SOIL STABILIZATION USING OPTIMUM QUANTITY OF CALCIUM CHLORIDE WITH CLASS F FLY ASH

A Thesis

by

HYUNG JUN CHOI

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

MASTER OF SCIENCE

August 2005

Major Subject: Civil Engineering

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Approved by:

Chair of Committee,	Charles Aubeny
Committee Members,	Giovanna Biscontin
	Christopher C. Mathewson
Head of Department,	David V. Rosowsky

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ABSTRACT

Soil Stabilization Using Optimum Quantity of Calcium Chloride

with Class F Fly Ash. (August 2005)

Hyung Jun Choi, B.S., Hong-ik University

Chair of Advisory Committee: Dr. Charles Aubeny

On-going research at Texas A&M University indicated that soil stabilization using calcium chloride filter cake along with Class F fly ash generates high strength. Previous studies were conducted with samples containing calcium chloride filter cake and both Class C fly ash and Class F fly ash. Mix design was fixed at 1.3% and 1.7% calcium chloride and 5% and 10% fly ash with crushed limestone base material. Throughout previous studies, recommended mix design was 1.7% calcium chloride filter cake with 10% Class F fly ash in crushed limestone base because Class F fly ash generates early high and durable strength.

This research paper focused on the strength increase initiated by greater than 1.7% pure calcium chloride used with Class F fly ash in soil to verify the effectiveness and optimum ratio of calcium chloride and Class F fly ash in soil stabilization. Mix design was programmed at pure calcium chloride concentrations at 0% to 6% and Class F fly ash at 10 to 15%.

Laboratory tests showed samples containing any calcium chloride concentration from 2% to 6% and Class F fly ash content from 10% to 15% obtained high early

strength however, optimum moisture content, different mix design, and mineralogy deposit analysis are recommended to evaluate the role and the effectiveness of calcium chloride in soil stabilization because of the strength decreasing tendency of the samples containing calcium chloride after 56 days.

DEDICATION

To my family, my sister, Eun Joo Choi, and my wife, Erika Rodriguez

ACKNOWLEDGEMENTS

I would like to express my appreciation to all those who gave me the possibility to complete this thesis. Most of all, I would like to express my deep and sincere gratitude to my advisor, Dr. Charles Aubeny. His encouragement, time, and personal guidance helped me to complete this thesis. I would like to thank Dr. Suren Mishra of TETEA Technologies, Inc. for his financial and technical support. I also would like to thank Dr. Don Saylak for offering me the opportunity to work on this project. I appreciate my committee members, Dr. Giovanna Biscontin and Dr. Christopher Mathewson, for their advice and encouragement.

Technical guidance was made by many people but I, especially, thank Cindy Estakhri and Stacy Hilbrich for their time and support. Their technical guidance was a big help to successfully complete this project.

I owe lots of love to my family. I deeply appreciate my sister, Eun Joo Choi, for her endless support and encouragement in my life. I would also like to thank to my brother, Kwang Jun Choi, sister, Bona Choi, and my parents. Last of all, I would like to express my appreciation to my lovely wife, Erika Rodriguez and her family. Her dedication and encouragement led me to the end.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

TABLE OF FIGURES

TABLE OF FIGURES (Cont'd)

TABLE OF FIGURES (Cont'd)

FIGURE Page

LIST OF TABLES

LIST OF TABLES (Cont'd)

TABLE Page

CHAPTER I

INTRODUCTION

In geotechnical engineering, soil stabilization or other methods are required when a given site does not have suitable engineering properties to support structures, roads, and foundations. One possibility is to adapt the foundation to the geotechnical conditions at the site. Another possibility is to try to stabilize or improve the engineering properties of the soils at the site. Depending on the circumstances, this second approach may be the most economical solution to the problem (Holtz and Kovacs 1981). This second approach includes mechanical as well as chemical stabilization. Mechanical stabilization is produced by compaction. Chemical stabilization is achieved by mixing the soils with additives such as calcium chloride, Portland cement, lime, and fly ash. This report focuses on mechanical stabilization and chemical stabilization using calcium chloride and class F fly ash as additives.

In general, stabilizing agents may be divided into two broad categories, based on the stabilization mechanisms utilized when the agents are incorporated into a soil or aggregate. Active stabilizers produce chemically induced cementing reaction within the

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This thesis follows the style of *The Journal of Geotechnical and Geoenvironmental Engineering.*

soil or aggregate, which in turn produces desirable changes in engineering characteristics of the stabilized soil or aggregate system. Inert stabilizers do not react chemically with the soil or aggregate. Rather, stabilization is obtained as a result of binding together and/or water-proofing the soil or aggregate with the inert stabilizer. Many stabilizers display various combinations of active and inert characteristics (Anderson et al.1978). Inert stabilizers attain strengths that normally do not change with time while active stabilizers develop strength over time as the chemical reaction progress. The stabilizers under consideration in this research are calcium chloride and Class F fly ash.

Generally speaking, calcium chloride mostly acts as an active stabilizer and Class F fly ash acts as an inert stabilizer. In this research, calcium chloride and Class F fly ash are evaluated through the results of unconfined compressive strength tests.

Calcium chloride ($CaCl_2$) has been used primarily as a dust palliative in roadway maintenance as well as an accelerator in cement manufactures as soil stabilization products. In secondary road construction, it has been shown to be effective not only for the development of strength, but also for dust control because its deliquescent nature tends to absorb atmospheric moisture and keep the fines from the soil surface. Fly ash has been proven to be a self-cementing additive for promoting the soil stabilization and compressive strength but not effective for dust control (Saylak et al. 1996; Sinn 2002; Hilbrich 2003). More recently, calcium chloride has been used as an accelerator, and it was found that pre-grinding of fly ash and lime with a calcium chloride accelerator lead to significant improvement in high early strength (Roy et al. 1984). According to the Virginia Transportation Research Council (VTRC), calcium chloride has been used as a dust suppressant, but it is also referred to as a stabilizer because of its ability to alter material properties such as strength, compressibility and permeability. Essentially, the function of this chemical is to agglomerate fine particles and bind them together (Bushman et al. 2004). On-going research at Texas A&M University found that an addition of calcium chloride ($CaCl_2$) and fly ash (Class C and F) to soils and crushed limestone significantly increased the effectiveness of road base stabilization and base stabilization along with dust control in Full-Depth-Recycling (FDR) of old asphalt roads. It was also shown that class F fly ash tends to give more durable early higher strength than Class C fly ash (McDonald 2003; Hilbrich 2003). The latter, which is significantly more cementicious than Class F fly ash, tends to become overly brittle and can produce swelling in soils continuing soluble sulfate.

The background and objective of this study on soil stabilization using calcium chloride and class F fly ash will be discussed in Chapter II. It will be explained what inspired this study and why optimum mix design is important. All the materials used for experiments and test methodologies will be covered in Chapter III. In this chapter, typical soil stabilization measurements and additives, calcium chloride and class F fly ash, will be introduced including their material character and source. Also soil properties were determined according to ASTM (American Society for Testing and Materials) and the methodologies will be covered. In Chapter IV, compaction properties will be analyzed and discussed. In Chapter V, unconfined strength will be analyzed with the cure times up to 90 days. Based on test results, implications on mix design will be discussed at Chapter VI to summarize desired laboratory strategies to guide current and future research. Finally, Chapter VII presents conclusions and recommendations for future work.

CHAPTER II

BACKGROUND AND STUDY OBJECTIVES

Previous research at Texas A&M University indicated that calcium chloride, which had been used primarily as a dust palliatives as well as accelerator for cement manufacturing (Saylak et al. 1996; Sinn 2002), also improves soil and roadbase strength. Sinn tested six different mix designs (control, 5% Class C fly ash, 10% Class C fly ash, 1.7% $CaCl_2$+5% Class C fly ash, and 1.7% $CaCl_2$+10 Class C fly ash) to evaluate the effectiveness of additives. Fly ash is classified according to the criteria outlined in Table 2-1.

Table 2-1. Fly Ash Classification Based on ASTM C-618-03

Parameter	ASTM C-618-03 Specification	
	Class C	Class F
Sum of SiO_2, Al_2O_3, and Fe_2O_3	50 Min.	70 Min.
Sulfur Trioxide (SO_3)	5.0 Max.	5.0 Max.
Moisture Content	3.0 Max.	3.0 Max.
Loss on Ignition	6.0 Max.	6.0 Max.
Fineness	34% Max.	34% Max.
Water Requirement, % Control	105% Max.	105% Max.
Autoclave Expansion, %	0.8% Max.	0.8% Max.
Strength Activity Index	75% Min.	75% Min.

Three materials, crushed limestone, calcium chloride filter cake, and Class C fly ash, were used to make specimens for unconfined compressive tests and suction tests. Both crushed limestone and calcium chloride filter cake were obtained from TETRA calcium chloride production plant in Lake Charles, Louisiana. This filter cake, which is a by-product of calcium chloride manufacturing obtained during the filtration process, has a dark gray color and the appearance of wet clay. The calcium chloride content of the filter cake is 33% based on total weight. Chemical analysis of the filter cake is shown Table 2-2.

Table 2-2. Chemical Analysis of Filter Cake from TETRA, Lake Charles, LA

Parameter	Water soluble	Total
Calcium, %	13.9	14.8
Chloride, %	21.0	21.0
% $CaCl_2$ based on Chloride$_1$	32.8	33.0
% $Ca(OH)_2$ based on Calcium$_2$	3.9	5.4
Magnesium, %	0.1	5.2
% $Mg(OH)_2$ based on Magnesium$_3$	0.3	12.4
Moisture, %	38.6	
pH	6.1	
Bulk specific gravity, g/mL	1.4	

The following assumptions were made in calculating % of $CaCl_2$, $Ca(OH)_2$, and $Mg(OH)_2$:

(1) All chloride is present as $CaCl_2$
(2) The calcium not accounted for by $CaCl_2$ is present as $Ca(OH)_2$.
(3) All magnesium is present as $Mg(OH)_2$

Based on these assumptions, the filter cake sample contains 38.6% moisture, 32.9% $CaCl_2$, 12.4% $Mg(OH)_2$, and 5.4% $Ca(OH)_2$ on a total basis. On a water-soluble basis, the sample contains 32.8% $CaCl_2$, 0.3% $Mg(OH)_2$,and 3.9% $Ca(OH)_2$.

Both filter cake and Class C fly ash when individually applied to a crushed limestone base material produced a significant strength increase compared with untreated specimens. Even a higher strength was obtained when filter cake and Class C fly ash were used simultaneously. The study investigated the addition of 1.3% to 1.7% calcium chloride and the addition of 5% and 10% Class C fly ash. The highest unconfined compressive strength was obtained from the specimen containing 1.7% $CaCl_2$+10% Class C fly ash. Suction tests were also performed with broken samples from the unconfined compressive test. Suction increased with higher additive quantity but it did not show consistency with time.

Hilbrich and McDonald conducted unconfined compressive strength, triaxial compressive strength, and suction tests using the same materials as Sinn's, except McDonald used Class C fly ash. Class F fly ash was used instead of Class C fly ash to compare their relative strength and service life. Even though high strength was obtained by using the filter cake and Class C fly ash, this strength was not stable with cure time and after 100 days decreased. The highest unconfined compressive strength was obtained from specimens containing 1.7% $CaCl_2$+10% Class F fly ash and it had higher and more stable strength than the samples made with 1.7% $CaCl_2$+10% Class C fly ash. The higher suction value also obtained from the same mix design samples (1.7% $CaCl_2$+10% Class F fly).

The following current optimum mix design factors were summarized from the previous research:

1. High strength was obtained from the samples treated with Class F fly ash and also Class C fly ash.
2. Higher strength was obtained from the samples treated with calcium chloride filter cake and fly ash simultaneously.
3. High early strength was obtained from 10% Class F fly ash and 1.7% calcium chloride (from filter cake) and also proven to be more durable.

Following recommendations were made for the future research from the investigation of Hilbrich and McDonald:

1. Focus should be given towards testing with Class F fly ashes.
2. Specimens should be prepared containing calcium chloride and fly ash to evaluate the effectiveness where calcium chloride is not introduced in the filter cake form.
3. Test should be repeated with 2 to 3 samples for each test at each test date in order to have an average of test values and to more accurately define any anomalies in the data.
4. Careful measures need to be taken during the storage of the samples to ensure that constant temperature and relative humidity are maintained.

The recommended mix design is 1.7 % calcium chloride and 10% Class F fly ash based on previous research. One of Hilbrich's recommendations was to conduct experiments to evaluate the effectiveness of calcium chloride not in a filter cake form. The filter cake contained 33% calcium chloride, 27% miscellaneous fine solids, and 40% water by weight. For this reason, it is hard to verify if high strength was achieved from calcium chloride, miscellaneous fine solids, or both. Filter cake was proven to be an effective additive that increases strength, but it should be verified that the addition of pure calcium chloride can achieve similar results. Also a limited range of calcium chloride percentages (1.3% and 1.7%$CaCl_2$) were investigated in previous studies. It is necessary to investigate a wider range of calcium chloride percentages to obtain the optimum calcium chloride ratio to achieve the highest strength economically.

This report focuses on effectiveness and optimum ratio of calcium chloride and Class F fly ash in soil stabilization. Soil from Riverside Campus was used instead of the crushed limestone. This was done because soil is more frequently utilized material in stabilization operations than crushed lime stone. It was also shown from previous research that calcium chloride is effective when used with fine particulates such as fly ash and clays.

This research will investigate the possibility of interparticulate mechanisms initiated by calcium chloride when used with class F fly ash and soil. Strength improvement should be shown to prove the performance characteristics of a soil. To prove the effectiveness of calcium chloride and achieve an optimum mix design, performance needs to be investigated at pure calcium chloride concentrations greater than 1.7%.

In this report, Class F fly ash was chosen as additive with calcium chloride. It is important to know the optimum fly ash quantity to get an economical mix design. A 10% fly ash concentration will be used based on the research of Prabakar et al. (2003), but an additional mix design, 4% $CaCl_2$ with 15% fly ash, was added to verify the economical quantity of fly ash. Three different soils were tested with fly ash to determine the effectiveness of fly ash. Soil-A (a liquid limit of 29 and a plasticity index of 14), Soil-B (a liquid limit of 39 and a plasticity of index of 15), and Soil-C (a liquid limit of 59 and a plasticity index of 30) are classified as CL, OL, and MH, respectively, based on Casagrande's plasticity chart. These three soils were tested with fly ash. None of the samples developed any reasonable California bearing ratio (CBR) at ash contents beyond 10% as shown in Table 2-3. The CBR test is used to determine the load bearing value of soils and soil-aggregates. All samples were compacted at their optimum moisture content to varying degrees of density using a 5.5lb (2.49kg) hammer dropped from a height of 12 in (305mm). The tests provide a target field density which is useful for evaluating subgrade soils and some subbase and base course materials containing only a small amount of material retained on the 19.0mm (3/4in.) sieve (AASHTO T193-81).

Table 2-3. Effect of Soils Mixed with Different Concentration of Fly Ash on California Bearing Ratio (CBR) (J.Prabakar, Dendorkar et al. 2003)

S.no	% Fly ash	CBR Value		
		Soil-A	Soil-B	Soil-C
1	0	4.70	2.03	3.53
2	9.0	7.00	5.47	4.40
3	20.0	8.84	6.12	5.30
4	28.5	9.24	7.26	5.83
5	35.5	9.93	9.05	6.70
6	41.2	10.67	10.84	7.73
7	46.0	11.60	11.41	8.24
8	100.0	–	12.40	–

This research paper will focus on the strength increase resulting from the addition of calcium chloride and class F fly ash to fine-grained soil. Fly ash contents are limited to 10% and 15%. The reason for investigating 10% and 15% class F fly ash contents is that the fly ash (from ALCOA in Rockdale, Texas) could have a different chemical content than that of the previous CBR study. In addition, previous research did not consider fly ash contents greater than 10%. Therefore15% fly ash was added to one mix design to evaluate the effectiveness of fly ash greater than 10%. Samples containing six different concentrations of calcium chloride (0%, 2%, 4%, and 6%) and two Class F fly ash contents (10% and 15%) were tested for strength at 3, 7, 28, 56, and 90 cure days. It should be noted that all calcium chloride percentages are based on dry solids weight, as follows:

$$\% Calcium\ chloride = \frac{W\ of\ Calcium\ Chloride}{\Sigma W\ of\ Soil + Fly\ Ash + Calcium\ Chloride}$$

Mixes to be investigated in this study include:

- Control (Soil only)
- Soil+10% Class F fly ash
- Soil+2% Calcium chloride+10% Class F fly ash
- Soil+4% Calcium chloride+10% Class F fly ash
- Soil+6% Calcium chloride+10% Class F fly ash
- Soil+4% Calcium chloride+15% Class F fly ash

CHAPTER III

MATERIALS

This research will determine the effectiveness of soil stabilization using calcium chloride and Class F fly ash. The fabrication of the lab samples will involve the following materials: Soil, Class F fly ash, and Calcium chloride.

Soil

Soil used in the lab was obtained from Texas A&M University, Riverside campus. The soil is dark brown clay. Water content, liquid limit, plastic limit, plastic index, unconfined compressive strength, and sieve analysis were determined according to the ASTM D 2216-98, ASTM D 4318-00, ASTM D 2166-00, and ASTM D 422-63, respectively. Sieve analysis, moisture content, and Atterberg limit tests were conducted and the results are shown in Figures 3-1 and Table 3-1. It should be noted that sieve analysis was performed to separate the dried soils into four groups so as to prepare uniform samples for optimum moisture content and unconfined compressive strength test. The gradation curve in Figure 3-1 represents the distribution of dried soil clods and is not indicative of the particle size distribution of individual soil grains.

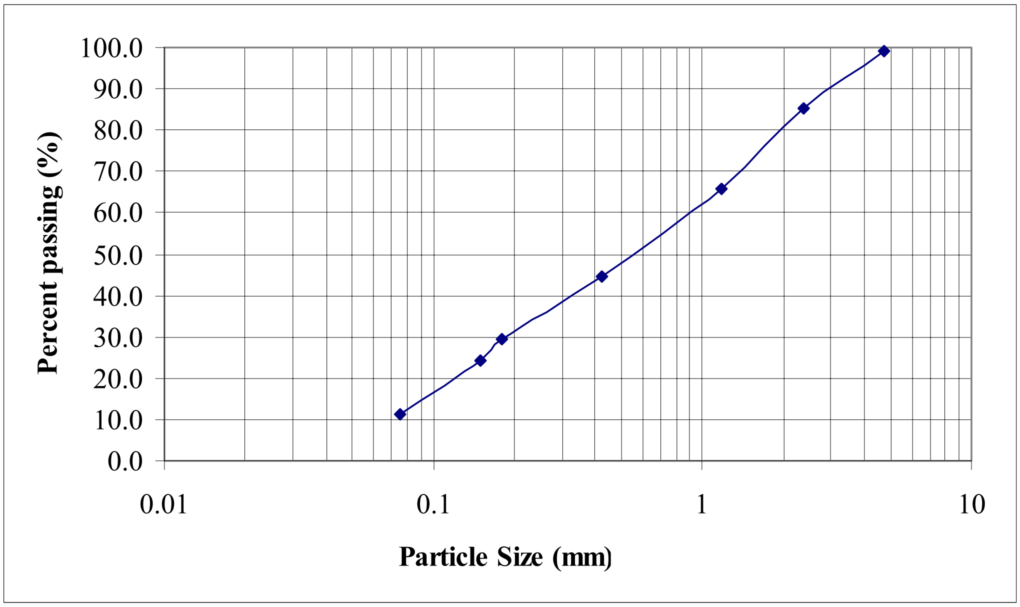


Figure 3-1. Sieve Analysis of Soil from Riverside Campus at Texas A&M University

Table 3-1. Atterberg Limit and Moisture Content of Soil from Riverside Campus at Texas A&M Univeristy

Liquid Limit	47
Plastic Limit	19
Plastic Index	28
Moisture, %	22.8

Calcium Chloride ($CaCl_2$)

According to TETRA Technologies, Inc., calcium chloride is used for numerous purposes at different concentrations depending on its use. This research used its highest percentage calcium chloride products. The chemical and physical analysis of TETRA 94™ is given in Tables 3-2 and 3-3. Water was added to achieve the desired concentration levels.

Table 3-2. Chemical Analysis of Calcium Chloride (TETRA 94™) from TETRA Technologies, Inc. in the Woodlands, TX

Calcium Chloride	>94%
Alkali Chlorides (as NaCI)	<2%
Total Magnesium (as $MgCl_2$)	<0.1%
Other Impurities (not H_20)	<1 %
Iron (Fe)	15 ppm

Table 3-3. Physical Analysis of Calcium Chloride (TETRA 94™) from TETRA Technologies, Inc. in the Woodlands, TX

Form	A white odorless granule
Assay	94% - 97% by weight calcium chloride
Bulk Density	Approximately 55 pounds per cubic foot
pH	6.5 to 10.0

Class F Fly Ash

According to the ASTM C618-03, fly ashes are classified as Class C and Class F based on the amount of silicon dioxide, aluminum oxide, and iron oxide percent, sulfur trioxide present. Other important ingredients that have an impact on stabilization include moisture content and loss on ignition. Calcium oxide (CaO) content is another basis for establishing the class F fly ash. Usually, CaO contents above 16 percent are considered Class C, while those with CaO contents below 16 percent are designated as Class F. Class F fly ash was chosen for this investigation because it was shown to generate earlier strength (at 3 cure days) and maintains this strength much longer than Class C fly ash (Hilbrich 2003). Class F fly ash used in this study was obtained from Alcoa in Rockdale, Texas. Fly ash color can be tan to dark gray, depending on its chemical and mineral constituents. Tan and light colors are typically associated with high lime content. A brownish color is typically associated with the iron content (FHA 2003). Chemical and physical analyses of Class F fly ash used in this investigation are shown in Tables 3-4 and 3-5, respectively. The Alcoa ash had a dark gray color.

Table 3-4. Chemical Analysis for Class F Fly Ash from Alcoa Inc. in Rockdale, Texas

CHEMICAL TESTS	**RESULTS**	**ASTM C 618 Class F Fly Ash**
Silicon Dioxide (SiO_2),%	56.2	
Aluminum Oxide (Al_2O_3),%	24.4	
Iron Oxide (Fe_2O_3), %	3.7	
Sum of SiO_2, Al_2O_3, Fe_2O_3,%	84.3	70.00 min.
Calcium Oxide (CaO), %	9.5	
Magnesium Oxide (MgO), %	2.0	
Sulfur Trioxide (SO_3), %	0.5	5.00 max.
Sodium Oxide (Na_2O), %	0.26	

Table 3-5. Physical Analysis for Class F Fly Ash from Alcoa Inc. in Rockdale, Texas

PHYSICAL TESTS	**RESULTS**	**ASTM C 618 Class F Fly Ash**
Moisture Content, %	0.2	3.0 max.
Loss on Ignition, %	0.9	6.0 max.
Amount Retained on No. 325 Sieve, %	14.3	34.0 max.
Specific Gravity	2.27	

CHAPTER IV

COMPACTION PROPERTIES

Moisture density relationships (ASTM D 1557-91) were investigated prior to preparing specimens for unconfined compressive strength tests. Soil from Riverside campus at Texas A&M University was sealed in barrels and transported to the laboratory. The soil was placed on steel trays and then dried in the oven for two to three days before sieving. Dried soil from the oven was crushed by a jaw crusher. Dried soil was separated into four groups based on sieve analysis as follows:

- 25% passing on #80 sieve
- 38% passing on #16 sieve
- 20% passing on #4 sieve
- 17% passing on 3/8 inch sieve

The mixing process followed the same procedure as soil stabilization in the field. Detail mix procedure is explained in Appendix. Each portion of dried soil and Class F fly ash were weighed individually and then mixed well in a large bowl to get a uniform distribution. Then, calcium chloride was weighed in a bowl and a prescribed amount of water was added to the bowl. The mixture was stirred until calcium chloride completely dissolved into the water. Finally, the calcium chloride solution was mixed with soil and fly ash in a large bowl until the liquid calcium chloride was uniformly distributed in the soil.

Compaction is the densification of soils by the application of mechanical energy. Proctor established that compaction is a function of four variables: dry density, water content, compactive effort, and soil type (Holtz and Kovacs 1981). Laboratory compaction was performed according to ASTM D1557-91. A 4 inch diameter and 4.5 inch height mold was used with a 10 pound rammer dropped from a height of 18 inches. The soil was compacted in 5 layers with 25 hammer blows applied per lift. It should be noted that water contents were calculated based on the amount of water added in samples because samples containing calcium chloride tended to slowly dry out. This tendency for drying was most noticeable at higher calcium chloride contents. The sample calculation approach was successfully made since all the materials used in the experiment had 0% water content. Each sample was placed with five layers and compacted by 25 blows per layer.

Optimum Moisture Content (OMC)

Samples containing six different concentrations of calcium chloride (0%, 2%, 4%, and 6%) and two Class F fly ash contents (10% and 15%) were tested. Dry density for each sample was calculated as follows:

$$\rho = \frac{M_t}{V_t} \tag{4-1}$$

$$\rho_d = \frac{\rho}{1 + w} \tag{4-2}$$

where,

ρ=total density

M_t=total mass

V_t=total volume

ρ_d=dry density

w=water content

The relationships between dry density and water content at different calcium chloride and fly ash concentrations were obtained as shown in Figures 4-1 through 4-6.

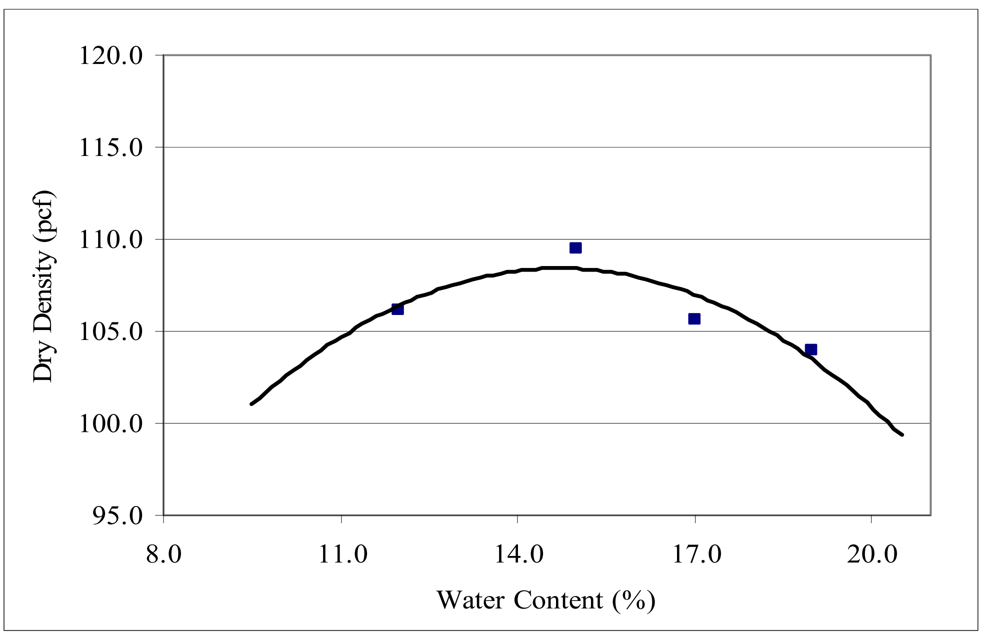


Figure 4-1. Dry Density vs. Water Content for Samples Containing 0% $CaCl_2$ and 0% Fly Ash

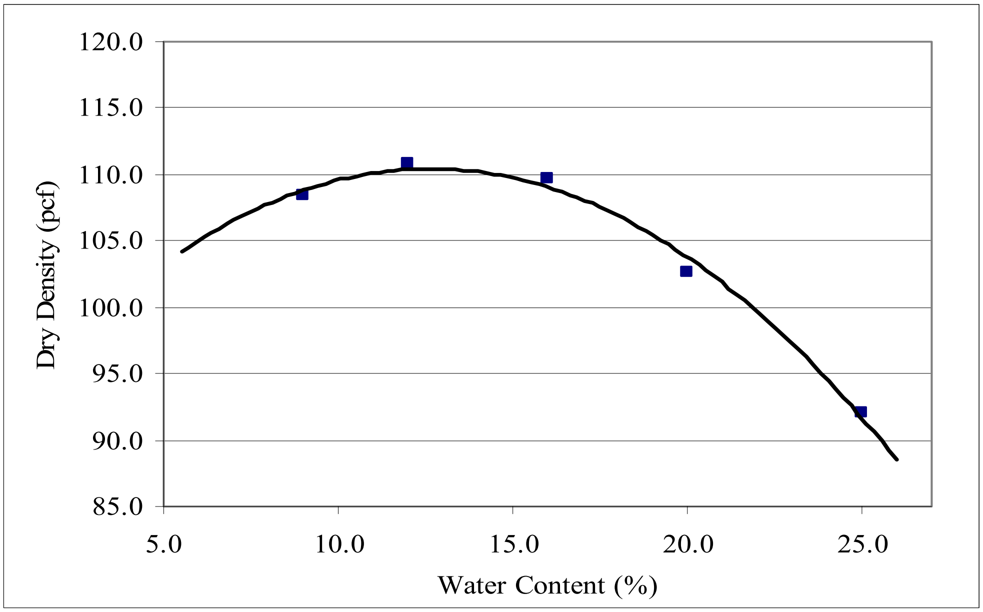


Figure 4-2. Dry Density vs. Water Content for Samples Containing 0% $CaCl_2$ and 10% Fly Ash

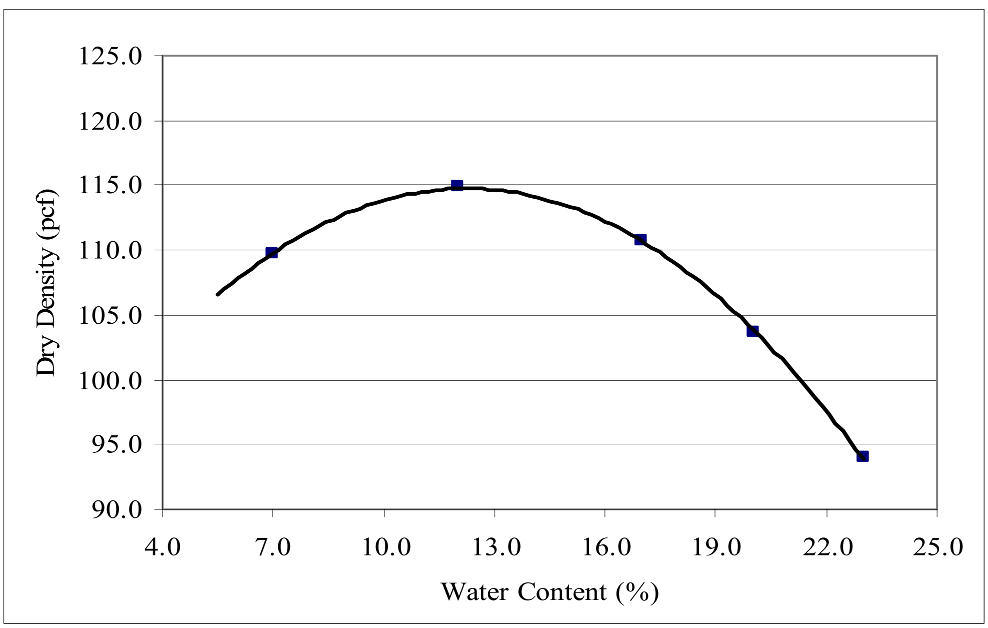


Figure 4-3. Dry Density vs. Water Content for Samples Containing 2% $CaCl_2$ and 10% Fly Ash

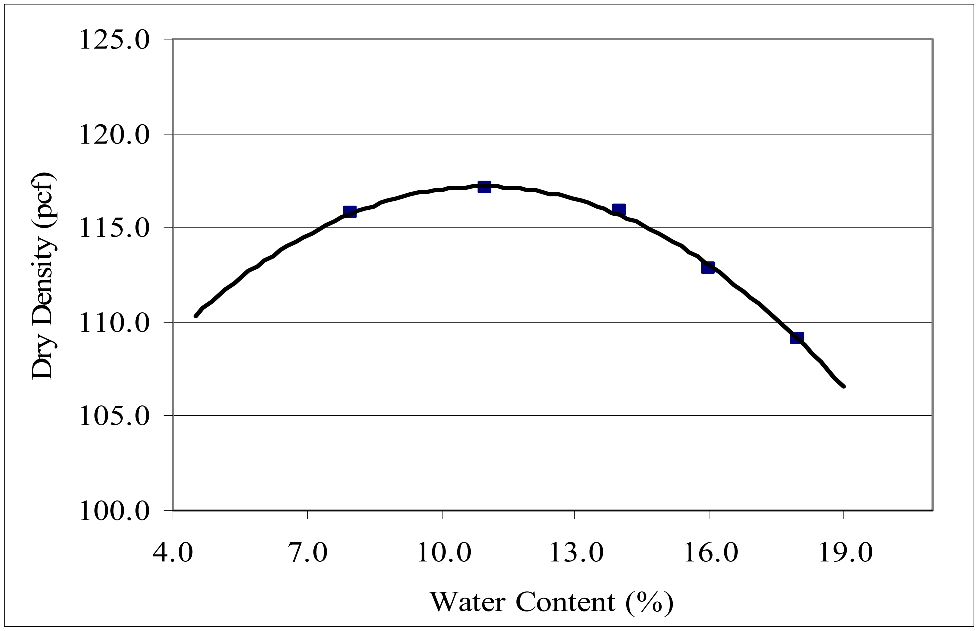


Figure 4-4. Dry Density vs. Water Content for Samples Containing 4% $CaCl_2$ and 10% Fly Ash

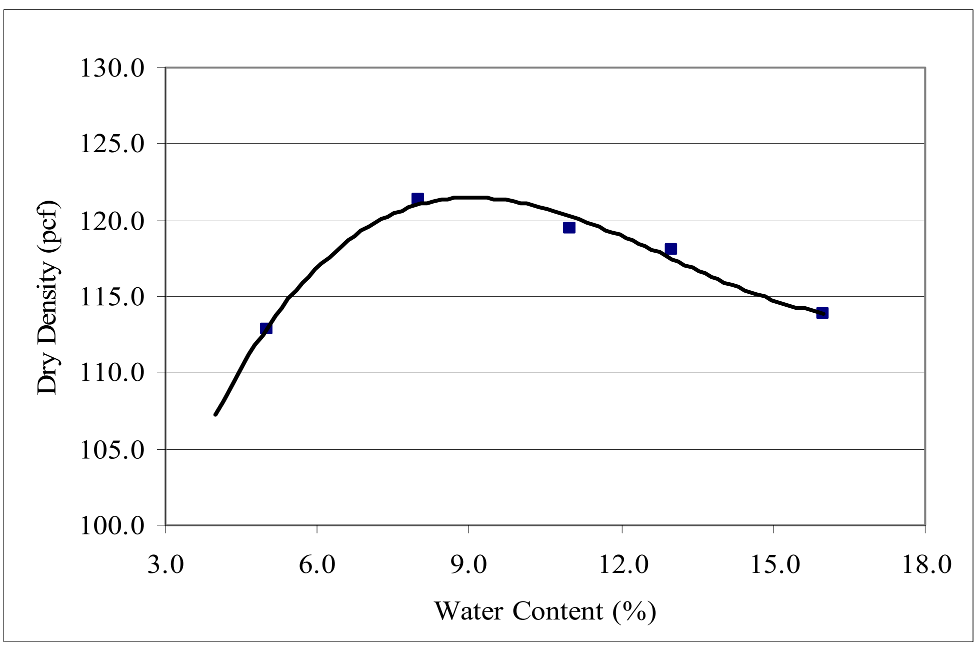


Figure 4-5. Dry Density vs. Water Content for Samples Containing 6% $CaCl_2$ and 10% Fly Ash

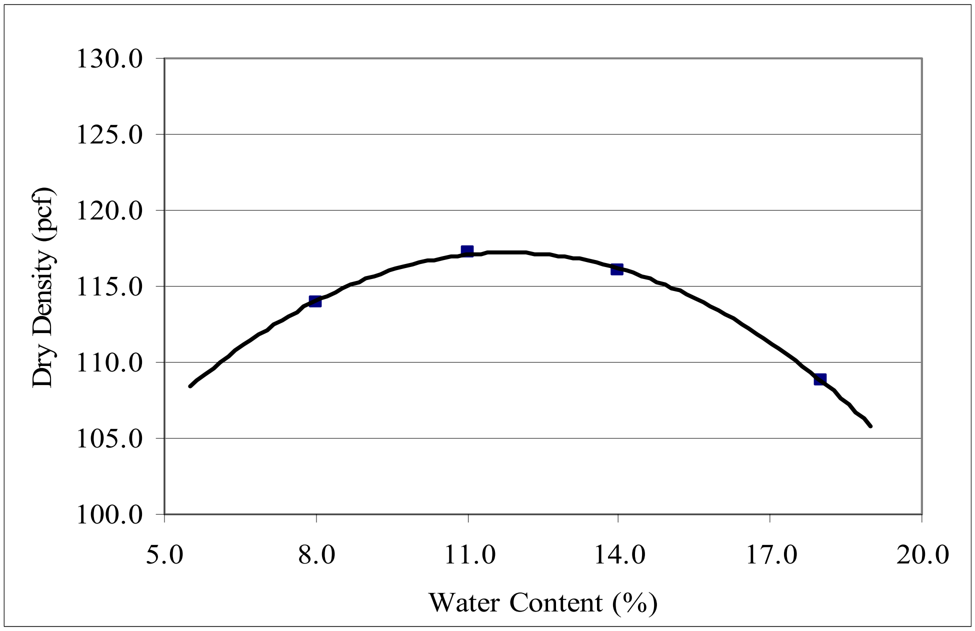


Figure 4-6. Dry Density vs. Water Content for Samples Containing 4% $CaCl_2$ and 15% Fly Ash

The optimum water contents were found using these compaction curves at different additive concentrations as shown Table 4-1. The sample calculation approach data and ASTM approach data are shown in Appendix. To ensure the optimum water content from the sample calculation, the same tests were performed twice at the optimum moisture content of each mix design. It was shown that the back calculation was satisfied as shown in Table 4-1.

Table 4-1. Data of Optimum Moisture Contents and Verification Tests

	OMC Tests		Verification Tests	
Mix Design	**OMC (%)**	**ρ_d (pcf)**	**ρ_d (pcf)**	**Deviation (%)**
Control	15.0	109.0	110.0	0.92
10% Class F fly ash	13.5	111.0	111.6	0.52
2% $CaCl_2$ +10% fly	12.0	114.9	115.5	0.52
4% $CaCl_2$ +10% fly	11.0	117.0	118.1	0.94
6% $CaCl_2$ +10% fly	9.0	121.0	122.4	1.16
4% $CaCl_2$ +10% fly	12.0	117.0	118.5	1.28

Based on the test result, dry density and optimum water content at different calcium chloride concentration with 10% fixed Class F fly ash were plotted in Figures 4-7 and 4-8. Dry density showed increasing tendency and optimum water contents decreased at higher calcium chloride concentrations.

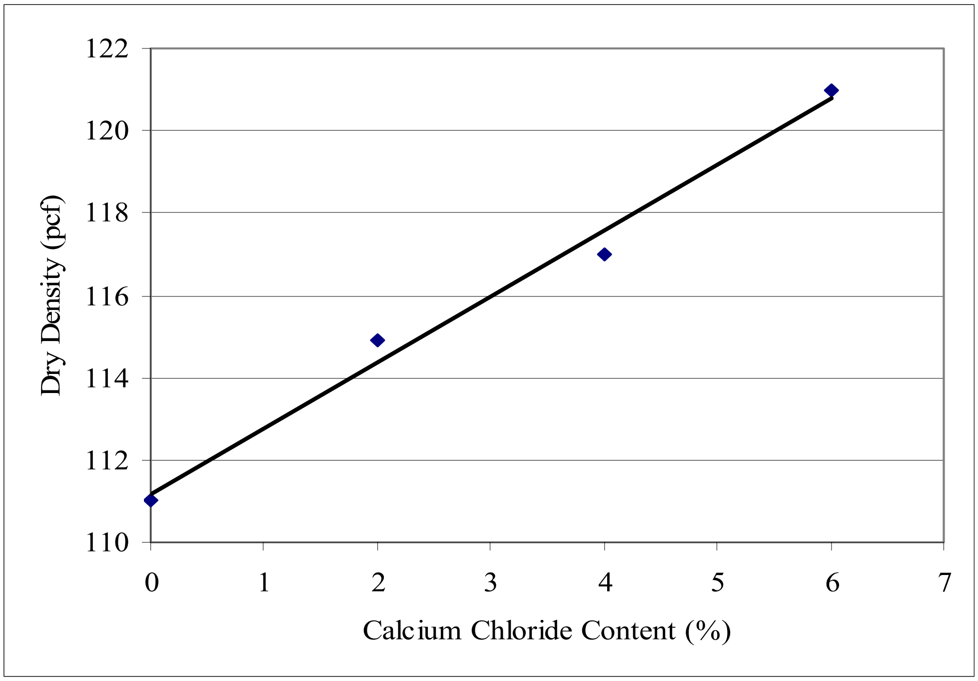


Figure 4-7. Dry Density vs. Calcium Chloride Content with 10% Fly Ash

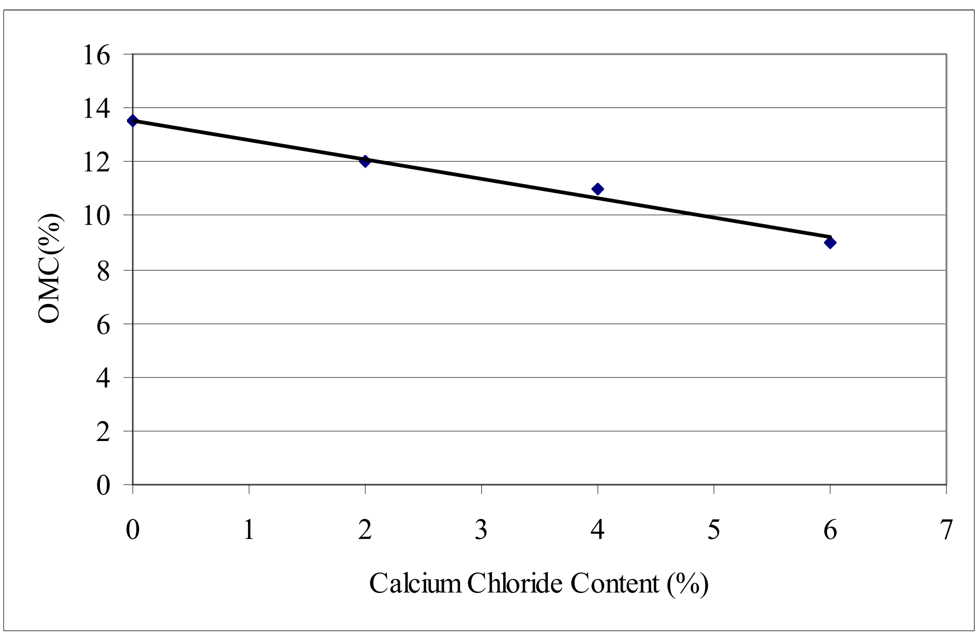


Figure 4-8. Optimum Moisture Content (OMC) vs. Calcium Chloride Content with 10% Fly Ash

Optimum Calcium Chloride Content

It is required to find out optimum calcium chloride content. There are two reasons why calcium chloride content should be limited. One is calcium chloride has a limited solubility. It means calcium chloride can not be used more than optimum water content in each sample to get highest strength because calcium chloride brings strength when it is used in solution. Because they will only be fines in the samples as long as calcium chloride stays in solid form and need more water to be dissolved. Each designed samples have different optimum water contents depending on calcium chloride and fly ash contents as shown Figure 4-9.

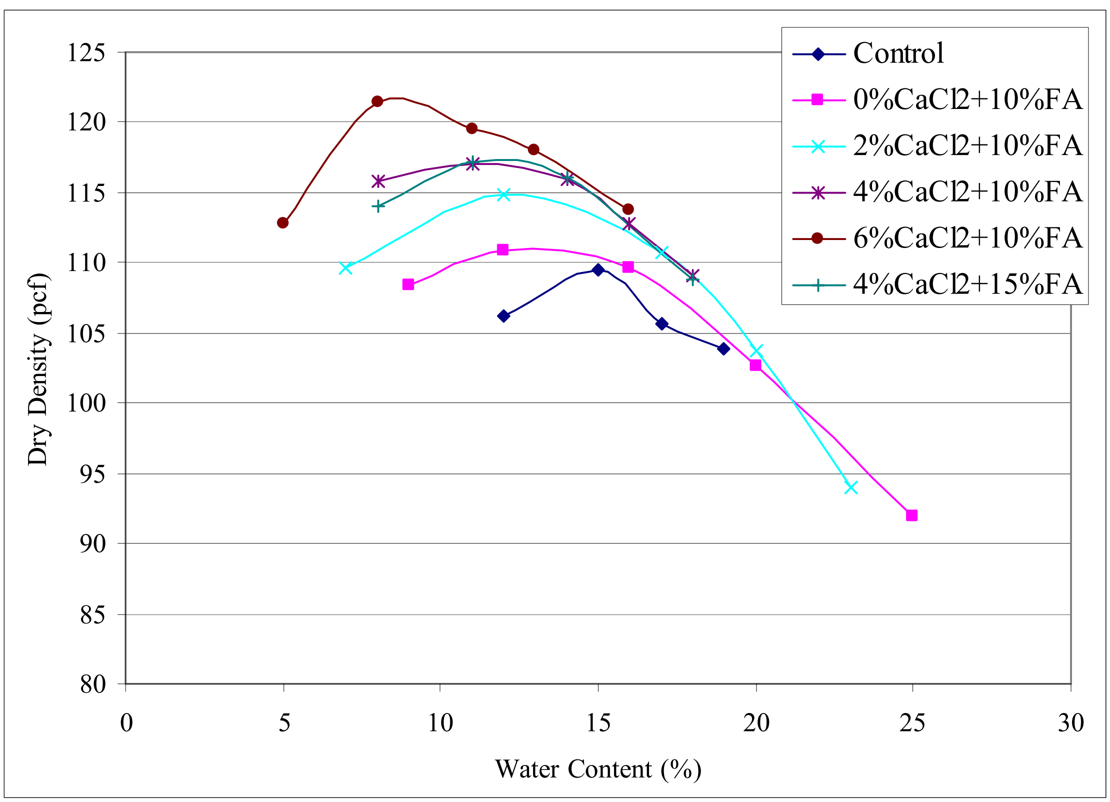


Figure 4-9. Moisture Density Curves

H_20 Absorption

Experiments were performed to determine how moisture contents change over time in the 6 different mix designs samples as shown in Figure 4-10. All samples were prepared with the same methods as the samples for unconfined compressive strength (ASTM D 2166-00). However, these samples were not compacted and were left in the containers without lids in a curing room (75 °F and 50% relative humidity) to determine the change of the water retention characteristics as a function of mix design. These test results in figure 4-10 clearly show one effect of adding calcium chloride: a tendency to retain water. Two mix designs, control (soil only) and 0% $CaCl_2$+10% FA (Soil + 0% $CaCl_2$+10% Fly Ash), lost more water than those samples which contained calcium chloride. All the samples achieved their final water content around 20 days except that containing 6% and 10% calcium chloride and fly ash, respectively. This mix appears to be still gathering water even after 20 days. This absorbed moisture will have to be taken into consideration depending on the calcium chloride quantity.

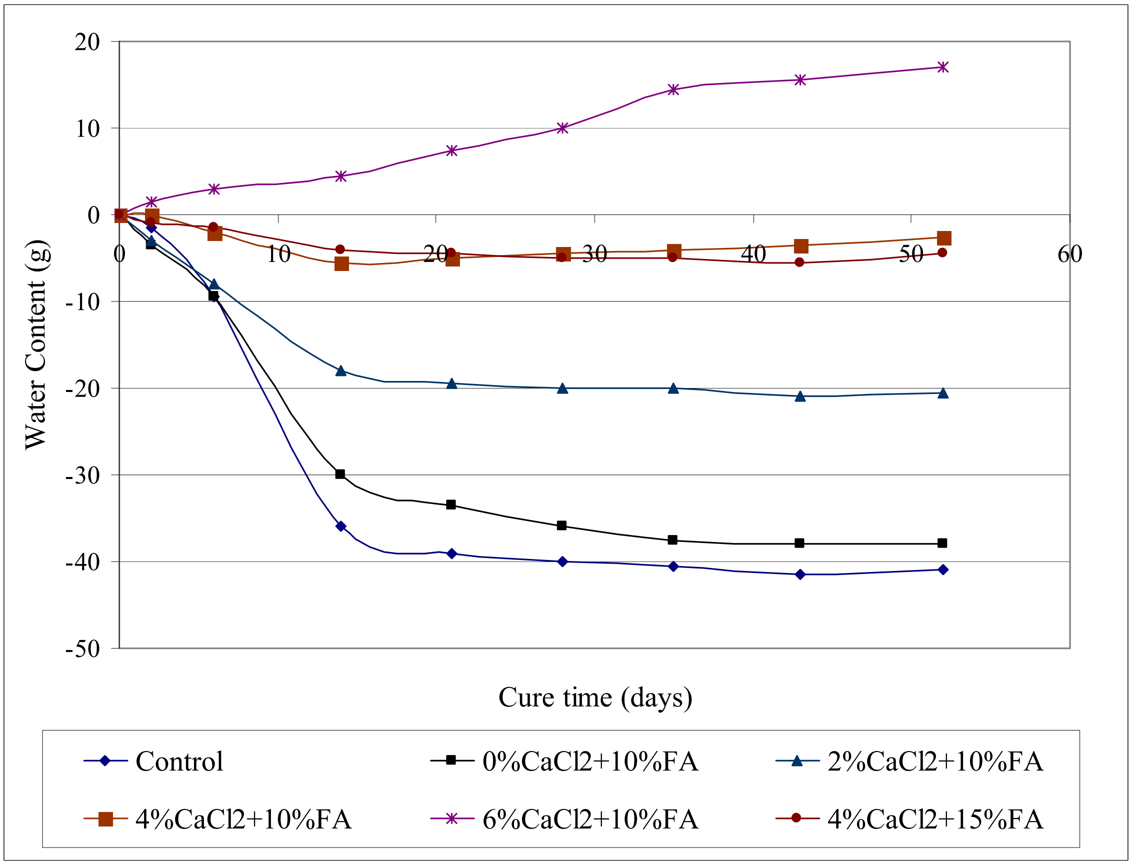


Figure 4-10. Water Content Change Depending on Time and Additives

CHAPTER V

UNCONFINED COMPRESSIVE STRENGTH

Unconfined compressive strength tests were performed to evaluate the effectiveness of calcium chloride with Class F fly ash at different concentrations. The primary purpose of the unconfined compression test is to quickly obtain the approximate compressive strength of soils that possess sufficient cohesion to permit testing in the unconfined state (ASTM D 2166-00). Six samples with different contents of calcium chloride (0%, 2%, 4%, and 6%) with class F fly ash (10% and 15%) were prepared for unconfined compressive strength tests at 1, 3, 7, 28, 56, and 90 cure days. It should be noted that all these samples were prepared at optimum moisture contents corresponding to their different respective concentrations as shown in Table 4-1. 4.5 inch high by 4 inch diameter specimens were prepared according to ASTM D 1557 compaction test procedures and covered in plastic wrap. Two samples were prepared for each mix design and cure time. Specimens then were stored in a curing room at 73°F and 50% relative humidity until the scheduled test time. Unconfined compressive strength tests were performed with a constant axial deformation rate at 0.08 inches per minute in accordance with ASTM D 2166-00. The axial strain and the axial normal compressive stress are given by the following relations:

$$\varepsilon = \Delta L / L_0 \qquad (5\text{-}1)$$

$$A = A_0 / (1 - \varepsilon) \qquad (5\text{-}2)$$

$$\sigma_C = P / A \qquad (5\text{-}3)$$

Where,

ε = axial strain for the given load, %

ΔL = length change of specimen, mm (in.)

L_0 = initial length of test specimen, mm (in.)

A = corresponding average cross-sectional area, mm^2 ($in.^2$)

A_0 = initial average cross-sectional area of the the specimen, mm^2 ($in.^2$)

σ_c = compressive stress, psi

P = corresponding average cross-sectional area, mm^2 ($in.^2$)

The relationships between unconfined compressive strength and curing time at different calcium chloride and Class F fly ash amount mix design were plotted in Figures 5-1 to 5-6.

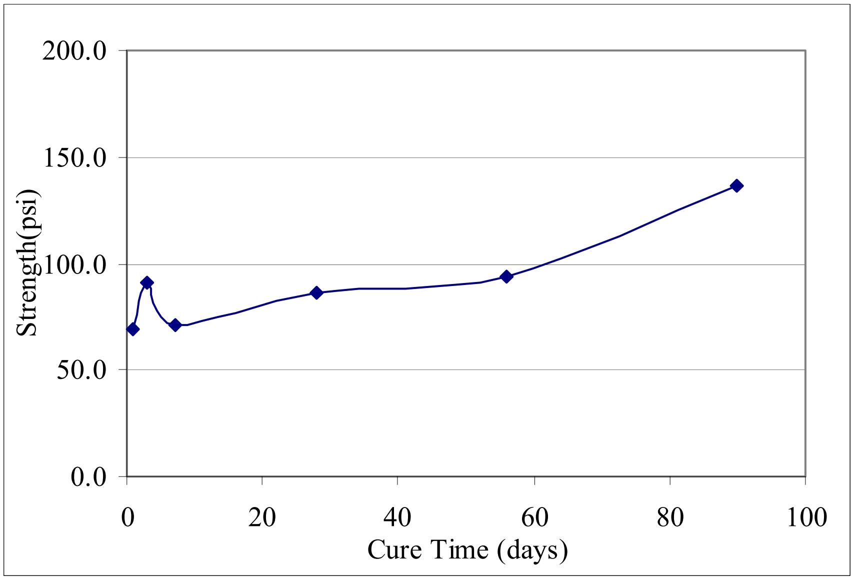


Figure 5-1. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 0% $CaCl_2$ and 0% Fly Ash

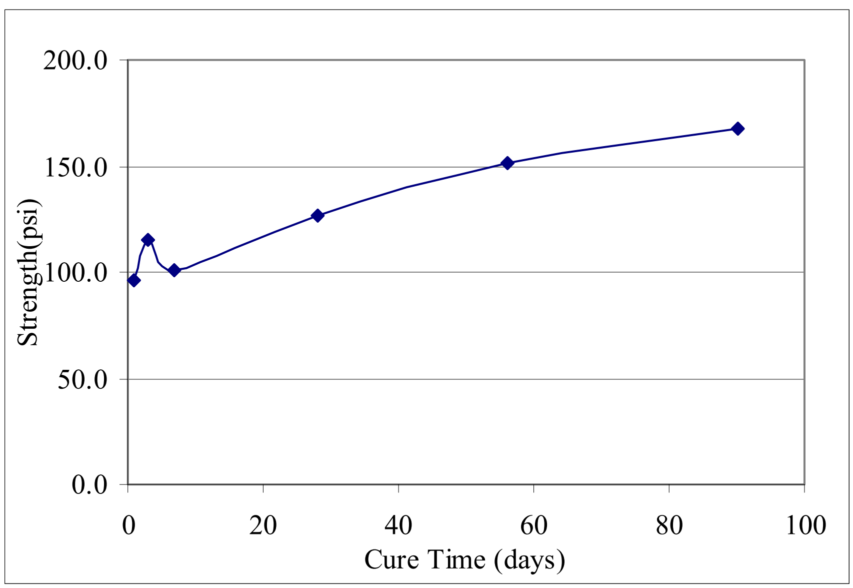


Figure 5-2. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 0% $CaCl_2$ and 10% Fly Ash

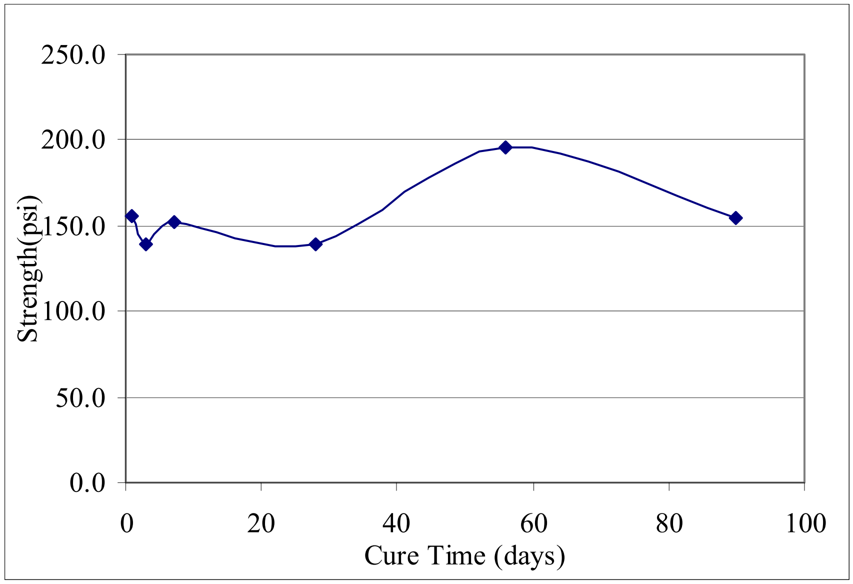


Figure 5-3. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 2% $CaCl_2$ and 10% Fly Ash

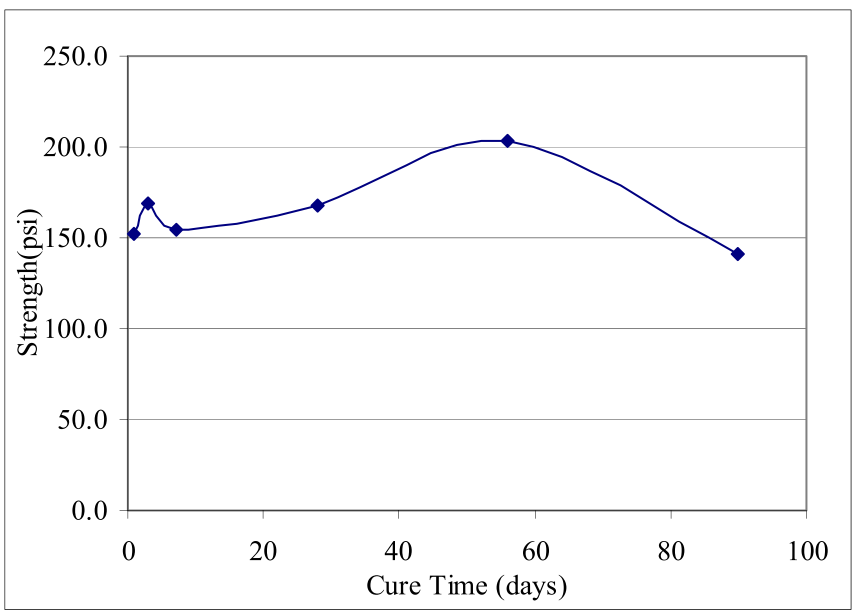


Figure 5-4. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 4% $CaCl_2$ and 10% Fly Ash

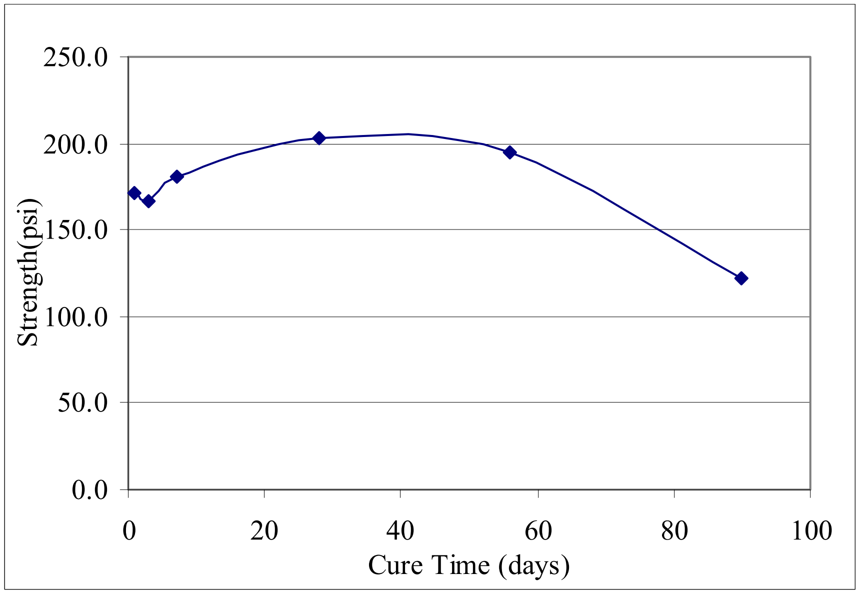


Figure 5-5. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 6% $CaCl_2$ and 10% Fly Ash

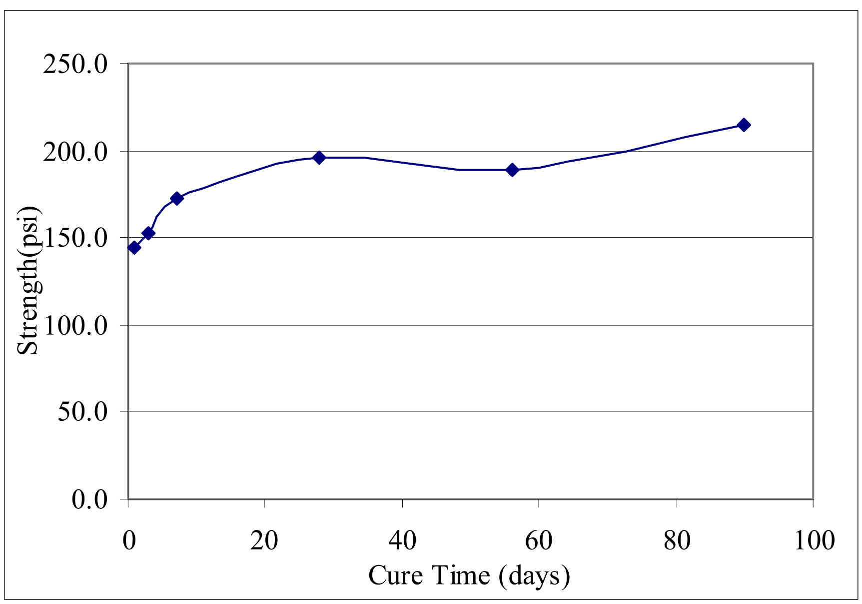


Figure 5-6. Peak Unconfined Compressive Strength vs. Cure Days for Samples Containing 4% $CaCl_2$ and 15% Fly Ash

Samples containing calcium chloride at all concentrations (2%, 4%, and 6% based on dry weight) showed a trend of increasing unconfined compressive strength within 24 hours and up to 56 days. However, this strength gain was lost at 90 days in the samples containing 10% fly ash as shown in Figure 5-7. The sample with 4% calcium chloride and 15% Class F fly ash showed a continued trend of increasing strength at 90 days. It should be noted that all samples with long cure times showed brittle failures. This trend was more noticeable either at high calcium chloride concentration or at 28 or longer cure days.

The control samples showed over 100% strength gain over 90 days. This trend is most likely due to drying during curing. Further, the soil samples containing calcium chloride may likely have lost moisture at a lower rate, or even gained moisture (Figure 4-10). Since the soil samples were not cured at constant moisture contents, definitive conclusions can not be mode regarding the effects of cure time.

High Early Strength

High early strength is one of the reasons why calcium chloride and fly ash are recommended to use for the soil stabilizations. Unconfined compressive tests were performed according to ASTM D 2166-00 as shown in Figure 5-7. The influence of the calcium chloride is shown by the increasing strength as none calcium chloride is used in the mixture. The sample, 4% $CaCl_2$+10% fly ash, achieved twice higher strength than the control up to 56days. This high early strength can save constructing time by reducing set time.

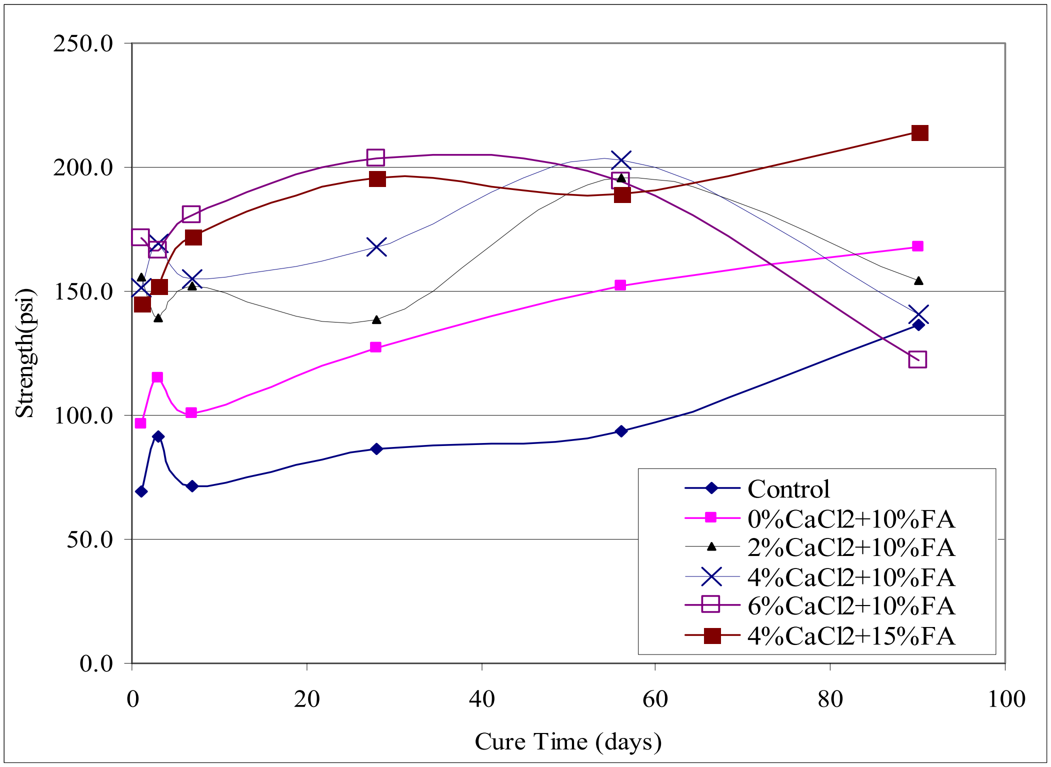


Figure 5-7. Peak Unconfined Compressive Strength vs. Cure Days for All Samples

Stress-Strain Curve

A typical stress-strain curve is known as Figure 5-8 and stress-strain curve on 90days samples are plotted as shown Figure 5-9 to Figure 5-14. Samples with additives reached high peak stress at less strain but residual stresses were reached at a lot less than peak stresses. All peak and residual stresses of the mix design are shown in Table 5-1.

The convexity of the stress-strain curves at low strains was due to the loading piston not being in full contact with the soil at the start of the test and should not be considered representative of real soil behavior.

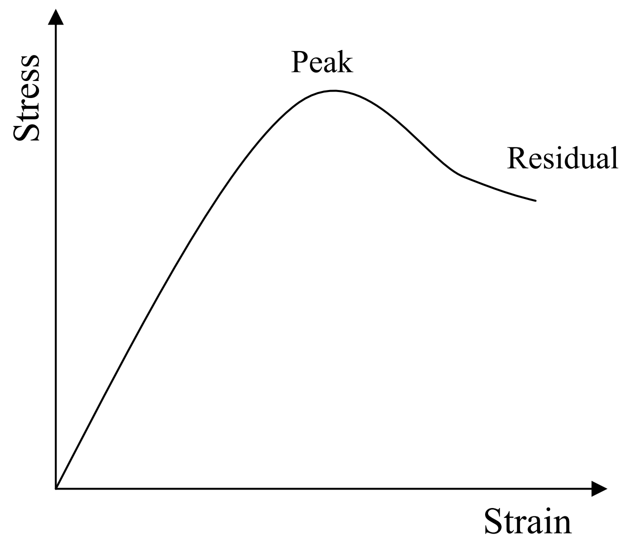


Figure 5-8. Typical Stress Strain Curve

Table 5-1. Peak and Residual Stresses of All Samples

		Mix Design (Calcium Chloride/Class F Fly Ash)					
Time	Strength	0%/0%	0%/10%	2%/10%	4%/10%	6%/10%	4%/15%
1day	Peak (psi)	69.00	91.34	147.70	144.16	164.13	137.03
	Residual(psi)	56.64	47.07	85.83	86.84	87.26	76.56
3days	Peak (psi)	89.21	109.15	132.28	160.49	157.81	144.19
	Residual(psi)	75.76	59.73	82.90	122.40	75.58	87.17
7days	Peak (psi)	69.52	95.41	144.56	146.94	171.39	163.30
	Residual(psi)	58.91	60.57	98.03	101.22	121.75	82.97
28days	Peak (psi)	84.94	119.76	130.60	158.34	192.60	183.84
	Residual(psi)	55.09	58.03	77.17	71.03	97.89	91.42
56days	Peak (psi)	92.18	142.62	183.56	190.98	183.37	177.84
	Residual(psi)	58.38	81.00	123.40	99.39	108.91	106.81
90days	Peak (psi)	132.31	158.36	145.79	133.86	116.68	201.95
	Residual(psi)	94.03	72.48	67.94	66.48	64.08	89.21

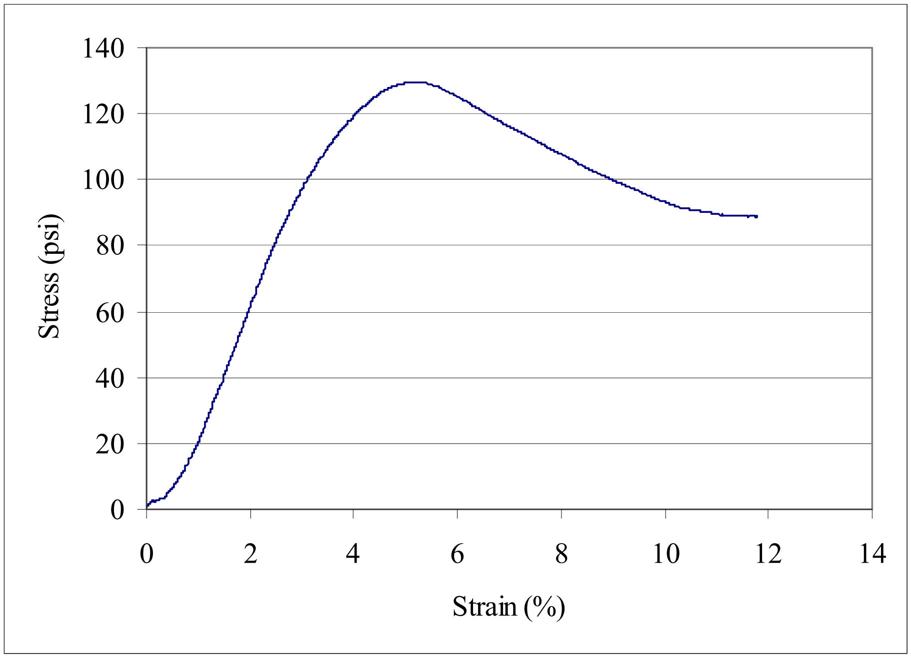


Figure 5-9. Stress Strain Curve of 0% $CaCl_2$+0% Fly Ash at 90days

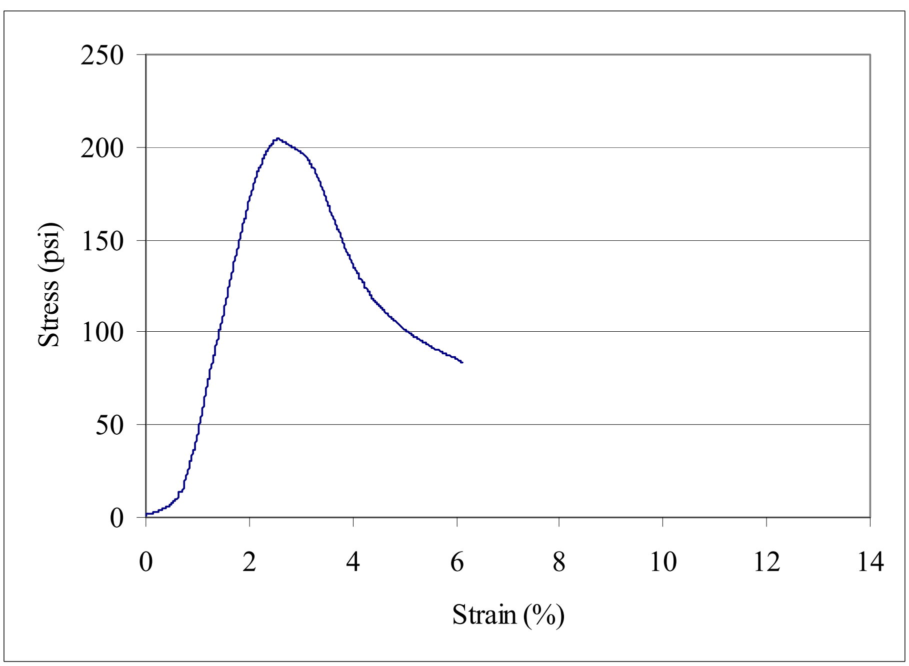


Figure 5-10. Stress Strain Curve of 0% $CaCl_2$+10% Fly Ash at 90days

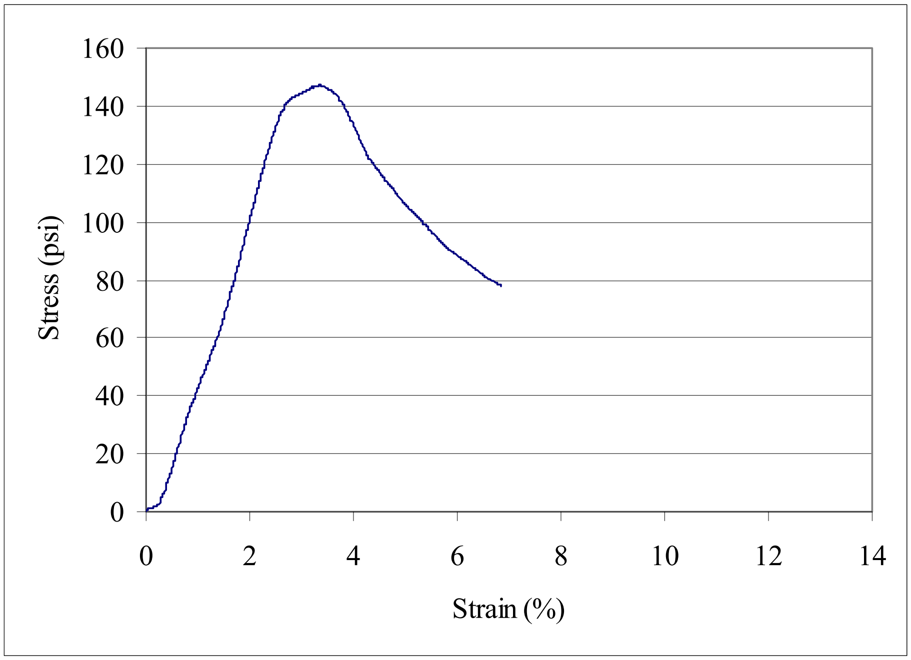


Figure 5-11. Stress Strain Curve of 2% $CaCl_2$+10% Fly Ash at 90days

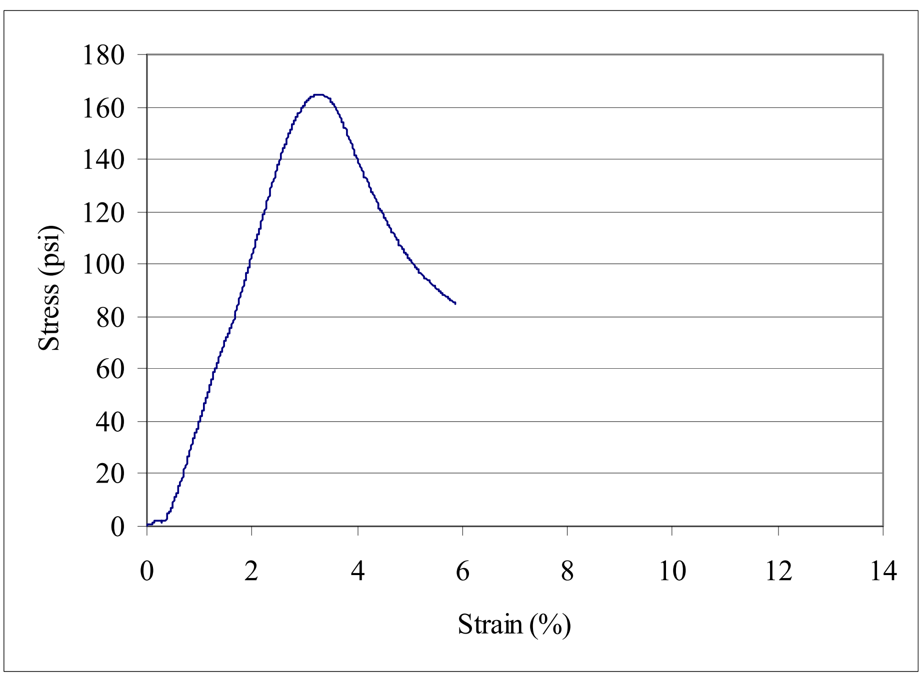


Figure 5-12. Stress Strain Curve of 4% $CaCl_2$+10% Fly Ash at 90days

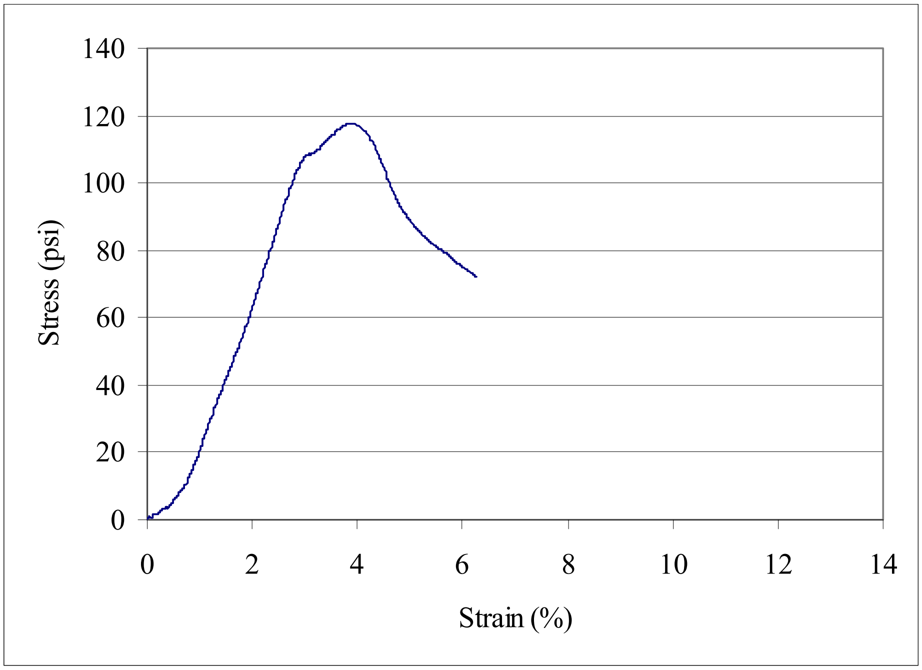


Figure 5-13. Stress Strain Curve of 6% $CaCl_2$+10% Fly Ash at 90days

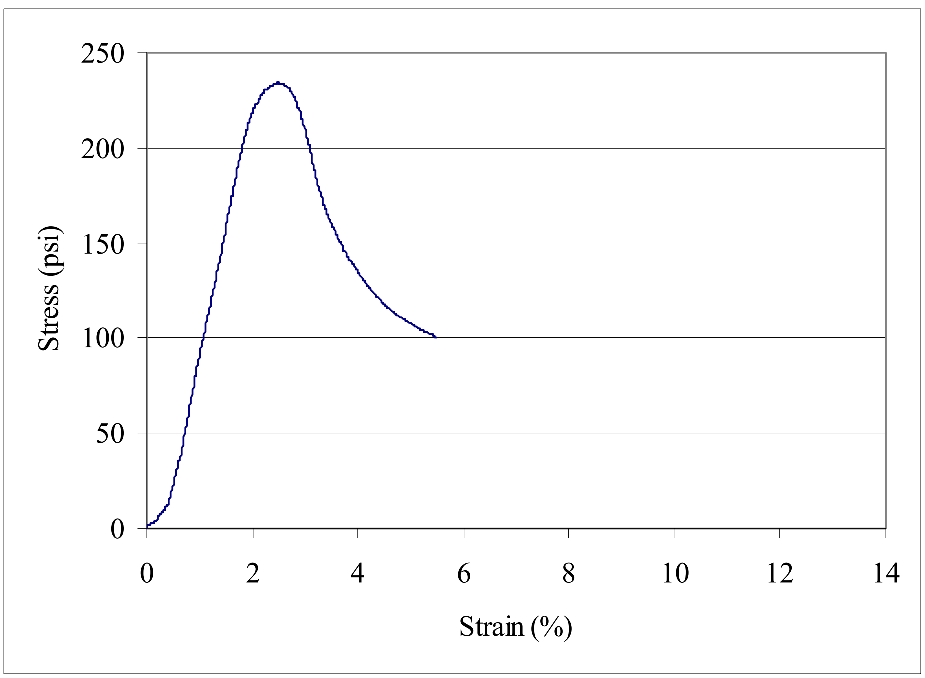


Figure 5-14. Stress Strain Curve of 4% $CaCl_2$+15% Fly Ash at 90days

Soil Fabric

Environmental scanning electron micrographs (E-SEM) were taken to look into the micro structures of fly ash, the control soil, and soil-fly ash mixture with 4% calcium chloride and 10% fly ash. The control soil and soil-fly ash specimens were taken from samples that had been tested for unconfined compressive strength; both specimens had been cured for 7days. The E-SEM of pure fly ash is shown in Figure 5-15. E-SEM of the control soil and soil-fly ash mixture are shown in Figures 5-16 and 5-17, respectively. Scanning electron micrographs (SEM) of the samples would have been desirable, but the moisture in the sample (9-15%) did not permit SEM analysis.

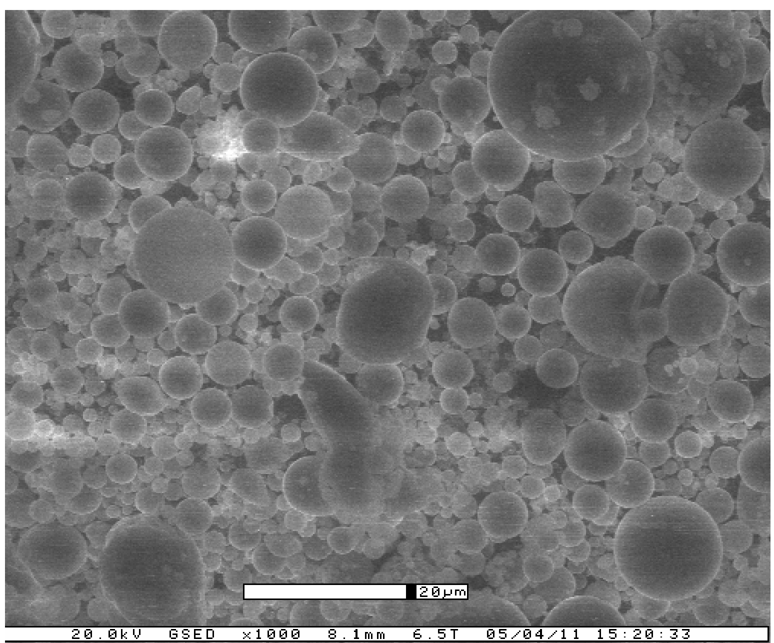


Figure 5-15. Environmental Scanning Electron Microscopy (E-SEM) of Class F Fly Ash

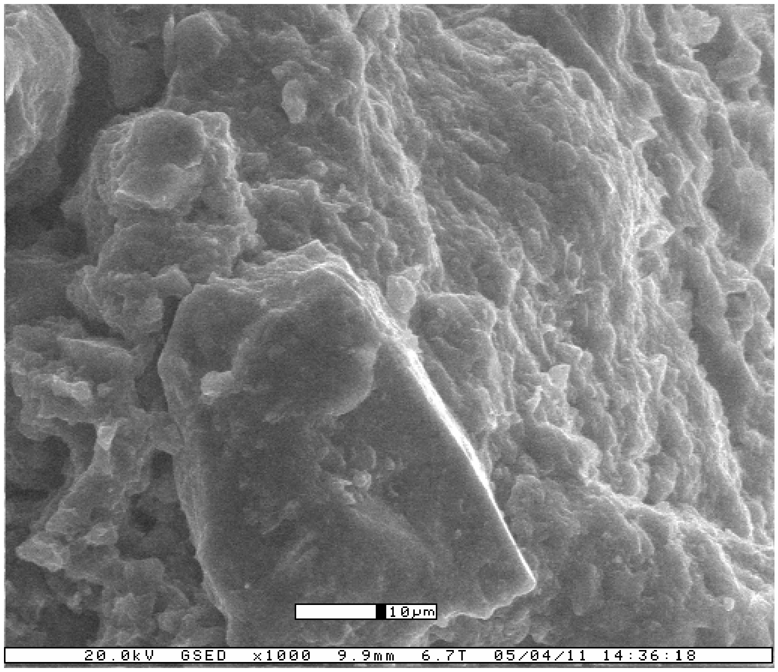


Figure 5-16. Environmental Scanning Electron Microscopy (E-SEM) of Control Soil after 7 days of Curing

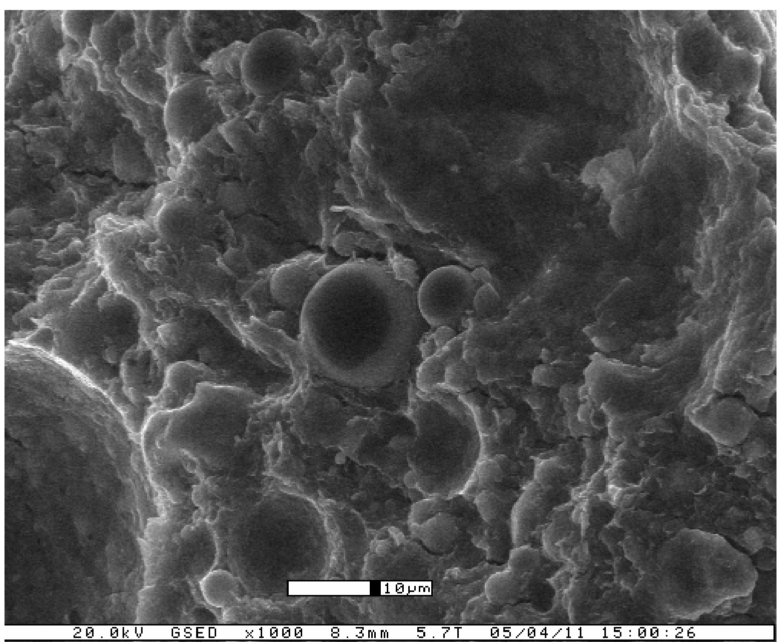


Figure 5-17. Environmental Scanning Electron Microscopy (E-SEM) of Soil-Fly Ash Mixture after 7 Days of Curing

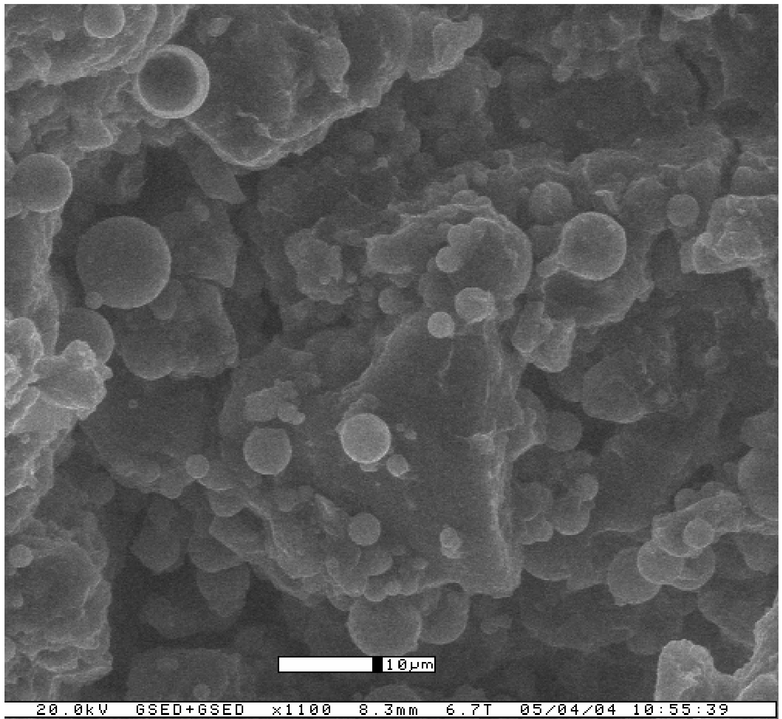


Figure 5-18. Environmental Scanning Electron Microscopy (E-SEM) of 4% $CaCl_2$+10% Fly Ash after 7 Days of Curing

CHAPTER VI

IMPLICATION ON MIX DESIGN

Soil stabilization using additives can be affected by many factors and a desired result can be achieved, more or less, through appropriate mix designs and materials. It is important to establish an optimum mix design in order to achieve an economical design capable of achieving higher strength with a minimum quantity of additives. Following implications on mix design were summarized based on the test result.

Design Considerations

- High Early Strength

  The potential for increasing the rate of strength increase over time is a primary motivation for adding calcium chloride. High early strength has the potential benefit of reducing construction time and costs.

- Long-term Strength

  Limited evidence is this research indicates that early strength gains due to addition of calcium chloride are not necessarily permanent. Therefore, the designer must verify the long-term strength of stabilized soils.

- Sensitivity

  The addition of stabilizers, particularly fly ash, will increase the strength, but also the sensitivity of soils. The effect of calcium chloride and Class F fly ash on

Sensitivity is as shown in Figures 6-1 and 6-2, respectively. Class F fly ash generates considerably more brittleness than calcium chloride. As sensitivity is generally undesirable, the effect of increased sensitivity should be factored into design decision.

Figure 6-1. Effect of Calcium Chloride Ash on Sensitivity ($CaCl_2$ / 10% FA)

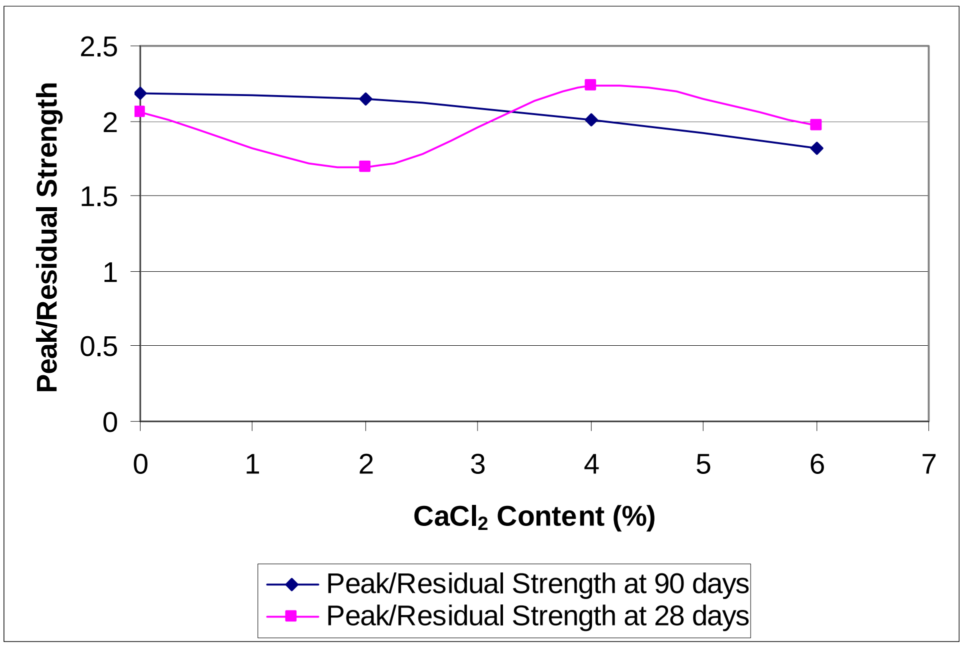
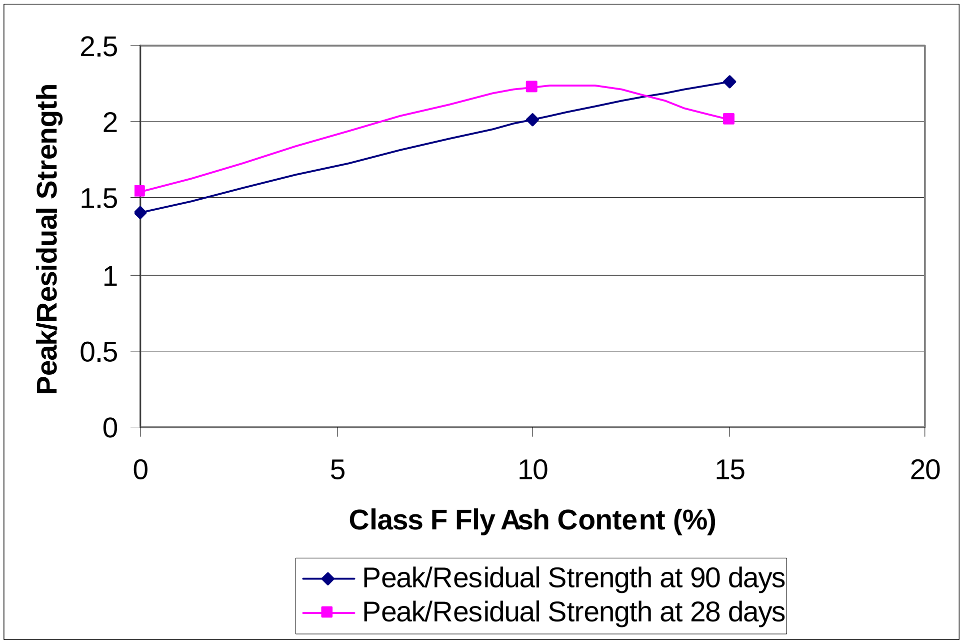


Figure 6-2. Effect of Class F Fly Ash on Sensitivity (Soil, 10% FA/4% $CaCl_2$, and 15% FA/4% $CaCl_2$)



Mix Design Parameters

- Soil Type

It should be noted that the effectiveness of fly ash and calcium chloride in soil stabilization may vary according to the base materials and the quantity of additives. If a different base material is used, experiments should be performed to estimate the effectiveness of additives.

- Fly Ash

Addition of 10 to 15% fly ash can increase the long-term (90 days) strength of soil by 20 to 50%, respectively. The amount of this strength gain increased sensitivity of soil. Adding 10 to 15% Class F fly ash can increase brittleness by

10 to 60%, respectively. Sensitivity in this study is defined as the ratio of peak to residual strength.

- Calcium Chloride

  1. The Addition of high amounts (6%) of calcium chloride leads to high early strength (50% strength increase at 30 days), but much of this strength gain is lost over time. Limited data indicate that addition of calcium chloride beyond 2% may significantly reduce the long-term strength of the soil.

  2. The addition of calcium chloride has little effect on soil sensitivity, although it may tend to decrease it somewhat.

  3. All of the soil specimens to which calcium chloride was added in combination with 10% fly ash show a trend of declining strength with time at 90 days. This trend is particularly troublesome; therefore, additional studies should be performed to verify that continued strength decline does not occur beyond 90 days.

  4. The addition of high levels of calcium chloride (4%) in combination with 15% fly ash leads to high early strength (100% increase over control sample at 30 days), high 90 days strength (50% increase over control

sample), and no tendency for strength decline. Since only one calcium chloride concentration (4%) was considered in conjunction with 15% fly ash content, it is not possible to draw any definitive conclusion regarding the effects of calcium chloride.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

Six samples containing four different contents of calcium chloride (0%, 2%, 4%, and 6%) with class F fly ash (10% and 15%) were tested at 1, 3, 7, 28, 56, and 90 cure days to verify the effectiveness and optimum ratio of calcium chloride and Class F fly ash in soil stabilization. Following determination of Atterberg limits, particle size distribution, optimum moisture content, moisture content variation depending on mix design with cure time and unconfined compression strength were determined according to ASTM method. Also, Environmental Scanning Electron Micrographs (E-SEM) were taken to look into the structures of Control, 10% Class F fly ash, and 4% $CaCl_2$+10% fly ash at 7 cure days. Based on the lab tests, the following conclusion and recommendations are made.

Significant water content variations appeared to have occurred during the curing period in this test program. Accordingly, any conclusions drawn regarding cure time must be considered tentative. Future investigations should address the issue of moisture changes during curing.

Conclusions

1. 2% calcium chloride with 10% Class F fly ash and 4% calcium chloride with 10% Class F fly ash are close to the optimum quantity for early high strength

and long-term strength.

2. Samples containing calcium chloride and Class F fly ash at any concentrations obtained early high strength. However, all the samples containing calcium chloride obtained around 190 psi unconfined compressive strength at 56 days and showed a decreasing tendency after 56 days except the sample with 4% calcium chloride and 15% Class F fly ash.
3. The addition of fly ash increases peak strength, but also increases sensitivity.

Recommendations

1. Future test programs investigating the effects of cure time should be redesigned to minimize moisture content changes during curing.
2. No more than 2% calcium chloride is recommended to obtain high early strength. If long-term strength is also required, then 4% calcium chloride with 15% Class F fly ash should be considered.
3. It should be noted that the effectiveness of fly ash and calcium chloride in soil stabilization may varies according to the base materials and the additives. If a different base material is considered, experiments should be performed to estimate the effectiveness of additives.
4. If a low concentration calcium chloride product or different fly ash is used, it could generate a different result.

Future Research

1. As wetting is a probable occurrence in the field, some specimens should be soaked following compaction and prior to curing to assess the effects of wetting on time-dependent strength behavior.
2. Samples at different moisture content from optimum moisture content should be considered with different curing methods in order to verify the water contents which bring highest strength.
3. It is necessary to verify mineral composition in samples through the research works such as Environmental Scanning electron microscopy (E-SEM) and X-ray diffraction analysis.
4. In the lab test, testing samples with up to 1 year cure time is recommended because the current test result shows a non stable unconfined strength tendency with cure time at 2%, 4%, and 6% calcium chloride concentrations.
5. Moisture contents should be checked with the samples for unconfined compressive strength test. It can be obtained from either weighing samples before or right after unconfined compressive strength test so that the data could be used to analyze the strength change tendency vs. water content at each mix design.
6. Different mix designs are recommended based on mineral composition for future research in order to attain economical mix designs since 2%, 4%, and 6% calcium chloride with 10% Class F fly ash showed strength decreasing tendency after 56 days.

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APPENDIX A

RESULTS OF COMPACTION

AND UNCONFIEND COMPRESSIVE STRENGTH TESTS

Table A-1. Compaction Data of Samples Containing 0% $CaCl_2$ and 0% Class F Fly Ash

Wet Density	Water 12%	Water 15%	Water 17%	Water 19%
Wet sample(g)+Mold(g)	6108.5	6231	6209	6228
Mold(g)	4318	4318.5	4319.5	4323.5
Wet sample(g)	1790.5	1912.5	1889.5	1904.5
Diameter(in)	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	1932.2	2063.9	2039.0	2055.2
Wet density(kN/m^3)	18.9	20.2	20.0	20.2
Wet density(lb/ft^3)	120.6	128.8	127.3	128.3

Moisture Content				
Wet Sample(g)	1790.5	1912.5	1889.5	1904.5
Dry Sample(g)	1595.5	1663	1613	1592
Water content(g)	195	249.5	276.5	312.5
Water content (%) Dry basis	12.2	15.0	17.1	19.6

Dry Density				
Wet sample(g)	1790.5	1912.5	1889.5	1904.5
Water content(g)	195	249.5	276.5	312.5
Dry Sample(g)	1595.5	1663	1613	1592
Dry density(Kg/m^3)	1721.8	1794.6	1740.7	1718.0
Dry density(kN/m^3)	16.9	17.6	17.1	16.8
Dry density(lb/ft^3)	107.5	112.0	108.7	107.3

Dry Density (Back Cal.)				
Wet sample(g)	1790.5	1912.5	1889.5	1904.5
Water content(g)	214.9	286.9	321.2	361.855
Water content (%) Cal. basis	12.0	15.0	17.0	19
Dry Sample(g)	1575.6	1625.6	1568.3	1542.6
Dry density(Kg/m^3)	1700.3	1754.3	1692.4	1664.7
Dry density(kN/m^3)	16.7	17.2	16.6	16.3
Dry density(lb/ft^3)	106.2	109.5	105.7	103.9

Table A-2. Compaction Data of Samples Containing 0% $CaCl_2$ and 10% Class F Fly Ash

Wet Density	Water 9%	Water 12%	Water 16%	Water 20%	Water 25%
Wet sample(g)+Mold(g)	6086	6188	6263.5	6228	6147
Mold(g)	4318	4318	4325	4322.5	4325.5
Wet sample(g)	1768	1870	1938.5	1905.5	1821.5
Diameter(in)	4	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	1907.9	2018.0	2091.9	2056.3	1965.7
Wet density(kN/m^3)	18.7	19.8	20.5	20.2	19.3
Wet density(lb/ft^3)	119.1	126.0	130.6	128.4	122.7

Moisture Content					
Wet Sample(g)	1768	1870	1938.5	1905.5	1821.5
Dry Sample(g)		1666	1672.5	1577.5	1457.5
Water content(g)		204	266	328	364
Water content (%) dry basis		**12.2**	**15.9**	**20.8**	**25.0**

Dry Density					
Wet sample(g)	1768	1870	1938.5	1905.5	1821.5
Water content(g)		204	266	328	364
Dry Sample(g)		1666	1672.5	1577.5	1457.5
Dry density(Kg/m^3)		1797.8	1804.9	1702.3	1572.8
Dry density(kN/m^3)		17.6	17.7	16.7	15.4
Dry density(lb/ft^3)		**112.2**	**112.7**	**106.3**	**98.2**

Dry Density (Back Cal.)					
Wet sample(g)	1768	1870	1938.5	1905.5	1821.5
Water content(g)	159.1	224.4	310.2	381.1	455.375
Water content (%) Cal. basis	9.0	12.0	16.0	20.0	25
Dry Sample(g)	1608.9	1645.6	1628.3	1524.4	1366.1
Dry density(Kg/m^3)	1736.2	1775.8	1757.2	1645.0	1474.2
Dry density(kN/m^3)	17.0	17.4	17.2	16.1	14.5
Dry density(lb/ft^3)	108.4	110.9	109.7	102.7	92.0

Table A-3. Compaction Data of Samples Containing 2% $CaCl_2$ and 10% Class F Fly Ash

Wet Density	Water 7%	Water 12%	Water 17%	Water 20%	Water 23%
Wet sample(g)+Mold(g)	6069	6254.5	6298	6241.5	6170.5
Mold(g)	4318	4317	4317.5	4318	4357.5
Wet sample(g)	1751	1937.5	1980.5	1923.5	1813
Diameter(in)	4	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	1889.6	2090.8	2137.2	2075.7	1956.5
Wet density(kN/m^3)	18.5	20.5	21.0	20.4	19.2
Wet density(lb/ft^3)	118.0	130.5	133.4	129.6	122.1
Moisture Content					
Wet Sample(g)	1751	1937.5	1980.5	1923.5	1813
Dry Sample(g)		1736.5	1707.5	1611.5	1471.5
Water content(g)		201	273	312	341.5
Water content (%) dry basis		11.6	16.0	19.4	23.2
Dry Density					
Wet sample(g)	1751	1937.5	1980.5	1923.5	1813
Water content(g)		201	273	312	341.5
Dry Sample(g)		1736.5	1707.5	1611.5	1471.5
Dry density(Kg/m^3)		1873.9	1842.6	1739.0	1588.0
Dry density(kN/m^3)		18.4	18.1	17.1	15.6
Dry density(lb/ft^3)		117.0	115.0	108.6	99.1
Dry Density (Back Cal.)					
Wet sample(g)	1751	1937.5	1980.5	1923.5	1813
Water content(g)	122.6	232.5	336.7	384.7	416.99
Water content (%) Cal. basis	7.0	12.0	17.0	20.0	23
Dry Sample(g)	1628.4	1705.0	1643.8	1538.8	1396.0
Dry density(Kg/m^3)	1757.3	1839.9	1773.9	1660.6	1506.5
Dry density(kN/m^3)	17.2	18.0	17.4	16.3	14.8
Dry density(lb/ft^3)	109.7	114.9	110.7	103.7	94.0

Table A-4. Compaction Data of Samples Containing 4% $CaCl_2$ and 10% Class F Fly Ash

Wet Density	Water 8%	Water 11%	Water 14%	Water 16%	Water 18%
Wet sample(g)+Mold(g)	6185	6269.5	6318	6311.5	6292
Mold(g)	4317	4317	4317.5	4318	4317
Wet sample(g)	1868	1952.5	2000.5	1993.5	1975
Diameter(in)	4	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	2015.8	2107.0	2158.8	2151.3	2131.3
Wet density(kN/m^3)	19.8	20.7	21.2	21.1	20.9
Wet density(lb/ft^3)	125.8	131.5	134.8	134.3	133.1

Moisture Content					
Wet Sample(g)	1868	1952.5	2000.5	1993.5	1975
Dry Sample(g)		1770.5	1771	1734.5	1688
Water content(g)		182	229.5	259	287
Water content (%) dry basis		10.3	13.0	14.9	17.0

Dry Density					
Wet sample(g)	1868	1952.5	2000.5	1993.5	1975
Water content(g)		182	229.5	259	287
Dry Sample(g)		1770.5	1771	1734.5	1688
Dry density(Kg/m^3)		1910.6	1911.2	1871.8	1821.6
Dry density(kN/m^3)		18.7	18.7	18.4	17.9
Dry density		119.3	119.3	116.9	113.7

Dry Density (Back Cal.)					
Wet sample(g)	1868	1952.5	2000.5	1993.5	1975
Water content(g)	149.4	214.8	280.1	319.0	355.5
Water content (%) Cal. basis	8.0	11.0	14.0	16.0	18
Dry Sample(g)	1718.6	1737.7	1720.4	1674.5	1619.5
Dry density(Kg/m^3)	1854.6	1875.3	1856.6	1807.1	1747.7
Dry density(kN/m^3)	18.2	18.4	18.2	17.7	17.1
Dry density(lb/ft^3)	115.8	117.1	115.9	112.8	109.1

Table A-5. Compaction Data of Samples Containing 6% $CaCl_2$ and 10% Class F Fly Ash

Wet Density	Water 5%	Water 8%	Water 11%	Water 13%	Water 16%
Wet sample(g)+Mold(g)	6079.5	6275.6	6312	6332	6331.5
Mold(g)	4317	4317	4319	4318	4320.5
Wet sample(g)	1762.5	1958.6	1993	2014	2011
Diameter(in)	4	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	1902.0	2113.6	2150.7	2173.4	2170.2
Wet density(kN/m^3)	18.7	20.7	21.1	21.3	21.3
Wet density(lb/ft^3)	118.7	132.0	134.3	135.7	135.5

Moisture Content					
Wet Sample(g)	1762.5	1958.6	1993	2014	2011
Dry Sample(g)		1821	1823.5	1815.5	1766.5
Water content(g)		137.6	169.5	198.5	244.5
Water content (%) dry basis		7.6	9.3	10.9	13.8

Dry Density					
Wet sample(g)	1762.5	1958.6	1993	2014	2011
Water content(g)		137.6	169.5	198.5	244.5
Dry Sample(g)		1821	1823.5	1815.5	1766.5
Dry density(Kg/m^3)		1965.1	1967.8	1959.2	1906.3
Dry density(kN/m^3)		19.3	19.3	19.2	18.7
Dry density(lb/ft^3)		122.7	122.8	122.3	119.0

Dry Density (Back Cal.)					
Wet sample(g)	1762.5	1958.6	1993	2014	2011
Water content(g)	88.1	156.7	219.2	261.8	321.76
Water content (%) Cal. basis	5.0	8.0	11.0	13.0	16
Dry Sample(g)	1674.4	1801.9	1773.8	1752.2	1689.2
Dry density(Kg/m^3)	1806.9	1944.5	1914.1	1890.8	1822.9
Dry density(kN/m^3)	17.7	19.1	18.8	18.5	17.9
Dry density(lb/ft^3)	112.8	121.4	119.5	118.0	113.8

Table A-6. Compaction Data of Samples Containing 4% $CaCl_2$ and 15% Class F Fly Ash

Wet Density	Water 8%	Water 11%	Water 14%	Water 18%
Wet sample(g)+Mold(g)	6155.5	6271.5	6321	6288
Mold(g)	4316.5	4317	4317.5	4318.5
Wet sample(g)	1839	1954.5	2003.5	1969.5
Diameter(in)	4	4	4	4
Molded sample height(in)	4.5	4.5	4.5	4.5
Sample Volume(m^3)	0.0009267	0.0009267	0.0009267	0.0009267
Wet density(Kg/m^3)	1984.5	2109.2	2162.1	2125.4
Wet density(kN/m^3)	19.5	20.7	21.2	20.8
Wet density(lb/ft^3)	123.9	131.7	135.0	132.7

Moisture Content				
Wet Sample(g)	1839	1954.5	2003.5	1969.5
Dry Sample(g)	1713.5	1776.5	1777.5	1687.5
Water content(g)	125.5	178	226	282
Water content(%) Dry basis	7.3	10.0	12.7	16.7

Dry Density				
Wet sample(g)	1839	1954.5	2003.5	1969.5
Water content(g)	125.5	178	226	282
Dry Sample(g)	1713.5	1776.5	1777.5	1687.5
Dry density(Kg/m^3)	1849.1	1917.1	1918.2	1821.1
Dry density(kN/m^3)	18.1	18.8	18.8	17.9
Dry density(lb/ft^3)	115.4	119.7	119.7	113.7

Dry Density (Back Cal.)				
Wet sample(g)	1839	1954.5	2003.5	1969.5
Water content(g)	147.1	215.0	280.5	354.51
Water content(%) Cal. basis	8.0	11.0	14.0	18
Dry Sample(g)	1691.9	1739.5	1723.0	1615.0
Dry density(Kg/m^3)	1825.8	1877.2	1859.4	1742.8
Dry density(kN/m^3)	17.9	18.4	18.2	17.1
Dry density(lb/ft^3)	114.0	117.2	116.1	108.8

Table A-7. Unconfined Compressive Strength Test Results of 1 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	936.86	0.34	0.07556	13.59343	68.9	**69.0**
Control	953.84	0.4	0.08889	13.79236	69.2	
0%CaCl2+10%FA	1285.18	0.15	0.03333	12.99969	98.9	**96.2**
0%CaCl2+10%FA	1217.53	0.16	0.03556	13.02965	93.4	
2%CaCl2+10%FA	2099.81	0.14	0.03111	12.96988	161.9	**155.7**
2%CaCl2+10%FA	1947.19	0.16	0.03556	13.02965	149.4	
4%CaCl2+10%FA	1967.66	0.15	0.03333	12.99969	151.4	**151.8**
4%CaCl2+10%FA	1982.37	0.16	0.03556	13.02965	152.1	
6%CaCl2+10%FA	2274.23	0.19	0.04222	13.12034	173.3	**171.4**
6%CaCl2+10%FA	2222.89	0.19	0.04222	13.12034	169.4	
4%CaCl2+15%FA	1796.82	0.14	0.03111	12.96988	138.5	**144.7**
4%CaCl2+15%FA	1957.71	0.14	0.03111	12.96988	150.9	

Table A-8. Unconfined Compressive Strength Test Results of 3 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	1237.26	0.26	0.05778	13.33695	92.8	**91.4**
Control	1207.22	0.28	0.06222	13.40016	90.1	
0%CaCl2+10%FA	1743.88	0.15	0.03333	12.99969	134.1	**115.0**
0%CaCl2+10%FA	1246.94	0.15	0.03333	12.99969	95.9	
2%CaCl2+10%FA	1812.87	0.15	0.03333	12.99969	139.5	**139.1**
2%CaCl2+10%FA	1811.64	0.17	0.03778	13.05974	138.7	
4%CaCl2+10%FA	2289.1	0.14	0.03111	12.96988	176.5	**169.2**
4%CaCl2+10%FA	2108.43	0.16	0.03556	13.02965	161.8	
6%CaCl2+10%FA	2177.22	0.14	0.03111	12.96988	167.9	**166.5**
6%CaCl2+10%FA	2146.88	0.15	0.03333	12.99969	165.1	
4%CaCl2+15%FA	2060.68	0.15	0.03333	12.99969	158.5	**152.3**
4%CaCl2+15%FA	1890.21	0.13	0.02889	12.9402	146.1	

Table A-9. Unconfined Compressive Strength Test Results of 7 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	1005.8	0.26	0.05778	13.33695	75.4	**71.3**
Control	898.98	0.28	0.06222	13.40016	67.1	
0%CaCl2+10%FA	1215.43	0.15	0.03333	12.99969	93.5	**100.5**
0%CaCl2+10%FA	1398.67	0.15	0.03333	12.99969	107.6	
2%CaCl2+10%FA	2143.3	0.15	0.03333	12.99969	164.9	**152.0**
2%CaCl2+10%FA	1817.55	0.17	0.03778	13.05974	139.2	
4%CaCl2+10%FA	2005.3	0.14	0.03111	12.96988	154.6	**154.8**
4%CaCl2+10%FA	2020.74	0.16	0.03556	13.02965	155.1	
6%CaCl2+10%FA	2423.77	0.14	0.03111	12.96988	186.9	**180.8**
6%CaCl2+10%FA	2272.21	0.15	0.03333	12.99969	174.8	
4%CaCl2+15%FA	2298.55	0.15	0.03333	12.99969	176.8	**172.5**
4%CaCl2+15%FA	2175.92	0.13	0.02889	12.9402	168.2	

Table A-10. Unconfined Compressive Strength Test Results of 28 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	1145.01	0.29	0.06444	13.43199	85.2	**86.4**
Control	1182.25	0.31	0.06889	13.4961	87.6	
0%CaCl2+10%FA	1793.7	0.11	0.02444	12.88125	139.2	**127.0**
0%CaCl2+10%FA	1487.66	0.14	0.03111	12.96988	114.7	
2%CaCl2+10%FA	1698.44	0.12	0.02667	12.91065	131.6	**138.9**
2%CaCl2+10%FA	1879.88	0.1	0.02222	12.85197	146.3	
4%CaCl2+10%FA	2171.31	0.13	0.02889	12.9402	167.8	**167.6**
4%CaCl2+10%FA	2167.16	0.13	0.02889	12.9402	167.5	
6%CaCl2+10%FA	2997.61	0.14	0.03111	12.96988	231.1	**203.2**
6%CaCl2+10%FA	2279.56	0.15	0.03333	12.99969	175.4	
4%CaCl2+15%FA	2586.51	0.11	0.02444	12.88125	200.8	**195.7**
4%CaCl2+15%FA	2450.72	0.1	0.02222	12.85197	190.7	

Table A-11. Unconfined Compressive Strength Test Results of 56 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	1311.42	0.31	0.06889	13.4961	97.2	**93.7**
Control	1214.43	0.3	0.06667	13.46397	90.2	
0%CaCl2+10%FA	1866	0.1	0.02222	12.85197	145.2	**151.9**
0%CaCl2+10%FA	2041.82	0.11	0.02444	12.88125	158.5	
2%CaCl2+10%FA	2756.09	0.1	0.02222	12.85197	214.4	**195.9**
2%CaCl2+10%FA	2273.46	0.09	0.02	12.82283	177.3	
4%CaCl2+10%FA	2490.18	0.12	0.02667	12.91065	192.9	**203.1**
4%CaCl2+10%FA	2742.58	0.1	0.02222	12.85197	213.4	
6%CaCl2+10%FA	2721.04	0.13	0.02889	12.9402	210.3	**194.3**
6%CaCl2+10%FA	2303.2	0.12	0.02667	12.91065	178.4	
4%CaCl2+15%FA	2566.57	0.11	0.02444	12.88125	199.2	**188.9**
4%CaCl2+15%FA	2306.1	0.12	0.02667	12.91065	178.6	

Table A-12. Unconfined Compressive Strength Test Results of 90 Day Samples

Mix design	Peak L(lbf)	Exten.(in)	E	A(in^2)	Strength(psi)	Average(psi)
Control	1627.99	0.23	0.05111	13.24325	122.9	**136.7**
Control	1997.28	0.24	0.05333	13.27434	150.5	
0%CaCl2+10%FA	2568.28	0.12	0.02667	12.91065	198.9	**168.0**
0%CaCl2+10%FA	1770.66	0.12	0.02667	12.91065	137.1	
2%CaCl2+10%FA	1849.56	0.15	0.03333	12.99969	142.3	**154.0**
2%CaCl2+10%FA	2145.09	0.13	0.02889	12.9402	165.8	
4%CaCl2+10%FA	1598.86	0.17	0.03778	13.05974	122.4	**140.8**
4%CaCl2+10%FA	2068.94	0.15	0.03333	12.99969	159.2	
6%CaCl2+10%FA	1478.16	0.18	0.04	13.08997	112.9	**122.1**
6%CaCl2+10%FA	1718.91	0.18	0.04	13.08997	131.3	
4%CaCl2+15%FA	2591.26	0.12	0.02667	12.91065	200.7	**214.6**
4%CaCl2+15%FA	2942.19	0.11	0.02444	12.88125	228.4	

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