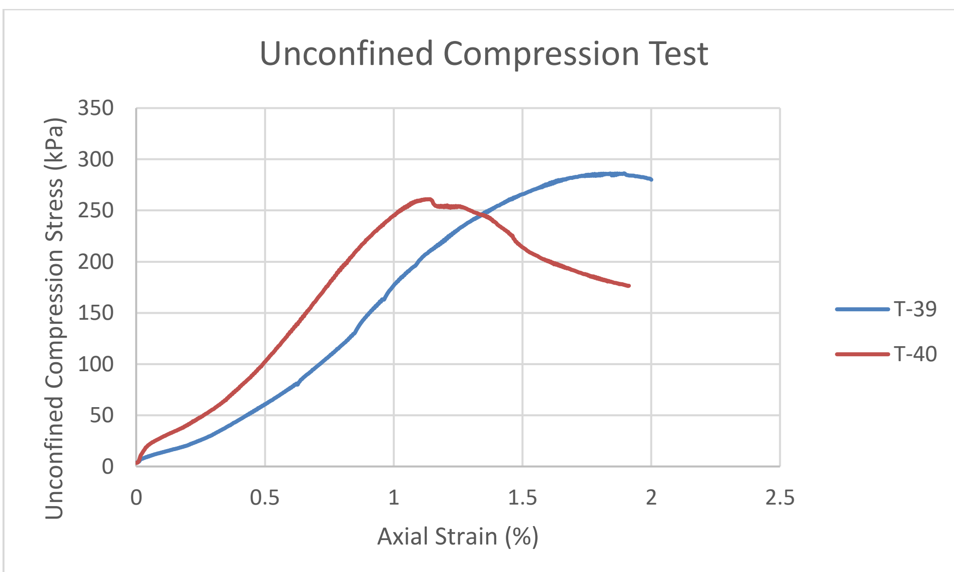

Figure 14 Stress Vs Strain Graph for Unconfined Compression test for Type C sample over 7 Days Curing Period

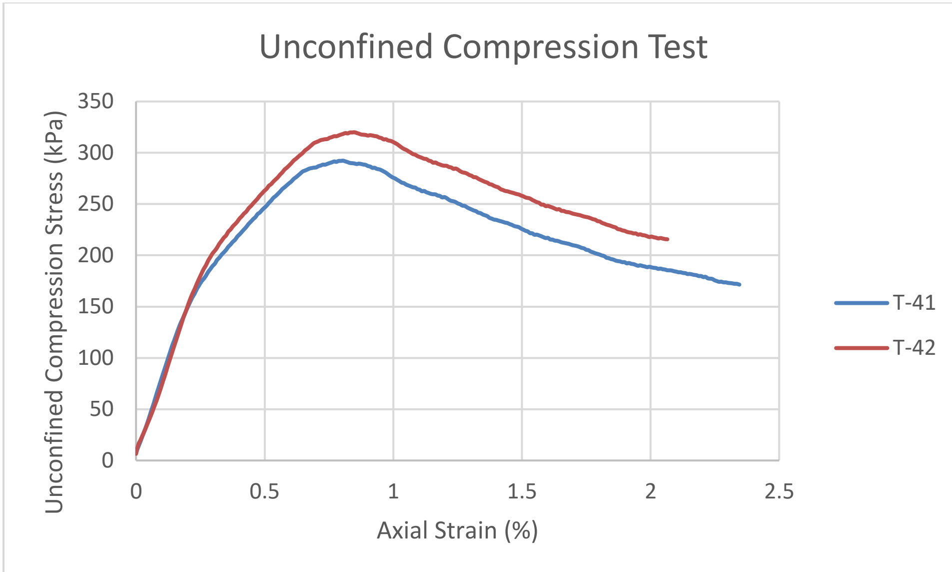

Figure 15 Stress Vs Strain Graph for Unconfined Compression test for Type C sample over 28 Days Curing Period

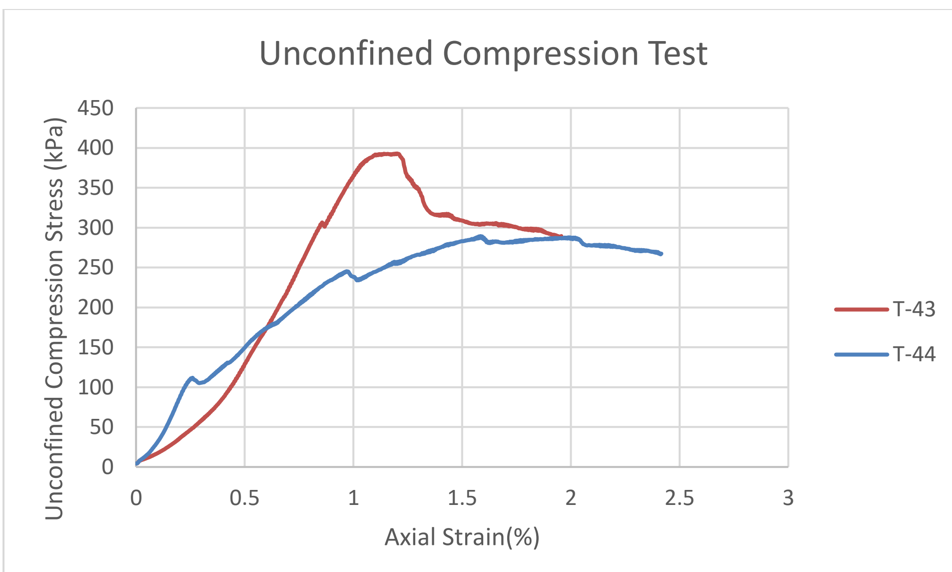

Figure 16 Stress Vs Strain Graph for Unconfined Compression test for Type C sample over 56 Days Curing Period

The error bar for unconfined compression strength of type C samples over different curing periods is plotted in Figure 17. Samples tested at 7 and 28 days have very less deviation from average value as compared to those tested at 56 days. The deviation in the stress values after 56 days might be misleading in calculating the actual stress after 56 days so to get the exact value, samples should be prepared and tested with extra care.

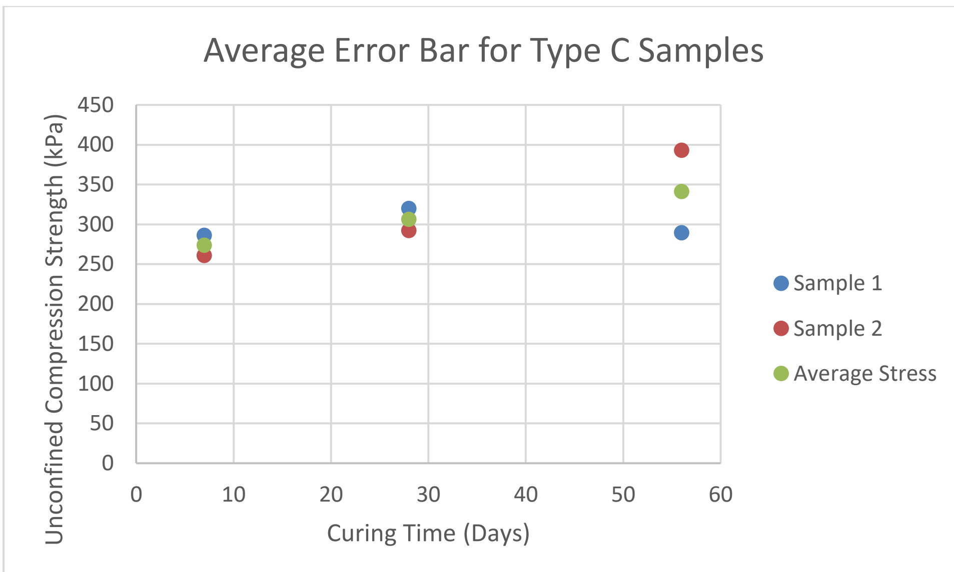

Figure 17 Average Error Bar for Unconfined Compression Strength of Type C Samples

To Summarize the effect of the cement treatment on the unconfined compression strength of the soil, it is observed that the strength has been increased with increase in the cement to soil proportion and curing period too. Bonding between soil particles might have increased with increase in the amount of cement which provides the higher strength. Though the strength has increased with increase in cement content, the relation between the amount of cement used for the treatment and unconfined compression strength has not followed any fixed pattern so strength at any time or with specific cement content was unpredictable. As per ASTM D4609, the treatment may be considered effective for type C samples as the strength is increased by almost 345 KPa. Table 8 summarizes the variation in the unconfined compression strength with respect to different cement to soil proportion and curing period. This data has been represented graphically in Figure 15.

Table 8 Unconfined Compressive Strength (in KPa) of All Samples

	Mixture Type	**A**	**B**	**C**
	Dry Cement / Weight of soil (%)	**7.5**	**11.5**	**15.5**
Curing Period in Days	**7**	110.85 (Average of T-27 and T-28)	132.73 (Average of T-33 and T-34)	273.61 (Average of T-39 and T-40)
	28	168.42 (Average of T-29 and T-30)	227.36 (Average of T-35 and T-36)	306.15 (Average of T-41 and T-42)
	56	228.24 (Average of T-31 and T-32)	247.74 (Average of T-37 and T-38)	341.18 (Average of T-43 and T-44)

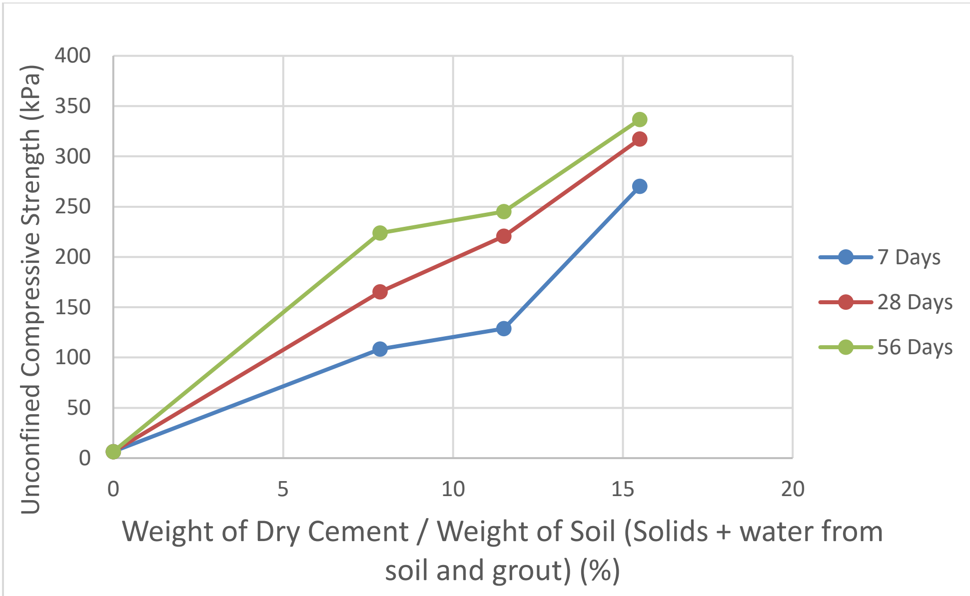

Figure 18 Variation in Unconfined Compressive Strength with respect to Mixture Type and Curing Period

4.2 Effect of Cement Treatment on Split Tensile Strength

Due to higher water content present in the soil, it was difficult to measure the split tensile strength of the soil before treatment. This parameter is monitored to check the effect of cement treatment on other parameters of the soil except compression strength, so the only expectation was not to lose the existing split tensile strength and measure the increment in the strength if observed. If it would have been observed that split tensile strength is reducing, then cement treatment might not have been suggested for some projects where tensile strength is also one of the governing factors in design. Table 9 shows different values of split tensile strength for type A samples over varying curing period. Figure 19, 20 and 21 show the split tensile strength Vs axial strain patterns for type A samples over 7, 28 and 56 days curing period.

Table 9 Split Tensile Strength (kPa) of Type A samples

Curing Period in Days	Strength of Sample 1 (kPa)	Strength of Sample 2 (kPa)	Average Split Tensile Strength (kPa)
7	17.83 (T-10)	31.25 (T-09)	24.54 (Average of T-09 and T-10)
28	33.69 (T-11)	51.58 (T-12)	42.63 (Average of T-11 and T-12)
56	68.23 (T-13)	35.28 (T-14)	51.75 (Average of T-13 and T-14)

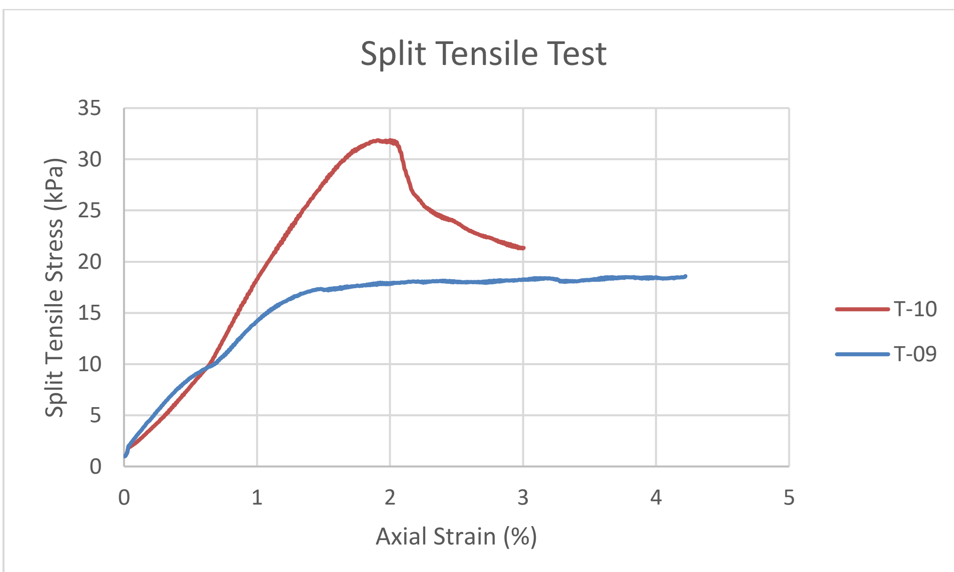

Figure 19 Stress Vs Strain Graph for Split Tensile Test for Type A sample over 7 Days Curing Period

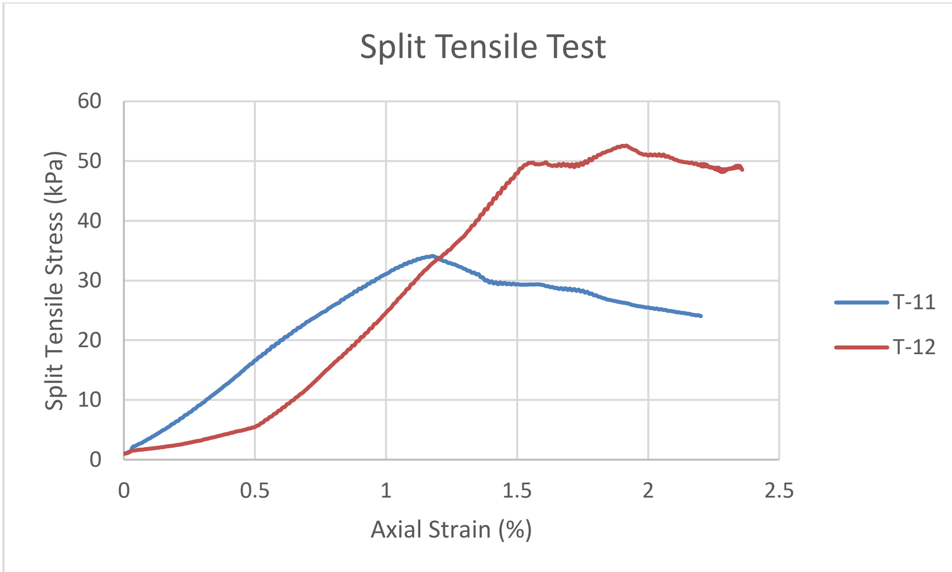

Figure 20 Stress Vs Strain Graph for Split Tensile Test for Type A sample over 28 Days Curing Period

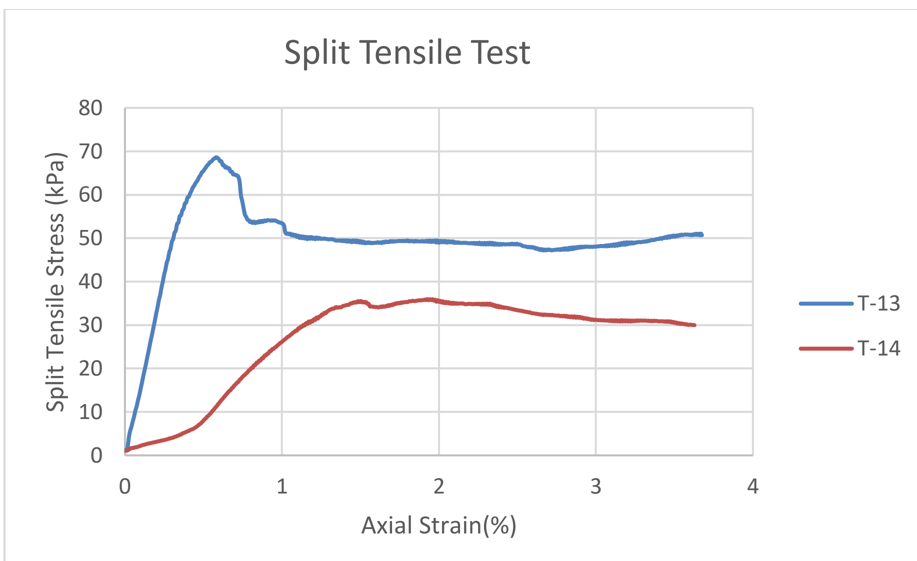

Figure 21 Stress Vs Strain Graph for Split Tensile Test for Type A sample over 56 Days Curing Period

The error bar for split tensile strength of type A samples over different curing periods is plotted in Figure 22. Basically, all samples have deviation from the average stress in different proportions, but the deviation has increased with increase in the curing period. The error bar should be optimized to know the precise values.

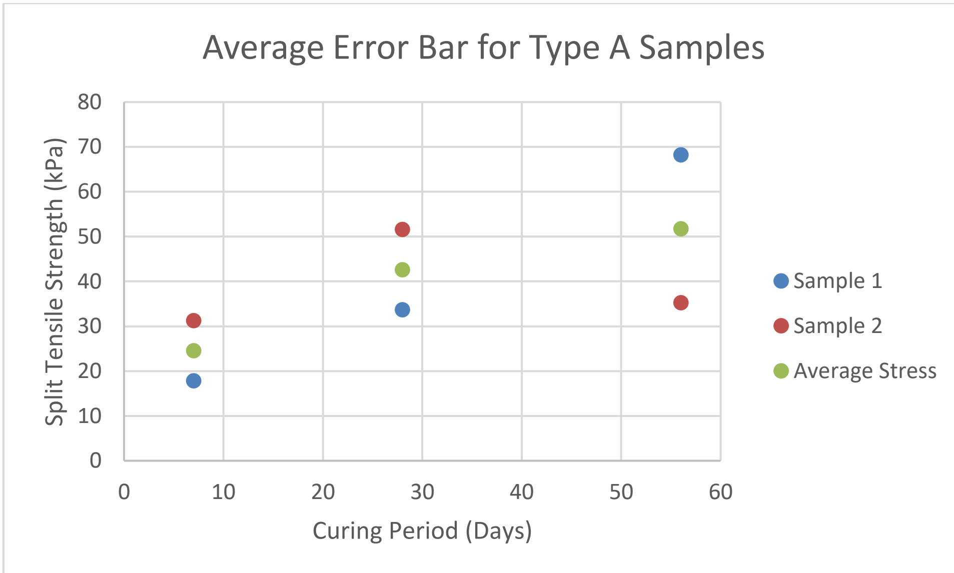

Figure 22 Average Error Bar for Split Tensile Strength of Type A Samples

For moderate binder content of 11.5% by weight, the Split tensile strength of the soil has been increased to 39.67 KPa over 7 days curing period which is higher than that for type A samples. Table 10 shows Split tensile strength for type B samples over different curing periods. The ratio of residual strength to peak strength is observed to be reduced with increase in curing period.

Split tensile strength Vs axial strain patterns for type B samples cured for 7, 28 and 56 days are showed in Figure 23, 24 and 25 respectively. The error bar for split tensile strength of type B samples over different curing periods is plotted in Figure 26. The error bar should be optimized to know the precise values.

Table 10 Split Tensile Strength (kPa) of Type B samples

Curing Period in Days	Strength of Sample 1 (kPa)	Strength of Sample 2 (kPa)	Average Strength (kPa)
7	47.01 (T-15)	32.33 (T-16)	39.67 (Average of T-15 and T-16)
28	57.77 (T-17)	98.62 (T-18)	78.20 (Average of T-17 and T-18)
56	83.34 (T-19)	67.68 (T-20)	75.51 (Average of T-19 and T-20)

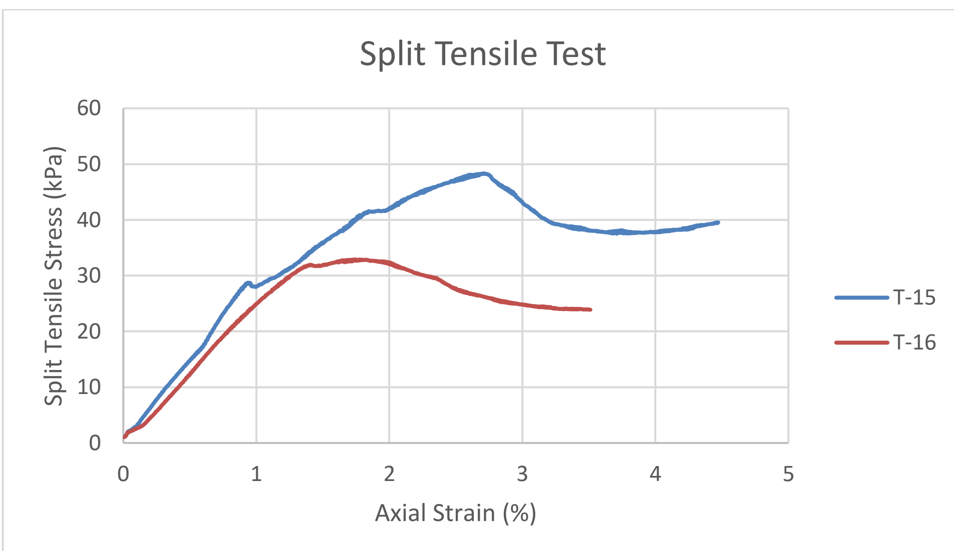

Figure 23 Stress Vs Strain Graph for Split Tensile Test for Type B sample over 7 Days Curing Period

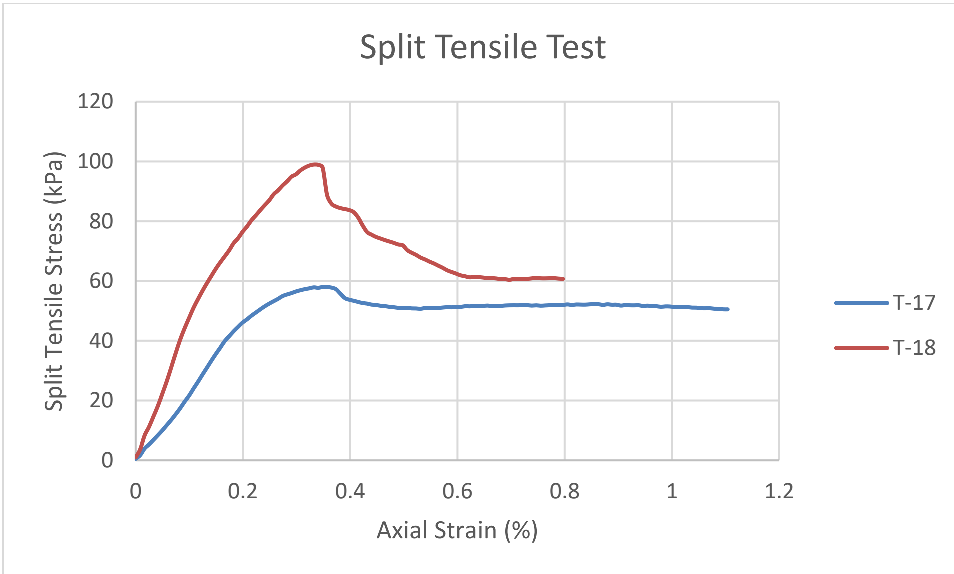

Figure 24 Stress Vs Strain Graph for Split Tensile Test for Type B sample over 28 Days Curing Period

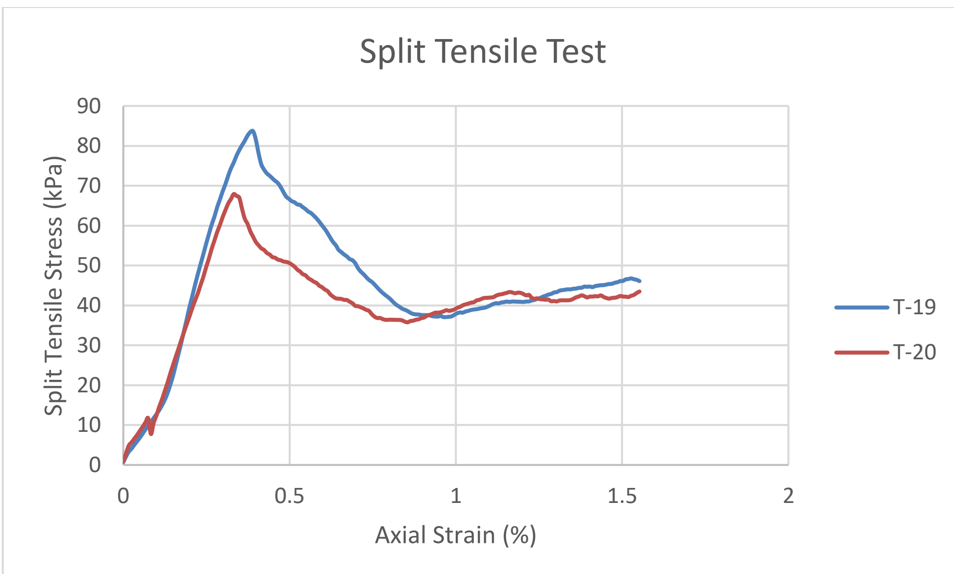

Figure 25 Stress Vs Strain Graph for Split Tensile Test for Type B sample over 56 Days Curing Period

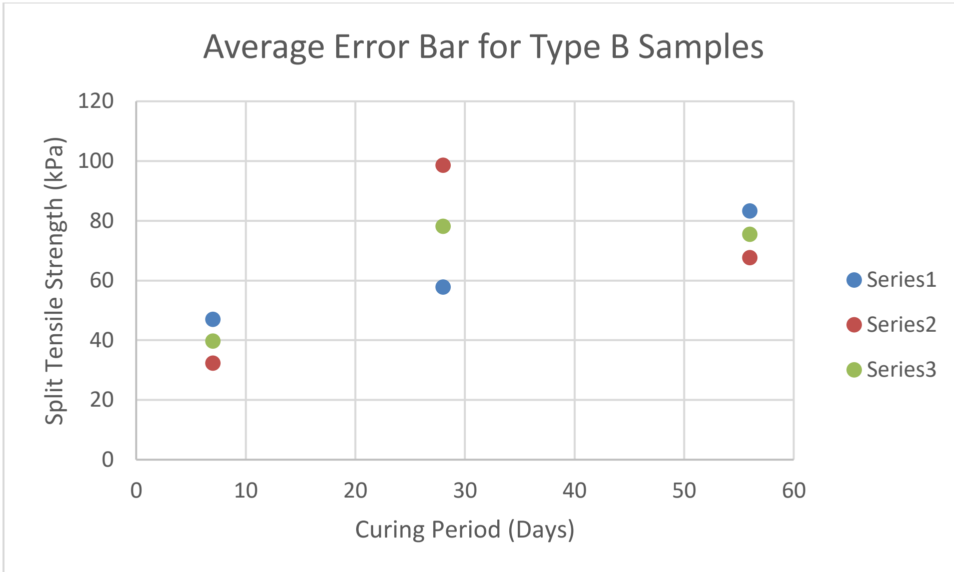

Figure 26 Average Error Bar for Split Tensile Strength of Type B Samples

For binder content of 15.5% by weight, the Split tensile strength of the soil has been increased proportionally. Two samples of type C tested after 28 days curing period have shown unexpected increase in the strength up to 134.81 KPa which is highest amongst all types of mixture and curing period. This can be happened due to inadequate mixing of cement and soil. Table 11 shows split tensile strength for type C samples over different curing periods. The ratio of residual strength to peak strength is observed to be reduced with increase in curing period. Split tensile strength Vs axial strain patterns for type C samples cured for 7, 28 and 56 days are showed in Figure 27, 28 and 29 respectively.

The error bar for split tensile strength of type C samples over different curing periods is plotted in Figure 30. Almost no deviation is observed for samples tested at 7 and 56 days while there is a large deviation in the samples tested at 28 days.

Table 11 Split Tensile Strength (kPa) of Type C samples

Curing Period in Days	Strength of Sample 1 (kPa)	Strength of Sample 2 (kPa)	Average Split Tensile Strength (kPa)
7	65.44 (T-21)	63.32 (T-22)	64.38 (Average of T-21 and T-22)
28	154.83 (T-23)	114.78 (T-24)	134.81 (Average of T-23 and T-24)
56	81.44 (T-25)	86.52 (T-26)	83.98 (Average of T-25 and T-26)

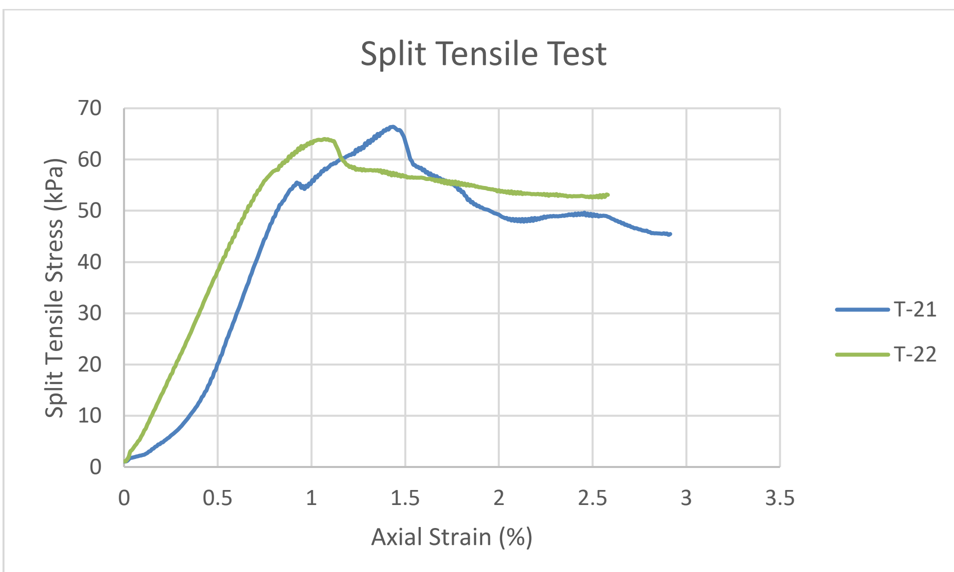

Figure 27 Stress Vs Strain Graph for Split Tensile Test for Type C sample over 7 Days Curing Period

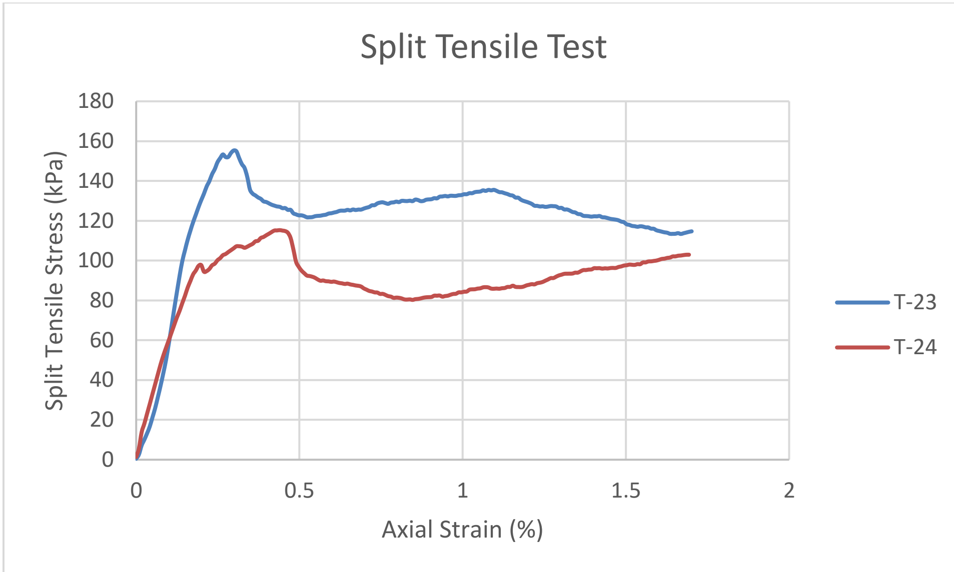

Figure 28 Stress Vs Strain Graph for Split Tensile Test for Type C sample over 28 Days Curing Period

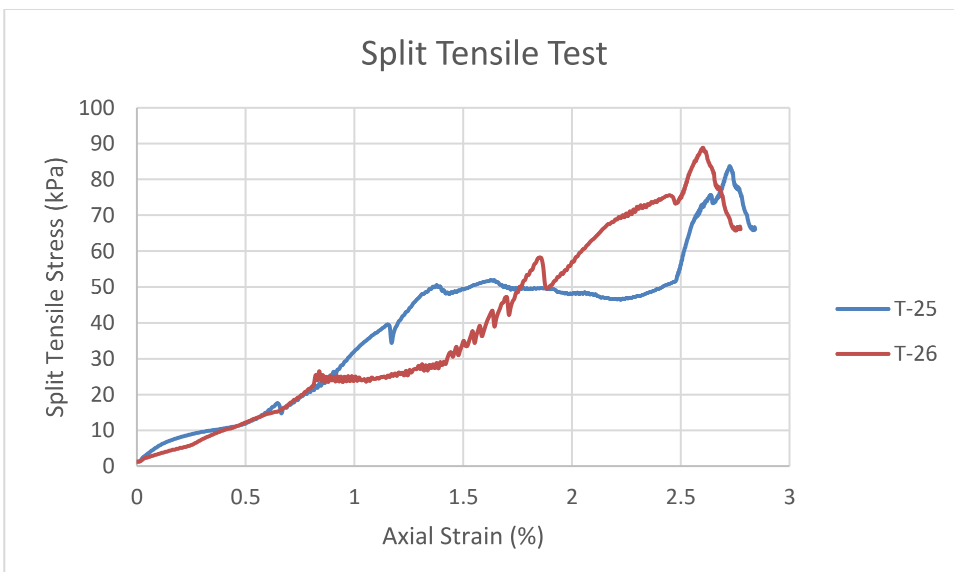

Figure 29 Stress Vs Strain Graph for Split Tensile Test for Type A sample over 56 Days Curing Period

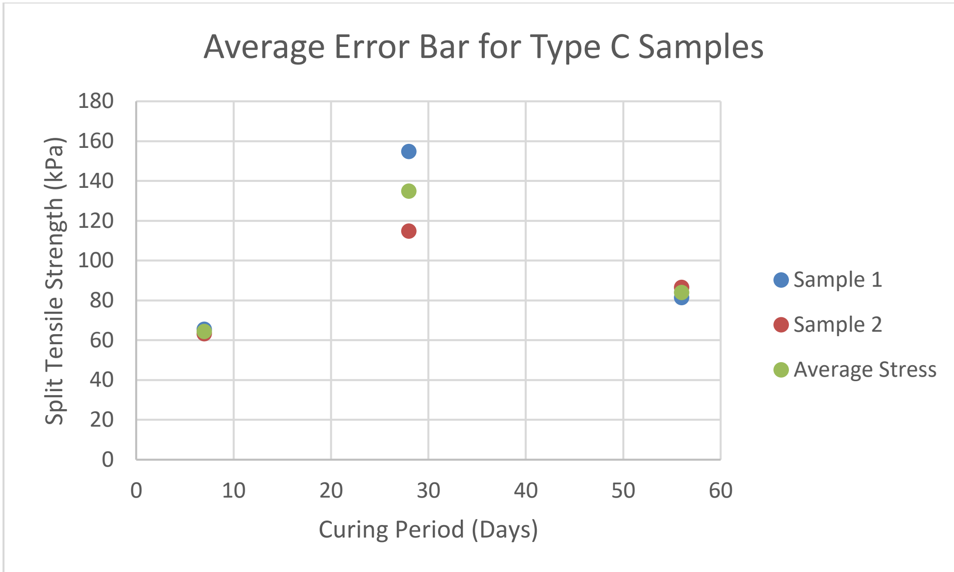

Figure 30 Average Error Bar for Split Tensile Strength of Type C Samples

From the test data, it can be concluded that the split tensile strength of the soil is also increased with respect to increase in the cement content and curing period, but the increase is not that much as compared to the increase in the unconfined compression strength. It can be affirmed from the data that there is no adverse effect of cement treatment on split tensile strength of the soil. Table 12 summarizes the variation of split tensile strength for all types of samples and curing periods. Figure 31 shows the relation between the cement to soil ratio (by weight) and split tensile strength for different curing periods of 7, 28 and 56 days.

Table 12 Split Tensile Strength (in KPa) of All Samples

	Mixture Type	**A**	**B**	**C**
	Dry Cement / Weight of soil (%)	**7.5**	**11.5**	**15.5**
Curing Period in Days	**7**	24.54 (Average of T-09 and T-10)	39.67 (Average of T-15 and T-16)	64.38 (Average of T-21 and T-22)
	28	42.63 (Average of T-11 and T-12)	78.20 (Average of T-17 and T-18)	134.81 (Average of T-23 and T-24)
	56	51.75 (Average of T-13 and T-14)	75.51 (Average of T-19 and T-20)	83.98 (Average of T-25 and T-26)

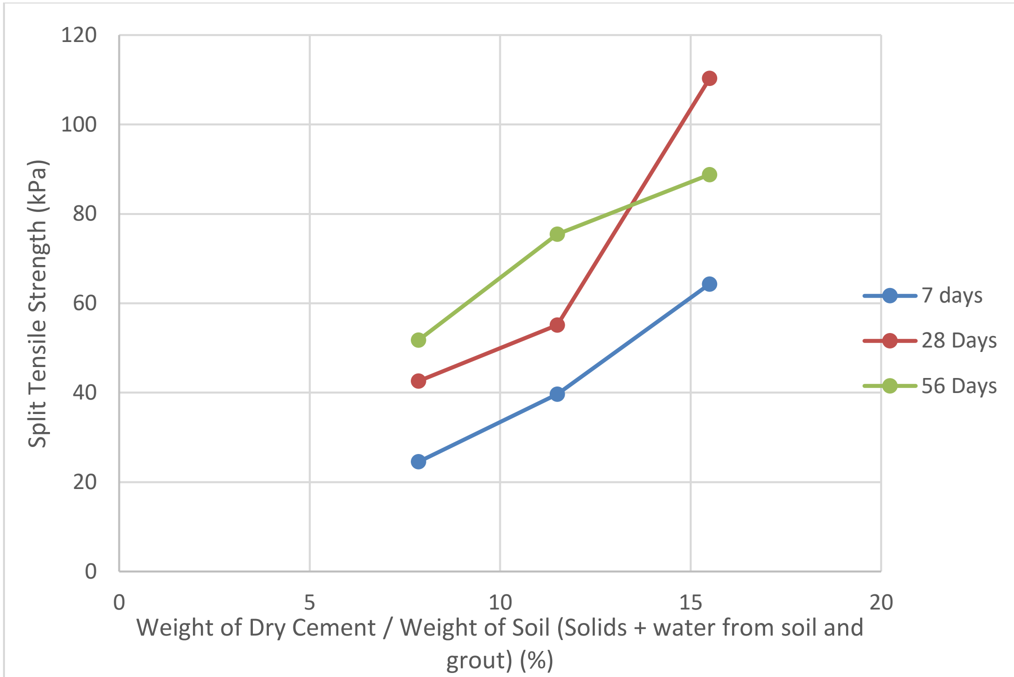

Figure 31 Variation in Split Tensile Strength with respect to Mixture Type and Curing Period

4.3 Effect of Cement Treatment on Confined Compression Strength

4.3.1 Application of Confining Pressure of 34 KPa

Provision of low confinement and low cement content has shown the reduction in the stiffness of the sample with increase in the curing period. The stress resisted by the sample with low confinement before shearing is lesser than that by unconfined samples for samples tested after 28 and 56 days. The strength $\sigma 1$ of the sample after 7 days curing is little more than one tested without confining pressure. Hereafter in this thesis, the term confined compression stress of the sample describes the axial stress $\sigma 1$ at failure. Table 13 shows the stress capacity of type A samples for low confinement.

Table 13 Confined Compression Strength (kPa) of Type A samples with Confining Pressure of 34 KPa

Curing Period in Days	Strength of Sample 1 (σ1) (kPa)	Strength of Sample 2 (σ1) (kPa)	Average Compression Strength (σ1) (kPa)
7	151 (T-45)	139.89 (T-46)	145.45 (Average of T-45 and T-46)
28	156.82 (T-47)	110.17 (T-48)	133.50 (Average of T-47 and T-48)
56	201.25 (T-49)	253.62 (T-50)	227.44 (Average of T-49 and T-50)

Figure 32, 33 and 34 show the stress Vs Strain pattern of confined compression test for type A samples over 7, 28 and 56 days curing period respectively. The error bar for confined compression strength of type A samples over different curing periods is plotted in Figure 35. Almost no deviation is observed for samples tested at 7 days while there is a small deviation in the samples tested at 28 and 56 days. Mixing process for samples at 28 and 56 days might need some more attention to reduce the error bar.

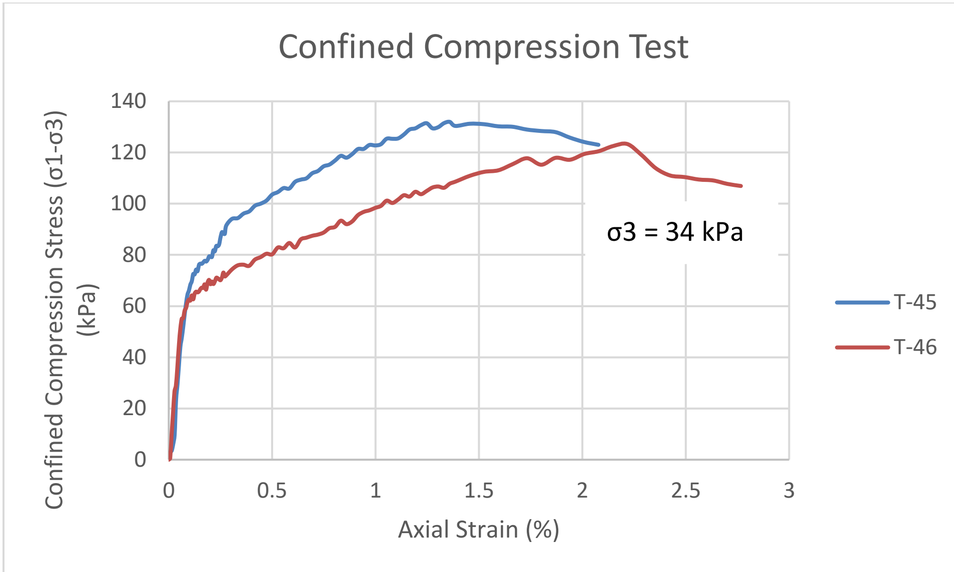

Figure 32 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 7 Days Curing Period and 34 KPa confining Pressure

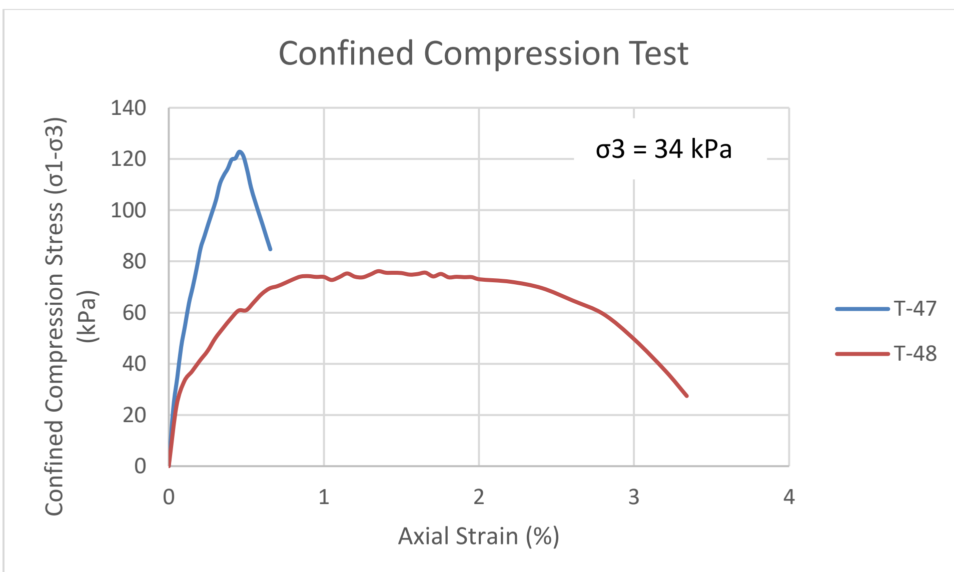

Figure 33 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 28 Days Curing Period and 34 KPa confining Pressure

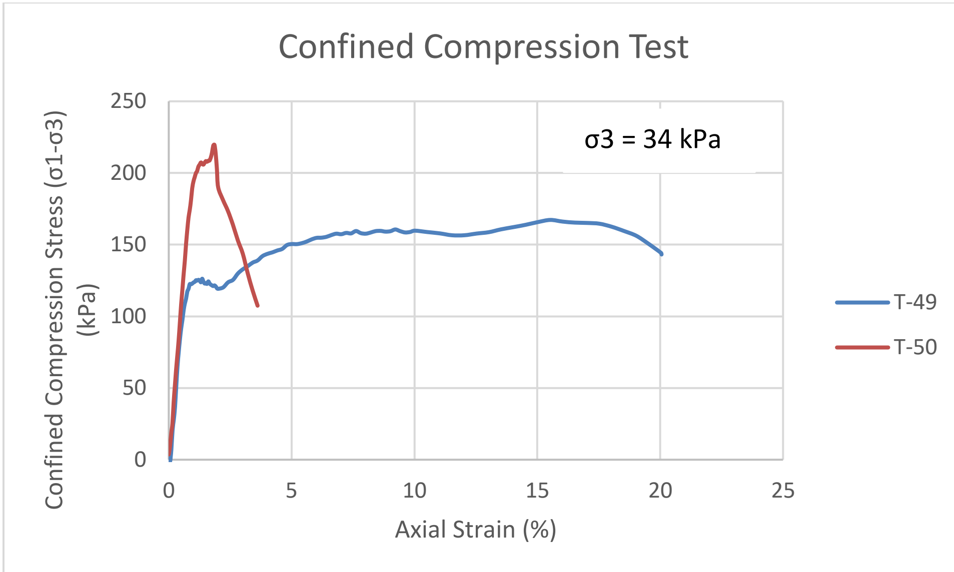

Figure 34 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 56 Days Curing Period and 34 KPa confining Pressure

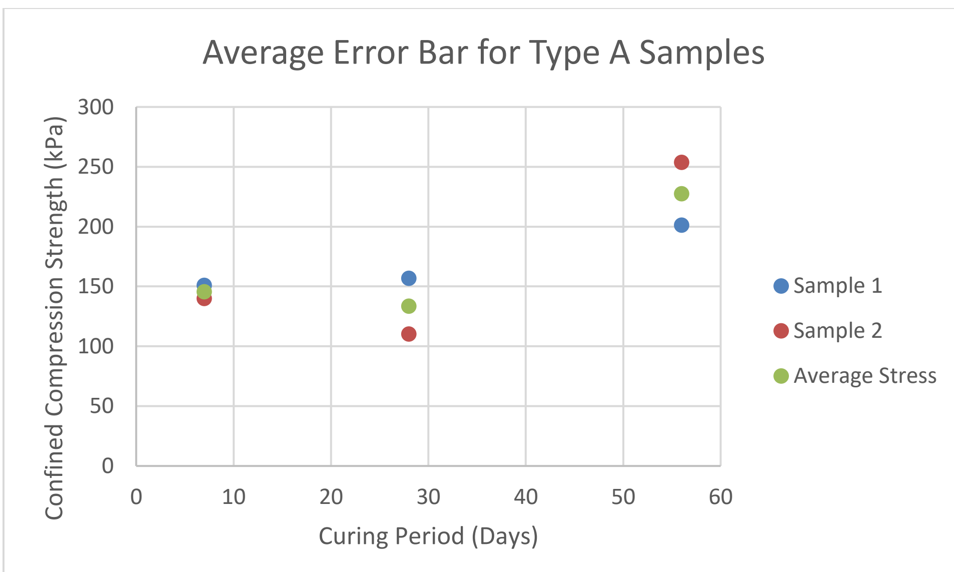

Figure 35 Average Error Bar for Confined Compression Strength of Type A Samples

For moderate cement content and low confinement, trend of higher stress at failure than unconfined samples till 28 days and lower for samples cured for 56 days has been observed. Stiffness of these samples is observed to be the lowest among other types of samples and decreased with curing period. The main difference between type A and B samples except cement content is the amount of water added with cement so the extra water than type A samples might have kept the specimen plastic because of which the low confining pressure also affected the stress values. In case of samples cured for 56 days, the confining pressure didn't have any effect.

Figure 36, 37 and 38 show the stress-strain plots for type B samples with low confinement over curing periods and observed stress values are mentioned in Table 14.

Table 14 Confined Compression Strength (kPa) of Type B samples with Confining Pressure of 34 KPa

Curing Period in Days	Strength of Sample 1 (σ1) (kPa)	Strength of Sample 2 (σ1) (kPa)	Average Compression Strength (σ1) (kPa)
7	180.59 (T-51)	262.28 (T-52)	221.43 (Average of T-51 and T-52)
28	305.20 (T-53)	280.81 (T-54)	293.00 (Average of T-53 and T-54)
56	192.05 (T-55)	112.19 (T-56)	152.12 (Average of T-55 and T-56)

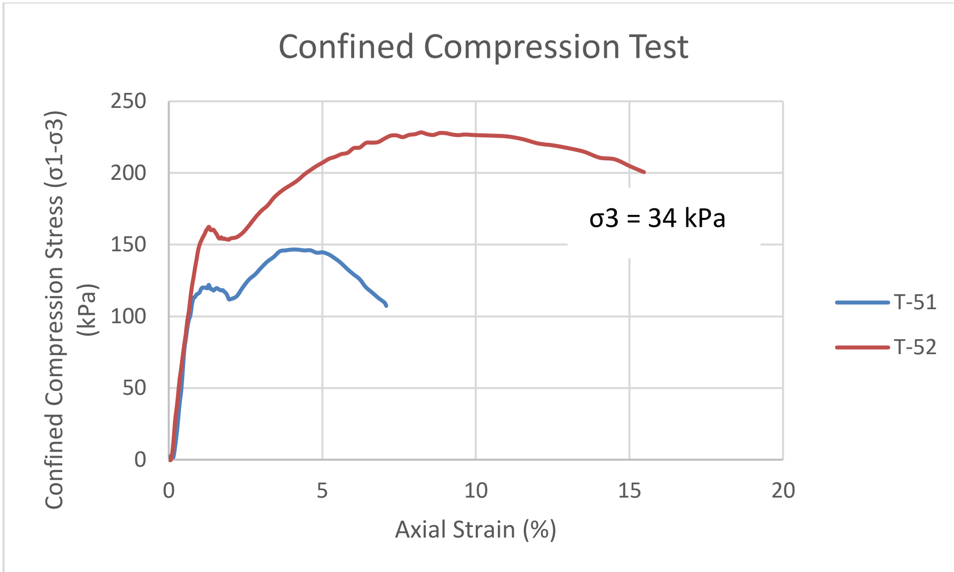

Figure 36 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 7 Days Curing Period and 34 KPa confining Pressure

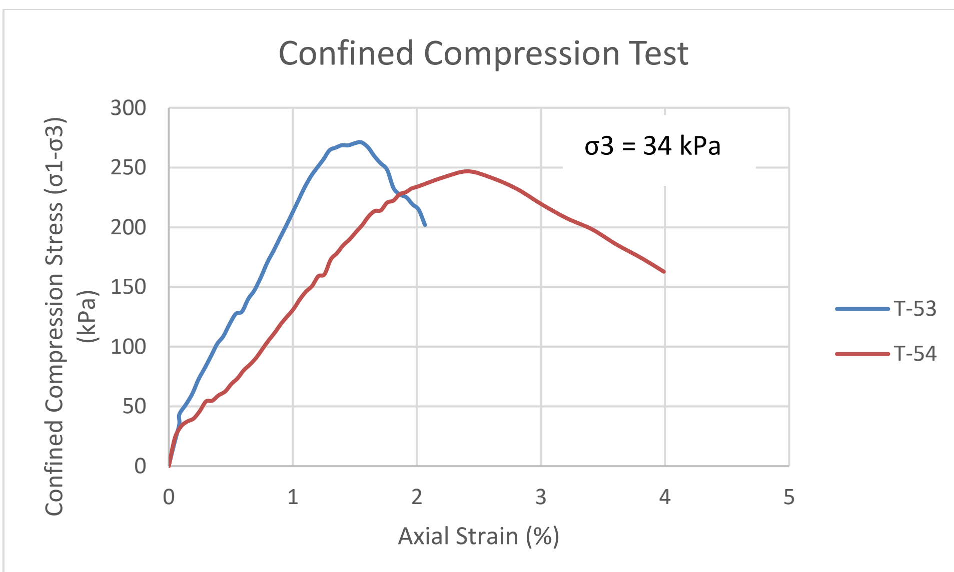

Figure 37 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 28 Days Curing Period and 34 KPa confining Pressure

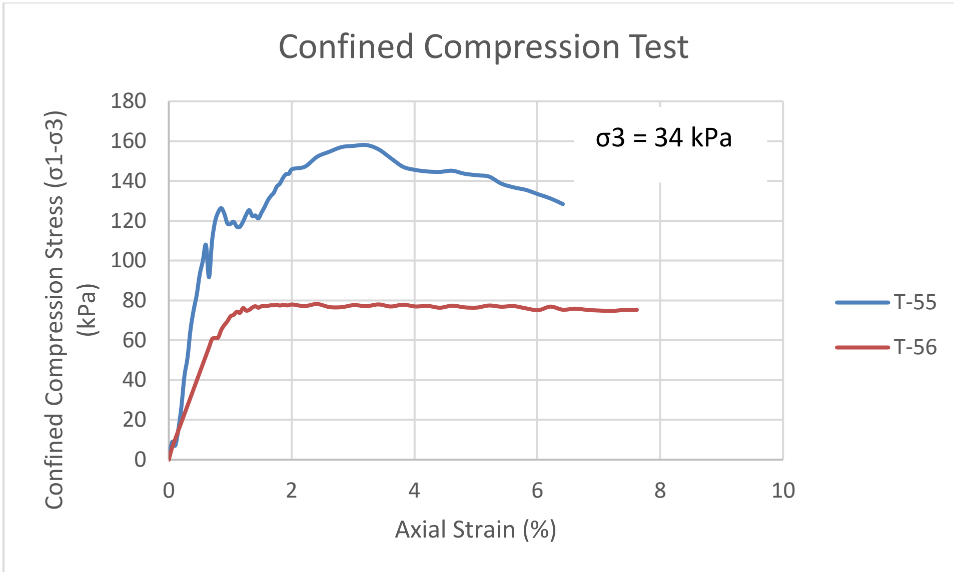

Figure 38 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 56 Days Curing Period and 34 KPa confining Pressure

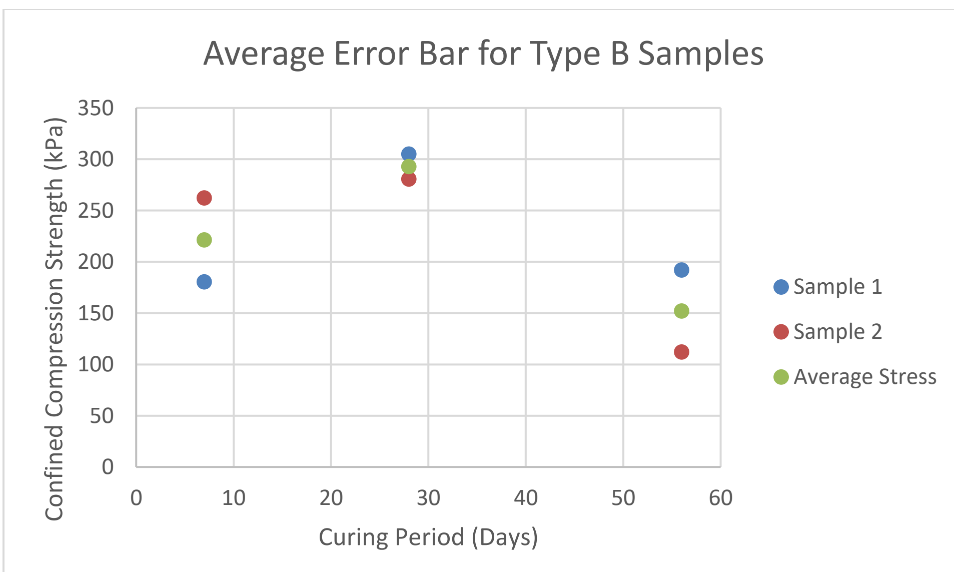

Figure 39 Average Error Bar for Confined Compression Strength of Type B Samples

The error bar for confined compression strength σ1 of type B samples over different curing periods is plotted in Figure 39. Mixing process for samples at 7 and 56 days might need some more attention to reduce the error bar. To avoid the misjudgment, the value of the stress deviation can be fixed.

For comparatively high cement content and low confinement, the pattern of low stiffness with curing is followed like other two types but these samples have higher stiffness than type B samples. Application of low confinement has increased the stress capacity till 28 days and decreased in case of samples cured for 56 days as compared to samples without confinement. Table 15 describes the stress values of type C samples with low confinement whereas Figure 40, 41 and 42 show stress Vs strain diagrams for all these samples.

Table 15 Confined Compression Strength (kPa) of Type C samples with Confining Pressure of 34 KPa

Curing Period in Days	**Strength of Sample 1 (σ1) (kPa)**	**Strength of Sample 2 (σ1) (kPa)**	**Average Compression Strength (σ1) (kPa)**
7	348.85 (T-57)	315.56 (T-58)	332.21 (Average of T-57 and T-58)
28	396.68 (T-59)	427.58 (T-60)	412.13 (Average of T-59 and T-60)
56	276.62 (T-61)	250.25 (T-62)	263.44 (Average of T-61 and T-62)

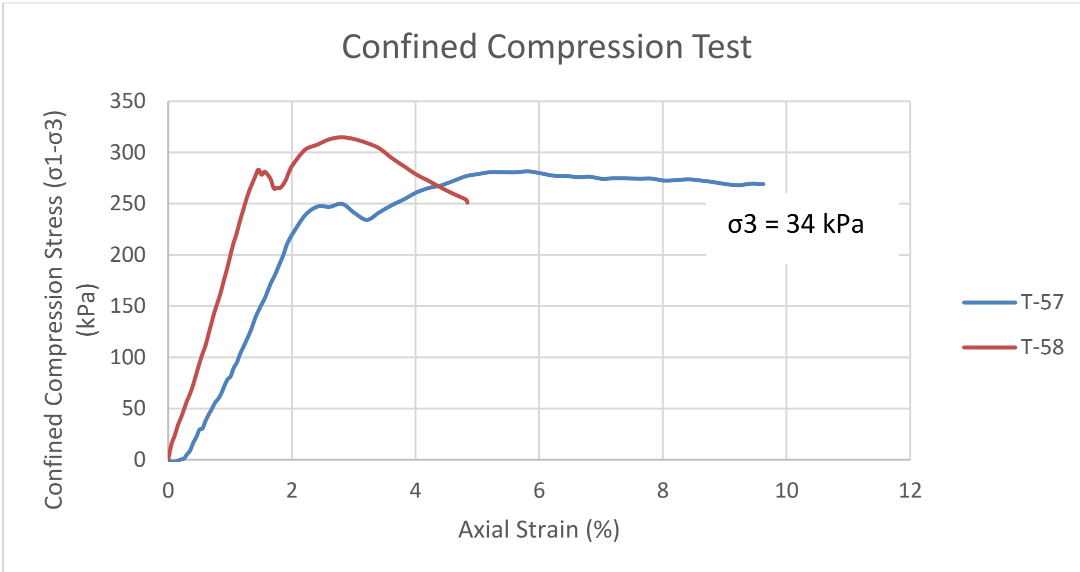

Figure 40 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 7 Days Curing Period and 34 KPa confining Pressure

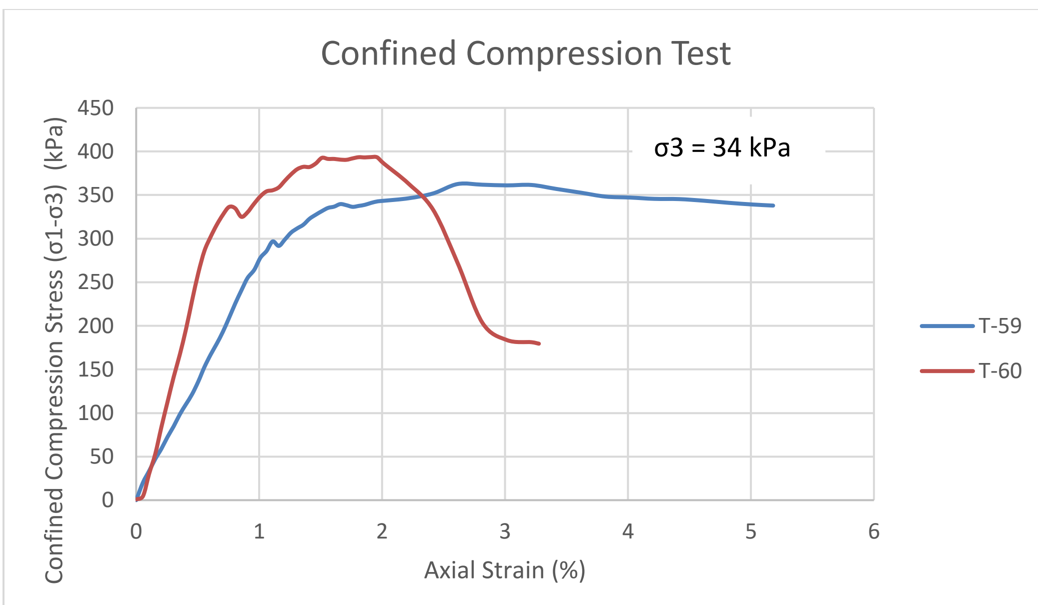

Figure 41 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 28 Days Curing Period and 34 KPa confining Pressure

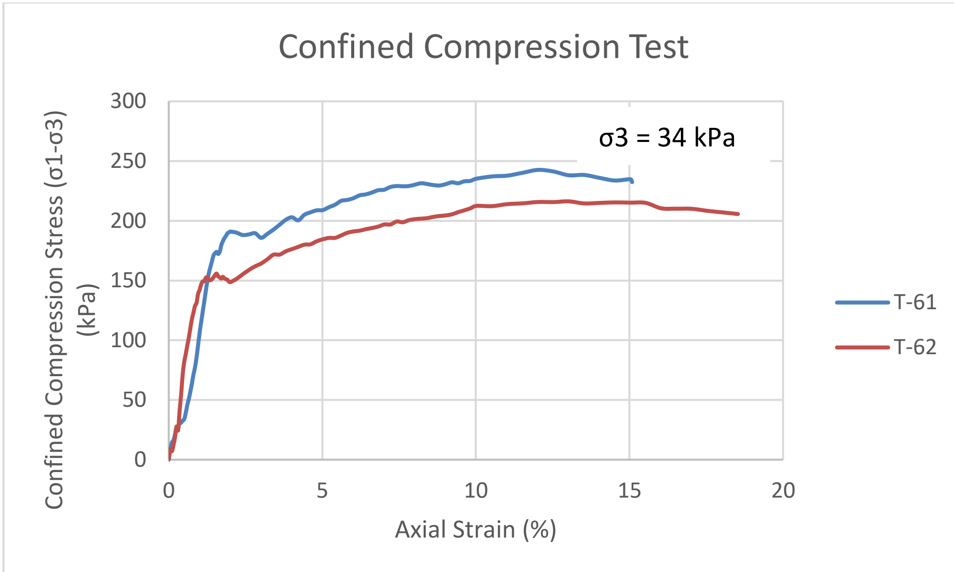

Figure 42 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 56 Days Curing Period and 34 KPa confining Pressure

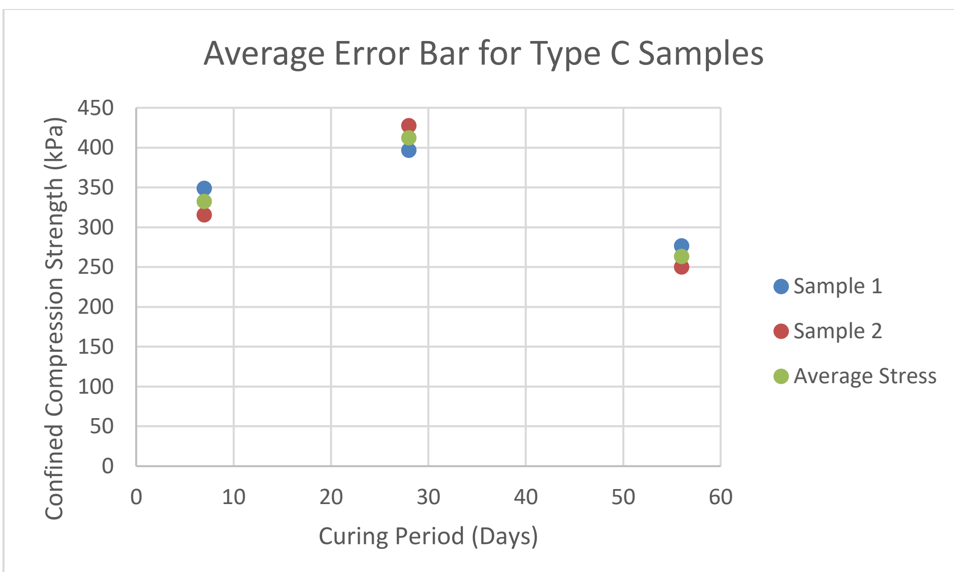

Figure 43 Average Bar for Confined Compression Strength of Type C Samples

The error bar for confined compression strength of type C samples over different curing periods is plotted in Figure 43. Almost no deviation is observed for samples tested after any curing period.

4.3.2 Application of Confining Pressure of 103 KPa

Upon application of comparatively high confining pressure the stress at failure has been increased for few samples than that for unconfined compression and compression test run with lower confinement but there is no any regular pattern observed in case of these samples which can define the effect of higher confining pressure on these samples. Stiffness of samples cured for 28 days is observed to be more than samples cured for 7 and 56 days. It implies that stiffness of samples tested with a confining pressure of 103 KPa is increased in the initial time frame and has reduced with further curing.

Table 16 Confined Compression Strength (kPa) of Type A samples with Confining Pressure of 103 KPa

Curing Period in Days	**Strength of Sample 1 (σ1) (kPa)**	**Strength of Sample 2 (σ1) (kPa)**	**Average Compression Strength (σ1) (kPa)**
7	259.76 (T-63)	231.18 (T-64)	245.47 (Average of T-63 and T-64)
28	209.58 (T-65)	227.64 (T-66)	218.61 (Average of T-65 and T-66)
56	287.20 (T-67)	256.19 (T-68)	271.70 (Average of T-67 and T-68)

The varied parameters between these samples are amount of cement and water in the mixture so as the water available for the chemical reaction between soil and cement is reduced after 28 days might have influenced the stiffness. Still there is a need to determine the reason behind this soil behavior. Table 16, 17 and 18 show the different values of stresses at failure for all types of samples upon applying confining pressure of 103 KPa. Figure 44,45 and 46 for type A, 48, 49 and 50 for type B while 52, 53 and 54 for type C are plotted to show stress Vs strain pattern respectively. Error bars for all these samples are plotted in Figure 47 for Type A, 51 for Type B and Figure 55 for Type C respectively.

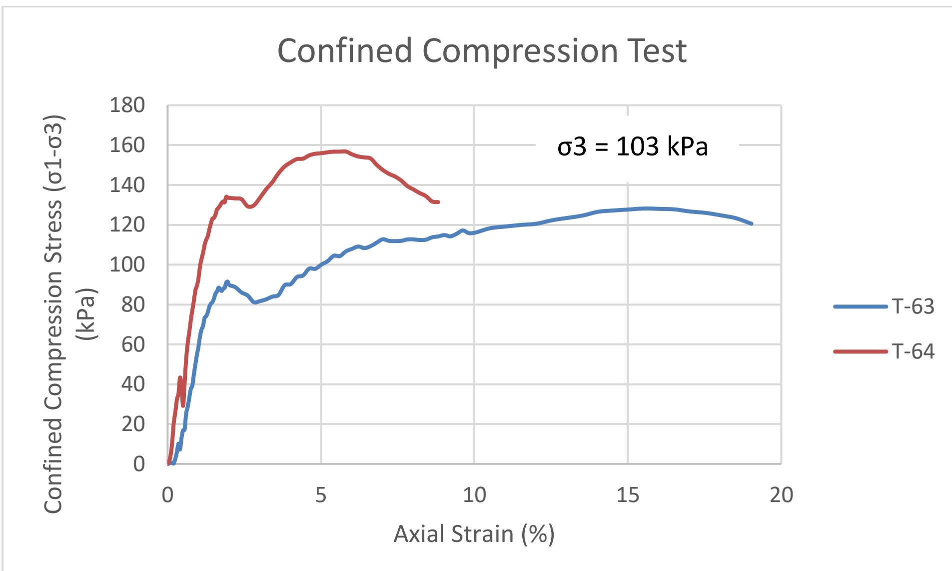

Figure 44 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 7 Days Curing Period and 103 KPa confining Pressure

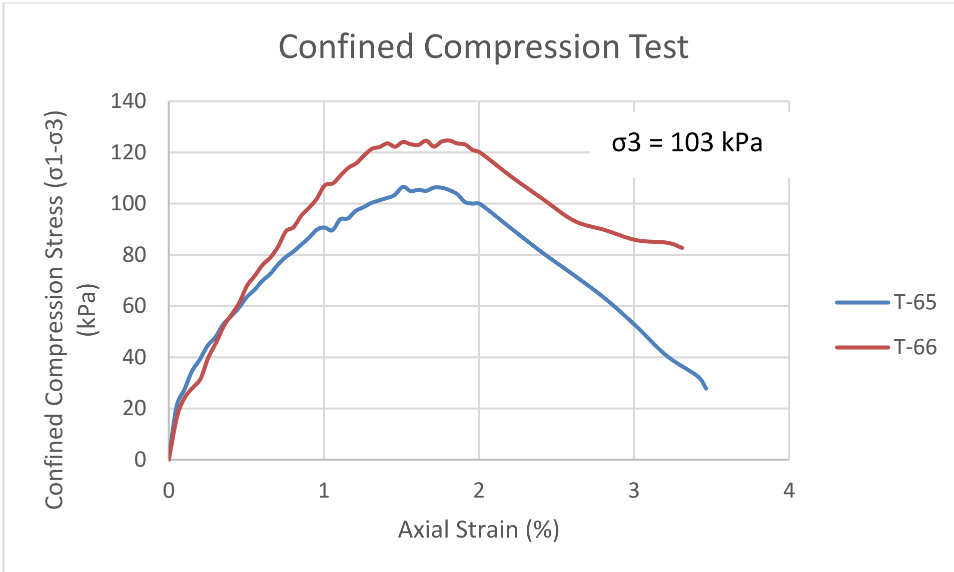

Figure 45 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 28 Days Curing Period and 103 KPa confining Pressure

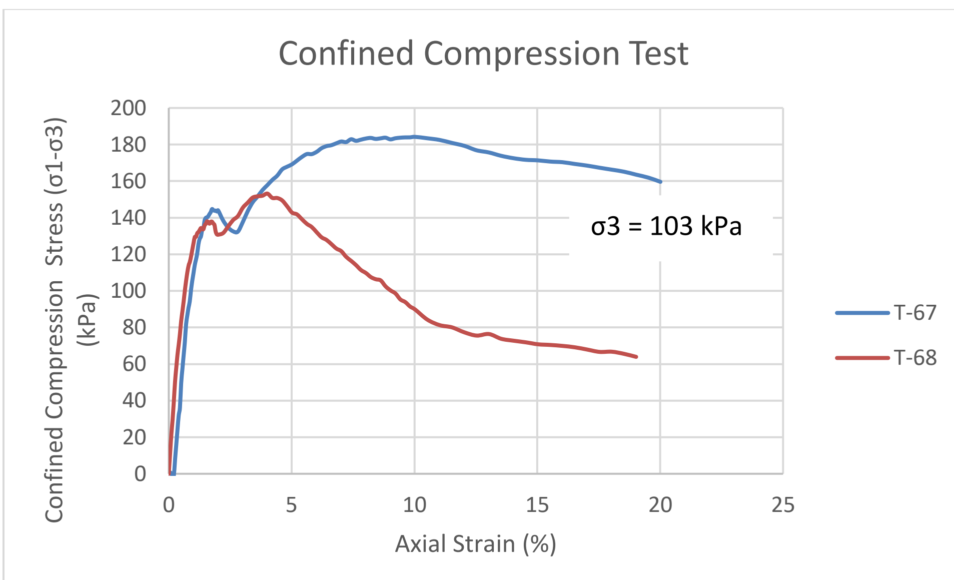

Figure 46 Stress Vs Strain Graph for Confined Compression Test for Type A sample over 56 Days Curing Period and 103 KPa confining Pressure

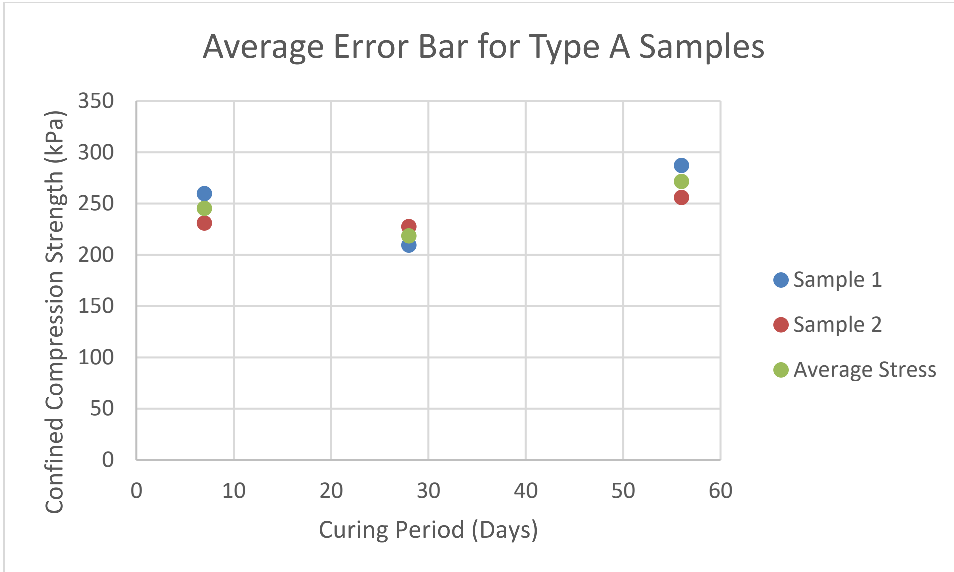

Figure 47 Average Error Bar for Confined Compression Strength of Type A Samples

Table 17 Confined Compression Strength (kPa) of Type B samples with Confining Pressure of 103 KPa

Curing Period in Days	**Strength of Sample 1 (σ1) (kPa)**	**Strength of Sample 2 (σ1) (kPa)**	**Average Compression Strength (σ1) (kPa)**
7	276.05 (T-69)	210.31 (T-70)	243.18 (Average of T-69 and T-70)
28	296.69 (T-71)	253.09 (T-72)	274.89 (Average of T-71 and T-72)
56	383.60 (T-73)	328.59 (T-74)	356.09 (Average of T-73 and T-74)

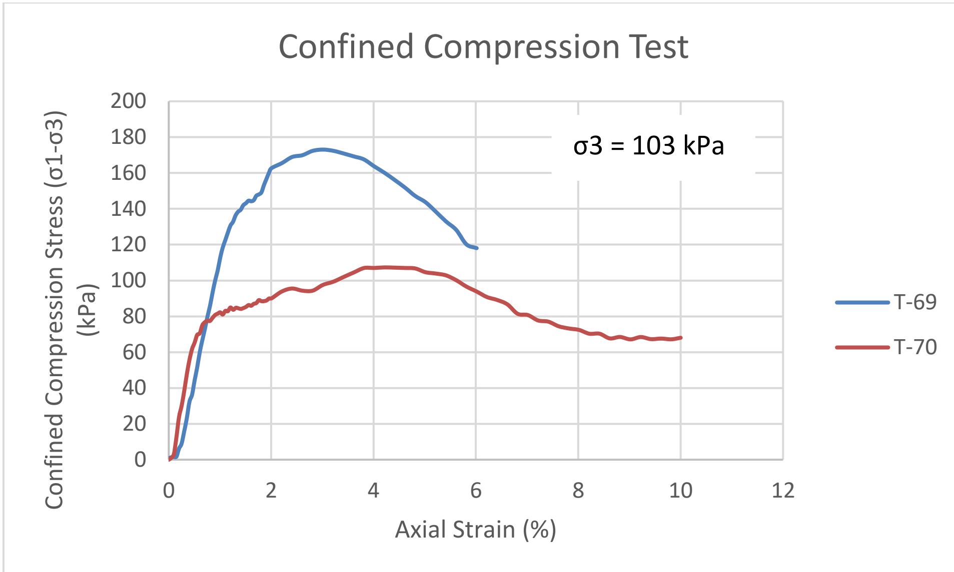

Figure 48 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 7 Days Curing Period and 103 KPa confining Pressure

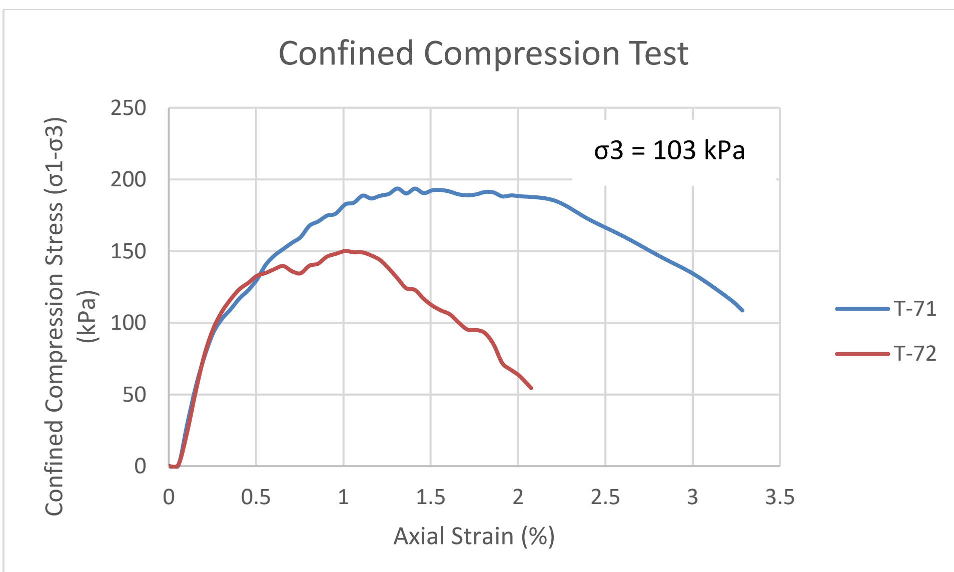

Figure 49 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 28 Days Curing Period and 103 KPa confining Pressure

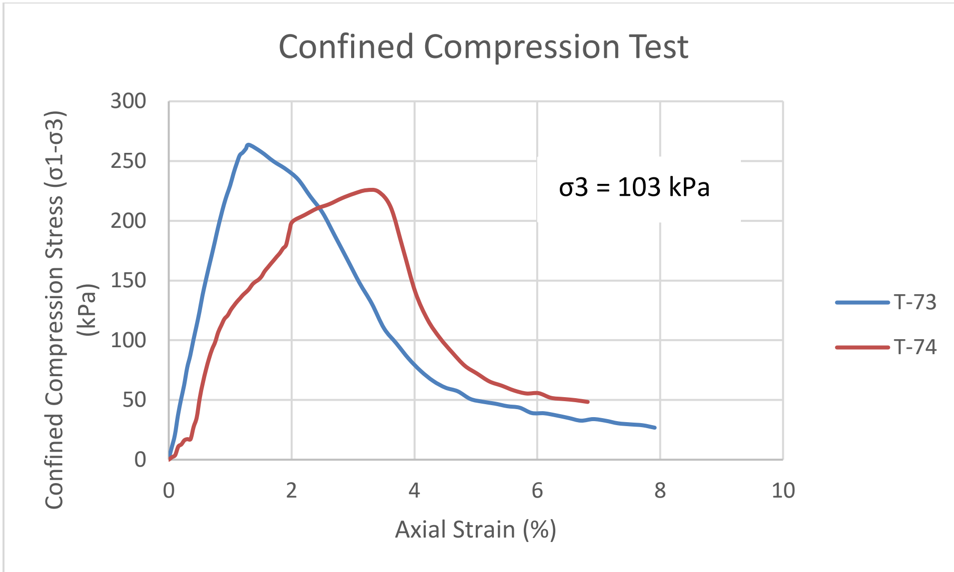

Figure 50 Stress Vs Strain Graph for Confined Compression Test for Type B sample over 56 Days Curing Period and 103 KPa confining Pressure

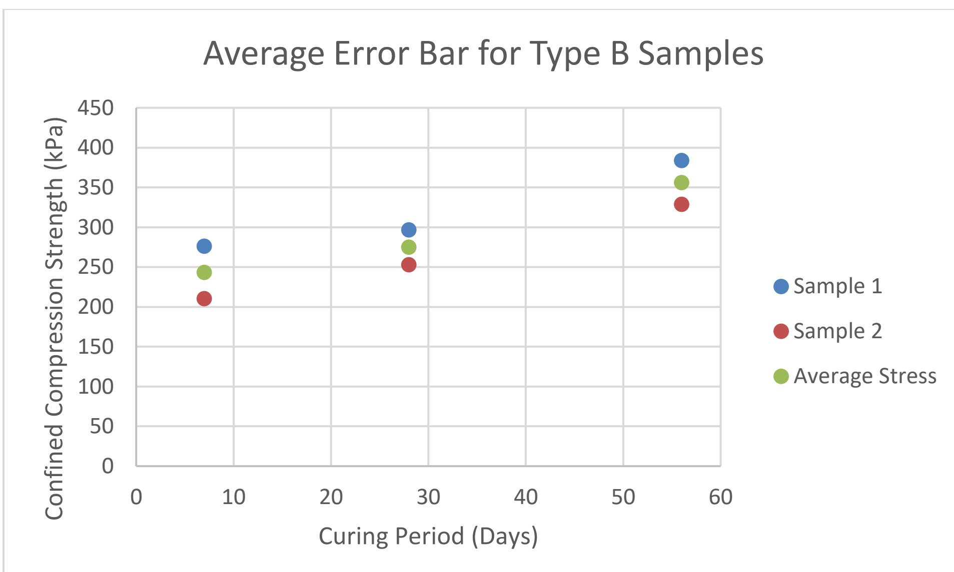

Figure 51 Average Error Bar for Confined Compression Strength of Type B Samples

Table 18 Confined Compression Strength (kPa) of Type C samples with Confining Pressure of 103 KPa

Curing Period in Days	Strength of Sample 1 (σ1) (kPa)	Strength of Sample 2 (σ1) (kPa)	Average Compression Strength (σ1) (kPa)
7	404.73 (T-75)	327.73 (T-76)	366.23 (Average of T-75 and T-76)
28	686.30 (T-77)	805.63 (T-78)	745.97 (Average of T-77 and T-78)
56	380.28 (T-79)	306.22 (T-80)	343.25 (Average of T-79 and T-80)

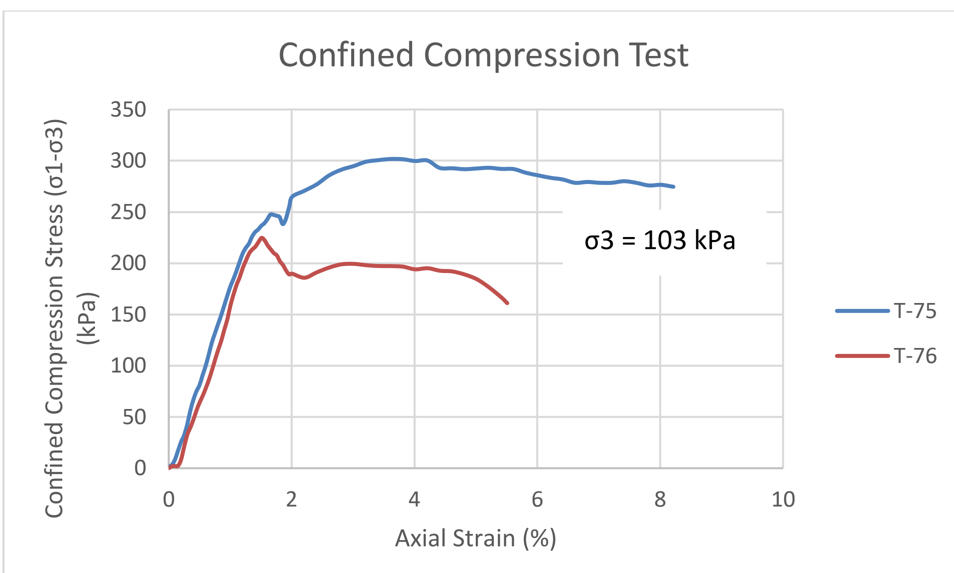

Figure 52 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 7 Days Curing Period and 103 KPa confining Pressure

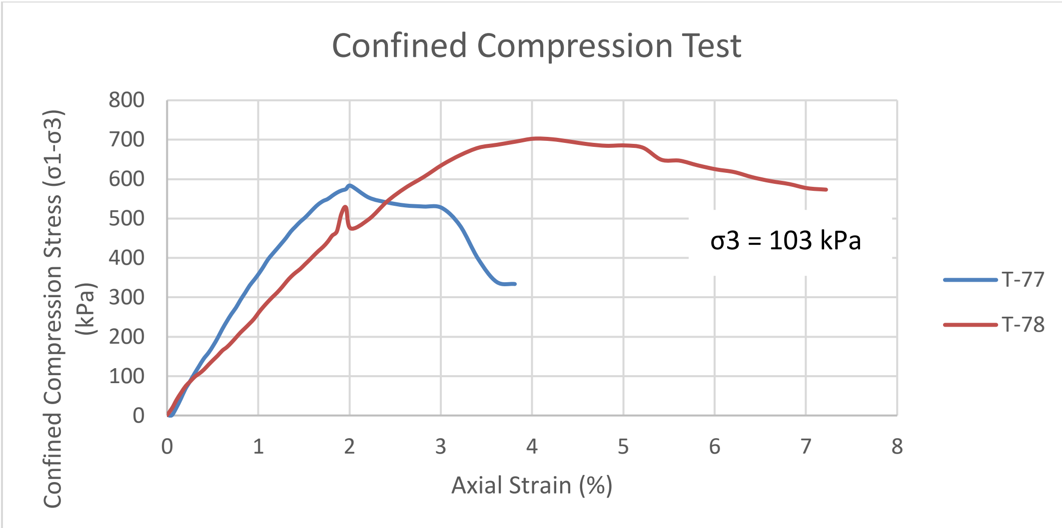

Figure 53 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 28 Days Curing Period and 103 KPa confining Pressure

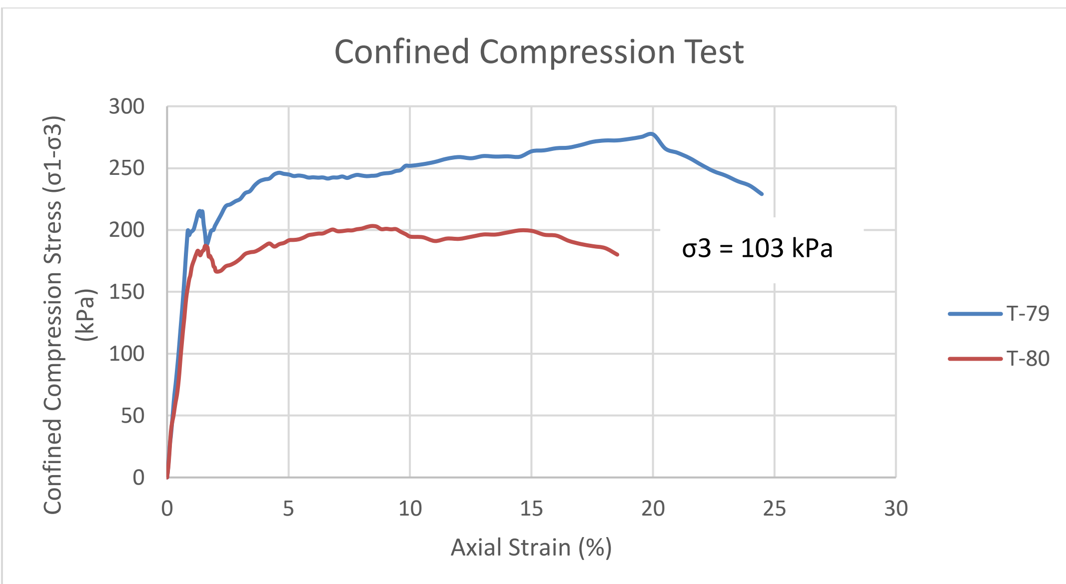

Figure 54 Stress Vs Strain Graph for Confined Compression Test for Type C sample over 56 Days Curing Period and 103 KPa confining Pressure

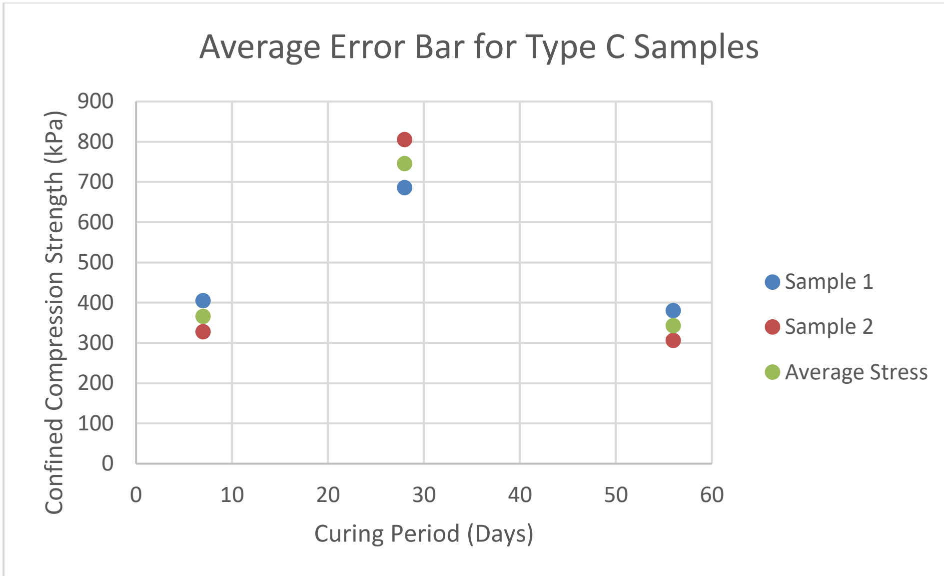

Figure 55 Average Error Bar for Confined Compression Strength of Type C Samples

To summarize the effect of the confinement on samples with lower cement content, the samples which are cured for 7 days showed an increment in the compression strength on applying low or high confining pressures. No increment in strength is observed for samples cured for 28 and 56 days and tested with low confining pressure while these samples showed the increment upon applying high confining pressure. Different values of compression strength under these conditions for Type A samples are listed in Table 19 while Figure 56 Shows the variation in the strength parameters in a graphical way.

Table 19 Effect of Confinement on Compression Strength of Type A samples

Curing Period in Days	Unconfined Compression Strength	Compression Strength (σ1) with 34 KPa Confinement	Compression Strength (σ1) with 103 KPa Confinement
7	110.85 (Average of T-27 and T-28)	145.45 (Average of T-45 and T-46)	245.47 (Average of T-63 and T-64)
28	168.42 (Average of T-29 and T-30)	133.5 (Average of T-47 and T-48)	218.61 (Average of T-65 and T-66)
56	228.24 (Average of T-31 and T-32)	227.44 (Average of T-49 and T-50)	271.7 (Average of T-67 and T-68)

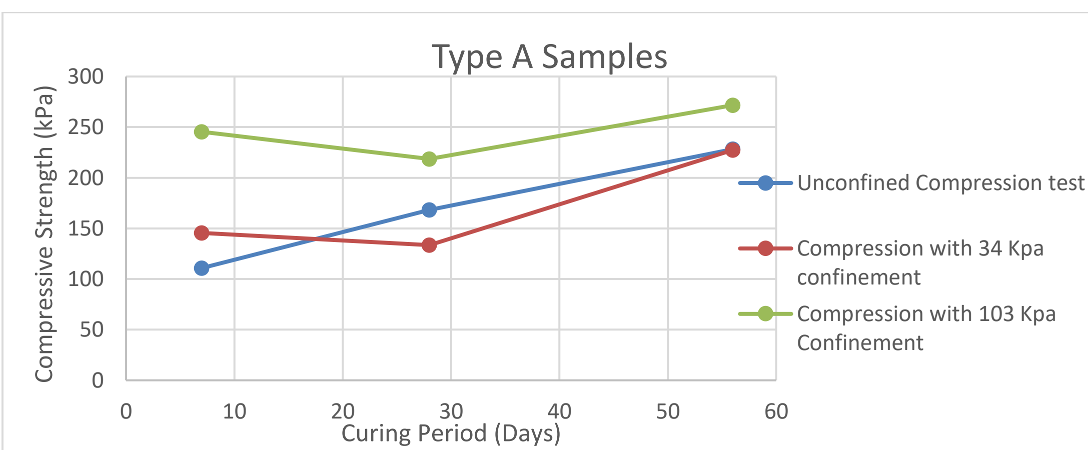

Figure 56 Effect on confinement on compressive strength of Type A samples

In case of medium cement content, the compression strength is affected by the low confining pressure till 28 days which is quite logical as per the explanation given for type A samples because the water added for type B samples is more than A so the plastic state might be maintained for longer time. For same composition, application of higher confining pressure has increased the confined compression strength of samples after all curing periods. Table 20 represents these strength values and are plotted in Figure 57.

Table 20 Effect of Confinement on Compression Strength of Type B Samples

Curing Period in Days	**Unconfined Compression Strength**	**Compression Strength (σ1) with 34 KPa Confinement**	**Compression Strength with (σ1) 103 KPa Confinement**
7	132.73 (Average of T-33 and T-34)	221.43 (Average of T-51 and T-52)	243.18 (Average of T-69 and T-70)
28	227.36 (Average of T-35 and T-36)	293 (Average of T-53 and T-54)	274.89 (Average of T-71 and T-72)
56	247.74 (Average of T-37 and T-38)	152.12 (Average of T-55 and T-56)	356.09 (Average of T-73 and T-74)

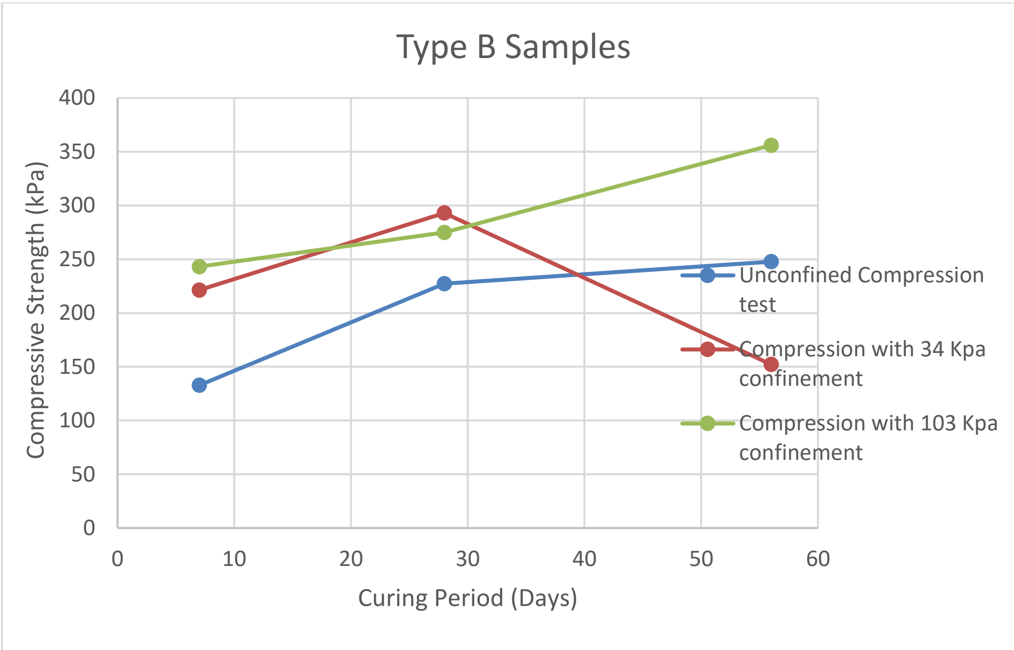

Figure 57 Effect of Confinement on Compressive Strength of Type B samples

For higher cement content and low confinement, trend of stress variation is observed like type B samples but stress values for high confinement were widely varied which proves the non-linear relation between confining pressure and curing period. The compression strength is increased upon applying high confining pressure for samples tested after any curing period. Compressive strength of higher cement content or type C samples for unconfined compression test, confined compression test with a confining pressure of 34 kPa and 103 kPa are listed in the Table 21. These variation in these values is plotted graphically in the Figure 58.

Table 21 Effect of Confinement on Compression Strength of Type C Samples

Curing Period in Days	Unconfined Compression Strength	Compression Strength (σ1) with 34 KPa Confinement	Compression Strength (σ1) with 103 KPa Confinement
7	273.61 (Average of T-39 and T-40)	332.21 (Average of T-57 and T-58)	366.23 (Average of T-75 and T-76)
28	306.15 (Average of T-41 and T-42)	412.13 (Average of T-59 and T-60)	745.97 (Average of T-77 and T-78)
56	341.18 (Average of T-43 and T-44)	263.44 (Average of T-61 and T-62)	343.25 (Average of T-79 and T-80)

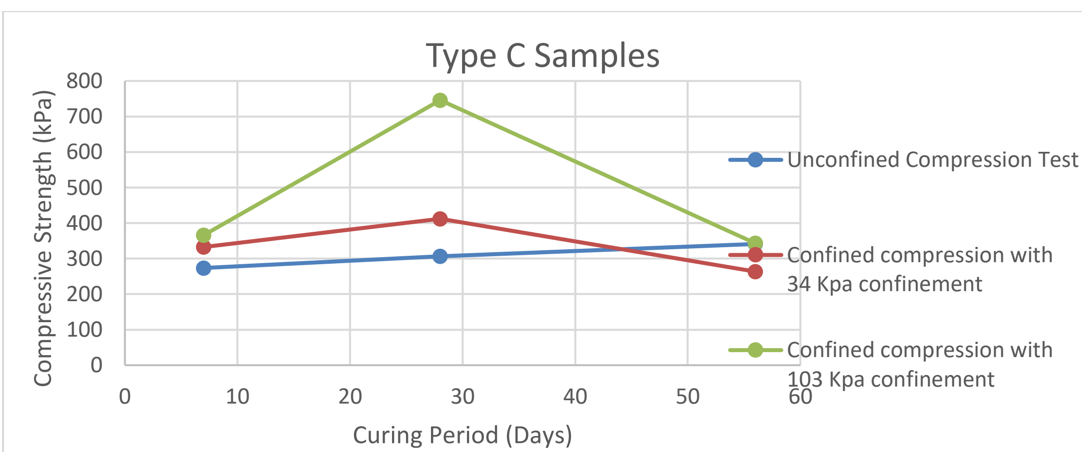

Figure 58 Effect of Confinement on Compressive Strength of Type C Samples

The actual motive behind this research was to find out the coefficient of linear increment/decrement in the compression strength of the cement treated soil, with increase in the confining pressure. For samples cured for 7 days, the coefficient of increment for lower cement content or type A samples is observed to be 121%, for moderate cement content it is 83% while for highest cement content is 34%. For these samples, the coefficient decreased with increase in the cement content. The plot of the axial stress at failure and radial stress or confining pressure for samples cured for 7 days is shown in Figure 59. Linear trendlines are plotted to find out the relation between these stresses and equations are mentioned in Table 22.

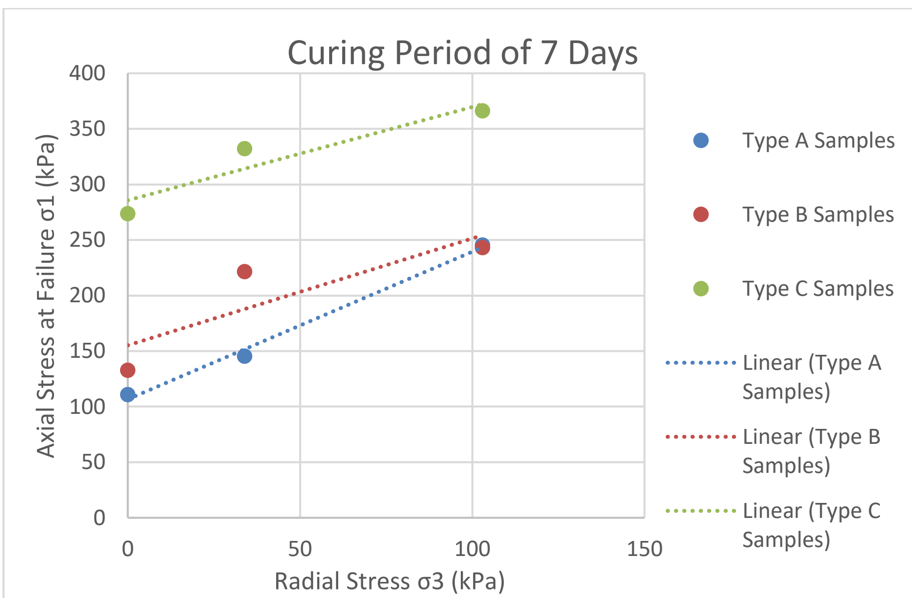

Figure 59 Relationship Between Axial Stress at Failure and Radial Stress for Samples Cured For 7 Days

Table 22 Equation of the Trendline between Axial and Radial Stress for All Types of Samples Cured for 7 Days

Type of Sample	Equation of the Trendline
A	Y=1.3278 x + 106.62
B	Y=0.9617 x + 155.2
C	Y= 0.8399 x + 285.66

For samples cured for 28 days, the coefficient of increment for lower cement content or type A samples is observed to be 30%, for moderate cement content it is 21% while for highest cement content is 143%. For these samples, the coefficient hasn't shown any specific relation with the cement content. The plot of the axial stress at failure and radial stress or confining pressure for samples cured for 28 days is shown in Figure 60.

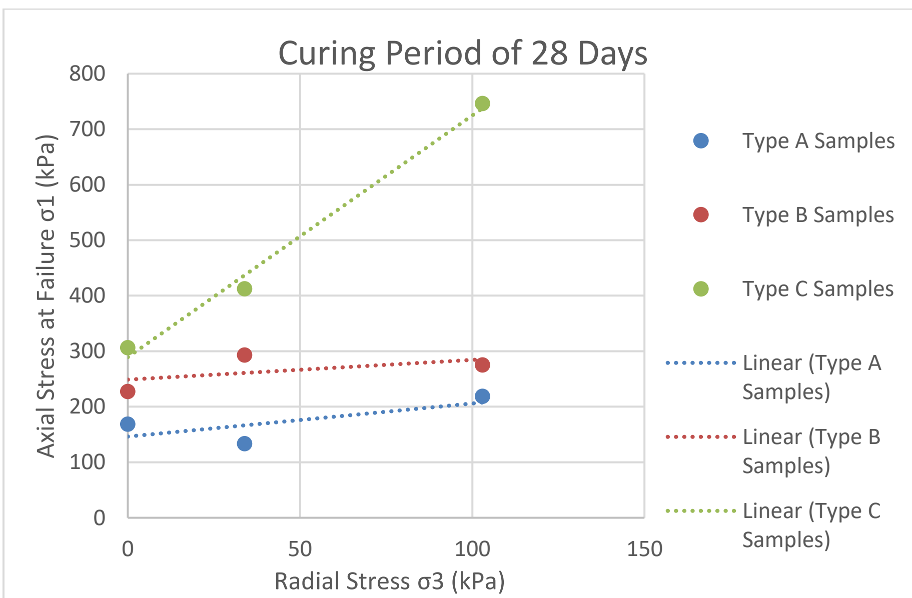

Figure 60 Relationship Between Axial Stress at Failure and Radial Stress for Samples Cured For 28 Days

Linear trendlines are plotted to find out the relation between these stresses and equations are mentioned in Table 23.

Table 23 Equation of the Trendline between Axial and Radial Stress for All Types of Samples Cured for 28 Days

Type of Sample	Equation of the Trendline
A	Y=0.5963 x + 146.28
B	Y=0.3557 x + 248.84
C	Y= 4.3531 x + 289.29

For samples cured for 56 days, the coefficient of increment for lower cement content or type A samples is observed to be 18%, for moderate cement content it is 44% while for highest cement content the strength is almost constant and the coefficient is 1%. For these samples also, the coefficient hasn't shown any specific relation with the cement content. The plot of the axial stress at failure and radial stress or confining pressure for samples cured for 28 days is shown in Figure 61. Linear trendlines are plotted to find out the relation between these stresses and equations are mentioned in Table 24.

Table 24 Equation of the Trendline between Axial and Radial Stress for All Types of Samples Cured for 56 Days

Type of Sample	Equation of the Trendline
A	Y=0.4477 x + 221.64
B	Y=1.3302 x + 191.24
C	Y= 0.1862 x + 307.45

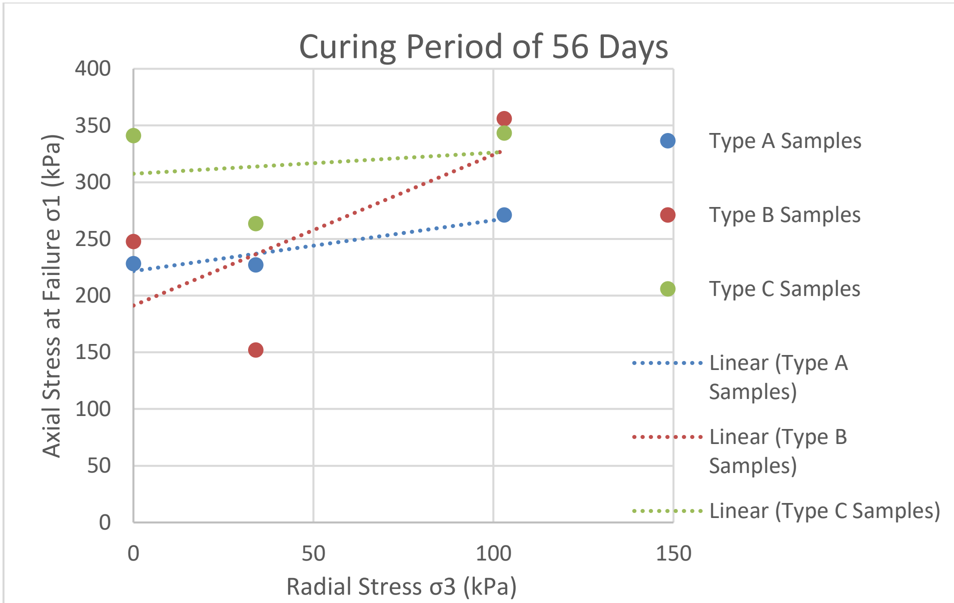

Figure 61 Relationship Between Axial Stress at Failure and Radial Stress for Samples Cured For 56 Days

4.4 Effect of Cement Treatment on Shear Parameters of Soil

In case of the undrained unconsolidated confined compression test run on the natural soil samples, as the test proceeds with a high speed and doesn't allow water to dissipate so the applied load is carried by both water and solids together. This phenomenon generates the result of compression test as shown in Figure 62.

In case of cement treated specimen, added cement will increase the bonding between soil solids. Also, as the water in the soil and grout is used during the chemical process between soil and cement so there may not be free water available in the soil after curing. Hence the confined compression test results may not be similar to that of undrained unconsolidated test run on only soil, so it's expected to observe an increase in the shear strength parameters with increase in the confining pressure.

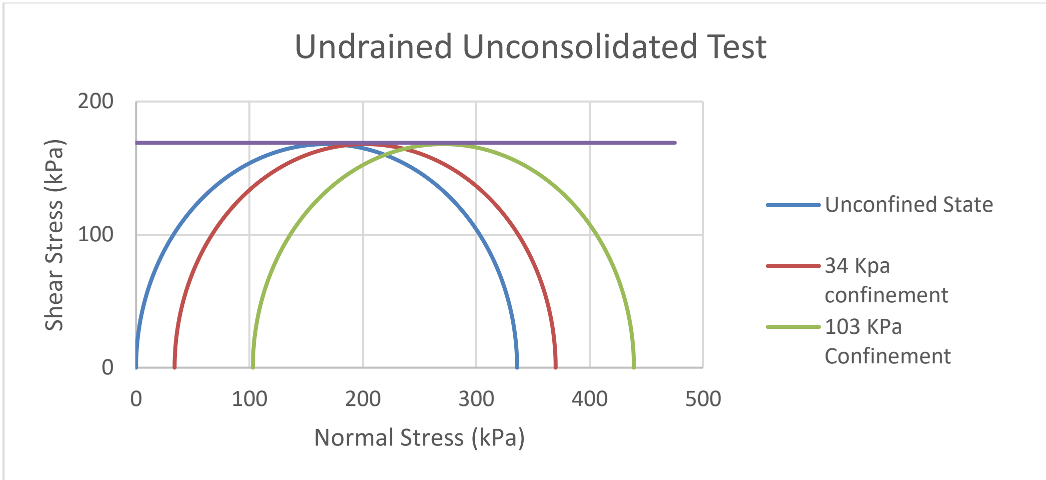

Figure 62 Variation in Confined Compression Strength of Soil with respect to Confinement Pressure.

As the availability of the water in the specimen is questionable so Mohr circles are plotted with total stress rather than plotting effective stress Mohr circle. Figure 63, 64 and 65 show Failure envelopes for type A samples after 7, 28, 56 days curing and under different confining pressures respectively. Cohesion and internal angle of friction of samples tested after 28 days and 56 days of curing couldn't be determined reliably as Mohr circles were varied drastically. These parameters for type A samples are mentioned in the Table 25.

Table 25 Shear Parameters of Type A samples

Curing Period in Days	Cohesion (kPa)	Angle of Friction (Degrees)
7	49	7.86
28	-	-
56	-	-

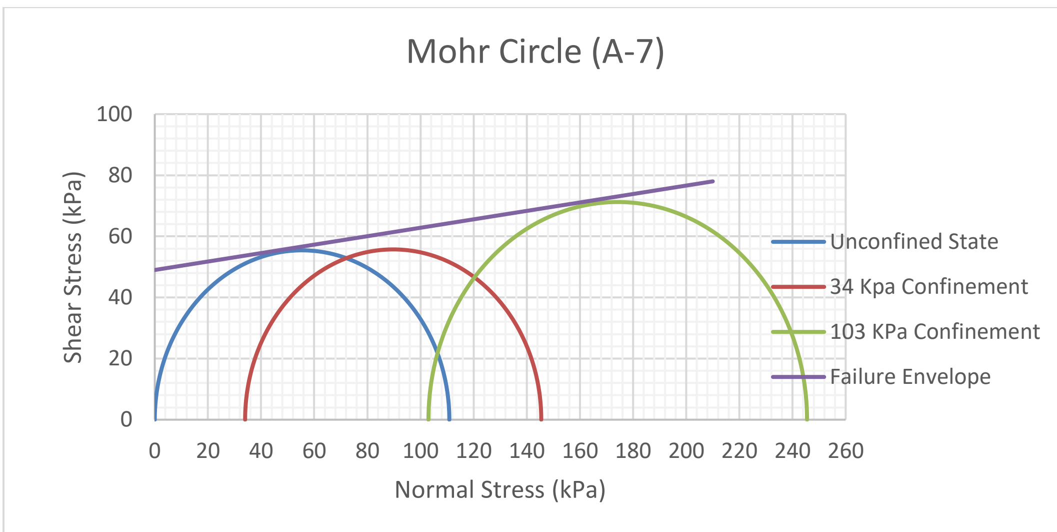

Figure 63 Failure Envelope for Type A sample over 7 Days Curing Period

For Moderate cement content, cohesion increased for samples cured for 28 days than samples cured for 7 days while internal angle of friction decreased for same. In Case of type B samples cured for 56 days, Mohr circles varied significantly so shear parameters for those samples couldn't be found out. Table 26 mentions all shear parameters for type B samples while Figure 66, 67 and 68 show shear parameters for type B samples cured for 7, 28 and 56 days respectively.

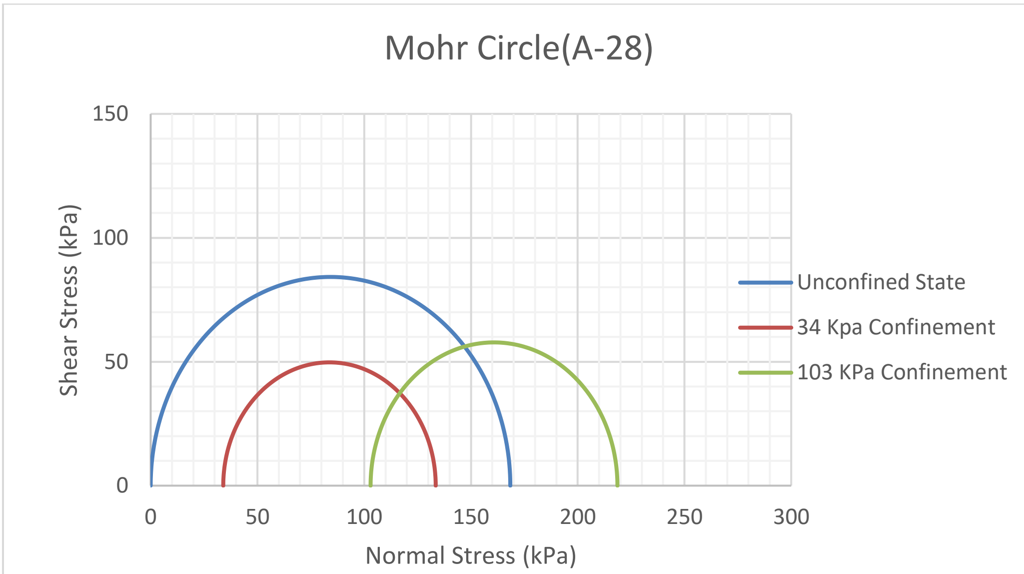

Figure 64 Failure Envelope for Type A sample over 28 Days Curing Period

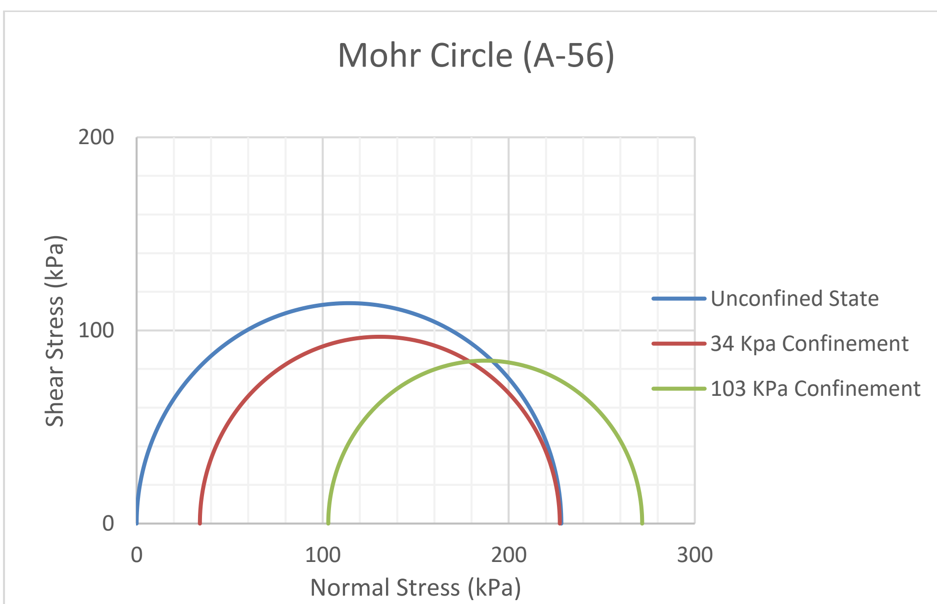

Figure 65 Failure Envelope for Type A sample over 56 Days Curing Period

Table 26 Shear Parameters of Type B samples

Curing Period in Days	Cohesion (kPa)	Angle of Friction (Degrees)
7	42	27.99
28	85	18.00
56	-	-

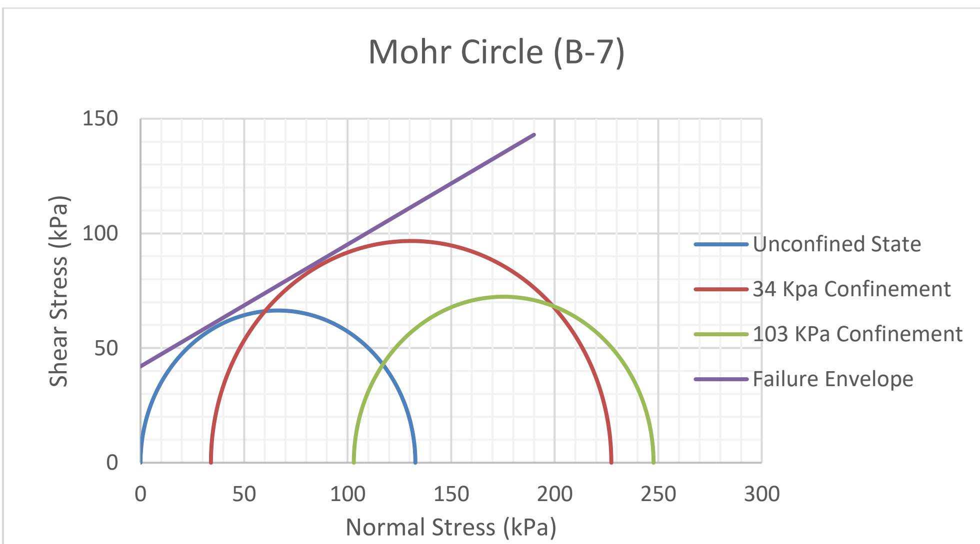

Figure 66 Failure Envelope for Type B sample over 7 Days Curing Period

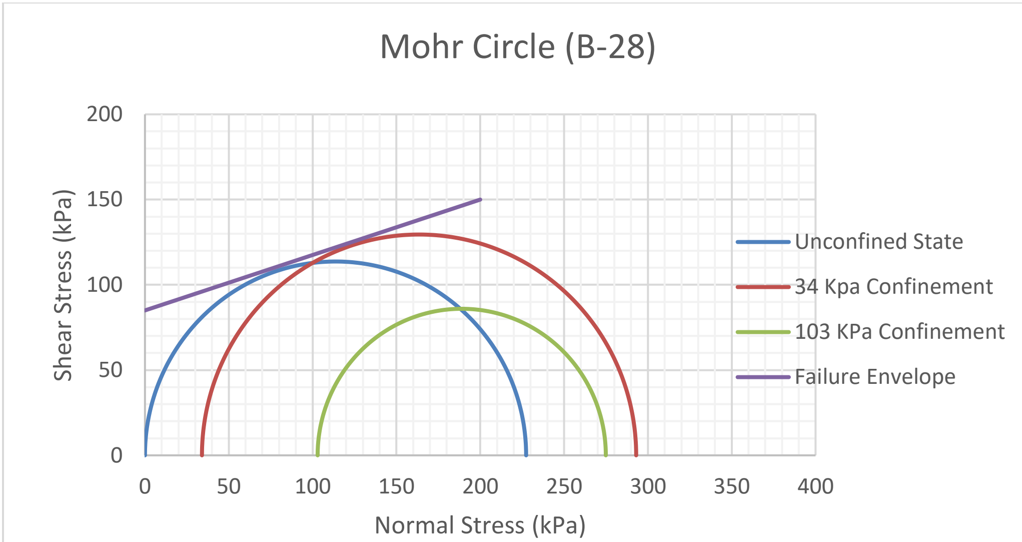

Figure 67 Failure Envelope for Type B sample over 28 Days Curing Period

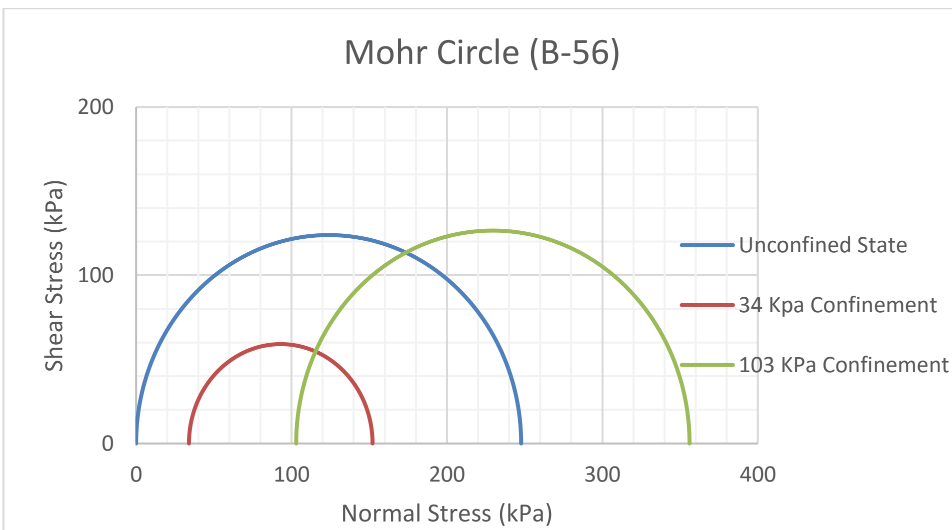

Figure 68 Failure Envelope for Type B sample over 56 Days Curing Period

For cement content of 15.5%, Cohesion value is decreased with curing period and Another shear parameter i.e. internal angle of friction is increased with curing period till 28 days. Shear Parameters were difficult to be determined for samples cured for 56 days because of variability in the Mohr circles. All the values of shear parameters for type C samples are mentioned in the Table 27.

Table 27 Shear Parameters of Type C samples

Curing Period in Days	Cohesion (kPa)	Angle of Friction (Degrees)
7	109	14.24
28	80	37.77
56	-	-

Figure 69, 70 and 71 show failure envelop for type C samples cured over different curing periods

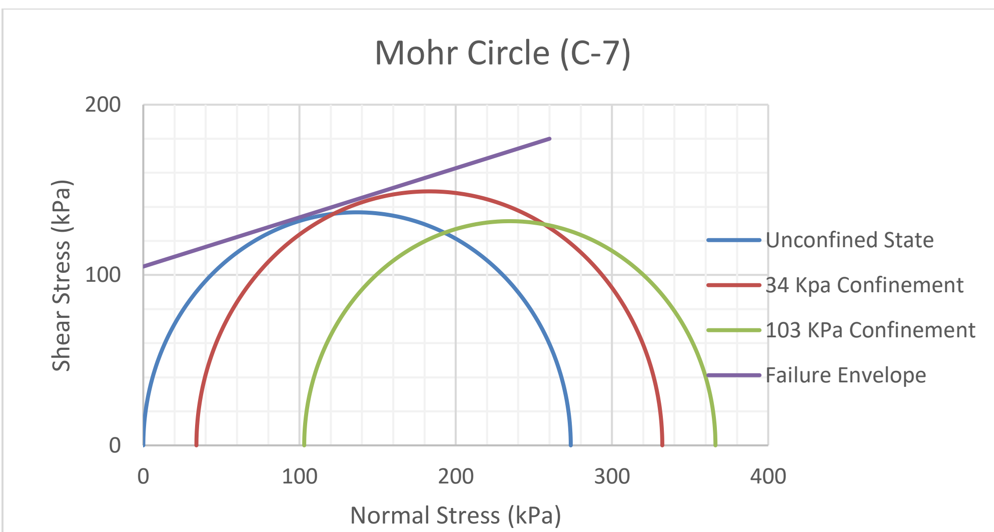

Figure 69 Failure Envelope for Type C sample over 7 Days Curing Period

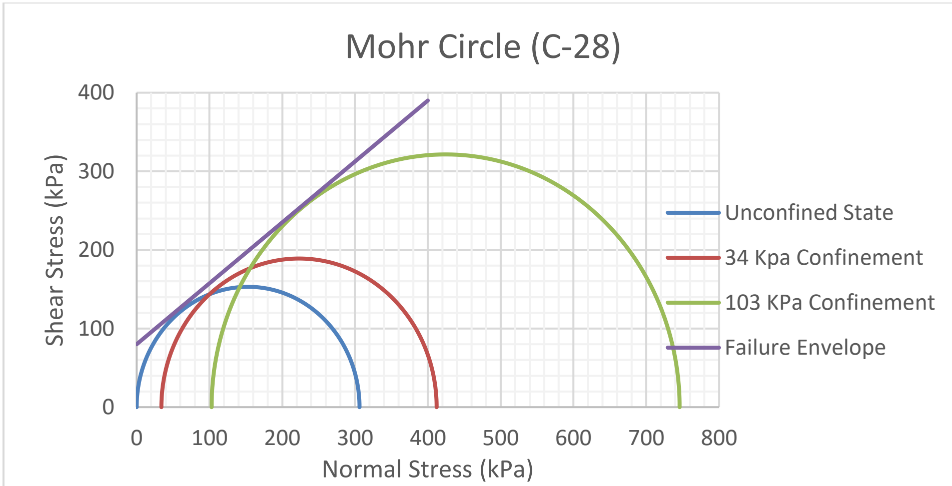

Figure 70 Failure Envelope for Type C sample over 28 Days Curing Period

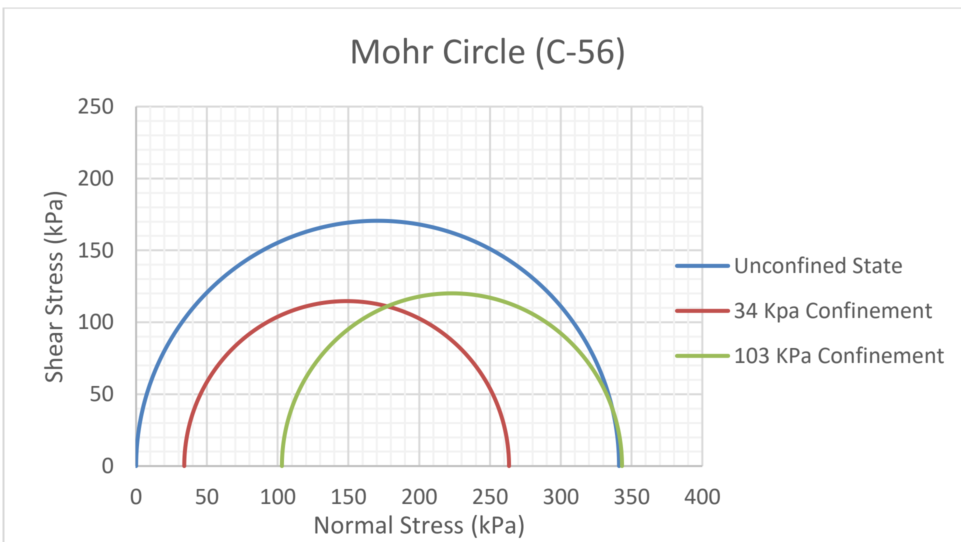

Figure 71 Failure Envelope for Type C sample over 56 Days Curing Period

4.5 Effect of Cement Treatment on Modulus of Deformation of Soil

As discussed in the literature part and observed from experimental data modulus of elasticity increases with increase in the cement content but it is observed that it has decreased after 28 days curing. It has been discussed in literature also that almost after 25 days, Young's modulus is more sensitive to the cement content than the curing time[16]. The reason might be scarcity of the available water for chemical reaction which reduces the stiffness of the soil after 28 days but still it requires further investigation to find out the cause. Also, the modulus of elasticity for almost all types of sample and curing period decreases with increase in the confining pressure except few samples. This difference in behavior proves that there is a non-linear relation between modulus of elasticity, confining pressure and cement content. Table 28 shows all values of modulus of elasticity for different samples under varying conditions.

Table 28 Variation in the Modulus of Deformation of Treated Soil Samples

Mixture Type	**Curing Period (Days)**	**Confining Pressure (kPa)**	**Modulus of Elasticity for Sample 1 (MPa)**	**Modulus of Elasticity for Sample 2 (MPa)**	**Average Modulus of Elasticity (MPa)**
A	**7**	**0**	6.5	6.08	6.29
		34	75.7	69.32	72.51
		103	8.21	9.27	8.74
	28	**0**	20	18.73	19.36
		34	39.21	31.8	35.5
		103	26.3	15.5	20.9

Table 28. Continued

Mixture Type	Curing Period (Days)	Confining Pressure (kPa)	Modulus of Elasticity for Sample 1 (MPa)	Modulus of Elasticity for Sample 2 (MPa)	Average Modulus of Elasticity (MPa)
A	**56**	**0**	17.78	17.50	17.64
		34	16.6	15.5	16.05
		103	12.4	15.4	13.9
B	**7**	**0**	5.107	9.266	7.18
		34	18.01	14.7	16.35
		103	13.9	21.3	17.6
	28	**0**	89.36	78.93	84.15
		34	22.5	13.0	17.75
		103	37.15	49.7	43.42
	56	**0**	31.82	31.92	31.87
		34	10.68	20.0	15.34
		103	25.7	16.5	21.1
C	**7**	**0**	14.92	24.52	19.72
		34	11.7	20.6	16.15
		103	18.72	17.61	18.16

Table 28. Continued

Mixture Type	Curing Period (Days)	Confining Pressure (kPa)	Modulus of Elasticity for Sample 1 (MPa)	Modulus of Elasticity for Sample 2 (MPa)	Average Modulus of Elasticity (MPa)
C	28	0	70.40	72.75	71.57
		34	50.67	28.24	39.45
		103	35.97	27.3	31.63
	56	0	37.60	34.07	35.83
		34	11.16	12.04	11.6
		103	20.21	28.63	24.42

Deformation modulus is calculated by calculating the slope of elastic part of the stress strain curve. In case of confined compression, it has been calculated by using the formula mentioned in Equation 1.

Equation 1 Modulus of Deformation

$$E = \frac{\sigma 1 - 2 * \upsilon * \sigma 3}{\varepsilon 1}$$

Where, $\sigma 1$ = Axial Stress at failure

υ = Poisson's ratio (it's assumed to be 0.3 in this study)

$\sigma 3$ = Radial Stress

ε1 = Axial Strain

At 7 days and for type A samples, deformation modulus at 34 kPa confining pressure was 11 times higher while at 103 kPa confining pressure, it was 38% larger than that of the unconfined compression test. For type B samples, at 34 kPa, it was 2.3 times larger while at 103 KPa it was 2.45 times larger than that of the unconfined compression test. For type C samples, it was decreased by 19% of that for unconfined compression test while at 103 KPa, it decreased by 8% compared to that of the unconfined compression test. Figure 57 shows the effect of confining pressure on the deformation modulus of cement treated silt tested after 7 days of curing period.

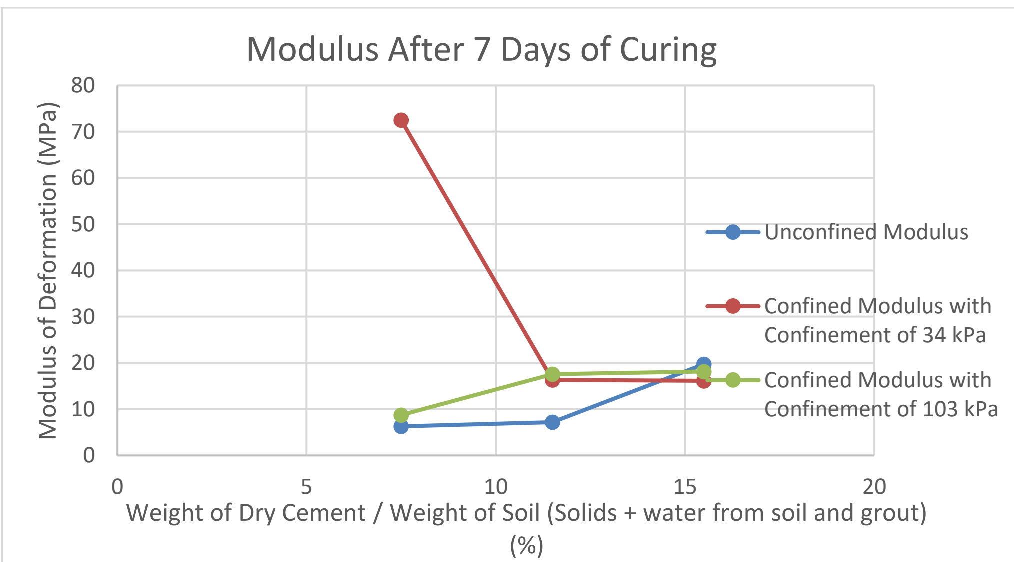

Figure 72 Effect of Confining Pressure on Deformation Modulus of Cement Treated Silt After 7 Days Curing Period

At 28 days and for type A samples, deformation modulus at 34 kPa was 83% larger than that of the unconfined compression test while at 103 kPa it increased by 7% compared to that of the unconfined compression test. For type B samples, it was 20% of that of the unconfined compression test while at 103 KPa it was 49% less than that of the unconfined compression test. For type C samples and at 34 kPa, it was 45% less than that of the unconfined compression test while at 103 kPa, it was 56% less than that of the unconfined compression test. Figure 58 shows the effect of confining pressure on the deformation modulus of cement treated silt tested after 28 days of curing period.

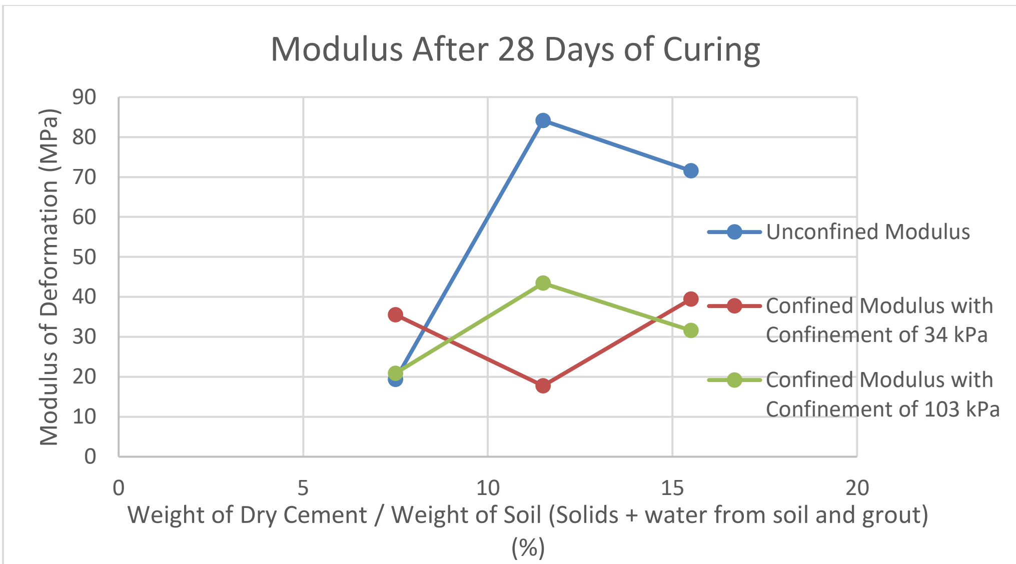

Figure 73 Effect of Confining Pressure on Deformation Modulus of Cement Treated Silt After 28 Days Curing Period

At 56 days and for type A samples, deformation modulus decreased with increase in the confining pressure while it decreased for sample type B and C also. The percentage of decrement in the modulus is increased with cement content. Lesser decrement is observed for type A samples while maximum decrement is observed in case of type C samples. Figure 59 shows the effect of confining pressure on the deformation modulus of cement treated silt tested after 56 days of curing period.

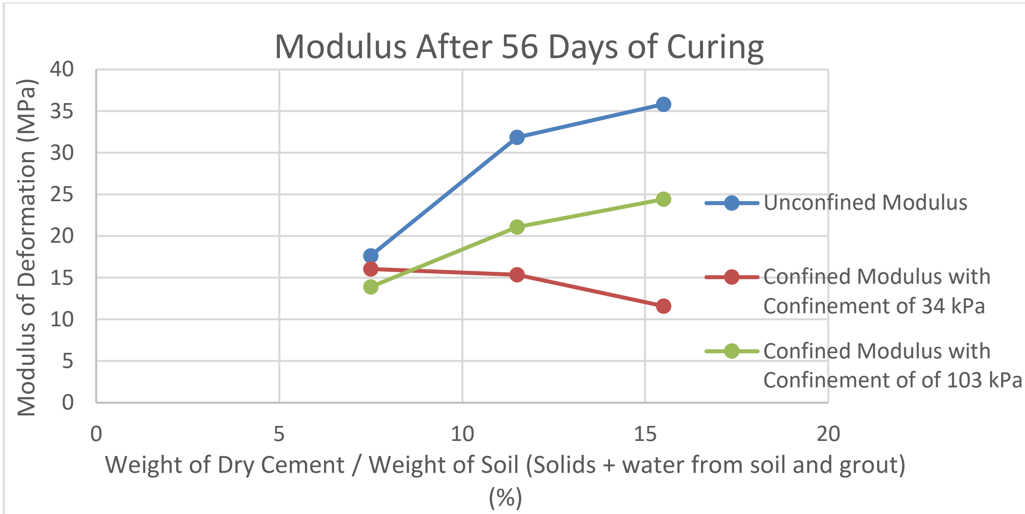

Figure 74 Effect of Confining Pressure on Deformation Modulus of Cement Treated Silt After 56 Days Curing Period

In a summary, deformation modulus in increased with cement content and confining pressure but the increment is not observed in all samples so the relation between deformation modulus and confining pressure cannot be determined.

CHAPTER V

CONCLUSION

It has been well documented that cement strengthens weak soils. This is typically quantified by measuring the unconfined compression strength of the cement treated soil compared to the untreated soil. However very little has been done to quantify the influence of the confinement on the strength improvement. This was studied in this thesis.

The soil used was a soft high plasticity silt with a low organic content (2.2%). The mini-vane shear strength of that silt was 6.5 kPa. The cement was a Type I/II cement and three different mix designs were used. The samples were tested at 7, 28, and 56 days. The stress-strain tests performed included unconfined compression tests, split tensile tests, and confined compression tests with two confining pressures (34 and 103 kPa).

The results of these tests were in the form of stress strain curves. These curves gave the strength and the modulus of the treated soil.

5.1 Strength

The findings are:

- The unconfined compression strength of the treated soil increased dramatically with the cement content and the curing period. At 7 days and for 7.5% cement content by weight (dry weight of cement divided by weight of soil plus weight of water from grout) the strength was 16 times higher than the strength of the untreated soil. At 7 days and for 11.5% cement content, it was 20 times higher and at 7 days and for 15.5% cement content, it was 40 times higher. At 28 days and for

7.5% cement content by weight, the strength was 25 times higher than the strength of the untreated soil. At 28 days and for 11.5% cement content, it was 34 times higher and at 28 days and for 15.5% cement content, it was 49 times higher. At 56 days and for 7.5% cement content by weight, the strength was 34 times higher than the strength of the untreated soil. At 56 days and for 11.5% cement content, it was 37 times higher and at 56 days and for 15.5% cement content, it was 52 times higher.

- The split tensile strength of the treated soil increased as well. At 7 days and for 7.5% cement content (dry weight of cement divided by weight of soil plus weight of water from grout) the average split tensile strength was 24 KPa. At 7 days and for 11.5% cement content, it was 39 KPa and at 7 days and for 15.5% cement content, it was 64 KPa. At 28 days and for 7.5% cement content by weight the strength was 42 KPa. At 28 days and for 11.5% cement content, it was 55 KPa and at 28 days and for 15.5% cement content, it was 110 KPa. At 56 days and for 7.5% cement content by weight the strength was 51 KPa. At 56 days and for 11.5% cement content, it was 75 KPa and at 56 days and for 15.5% cement content, it was 89 KPa.
- The confined compression strength of the treated soil was measured for two confining pressures: 34 kPa and 103 kPa. At 34 KPa the confined compression strength, at 7 days and for 7.5% cement content (dry weight of cement divided by weight of soil plus weight of water from grout) was 31% larger than the unconfined compression strength. At 7 days and for 11.5% cement content, it was 67% larger

than the unconfined compression strength. and at 7 days and for 15.5% cement content, it was 21% larger than the unconfined compression strength. At 28 days and for 7.5% cement content by weight the strength was 20% less than the unconfined compression strength. At 28 days and for 11.5% cement content, it was 28 % larger than the unconfined compression strength. and at 28 days and for 15.5% cement content, it was 35 % larger than the unconfined compression strength. At 56 days and for 7.5% cement content by weight the strength was almost equal to the unconfined compression strength. At 56 days and for 11.5% cement content, it was 39 % less than the unconfined compression strength. and at 56 days and for 15.5% cement content, it was 22 % less than the unconfined compression strength.

- At 103 KPa, the confined compression strength, at 7 days and for 7.5% cement content (dry weight of cement divided by weight of soil plus weight of water from grout) was 121 % larger than the unconfined compression strength. At 7 days and for 11.5% cement content, it was 83% larger than the unconfined compression strength. and at 7 days and for 15.5% cement content, it was 34 % larger than the unconfined compression strength. At 28 days and for 7.5% cement content by weight the strength was 30% larger than the unconfined compression strength. At 28 days and for 11.5% cement content, it was 20 % larger than the unconfined compression strength. and at 28 days and for 15.5% cement content, it was 144 % larger than the unconfined compression strength. At 56 days and for 7.5% cement content by weight, the confined compression strength was 19% larger than the strength of the unconfined compression strength. At 56 days and for 11.5% cement content, it was 44 % larger than the unconfined compression strength. and at 56 days and for 15.5% cement content, it was equal to the unconfined compression strength. Overall and on the average, the confined compression strength was 33% larger than the unconfined compression strength but the results varied between +143% and –38%.

- The friction angle and cohesion could not be determined with reliability because of the variability between samples. This variability made it impossible to draw the strength envelope tangent to the Mohr circles as those circles varied significantly.

5.2 Modulus

- The modulus of deformation of the soil was also affected by the cement content (dry weight of cement divided by weight of soil plus weight of water from grout), curing period and confining pressure. At 7 days and for 7.5% cement content it was 6.3 MPa for the unconfined compression test. At 34 kPa confining pressure, it was 11 times higher than that of the unconfined compression test while at 103 kPa confining pressure, it was 38% larger than that of the unconfined compression test. At 7 days and for 11.5% cement content it was 7.18 MPa for the unconfined compression test. At 34 kPa, it was 2.3 times larger than that of the unconfined compression test while at 103 KPa it was 2.45 times larger than that of the unconfined compression test. At 7 days and for 15.5% cement content it was 19.72 MPa for the unconfined compression test. At 34 kPa, it was decreased by 19% of that for unconfined compression test while at 103 KPa, it decreased by 8% compared to that of the unconfined compression test.

- At 28 days and for 7.5% cement content it was 19.36 MPa for the unconfined compression test. At 34 kPa, it was 83% larger than that of the unconfined compression test while at 103 kPa it increased by 7% compared to that of the unconfined compression test. At 28 days and for 11.5% cement content it was 84.15 MPa for unconfined compression test. At 34 kPa, it was 5 times less than that of the unconfined compression test while at 103 KPa it was 49% less than that of the unconfined compression test. At 28 days and for 15.5% cement content it was 71.57 MPa for the unconfined compression test. At 34 kPa, it was 45% less than that of the unconfined compression test while at 103 kPa, it was 56% less than that of the unconfined compression test.
- At 56 days and for 7.5% cement content it was 17.64 MPa for unconfined compression test. At 34 kPa confinement, it decreased by 10% compared to that of the unconfined compression test while at 103 kPa it was 22% less than that of the unconfined compression test. At 56 days and for 11.5% cement content it was 31.9 MPa for the unconfined compression test. At 34 kPa, it was 48% less than that of the unconfined compression test while at 103 kPa, it was 34% less than that of the unconfined compression test. At 56 days and for 15.5% cement content it was 35.83 MPa for the unconfined compression test. At 34 kPa confinement, it was 68% less than that of the unconfined compression test while at 103 kPa, it was 32% less than that of the unconfined compression test.

Overall the results indicate that,

- The unconfined compression strength always increases with cement content.
- The unconfined compression strength always increases with the curing period as well.
- The split tensile strength also increases with cement content and curing time but not as much as the unconfined compression strength
- The confinement at 34 and 103 kPa does not produce any significant increase or decrease in compression strength compared to the unconfined compression results.
- On average the confined compression strength CCS is 3% higher than the unconfined compression strength UCS; however, the ratio CCS/UCS varies between 0.52 and 2.02
- On average the confined compression modulus CCM is 52% higher than the unconfined compression modulus UCM; however, the ratio varied from 0.07 to 11.
- The modulus calculated from the linear slope at the beginning of the stress strain curve increased with the cement content
- The modulus increased from the 7 day curing period to the 28 day curing period but decreased for the 56 day curing period.
- Overall, the results indicate that there is significant variation in strength and modulus between samples even when they are prepared with care and

for the same cement content and curing time. The lack of reproducibility of the samples does not permit to conclude with conviction. A much-improved way of preparing controlled mixing of the samples must be developed if conclusion on minor effects like confinement are to be evaluated precisely.

REFERENCES

1. Sariosseiri, F. and B. Muhunthan, *Effect of cement treatment on geotechnical properties of some Washington State soils.* Engineering Geology, 2009. **104**(1): p. 119-125.
2. Molaabasi, H., A. Khajeh, and S. Semsani, *Porosity/(SiO2 and Al2O3 Particles) Ratio Controlling Compressive Strength of Zeolite-Cemented Sands*. 2017.
3. Firoozi, A.A., et al., *Fundamentals of soil stabilization.* International Journal of Geo-Engineering, 2017. **8**(1): p. 26.
4. Lemaire, K., et al., *Effects of lime and cement treatment on the physicochemical, microstructural and mechanical characteristics of a plastic silt.* Engineering Geology, 2013. **166**: p. 255-261.
5. Sharma, R.K. and J. Hymavathi, *Effect of fly ash, construction demolition waste and lime on geotechnical characteristics of a clayey soil: a comparative study.* Environmental Earth Sciences, 2016. **75**(5): p. 377.
6. Sharma, L.K., et al., *Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study.* Applied Clay Science, 2018. **152**: p. 183-195.
7. Djelloul, R., et al., *Effect of Cement on the Drying–Wetting Paths and on Some Engineering Properties of a Compacted Natural Clay from Oran, Algeria*. Vol. 36. 2017.

8. D. Currin, D., J. J. Allen, and D. N. Little, *Validation of Soil Stabilization Index System with Manual Development*. 1976. 565.

9. Pakbaz, M.S. and R. Alipour, *Influence of cement addition on the geotechnical properties of an Iranian clay.* Applied Clay Science, 2012. **67-68**: p. 1-4.

10. Rabbi, A.T.M.Z. and J. Kuwano, *Effect of Curing Time and Confining Pressure on the Mechanical Properties of Cement-Treated Sand.* GeoCongress 2012: p. 996-1005.

11. Wu, X., et al., *Influence of confining pressure-dependent Young's modulus on the convergence of underground excavation.* Tunnelling and Underground Space Technology, 2019. **83**: p. 135-144.

12. Dutta, T.T. and S. Saride, *EFFECT OF CONFINING PRESSURE, RELATIVE DENSITY AND SHEAR STRAIN ON THE POISSON'S RATIO OF CLEAN SAND*. 2015.

13. Lopez-Querol, S., et al., *Improvement of the bearing capacity of confined and unconfined cement-stabilized aeolian sand.* Construction and Building Materials, 2017. **153**: p. 374-384.

14. Feng, K. and B.M. Montoya, *Influence of Confinement and Cementation Level on the Behavior of Microbial-Induced Calcite Precipitated Sands under Monotonic Drained Loading.* Journal of Geotechnical and Geoenvironmental Engineering, 2016. **142**(1): p. 04015057.

15. Xu, X., et al., *Effect of moisture content on mechanical and damage behavior of frozen loess under triaxial condition along with different confining pressures.* Cold Regions Science and Technology, 2019. **157**: p. 110-118.

16. Tinoco, J., A.G. Correia, and P. Cortez, *A novel approach to predicting Young's modulus of jet grouting laboratory formulations over time using data mining techniques.* Engineering Geology, 2014. **169**: p. 50-60.

17. Muhunthan, B., and Sariosseiri, F., *Interpretation of Geotechnical Propertoies of Cement Treated Soil.* Office of research and library services, Washington State Department of Transportation, 2008.

18. Engineering manual 1110-3-137., *Soil Stabilization for Pavements Mobilization Construction.* Department of the Army, Corps of engineers office of the chief of the engineers, 1984.