DEVELOPMENT OF A NEW DEVICE TO EVALUATE STABILIZATION DURABILITY OF EXPANSIVE SOILS BY ADDRESSING WETTING/DRYING AND LEACHATE ISSUES

by

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Presented to the Faculty of the Graduate School of

The University of Texas at Arlington in Partial Fulfillment

of the Requirements

for the Degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

THE UNIVERSITY OF TEXAS AT ARLINGTON

MAY 2012

ACKNOWLEDGEMENTS

I extend my sincere gratitude to Dr. Anand J. Puppala, Professor of Civil Engineering, for his direction and constant support throughout this research study. As an advisor, he explains complex problems with simple terminology that has helped further my understanding of the subject. He was supportive and patient at every turn, providing the friendship of him and his family. I would also like to express my sincere thanks to Dr. Laureano Hoyos, Associate Professor of Civil and Environmental Engineering, and Dr. Xinbao Yu, Assistant Professor of Civil and Environmental Engineering, for willingly accepting to serve on my committee and for their respected guidance in preparing an effective end product.

Additionally, I would like to thank the members of the Department of Civil Engineering staff: Ms. Ginny Bowers, Ms. Sara Ridenour, Ms. Eva Chapman, and Ms. Courtney Dickman for their friendly personality and unconditional help during my course work at UTA. I would like to thank TRWD for providing me with the opportunity to work on the present research study.

I would like to extend my sincere thanks to Dr. Bhaskar Chittoori, Faculty Associate of Civil and Environmental Engineering, for his unvarying support, dedication, and patience over the course of this research study. He has provided endless energy for every task and obstacle that transpired over the course of the research. My appreciations are due to my colleagues, Ahmed Gaily, Anil Raavi, Aravind Pedarla, Minh Le, Ranjan Rout, Naga Talluri, Tejo Bheemasetti, Justin Thomey, Tompinit Ruttana, Thorn Wejrungsikul, and Ujwal Patil for extending their sincere cooperation during laboratory studies. Special thanks to Rajini Karduri and Carlos Esparza for their understanding and support during the scheduling and testing involved in this research study.

Furthermore, I would like to thank my friends Yatish Mistry, Nickesh Mistry, Amita Karsen, Metel Patel, Swetha Shankar, Sneha Shankar, Channa Ranatunga, Sonal Patel, and Pooja Desai for their support, encouragement, and consistent follow up of my research and

personal activities. They have helped me remain sane by keeping me company at the most stressful times I have encountered while in graduate school.

I am grateful for the love, understanding and support provided by my parents (Pravin and Jyoti Lad), my brother and sister-in-law (Dharmish and Purva Lad), and my sister (Dhara Lad).

Finally, I would like extend my appreciation to those colleagues, who may have not been mentioned, for their direct or indirect cooperation and help during my time at UTA.

April 12, 2012

ABSTRACT

DEVELOPMENT OF A NEW DEVICE TO EVALUATE STABILIZATION DURABILITY OF EXPANSIVE SOILS BY ADDRESSING WETTING/DRYING AND LEACHATE ISSUES

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Expansive soils have been known to cause deterioration among all aspects of civil infrastructure for many years primarily due to the presence of clay minerals like Montmorillonite. Replacing these problematic soils is not a viable solution in that it is costly and time consuming.

Although many stabilization techniques are available, chemical stabilization has proven to be an important tool in arresting the swell/shrink behavior of expansive soil, which is a major source of distress problems for most infrastructures built on this type of soils. Of the chemical stabilizers available in the market, lime and cement stabilizers are the two most widely used chemical additives for improving expansive clays and increasing the overlying structures integrity; they improve the soil's workability, strength, swelling potential, and bearing capacity. Generally, lime stabilization develops due to base-exchange and cementation between the clay particles and lime (Croft, 1967). On the other hand, cement stabilization improves soil properties as a result of cementitious bonds between the calcium silicate and aluminate hydration products present in cement and soil particles (Nelson and Miller, 1992).

Furthermore, durability of the stabilization is an important aspect for any chemical stabilization design. To assess the durability of the stabilization design, chemically treated soil samples are subjected to wetting/drying studies to understand the longevity of the stabilization under climatic changes from summer to winter and vice versa. The samples are also subjected to leachate studies to determine the permanency of the stabilization due to rainfall infiltration. Both of these studies are often conducted as separate studies on separate soil samples. However, in reality the wetting process and the rainfall infiltration occur simultaneously. Hence, a new research study was undertaken in which an attempt was made to combine both phases of durability studies and perform a combined study that addresses both the wetting/drying and leachate aspects of durability. For this purpose a new device was developed which can replicate rainfall infiltration and wetting processes simultaneously. This process reduces the time required for durability studies by half and the data obtained show that this approach is repeatable and provides new insights in understanding the durability of the chemical stabilization.

A total of four soils were chosen along the pipe alignment in the IPL pipeline project for this study. These soils vary from low to high compressibility having plasticity index values ranging from 26 to 62, indicating medium to high expansiveness. Additionally, if these soils are used in the pipe bedding or haunch regions, they can cause excessive swelling pressures in the presence of water and damage the pipe, hence these soils were stabilized with either lime or cement-fly ash and were tested for durability in the newly developed combined device. Volumetric strains, weight changes, unconfined compressive strength changes and calcium ion concentrations were monitored over the course of the study. Many mix designs underwent durability, yet all four soils were stabilized effectively with 3% cement-10% fly ash as the treated soils completed 14 cycles of durability and maintained their strength.

Although previous studies have shown similar results when tested with the conventional methods, further testing is recommended with both the conventional and combined methods for soils with similar PI. These additional tests will help further understand the similarities in the modified (combined) approach and the conventional methods.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Expansive soils have been a major concern for many years now. Their shrink/swell characteristics have deteriorated many overlying structures, such as roads, low rise housing and public buildings primarily due to the presence of clay minerals like Montmorillonite. The replacement of these problematic soils is a tedious and costly process. An alternative to replacing soil is the use of chemical additives. Soil stabilization with chemical additives has been practiced for decades to improve the performance of base and subgrade materials (Tayabji et al., 1982). It has proven to effectively modify the engineering properties and limit the swell/shrink behavior of expansive soils while reducing the maintenance costs typically incurred over the course of a structures life.

As with many chemical stabilizers, the question often presented is whether or not the additive remains effective over the course of the treatments life. Oftentimes additives leach out due to a fluctuating water table, rainfall infiltration, etc. Various testing methods, design, construction, and quality assurance/quality control (QA/QC) methodologies have been developed for these stabilized materials to address the long-term performance of base and subgrade materials.

Of the chemical stabilizers available in the market, lime and cement stabilizers are the two most widely used chemical additives for improving expansive clays and increasing the overlying structures integrity; they improve the soil’s workability, strength, swelling potential, and bearing capacity (Croft, 1967). Generally, lime stabilization develops due to base-exchange and cementation between the clay particles and lime. Lime has been known to decrease the liquid limit, plasticity index and maximum dry density while increasing the optimum water content, shrinkage limit and durability of expansive clays when small dosages are used (Croft, 1967). On the other hand, cement stabilization improves soil properties as a result of cementitious bonds between the calcium silicate and aluminate hydration products present in cement and soil particles. A reduction in liquid limit, plasticity index, permeability and swelling potential occurs when cement stabilization is implemented (Nelson and Miller, 1992).

Additionally, most department of transportation's (DOT's) select a stabilizer based on the plasticity index (PI) and the gradation quality of the soil. However, there have been many instances in which a loss of stabilizer over time induces subgrade failures. Two such scenarios in which the stabilizer can leach out causing the soil to lose its strength include constant moisture fluctuation and rainfall infiltration. For this reason, durability studies are often conducted, which consist of alternating wetting/drying cycles and leachate collection to address the long-term effectiveness of chemical stabilization.

Durability studies are generally conducted in two stages, first stage consists of replicating the volumetric changes that occur due to moisture ingress and digress and this process is replicated by conducting wetting/drying studies in the laboratory. The second stage consists of replicating the rainfall infiltration which can sometimes leach the additive and reduce soil strength; this process is replicated in the laboratory by conducting leachate studies. Typically these two stages are conducted on two separate samples which increase the time and effort in conducting these tests and also the variability and uncertainty in the test results. However, if a modified durability device can be developed which could combine both the stages into one and thus can allow the durability studies to be conducted on the same sample avoiding sample variability and thus effectively and efficiently using time and materials. Hence, this main focus of this research is to develop such device and demonstrate its ability to conduct combined durability studies.

1.2 Research Objectives

The main objective of this research is to design and develop a device that accurately combines both phases of durability – wetting/drying cycles and leachate collection. This device will be used to address the stability of problematic soils with chemical stabilization. Four soils with different liquid limit and plasticity indices were chosen for the present research in which two forms of chemical stabilizations were administered. One treatment uses lime as an additive while the second treatment uses both cement and fly ash additives in combination; Texas Department of Transportation (TxDOT) stabilizer design methods Tex 120-E and Tex 121-E were utilized during treatment for cement and lime respectively. Each treatment was examined as to whether or not the stabilization adjusts soil properties such that their use as bedding and/or zone materials is possible. Additionally, mix designs were performed to determine the appropriate amount of chemical stabilizer required for each soil type.

Furthermore, durability studies were conducted to assess the long-term performance of each treatment and the leaching potential of the stabilized soil through wetting/drying cycles and leachate collection. These studies are typically performed separately, however, the main objective of this research study is to combine both phases of durability studies into a single device and hence a combined approach is used in this research.

1.3 Organization and Summary

Chapter 2 presents the available literature on expansive soils and their behavioral studies performed by numerous researchers. Additionally, stabilization of problematic soils with chemical additives followed by many state and federal agencies are detailed. Moreover, the durability and leachability of chemical stabilization have been reviewed to address the issue of losing of stabilizer over the course of its life.

Chapter 3 details the test procedures followed over the course of the current research. Procedures for preparing treated and untreated soil specimens for durability studies are provided. Wetting/Drying cycles and leachate collection processes used in previous studies as individual investigations have been accounted for. The new combined approach, where both phases of durability studies occur simultaneously, followed in this research has also been detailed.

Chapter 4 summarizes the results acquired from wetting/drying cycles and leachate studies conducted on treated and untreated soil specimens. Volumetric strains were monitored and recorded during wetting/drying cycles. Unconfined Compressive Strength (UCS) test results that were conducted for each chemical treatment at 0, 3, and 14 cycles of wetting/drying are provided. Additionally, calcium tests were performed on the leachate collected at select cycles to determine the amount of stabilizer lost.

Summary and conclusions from this research study, as well as the implication of the findings from laboratory studies, are addressed in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Expansive soils pose problems to overlying structures due to the swell-shrink characteristics, which are mainly due to the presence of clay minerals like Montmorillonite. Stabilization of these soils with chemical additives has been practiced for decades to improve the performance of base and subgrade materials (Tayabji et al., 1982). Chemical stabilization of expansive soils not only reduces maintenance costs of the infrastructure built on them, but also provides riding comforts for travels. Though these chemicals stabilize the soil temporarily, their effectiveness is lost over a period of time (McCallister and Petry, 1992). This effect of losing the additive from treated soils is mainly caused from external activities such as fluctuating water table, rainfall infiltration etc. The soil mass after losing the stabilizer does not perform according to the designed standards and exhibits premature failures (McCallister and Petry, 1992; Chittoori et al. 2011).

Different testing methods, design, construction, and quality assurance/quality control (QA/QC) methodologies have been developed for these stabilized materials. Many pavement projects constructed with stabilized materials have achieved satisfactory results. However, challenges remain in the optimal use of these stabilized materials. These challenges include developing better understanding of the long-term performance of the stabilized materials, better construction methods and using proper quality assurance/quality control (QA/QC) procedures that are effective predictors of the long-term performance of pavement infrastructure with minimal distress problems (Little et al., 2000). This chapter reviews the available literature on soil stabilization and identifies the potential problems of the existing test methods to assess durability and permanency of chemically treated expansive soils.

The first part of this chapter focuses on the functionality of expansive soils and how they have played a detrimental role in geotechnical engineering practice. Ways to improve or enhance expansive soils characteristics, by chemically altering the soil, have also been reviewed and discussed. Finally, existing test methods to assess the durability and permanency of chemical additives have been discussed by evaluating the available literature on durability studies and leachate collection conducted on expansive soils.

2.2 Expansive Soils

Expansive soils are a universal issue. They cause numerous costly damages to the infrastructure; whether its roadways, buildings, bridges or other civil engineering infrastructure. Maintenance and rehabilitation costs for the infrastructure on these soils reach billions of dollars annually in the US (Petry and Little, 2002). These problems primarily stem from the presence of Montmorillonite clay minerals which are derived from basic and ultrabasic igneous rocks; essentially the minerals are a byproduct of the decomposition of these rocks (Van der Merwe, 1964). These minerals swell when moisture is introduced and shrink when the same moisture is retracted. In the case where the soil undergoes excessive heat, i.e. drought, expansive soils tend to contract and shrink excessively. This phenomenon is further described in Chittoori (2008).

Al-Rawas et al. (2002) noted that clay minerals and cations come in various forms and that it is the relative quantities of each type of these minerals that are important factors contributing to the swell/shrink behavior along with the dry density, soil structure, and loading conditions present. Sirivitmaitrie et al. (2008) added that the arid climate, alkaline environment, and local geology are accountable for the expansive nature of soils.

When expansive soils are not treated, the volumetric change these soils undergo due to moisture content changes causes multiple distresses in structures built on them. For example, constant swelling and shrinking in the subbase or base materials of a pavement structure will cause cracks to form in the pavement itself (Sirivitmaitrie et al., 2008). These cracks tend to appear gradually due to a long-term swelling issue. This issue is oftentimes ignored in order to reduce costs (Petry and Little, 2002).

According to Wiseman et al. (1985), the following factors can be used to classify a soil as a problematic or non-problematic type:

1. Soil type that exhibits considerable volume changes associated with changes of moisture content
2. Climatic conditions such as extended wet or dry seasons
3. Changes in moisture content (climatic, man-made or vegetation)
4. Light structures that are very sensitive to differential movement

Expansive soils can be identified by using the following index tests (see Table 2.1) and the magnitudes of their test results:

Table 2.1 Expansive soils identification (from Wiseman et al., 1985)

Index Test	Usually No Problems	Almost Always Problematic
Plasticity Index	<20	>32
Shrinkage Limit	>13	<10
Free Swell (%)	<50	>100

A summary of various methods for identifying the expansive nature of soils can be found in Puppala et al. (2004).

Rather than noticing the discomfort caused by expansive soils as an aftermath, it is more economical to deal with it prior to construction. By implementing soil stabilization techniques, such as chemical additives, these issues can be hindered and averted. The following sections present some of the chemical additives that are typical used to treat these types of soils.

2.3 Chemical Additives

Chemical additives are commonly used to manipulate engineering properties of weak and/or expansive soils. The manipulation can occur through bonding, waterproofing, or a combination of bonding and waterproofing (Chittoori, 2008). Coating particles, binding particles together, and forming new compounds are the resulting outcomes when using an additive. How fast and to what extent the additive works heavily relies on the composition of the material being treated and the additive (Chittoori, 2008). Additives can be divided into three main categories: Traditional, Non-traditional, and Byproduct stabilizers. Traditional stabilizers include hydrated lime, Portland cement and Fly ash. Whereas Non-traditional stabilizers consist of sulfonated oils, ammonium chloride, enzymes, polymers, etc. and Byproduct stabilizers are cement kiln dust, lime kiln dust, etc. Out of these categories, Traditional stabilizers are widely used (NCHRP 114, 2009).

Traditional stabilizers typically depend on pozzolanic reactions and cation exchange to modify and stabilize soil (NCHRP 114, 2009). Pozzolanic reactions occur when siliceous and aluminous materials react chemically with calcium hydroxide at regular temperatures to form cementitious compounds (Mamlouk and Zanjewski, 2011). On the other hand, a cation exchange occurs when the soil is able to exchange free cations available in the exchange locations (Chittoori, 2008).

2.3.1 Types of Chemical Additives

Lime, cement, fly ash and secondary stabilizing agents are discussed in detail in this section.

2.3.1.1 Lime

Limestone is broken down at elevated temperatures to form lime (Chittoori 2008). As a result, three forms of lime are produced: quicklime (calcium oxide – CaO), hydrated lime (calcium hydroxide – $Ca[OH]_2$), and hydrated lime slurry; all of which can be used to treat soils. Quicklime is manufactured by chemically transforming calcium carbonate (limestone – $CaCO_3$) into calcium oxide. Furthermore, hydrated lime is created when quicklime chemically reacts with water. When hydrated lime is mixed with clay particles, it permanently forms strong cementitious bonds. (NLA, 2004)

Lime has been known to reduce the swelling potential, liquid limit, plasticity index and maximum dry density of the soil, and increases its optimum water content, shrinkage limit and strength (Croft, 1967). It improves the workability and compactability of subgrade soils (Jung et al., 2008). When clay soil is treated with lime, it reacts with the presence of water. New compounds are formed through the processes of cation exchange, flocculation, carbonation and pozzolanic reaction (Al-Rawas, 2005). These processes can vary with their time of completion depending on the type of clay being treated. Therefore the lime treated soil is allowed 1 to 4 days for mellowing; mellowing helps establish a consistent or homogeneous mixture (Chittoori 2008).

When lime is combined with water and the soluble silica and alumina present in clay, a chemical reaction occurs, resulting in the formation of new compounds. When combined with water, its primary function is alteration of particle structure and increased resistance to shrink-swell and moisture susceptibility. A secondary result is binding of particles (when combined with clay) and strength gain. Since alteration of particle structure occurs slowly, depending upon the type of clay present, a mellowing period from 1 to 4 days is allowed to obtain a homogeneous, friable mixture.

Lime can be used to treat soils to varying degrees, depending upon the objective of the stabilization for a specific project. The least amount of treatment is used to dry and temporarily modify soils (Sherwood, 1995). Such treatment produces a working platform for construction or temporary roads. The highest amount can be used when it is being used to improve the soil strength properties for supporting civil structures (Sherwood, 1995).

Many researchers have used lime as a stabilizer with appreciable amount of success. Lime stabilization is a widely used means of chemically transforming unstable soils into structurally sound construction foundations. Lime stabilization enhances engineering properties in soils, including improved strength; improved resistance to fracture, fatigue, and permanent deformation; improved resilient properties; reduced swelling; and resistance to the damaging effects of moisture. The most substantial improvements in these properties are seen in moderately to highly plastic clays (Little, 2000).

2.3.1.2 Cement

Portland cement production begins with two essential raw ingredients: a calcareous material and an argillaceous material. Limestone, chalk, and oyster shells are examples of calcareous materials, primarily containing calcium oxide. On the other hand, argillaceous material is a combination of silica and alumina that can be found from clay, shale, and blast furnace slag. These materials are crushed through a grinding mill using either a wet or dry process and then stored in silos until needed. The raw materials are then melted in a kiln at temperatures ranging from 1400°C to 1650°C (2500°F to 3000°F) to form cement clinkers, which are then cooled and stored. The last step in the process involves grinding the clinker into a fine powder. (Mamlouk and Zanjewski, 2011)

As previously noted, cement is a compilation of various minerals – typically composed of calcium, silica, alumina, and iron compounds. When water is mixed with cement, hydration occurs, meaning cementing compounds of calcium-silicate-hydrate (C-S-H) and calcium-aluminate-hydrate (C-A-H) are formed and excess calcium hydroxide (CaOH) is released, approximately 31% by weight. (Parsons and Milburn, 2003) C-S-H and C-A-H occurs when crystals begin forming a few hours after the water and cement are mixed; crystals will continue to form as long as unreacted cement particles and free water remain within the mixture (Mamlouk and Zanjewski, 2011).

Five standard types of Portland cement (Types I through V) are available as specified by ASTM C150. Table 2.2 details the five types.

Table 2.2 Types and Applications of Standard Portland Cement (Mamlouk and Zanjewski, 2011)

Type	Name	Application
I	Normal	General concrete work when the special properties of other types are not needed. Suitable for floors, reinforced concrete structures, pavements, etc.
II	Moderate Sulfate Resistance	Protection against moderate sulfate exposure, 0.1-0.2% weight water soluble sulfate in soil or 150-1500 ppm sulfate in water (sea water). Can be specified with a moderate heat of hydration, making it suitable for large piers, heavy abutments, and retaining walls. The moderate heat of hydration is also beneficial when placing concrete in warm weather.
III	High Early Strength	Used for fast-track construction when forms need to be removed as soon as possible or structure needs to be put in service as soon as possible. In cold weather, reduces time required for controlled curing.
IV	Low Heat of Hydration	Used when mass of structure, such as large dams, requires careful control of the heat of hydration.
V	High Sulfate Resistance	Protection from severe sulfate exposure, 0.2-2.0% weight water soluble sulfate in soils or 1500-10,800 ppm sulfate in water.

The process of cementation and the results of cement stabilization and lime stabilization are similar. Cement has been known to reduce the liquid limit, plasticity index and swelling potential, and increase the shrinkage limit and shear strength (Nelson and Miller, 1992). The use of cement in granular soils has proven to be economical and effective because smaller amounts of cement are required. Whereas cement used in fine grained soils have not been as effective. Soils that have a PI value higher than 30 have trouble mixing with cement. To by-pass this issue, lime can be added prior to mixing in cement; this initial step will keep soils more workable (Hicks, 2002).

Al-Rawas et al. (2005) found swell pressure to decrease as the stabilizer content increased in cement treated samples. Cementitious links develop between the calcium silicate and calcium aluminate found in Portland cement with the soil particles (Croft, 1967; NCHRP 114, 2009). Unlike lime, hydration in cement occurs at a faster pace which allows for an immediate strength gain. Therefore there is no need of a mellowing period when stabilizing with cement; compaction of cement treated soils is typically conducted within 2 hours of initial mixing. The strength gain achieved during compaction may be below the ultimate strength of a soil cement sample (NCHRP 114, 2009). However, the cement stabilized soil will continue to gain strength over the course of several days (Chittoori, 2008).

There are many factors contributing to the length of curing time required for strength gain in cement treated soils, they are as follows: ambient air temperature, relative humidity, wind speed, type of cement used, and concentration of cement used. These factors do not affect the initial strength gain after setting; they need to be considered when utilizing cement in the base material of a pavement system (Guthrie and Reese, 2008). Guthrie et al. (2008) found that the relative strength is sensitive to the previously mentioned factors, while the relative compaction is not. Higher wind speed, higher air temperature, lower relative humidity and higher compaction delay time generally result in a lower strength. Time is money and construction cannot be at a halt for a few days before continuing onto the construction of the roadway itself (Guthrie and Reese, 2008).

2.3.1.3 Fly Ash

Fly ash is one of four coal combustion products (CCPs) that are produced as a byproduct of burning coal for generating electricity in the United States. The remaining three types are bottom ash, boiler slag and flue gas desulfurization byproduct material (i.e. gypsum). Fly ash makes up 58% of CCPs; of this 58%, only 32% of it is reused in construction. Its primary construction application is its use as part of the base material in highways. Through its use in civil applications, less fly ash will be placed in a landfill. Therefore landfill costs will be reduced, which will mitigate environmental impacts. (Arora and Aydilek, 2005)

Coal burning power plants do not produce the same type of fly ash; each plant is operated differently and may use a different type of coal. Two major groups, Class C and Class F fly ash are produced. Burning lignite and subbituminous coal produces Class C fly ash. Whereas burning anthracite, other known as bituminous coal, produces Class F fly ash (Cokca, 2001). Although there can be multiple variations of the chemical additive, fly ash particles generally consist of hollow spheres of silicon, aluminum, and iron oxides and unoxidized carbon; all of which make both classes of fly ash pozzolans-siliceous or siliceous and aluminous materials (Arora and Aydilek, 2005; Cokca, 2001). It is typically viewed as non-plastic fine silt (ML) when using the Unified Soil Classification System (USCS) (Cabrera and Woolley, 1994; Rollings and Rollings, 1996).

Of the two, Class F fly ash is not used as often because it requires an activator, either lime or cement, to form pozzolanic stabilized mixtures (PSMs) since it is not a self-cementing material (Arora and Aydilek, 2005). Nicholson and Kashyap (1993) assessed the effect of off-specification fly ash on the engineering properties of tropical soils from Hawaii. They noticed fly ash decreased the liquid limit and plasticity index, and increased the California bearing ratio (CBR) and unconfined compressive strength. Vishwanathan et al. (1997) performed UCS and one-dimensional free swell tests on soil-lime mixtures altered with Class F fly ash. Observations showed that lime and fly ash are a good combination for stabilizing silty and sandy soils. It drastically increased the stiffness of the final product. Bergeson and Barnes (1998) used Class C fly ash with lime to develop guidelines for determining the structural layer coefficient for the base layer of flexible pavement. The required base layer thickness decreased with the addition of both additives.

2.3.1.4 Secondary Stabilizing Agents

Although lime, cement and fly ash are commonly used stabilizers, there are many other options in the market such as cement by-pass dust (CBPD) - also known as cement kiln dust (CKD), blast furnace slag, lime kiln dust, and others (Al-Rawas et al., 2002). These supplementary stabilizers are secondary stabilizers and do not work well alone; they require a primary stabilizing agent such as lime or cement additives (Chittoori, 2008).

Morgan and Hallf (1984) reported that cement kiln dust (CKD) is cost effective and an efficient solidifying agent when compared to lime, cement, fly ash, and sulphur. It was also reported that CKD results in a reduction in plasticity index and swell pressure, and increase in compressive strength (McCoy 1971; Zaman et al. 1992). Miller (2000) showed CKD provided strength gains in a short period of time-within 7 to 14 days; DCP was effectively used to measure the relative improvement in stabilized subgrades.

Al-Rawas et al. (2002) tested cement by-pass dust (CBPD), slag-cement, and granulated blast furnace slag (GBFS) samples. These treated samples showed a reduction in cation exchange capacity, liquid limit, and plasticity index. They also tested copper slag treated samples, which showed consistent increase in swell pressure, whereas the other treated samples showed a reduction.

2.3.2 Stabilization Procedure

Chittoori (2008) decribes a three step procedure that accounts for variables that effect soil stabilization, especially when the objective of stabilization is to provide long-term benefits. The procedure is as follows:

1. Soil Exploration, Material Sampling, Soil Classification and Acceptance Testing
2. Additive Selection
3. Mix Design

For ease of comprehension, TxDOT developed flowcharts to illustrate the steps required for successful subgrade and base material treatment. These flowcharts can be seen in Figure 2.1 and 2.2 respectively.

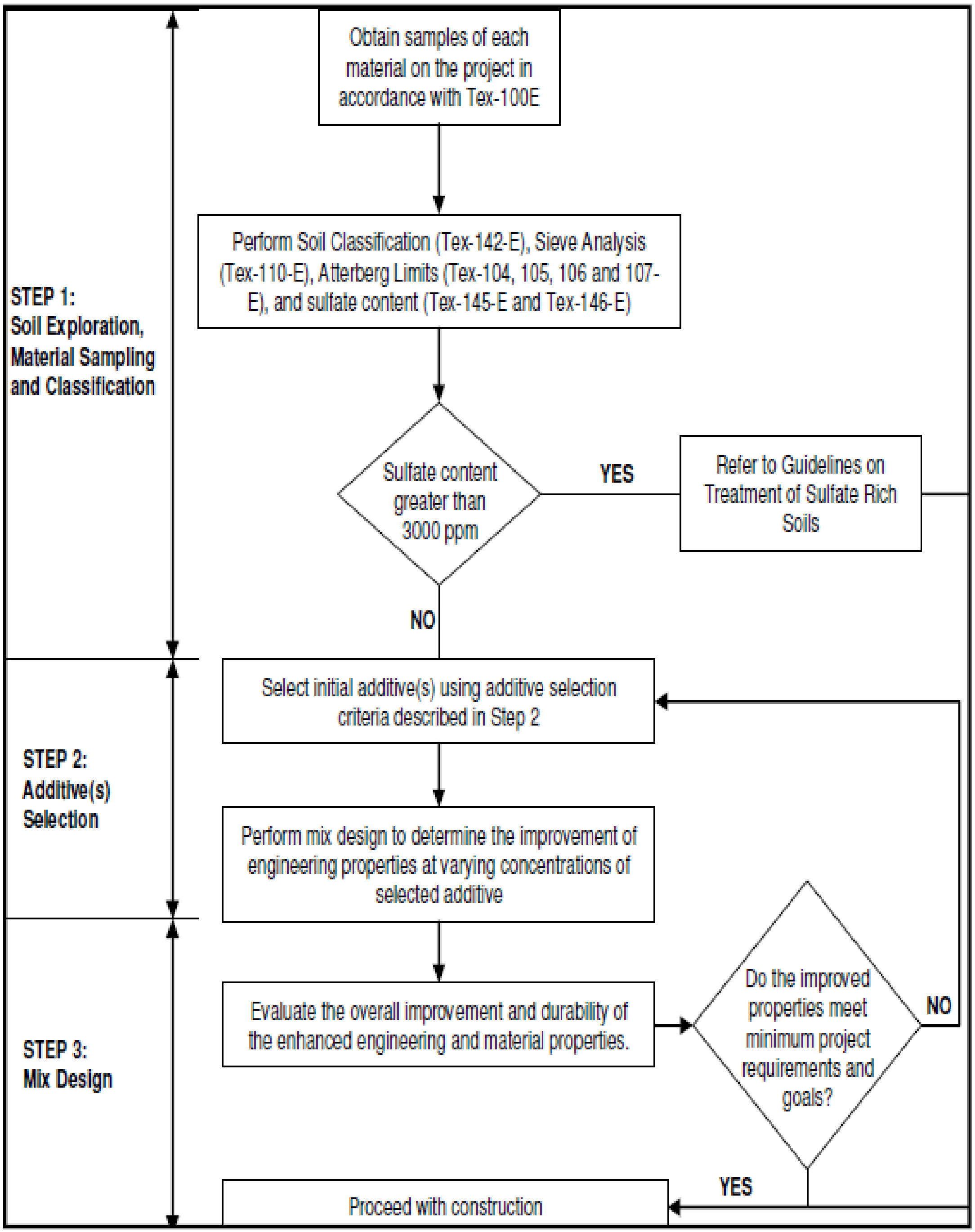


Figure 2.1 Flowchart for Subgrade Soil Treatment (TxDOT Guidelines)

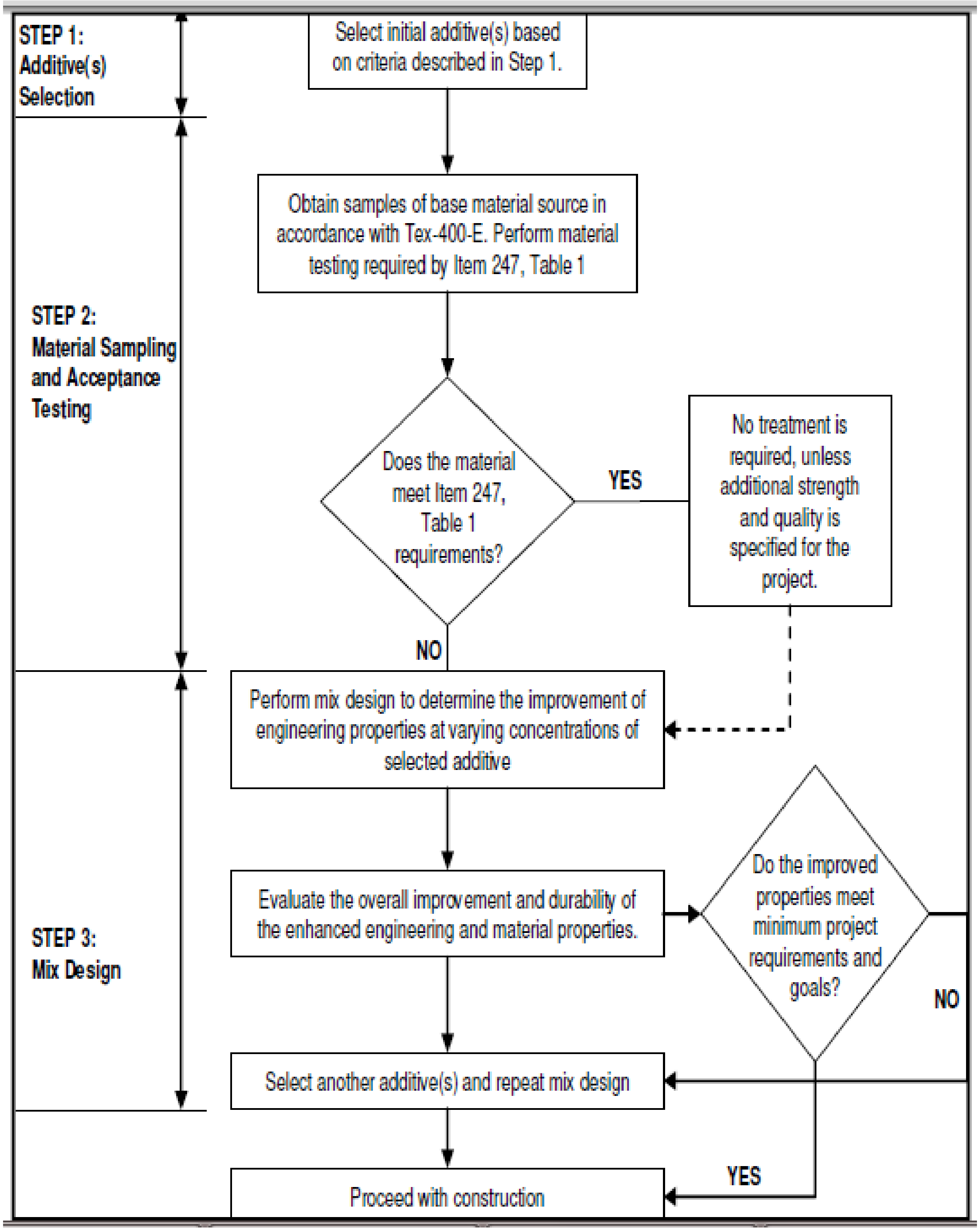


Figure 2.2 Flowchart for Base Soil Treatment (TxDOT Guidelines)

2.3.2.1 Soil Exploration

Prior to stabilizing soil, it is imperative to conduct material sampling and testing to characterize the material and assess the physical properties that can affect the performance of a civil structure, such as a pavement structure. Field investigations are crucial in understanding the conditions of the underlying strata which affects the performance any treated layers or structures above it.

2.3.2.2 Additive Selection

Stabilization design charts have been provided by the Texas Department of Transportation (TxDOT). These charts, Figures 2.3 and 2.4, offer steps for determining which chemicals are required for treating subgrade and base materials, respectively, on the basis of plasticity index (PI). Additionally, the following factors can aid in appropriately choosing additives:

- Soil mineralogy
- Soil Classification
- Treatment goals
- Mechanism of additives
- Design life
- Environmental conditions
- Project cost

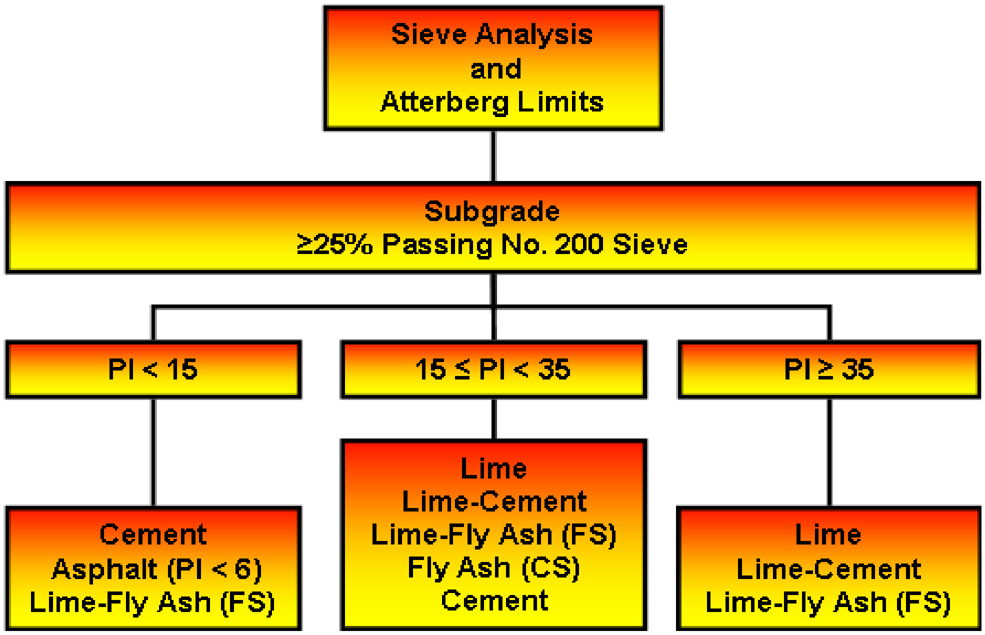


Figure 2.3 Additive Selection Criteria for Subgrade Material Using Soil Classification (TxDOT Manual)

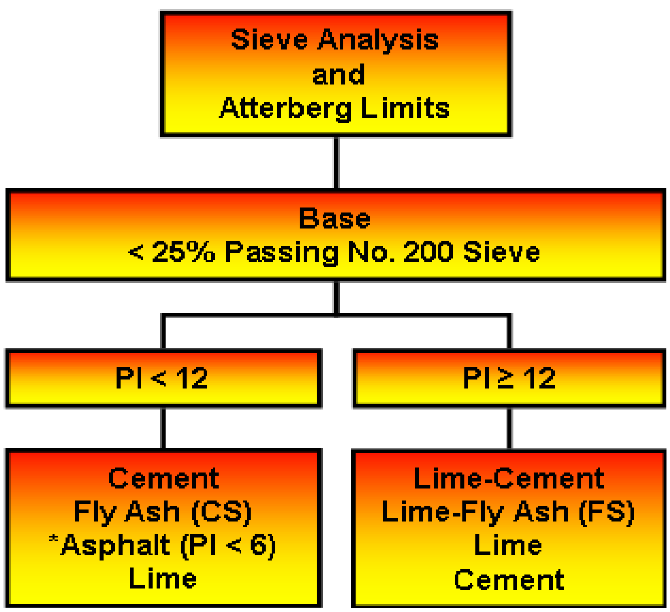


Figure 2.4 Additive Seleection Criteria for Base Material Using Soil Classification (TxDOT Manual)

2.3.2.3 Mix Design

Mix design is essential to optimize the material properties, calculate the right percent of additive, measure effectiveness and engineering properties and provide density and moisture control parameters for construction. TxDOT guidelines denote a few steps to achieve the mix design:

- ✓ Verifying that sulfate and organic contents are within acceptable limits,
- ✓ Developing moisture density curve (M/D) for field density control,
- ✓ Strength testing before and after moisture conditioning, and
- ✓ Determining the lowest modifier content to satisfy strength requirements.

2.3.2.4 Determination of Additive Concentration

The procedures to select the adequate percentage necessary to stabilize base and subgrades are separated by type of additive, particularly Tex-121-E for lime, Tex-120-E for cement and Tex-127-E for fly-ash stabilization.

2.3.2.4.1 Lime Stabilization Design

To obtain the amount of lime necessary to stabilize the soil, TxDOT specifications are based on the pH method. This method, also known as the “Eades-Grim” test (Eades and Grim, 1966), is fully described in ASTM D 6276 procedures and summarized in Tex-121-E part III. The basic objective of this method is to add sufficient lime to the soil to ensure a pH of 12.4 for sustaining the strength-producing lime-soil pozzalonic reaction. The lowest percentage of lime in soil that produces a laboratory pH of 12.4 is the minimum percentage for stabilizing the soil. A series of specimens with lime percentages ranging from 0 to 10% are tested in the lab to determine the required amount. Additional provisions for cases in which the measured laboratory pH is 12.3 or less are established. The minimum strength criterion for lime content is based on an unconfined compressive strength of 150 psi for base and 50 psi for soils.

In the Army and Air Force (AAF) guidelines the preferred method for determining initial design lime content is the pH test or “Eades-Grim” test, same as used in current TxDOT specifications (Chittoori, 2008). The lowest lime content at which a pH of about 12.4 (the pH of free lime) is obtained is the initial design lime content. An alternate method of determining initial design lime content is by the PI wet method (AASHTO T-220), as shown in Figure 2.5. Other than determination of lime content, unconfined compressive strength and durability tests are also performed to assure strength and durability requirements previously discussed. If results of the specimens tested do not meet both the strength and durability requirements, higher lime content may be selected and the mix design is evaluated again.

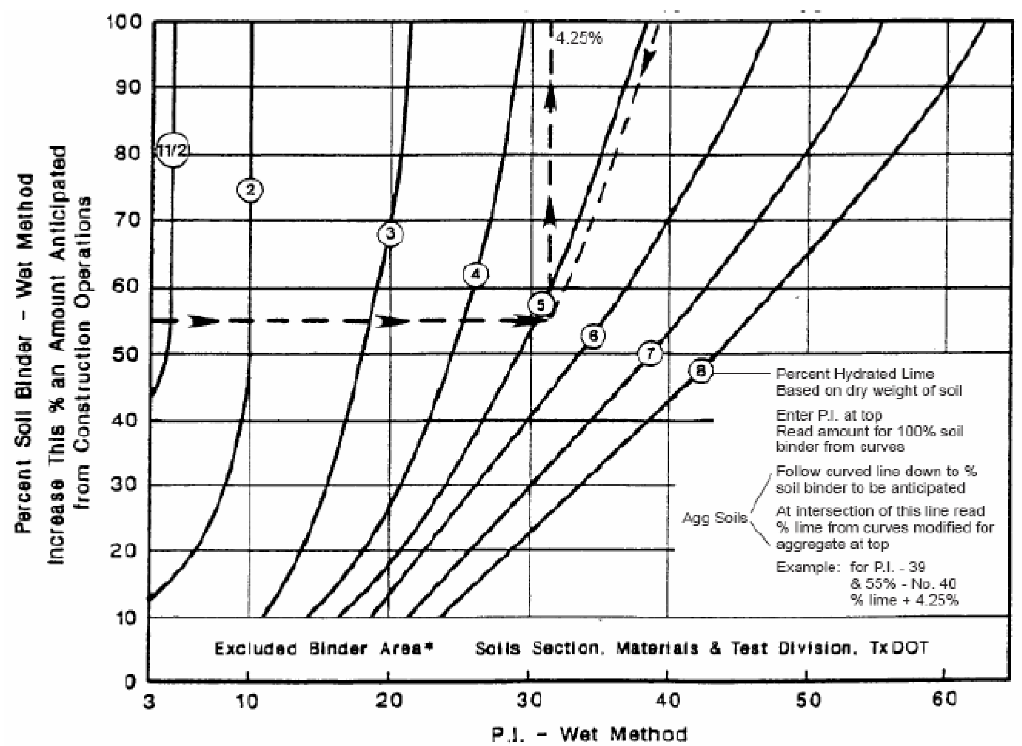


Figure 2.5 PI Wet Method to Calculate Amount of Lime for Stabilization (Tex-121 E)

Design lime contents are usually based on the effect of lime percentages on engineering properties of the soil mixture. Different design lime contents may be selected depending on the objectives of the lime treatment. A brief summary of several lime design procedures and criteria is presented in Table 2.6.

2.3.2.4.2 Cement Stabilization Design

TxDOT guidelines to determine the amount of cement required for soil-cement stabilization are primarily based on exceeding a minimum unconfined compressive strength and attaining a minimum strength after moisture conditioning in the laboratory. Minimum strength requirements for plant-mixed stabilized mixes are based on the class specified on the plans as summarized in Table 2.3 (TxDOT Item 246). As determined by the latest TxDOT Pavement Design Guide (2006), 300 psi should be the target strength for cement stabilized bases. Higher strengths are not recommended because they can lead to extreme environmental cracking.

According to AAF guidelines the cement content is initially estimated based on the soil classification (see Table 2.4). Using this cement content, maximum dry density and optimum water content of the soil-cement mixture is calculated. Triplicate specimens are prepared at recommended cement contents and also at ±2% cement content. Unconfined compressive strength and durability tests are performed on these specimens and the lowest cement content which meets the strength requirement and demonstrates the required durability is the design cement content. (Chittoori, 2008)

Unconfined compressive strength (UCS) is the most widely referenced property of soil cement. UCS serves as a criterion for determining the minimum cement content requirements. Typical ranges of UCS after 7 and 28 days of curing for soaked soil-cement mixtures are presented in Table 2.5, classified by several soil groups (American Concrete Institute, ACI 230.1R-90).

Table 2.3 Soil-Cement Strength Requirements as per TxDOT Item 246 Specifications

Class		**7-Day Unconfined Compressive Strength, Min. psi**
L	Flexible Pavements	300
M		175
N	Rigid Pavements	As shown on the plans

Table 2.4 Cement Requirements for Various Soils (Chittoori, 2008)

Soil Classification	Initial Estimated Cement Content (% Dry Weight)
GW, SW	5
GP, GW-GC, GW-GM, SW-SC, SW-SM	6
GC, GM, GP-GC, GP-GM, GM-GC, SC, SM, SP-SC, SP-SM, SM-SC, SP	7
CL, ML, MH	9
CH	11

Table 2.5 Ranges of UCS for Soil-Cement (ACI 230.1R-90)

Soil Type	7-Day Soaked Compressive Strength (psi)	28-Day Soaked Compressive Strength (psi)
Sandy and Gravelly Soils	300-600	400-1000
Silty Soils	250-500	300-900
Clayey Soils	200-400	250-600

2.3.2.4.3 Fly Ash (FA) and Lime-Fly Ash (LFA) Design

Like cement, the unconfined compressive strength is used as an index to determine the suitable amount of additive. A minimum unconfined compressive strength of 150 psi is suggested as adequate for FA or LFA stabilized soils. Unconfined compressive strengths for FA or LFA base courses should approach the strength requirements of soil cement presented in Table 2.3 above.

Table 2.6 Summary of Soil-Lime Mixture Design Procedures (Chittoori, 2008)

Mixture Design Procedure	Summary of Methods	Mixture Design Criteria
Eades and Grim	Based on pH	Design lime content is lime required to insure a pH of 12.4.
Thompson	Based on Unconfined Compressive Strength (UCS)	Increase of UCS of soil-lime over soil after 48 hour cure at 120□F must be at least 50 psi.
California	California Test 373, Based on UCS and optimum moisture content	Highest UCS at optimum moisture content using 4-in. diameter by 4-in. height specimens.
Illinois	Based on UCS, optimum moisture content and maximum dry density	Achieve a 50 psi increase in UCS in 48 hours at 120□F. Design lime content is % above which there is no added strength gain.
Oklahoma	Eades and Grom (ASTM D 6276 or ASTM C 977)	Design lime content is lime require to insure a pH of 12.4
South Dakota	South Dakota Test SD-107, similar to AASHTO T-193. Based on 96-hour soaked CBR and freeze thaw cycles	CBR of soil-lim is 3-4 times of CBR natural soil. Maximum 0.5% vertical expansion after 30 freeze-thaw cycles. UCS after 30 freeze-thaw cycles is at least 75% of initial UCS.
Virginia	Based on UCS	Design lime content based on cost effectiveness and benefit derived.

According to AAF guidelines design with LFA is somewhat different from stabilization with lime or cement (Chittoori, 2008). For a given combination of materials (aggregate, fly ash, lime), a number of factors can be varied in the mix design process such as percentage of lime-fly ash, the moisture content, and the ratio of lime to fly ash additives. The matrix material, defined as the content of fly ash, lime, and minus No. 4 aggregate fines of the total mixture, is another aspect to consider in the mix design. The optimum fines content is referred as the quantity of matrix required for maximum dry density of the total mixture. For LF mixtures it is recommended that the quantity of this matrix should be approximately 2 percent above the optimum fines content. To establish the amount of additives, the first step is to determine the optimum fines content that will give the maximum density. The initial fly ash content should be about 10% based on dry weight of the mix. Tests are run at increasing increments of fly ash, e.g. 2%, up to a total of about 20%. Moisture content – dry density tests are conducted afterward and the design fly ash content is then selected at 2% above that yielding maximum dry density. The ratio of lime to fly ash (LF) that will yield the highest strength and durability is determined, by using lime to fly ash ratios of 1:3, 1:4, and 1:5. Three specimens are prepared and tested for unconfined compression strength and wet-dry or free-thaw cycles (if applicable), and the lowest LF ratio content, i.e., ratio with the lowest lime content which meets the strength from Table 2.3 is recorded as the design LF content.

2.4 Durability Related Issues in Soil Stabilizations

Under any civil engineering structure, it is understood that the properties of stabilized layers will change over time. Strength and stiffness will increase as cementitious links form and bond the particles together. After full strength is reached, the layers will react and change with traffic and time. In any stabilization application, the stabilized material should be able to withstand climatic stresses, such as being subjected to severe wetting and drying, due to its affect on the properties of the layers. The action of wetting and drying plays an important role in the durability of soils (DoT, 1986).

Durability relates to the permanency of chemical stabilizers-the ability for the soil particles and stabilizers to hold together and remain intact for a long period of time. Durability studies are conducted on soil samples, either with or without stabilizers, to duplicate field climatic conditions in the laboratory within a shorter time period. ASTM D 559 provides a testing guideline to replicate moisture and temperature fluctuations occurring in the field. Two similar samples of each soil/additive combinations are prepared at the optimum moisture content. The lime-treated soil specimens are prepared after mellowing, whereas the cement and other chemically treated soil specimens are prepared within an hour of mixing. Soil specimens are then cured for seven days in a moisture room prior to subjecting them to wet-dry cycles. Each wet-dry cycle consists of submerging the two soil samples in water for 5 hours and then placing them in a 70℃ oven for 42 hours. After removal fro m the oven, one specimen is subjected to volume change and moisture content measurements. The second specimen is subjected to leachate tests to determine the chemical additive loss. The test is then continued until 12 wet-dry cycles are completed or until the sample failed.

The effect of freeze-thaw on strength can be explained in terms of the retardation or acceleration of the cementitious reactions. Freezing retards the reactions, which causes a reduction in stiffness. On the other hand, thawing accelerates the reactions and causes an increase in compressive strength (Arora and Aydilek, 2005). Cement-treated samples, prepared by Arora and Aydilek (2005), were cured for 7 days and underwent freeze-thaw cycles; each prepared specimen consisted of cement within the range of 0 to 7%. Specimens containing 7% cement saw an increase in strength with the number of freeze-thaw cycles compared to mixtures with 4 and 5% cement. The presence of kaolinite proved to have a damaging effect on the specimen's durability. On the other hand, lime-treated specimens successfully completed the freeze-thaw cycles, but their strengths decreased with increasing number of cycles. Lime-treated samples containing cohesive fines had the greatest strength loss.

Parsons and Miburn (2003) performed a series of tests to evaluate the relative performance of lime and cement with respect to Class C fly ash and an enzymatic stabilizer. These additives were mixed into seven different soils with classifications of CH, CL, ML, and SM. As samples were prepared, durability studies consisting of freeze-thaw, wet-dry, and leach testing were conducted. Samples treated with cement and fly ash showed lower soil losses than lime-treated soils when subjected to freeze-thaw cycles. Additionally, UCS tests were performed on the four different soils previously mentioned-low and high plasticity clay, low plasticity silt, and silty sand; higher strength gains were reported for low plasticity silt and silty sand treated with fly ash and cement.

Hoyos et al. (2005) at UTA performed a series of wet and dry cyclic tests on different types of chemically-treated sulfate soils to evaluate the strength, stiffness and volume change property variations with respect to these cycles as shown in Figure 2.6.

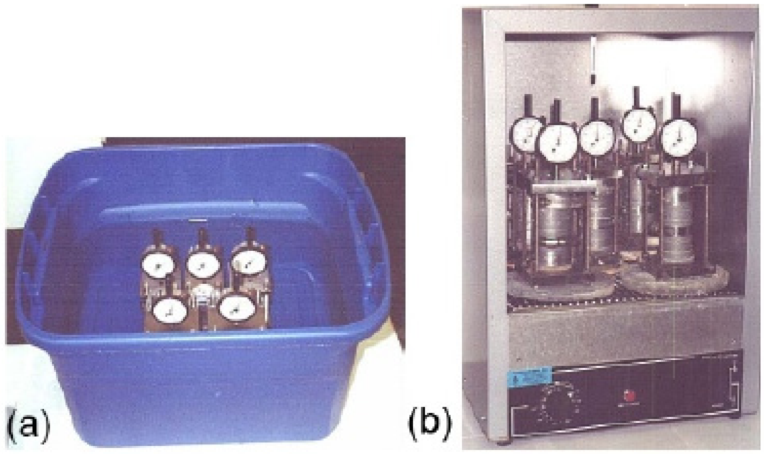


Figure 2.6 (a) Wet and (b) Dry cycles setup used by Hoyos et al. (2005)

Chittoori (2008) investigated highly expansive soils from various regions in Texas. Soils were subjected to accelerated curing since better results were achieved within a short period of time rather than the standard curing test provided by ASTM. Durability studies were conducted on all soils by alternating wetting and drying cycles. Both volumetric changes and strength loss were monitored and presented for all soil samples at various cycles.

For example, Soil I composed of 50% Montmorillonite, 25% Kaolinite and 25% Illite; it's plasticity index was 45 and was classified as a high compressible fat clay. The soil was stabilized with 4% lime and 4% cement according to the PI design procedures detailed in Tex 120 E (Cement) and Tex 121 (Lime). After sample preparation, samples underwent alternating wetting and drying cycles. Figures 2.7 and 2.8 demonstrate the difference in UCS strength of treated and untreated specimens undergoing wetting/drying cycles for lime and cement respectively. Untreated specimens failed after 2 cycles whereas treated specimens survived for 4 cycles of wetting/drying. Based on this result, it is observed that neither soil specimen survived 21 cycles. Figures 2.9 and 2.10 depict the volumetric strain of the treated and untreated specimens of Pharr-A for lime and cement respectively. Untreated soil exhibited a maximum volumetric strain of approximately 60% for 1 cycle of wetting and drying. On the other hand, lime controlled which strain to 30% for 4 cycles of wetting and drying and cement controlled the strain to 31%.

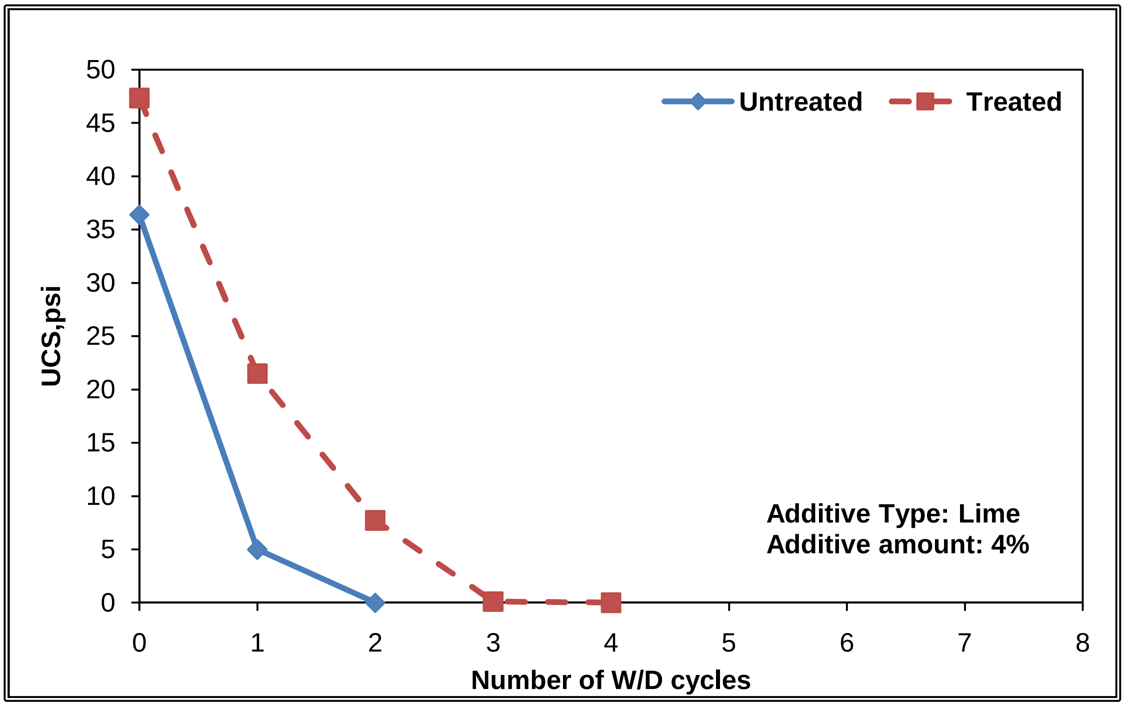


Figure 2.7 Changes in UCS with W/D Cycles for Lime Treated and Untreated Pharr-A Soil Specimens (Chittoori, 2008)

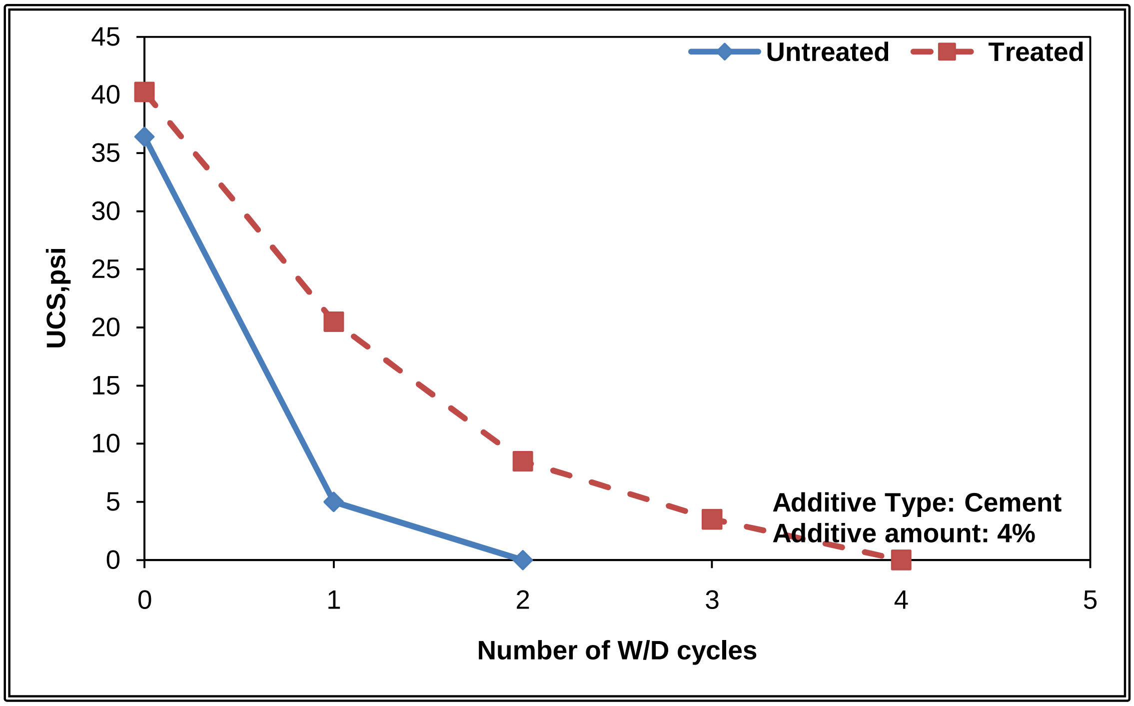


Figure 2.8 Changes in UCS with W/D Cycles for Cement Treated and Untreated Pharr-A Soil Specimens (Chittoori, 2008)

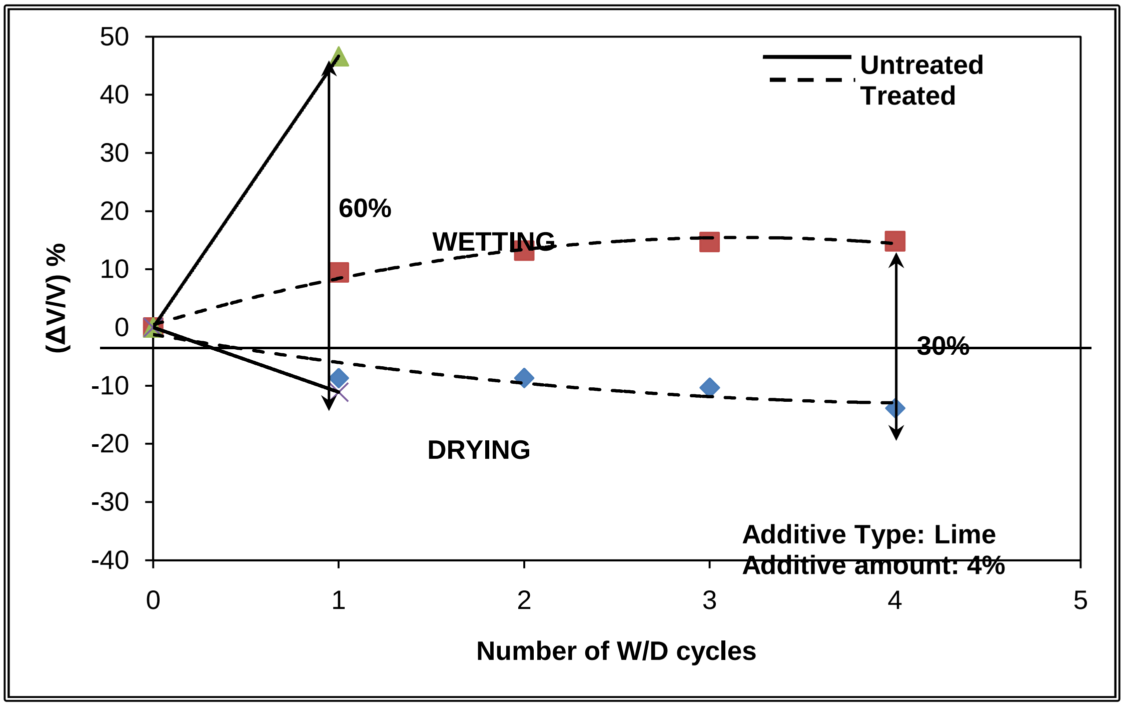


Figure 2.9 Volumetruc Changes with W/D Cycles for Lime Treated and Untreated Pharr-A Soil Specimens (Chittoori, 2008)

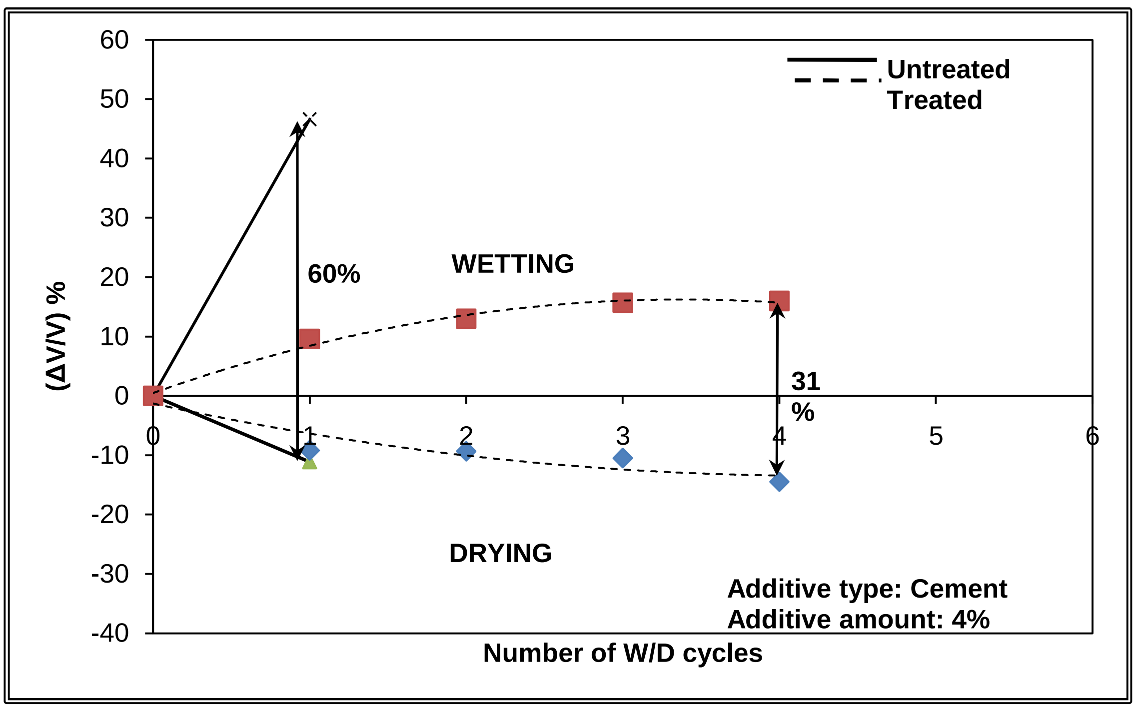


Figure 2.10 Volumetric Changes with W/D Cycles for Cement Treated and Untreated Pharr-A Soil Specimens (Chittoori, 2008)

Neither lime nor cement was able to stabilize the soil considerably as the volumetric strains were not within the threshold lime of 5% volumetric strain. Table 2.7 summarizes the number of cycles survived by each of the four soils with and without treatment.

Table 2.7 Number of Survivable Cycles for Treated and Untreated Soil Samples (Chittoori, 2008)

Soil	**Treatment**	**Number of Wetting/Drying Cycles Survived**		**% Mineral Montmorillonite**
		Untreated Soil	**Treated Soil**	
Pharr A	4% Lime	2	4	50
	4% Cement	2	4	
Pharr B	3% Lime	2	8	20
	3% Cement	2	15	
Austin	6% Lime	2	12	40
Fort Worth	6% Lime	1	11	60

2.5 Leachability Related Issues in Soil Stabilization

Another method of measuring the permanency of a stabilizer is to monitor the leachability of the soil specimen by monitoring moisture flows. Thompson (1968) observed that soil leaching has a direct influence on the properties such as soil pH, percentage base saturation and calcium/magnesium ratios and is directly related to the permeability of the soil. He stated that soil-lime reactivity decreases in areas of high permeability. In soils with very low permeability i.e. fine grained soils the leaching effects are minimized and hence maintaining the calcium/magnesium ratios and higher soil pH.

McCallister (1990) performed leachate tests on lime-treated clays in specially fabricated flexible cells for 45 to 90 days. Several variables including soil types, curing conditions and flow pressures were studied. The apparatus consists of a pressure cylinder, an acrylic cell to hold the sample in confinement. The leachate collected was collected based on the pore volume of the soil sample and tested for calcium and pH studies. This experiment simulates a field condition of a soil subjected to leachate after some time period. Figure 2.11 shows the leachate apparatus used by McCallister (1990) and Chittoori (2008).

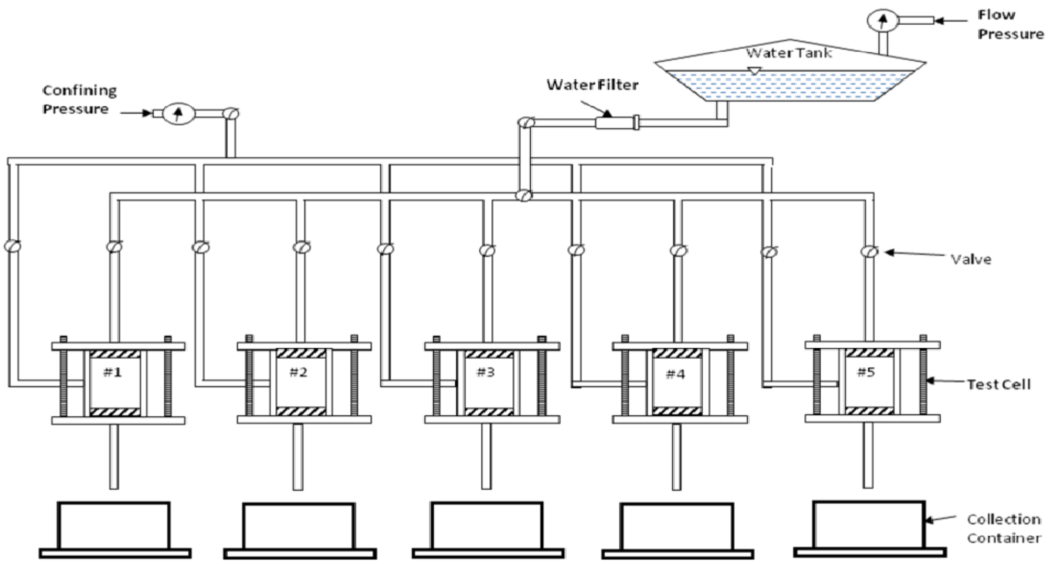


Figure 2.11 Schematic of Leachate Apparatus used by Chittoori (2008)

Few studies have been conducted on the leach test of chemically-treated soils to understand the leaching of chemicals from moisture flows (Barenberg, 1970; McCallister, 1990). Barenberg (1970) reported leach tests on lime, cement and fly ash-treated soil samples compacted at optimum moisture contents. Leach tubes of 2 ft long and 4 in. diameter were filled with chemically-treated soils that were subjected to water leaching at a rate comparable to the estimated local rainfall. The process was performed for ten days and the leachate and soil samples were then chemically analyzed. This analysis showed that small amounts of chemical stabilizer leached out during these tests.

Chittoori (2008) performed two series of moisture conditioning tests on highly expansive soils from various locations in Texas. The first test addresses issues correlating with rainfall infiltration whereas the second test observes the volumetric and strength changes of soil to evaluate the swell/shrink related volume changes during wetting and drying cycles from seasonal changes. Details and results of the second test conducted by Chittoori (2008) are discussed in Section 2.4. To address the first test, leachate samples were collected based on the pore volume of the sample and tested for pH and the presence of calcium ions, which explains the probable loss of stabilizer; an illustration of the leachate apparatus used is shown in Figure 2.12. Changes in pH were found to be minor and calcium ion concentrations were found to decrease over the course of 14 cycles of leaching. Table 2.8 summarizes the calcium concentration results of the four soils subjected to leachate studies.

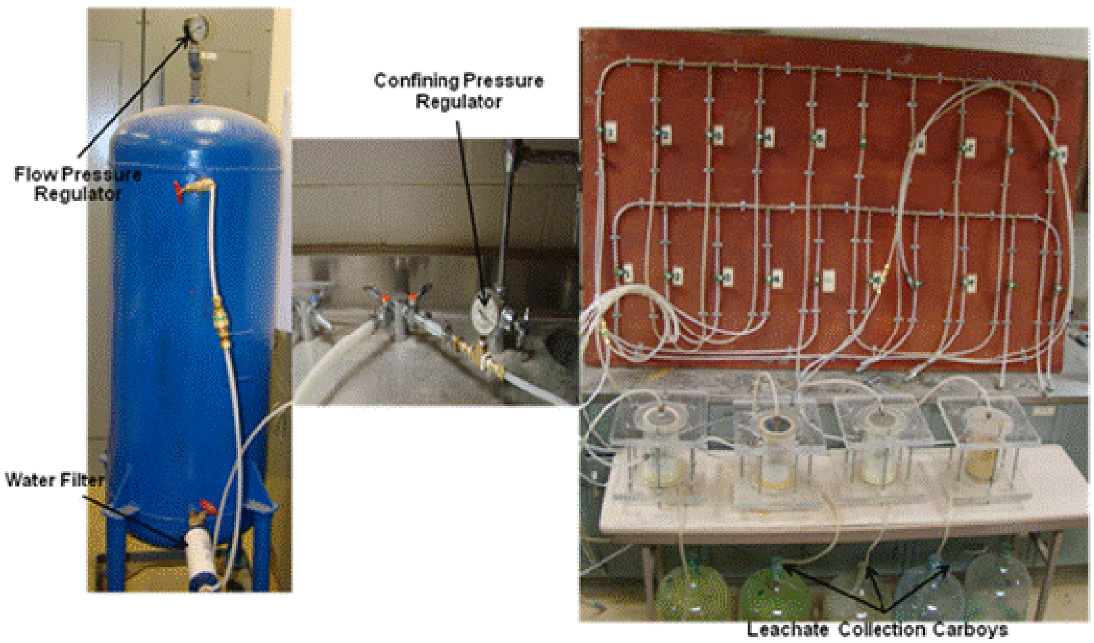


Figure 2.12 Leachate Studies Apparatus for Chittoori (2008)

Table 2.8 Calcium Concentrations of Soils Subjected to Leachate Studies (Chittoori, 2008)

Soil	Treatment	Initial Calcium Concentration (ppm)	Final Calcium Concentration (ppm)	Total Number of Cycles Studied
Pharr A	4% Lime	230	150	14
	4% Cement	310	200	14
Pharr B	4% Lime	200	200	14
	4% Cement	430	400	14
Austin	6% Lime	720	340	14
Fort Worth	6% Lime	560	400	14

2.6 Summary

This chapter reviewed the research conducted on expansive soils and their behavioral studies conducted by numerous researchers. Researchers' use of chemical additives have been looked into and assessed. Finally, the issues with respect to the loss of stabilizer and the durability of soils were discussed; the issues with conducting durability studies and leachate studies separately are detailed in the following chapter. The next chapter also details various test procedures and methods followed in the current research.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Introduction

The pipeline project under review entails the design and installation of a 147 mile pipe line under which varying geologic formations coincide. This research was conducted in two phases. The first phase was conducted by Karduri (2011) and focused on the selection and sampling of soils from multiple locations along the pipe line alignment; Figure 3.1 illustrates the locations, in brown, at which soil was collected. Locations are denoted with the letter B followed by a number; the B stands for Boring and the number provides a directional key. Various soil tests were performed for each boring location to address their reusability as bedding, zone or backfill materials. These tests included both basic and advance geotechnical testing.

Karduri (2011) found that most of the boring locations consisted of expansive clay minerals which is problematic and could result in heave related damage to pipe infrastructure; the only exceptions were B2 and B14. Table 3.1 summarizes the results of chemical tests performed. The results of these tests aided in determining which soils would be further analyzed during the second phase. Of the ten soils tested during the first phase, four soils were chosen to proceed to the second phase; this is illustrated in Table 3.2.

Table 3.1 Summary of Chemical Tests with Corresponding Mineral Percentages (Karduri, 2011)

Sample location ID	B1	B2	B4	B6	B7	B8	B9	B14	B15	B16
CEC, meq/100 g	85	13	96	99	116	112	88	59	93	154
SSA, m^2/g	250	26	192	141	318	195	164	77	138	168
TP, %	1.90	1.03	2.00	1.10	0.94	1.96	2.97	1.80	2.00	2.38
MM	35%	3%	37%	32%	56%	41%	33%	17%	45%	30%
Illite	32%	17%	33%	18%	16%	33%	50%	30%	40%	33%
Kaolinite	33%	80%	29%	50%	28%	27%	18%	53%	15%	36%

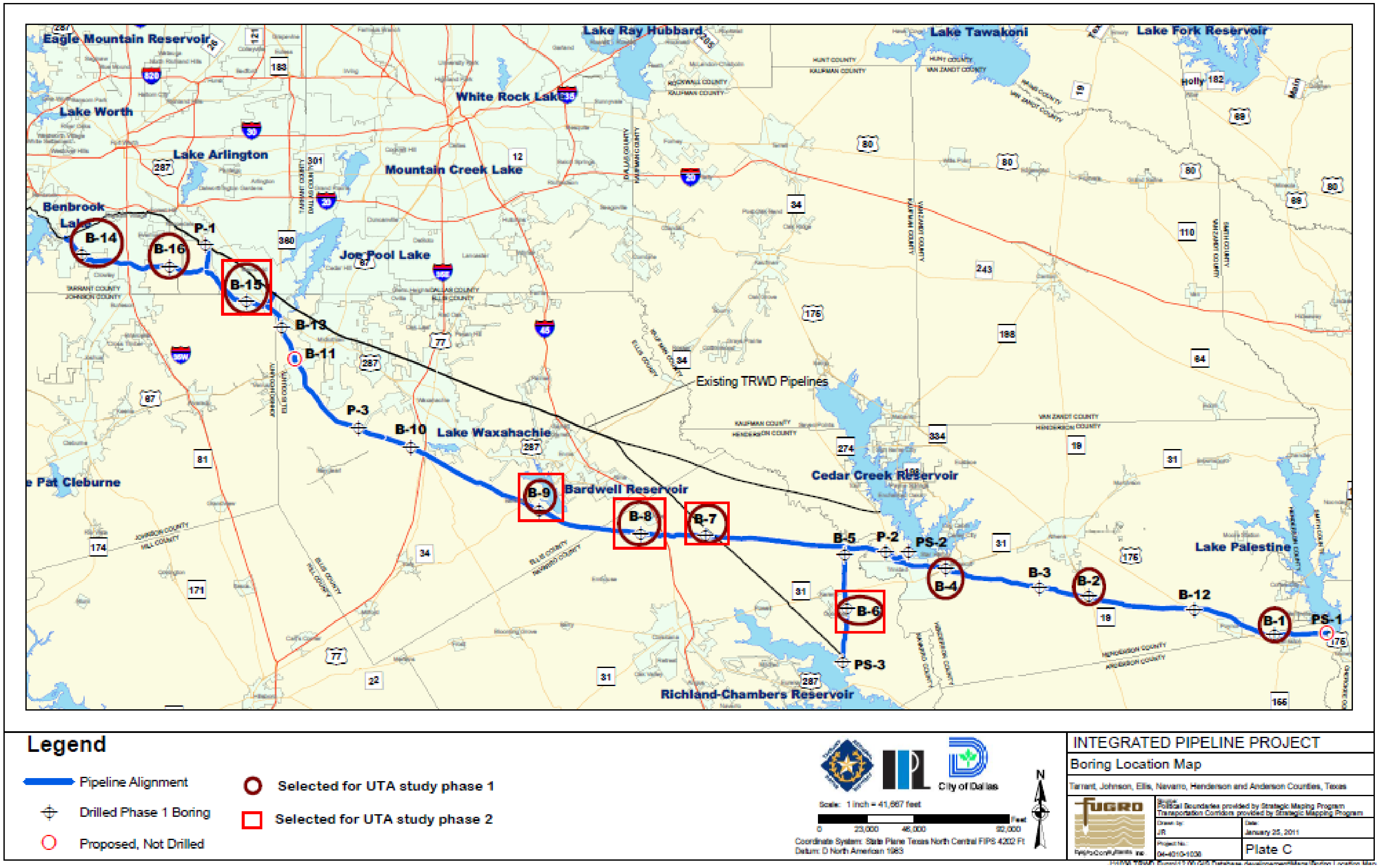


Figure 3.1 Boring Locations Along Pipe Line Alignment (Karduri, 2011)

The objective of phase two is to perform amendment studies on the selected soils, which includes the addition of chemical additives to soil samples. Additionally, whether or not the chemical treatment adjusts soils properties such that their use as bedding and/or zone materials is possible was examined. Mix designs were initially performed to determine the appropriate amount of chemical stabilizer needed for each soil type. Two types of chemical treatments were attempted in this study. One treatment uses lime as an additive while the second treatment uses both cement and fly ash additives in combinations. To assess the improvements chemical additives provide expansive soil, samples were prepared based on the developed mix designs and tested under moisture fluctuations (wetting/drying studies) and moisture infiltration (leachate studies) using a combined device. Typically the studies are conducted individually on separate samples, yet to use time and materials efficiently and effectively, a combined device was designed and assembled.

This chapter details the equipment used and test procedures conducted over the course of the research. Figures 3.2 and 3.3 illustrate the step by step process followed for each chemical treatment type.

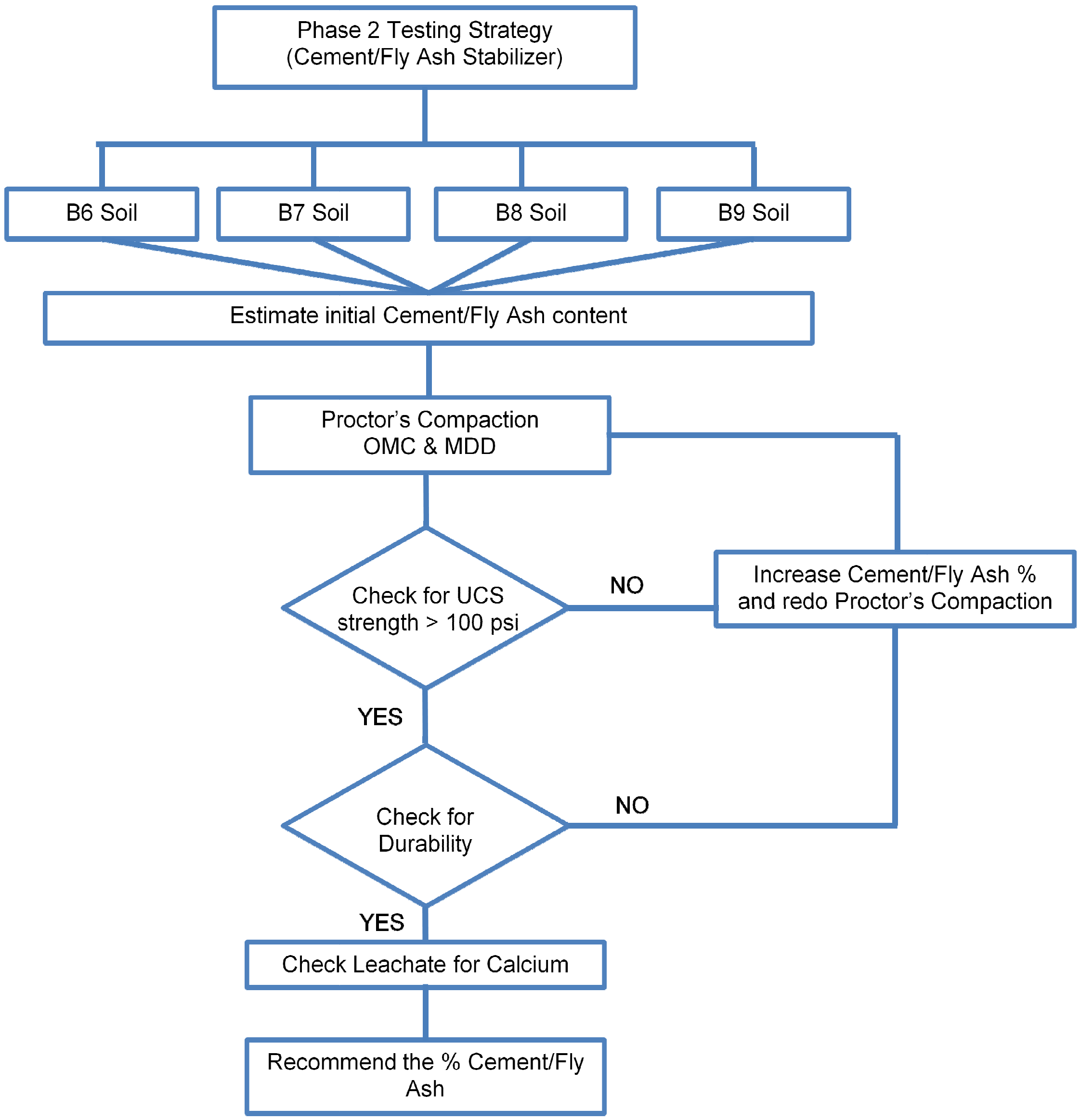


Figure 3.2 Experimental Program for Cement-Fly Ash Treatment of Subgrades

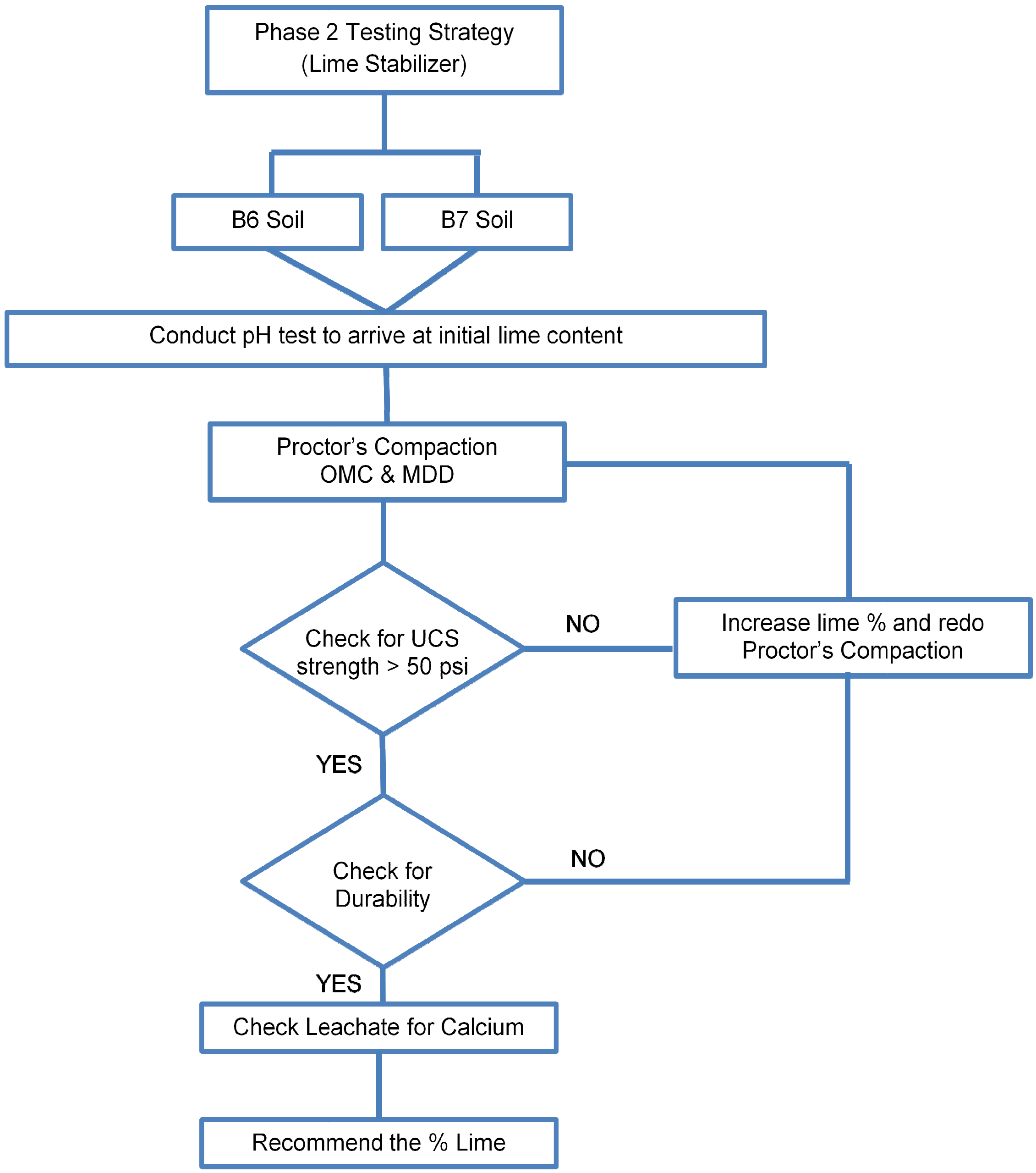


Figure 3.3 Experimental Program for Lime Treatment of Subgrades

3.2 Tests Conducted on Untreated Soils

3.2.1 Grain Size Distribution

Soils vary in particle or grain sizes; they can be coarse, fine, or in-between. In order to classify a soil, it is important to know its grain size distribution. Sieve analysis is typically used for coarse grained soils, whereas hydrometer analysis is generally used for fine grained soils.

3.2.1.1 Sieve Analysis

Sieve analysis is conducted according to TxDOT's Tex-110-E method. Other procedures are available; for example, ASTM (2010) standard C 136 and AASHTO (2007) standard T 27. Soil is dried and well-pulverized prior to passing it through a stack of progressively finer sieves with a pan at the bottom. The amount of soil retained on each sieve is measured and the cumulative percentage of soil passing each sieve is determined-percent finer. Soil particles remaining in the pan, or passing sieve No. 200, is further analyzed with hydrometer analysis.

3.2.1.2 Hydrometer Analysis

Hydrometer analysis is conducted according to TxDOT's Tex-110-E method. Other procedures are available; for example, ASTM (2010) standard D 422 and AASHTO (2009) standard T 88. This method of determining the grain size distribution differs from the previous in that it is based on the principle of sedimentation of soil particles in water. Fifty grams of dry soil is mixed with a deflocculating agent, typically hexametaphosphate at 125 cc of 4% solution, for 16 hours. Distilled water is added, the mixture is agitated and transferred to a graduated cylinder and filled with water to the 1000-ml mark. A hydrometer is placed in the cylinder to measure the specific gravity of the suspended soil particles.

3.2.2 Atterberg Limits

The water content of the soil plays an important role in its plasticity. When clayey soil is mixed with excessive water, it can become a semi-liquid. If the soil is steadily dried, depending on its moisture content, it will behave like a plastic, semisolid, or solid material. To determine the water content boundaries between these states, it is important to perform Atterberg limits. These boundaries are known as shrinkage limit (SL), plastic limit (PL) and liquid limit (LL); they divide the soil states in the following order: dry, semi-solid, plastic, and liquid. Of the three states, LL and PL are the most crucial factors; the mathematical difference in these values is known as plasticity index (PI). PI characterizes the plasticity of soil numerically. The higher the PI, the more plastic the soil is.

Cassagrande developed a LL device in which the LL cup lifts and drops 10 mm on a hard rubber plastic base (ASTM D-4318). The number of blows, the goal is 25 blows, is counted until the groove, made by a grooving tool, closes a distance of 13 mm (1/2 in); this determines the moisture content within the soil. Typically the test is performed 2 to 3 times, as 25 blows is hard to achieve the first time. Therefore one point above and below is found and the moisture content is interpolated at 25 blows.

The test to determine the PL is subjective to the user in that it requires practice for consistent results. It is defined as the moisture content at which the soil crumbles when rolled into a thread of 3.18 mm (1/8 in) in diameter. ASTM D-4318 provides a detailed procedure.

3.2.3 Standard Proctor Compaction

Compaction moisture content and dry unit weight relationships of the soils were determined by conducting Standard Proctor compaction tests in the present research program. Standard Proctor compaction tests are necessary to conduct on soils because it establishes compaction relationships. The optimum moisture content of the soil is the water content at which the soils were compacted to a maximum dry unit weight condition. Specimens exhibiting a high compaction unit weight are best in supporting civil infrastructure since the void spaces are minimal and settlement is less. Tex-114-E procedure was followed to determine the optimum moisture content and maximum dry density of the control soil, as well as treated soil specimens.

3.2.4 Summary of Untreated Soil Tests

Untreated soil tests were conducted on ten soils during Phase 1 of the project. Table 3.2 below presents a summary of the tests performed. Although many locations required treatment, not all were chosen to proceed to Phase 2; treated soil tests have been conducted only on the four highlighted soils.

Table 3.2 Summary of Basic Soil Tests Conducted

Site Location	Grain Size Analysis				Atterberg's Limits			Soil Classification	Standard Proctor	
	Sieve Analysis		Hydrometer		LL (%)	PL (%)	PI (%)		MDD (pcf)	OMC (%)
	%G	%S	%Si	%C						
B1	1	51	20	28	38	15	23	SC	116.8	15.4
B2	0	58	32	10	Non Plastic			SM	120.3	11.2
B4	1	32	51	16	30	19	11	CL	115.0	13.0
B6	0	22	62	16	40	14	26	CL	108.1	16.2
B7	0	12	78	10	82	20	62	CH	95.5	22.8
B8	0	14	66	20	49	15	34	CL	89.8	18.1
B9	0	45	37	18	53	16	37	CH	102.1	19.0
B14	12	25	61	2	42	19	23	CL	112.3	15.0
B15	0	5	31	64	66	23	43	CH	96.8	21.0
B16	0	14	43	43	52	22	31	CH	105.0	16.5

3.3 Tests Conducted on Treated Soils

3.3.1 Mix Designs

The primary objective of a stabilizer mix design is to establish an optimum dosage of stabilizer. This is typically accomplished by assessing the engineering properties of a soil mix after each dosage of stabilizer is added; essentially, it is a trial and error procedure by varying the concentration of the additive till an appropriate improvement in the soil is observed. Optimizing engineering properties is one of many benefits to performing mix designs because it mitigates cracking and premature failures.

Mix designs were developed for both types soil treatments used in this project. Each type of stabilizer requires a different approach to achieve its optimum dosage. The following sections detail the procedures followed for arriving at the optimum dosage.

3.3.1.1 Cement-Fly Ash

Unlike lime, cement and fly ash stabilization is not as common. There is no pH test, or a similar test procedure, to determine the amount of additive to add to a particular soil. The minimum amount of stabilizer required to stabilize the soil was solely based on literature research-what other researchers found to be effective.

A trial and error procedure was used. Specimens were prepared for a specific dosage and then tested for unconfined compressive strength. If the soil specimen did not achieve the minimum strength requirement, in this case it is 70 to 150 psi, a new dosage was determined and retested. Once strength requirements are achieved, specimens are prepared for durability studies, which are discussed in the following sections.

3.3.1.2 Lime

The minimum amount of stabilizer required to stabilize the soil is based on the pH. The Eades and Grim test was typically performed in accordance with Tex-121-E method. Lime dosages in the order of 0, 2, 4, 6, 8 and 10% are added to 20 grams of air dried soil passing No. 40 sieve. The lime treated soil samples are then transferred into a 250 ml plastic bottle and then 100 ml distilled water free of carbon-di-oxide (CO_2) is added to these mixtures. The samples are then shaken in an Eberbach shaker for a minimum of 30 seconds. This process of shaking is repeated every 10 minutes and is continued for at least one hour to ensure proper mixing of the binder and soil. The sample is then removed from the shaker and the pH was measured using the pH meter.

After determining the optimum dosage of stabilizer using the above procedure, the soil specimen was then subjected to proctor compaction test to determine the optimum moisture content for that dosage. This was followed by the preparation of soil specimen as discussed in the following section. The soil specimen is ready for testing after it is cured. If the specimen meets strength requirements, soil specimens can be prepared for durability studies. The samples were cured for 7 days in a wet room where the relative humidity was maintained at 100%. The target strength for these samples was between 70 to 150 psi.

3.3.2 Sample Preparation for UCS Testing and Durability Studies

In the current research, static compaction method was followed for specimen preparation as per the procedure outlined in Wanyan et al. (2008). A static compactor, suggested in the AASHTO T-307 for preparing fine-grained soil specimens, was used. With this method, specimens with targeted moisture and density levels can be prepared in a short time. The steps involved in preparing a soil specimen are as follows:

1. The required material to make a soil specimen is calculated based on the desired dry density, degree of compaction and optimum moisture content.
2. A metal mould used to prepare the specimen is cleaned and lubricated for ease of extraction of the soil specimen.
3. Two cylindrical blocks one at the top and the other at the bottom were placed in order to compact the soil specimen.
4. The soil specimen is compacted by a force applied on the top surface and is finished when the top of the block is flush with the mould.
5. After 1 minute the same procedure is repeated by reversing the direction of application of load. A thicker block replaces the old one.
6. The load is applied on the top of this block till the desired height of the soil specimen is achieved.
7. At the end, the blocks are removed and the sample is extruded from the mould with the help of a hydraulic jack.

Detailed procedural steps are shown in Figure 3.4.

(a) (b)

(c) (d) (e)

Figure 3.4 Showing sample preparation procedure (a) Prepared soil mixture (b) Soil filled into the mould (c) Soil is being compacted (d) Extraction of soil sample using a hydraulic jack (e) Extracted soil specimen

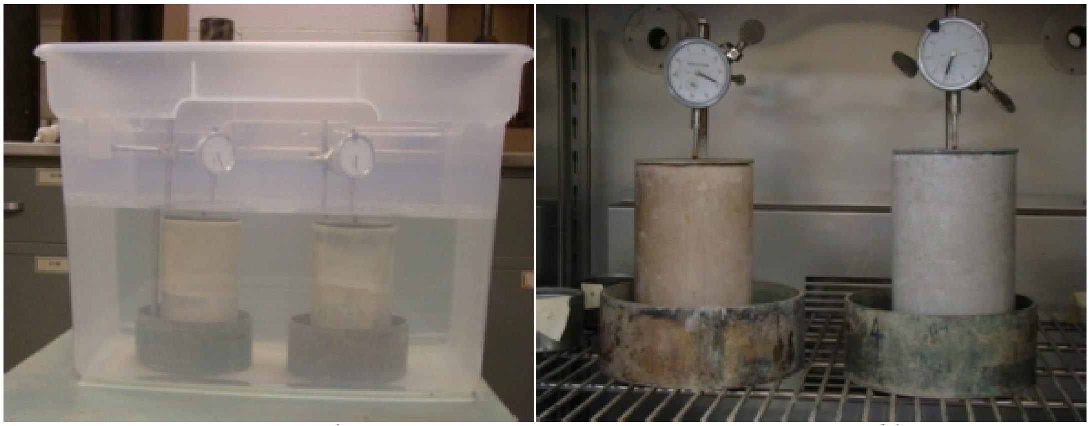
3.3.3 *Durability Studies*

Durability studies were conducted by subjecting the soil specimens to alternative wetting and drying processes. The standard method used to conduct these wet/dry cycle study is ASTM D 559. It is in this research that a modified approach is used. In both approaches, the volumetric strain, strength and stiffness parameters are studied during select cycles. Identification of these properties helps to understand how the soil responds to the stabilizing additive and its dosage. The following sections explain the standard test procedure and the modified test procedure.

3.3.3.11 Standard Approach

3.3.3.1.1 Wetting/Drying Procedure

The wetting and drying of soil specimens are typically carried out on the basis of ASTM D 559. This method simulates field conditions, similar to that of wetting and drying conditions, within a short period of time. According to the ASTM D 559 method the prepared soil specimens are cured and then submerged in water for 5 hours and then oven dried at 160ºF for 42 hours to complete one wetting/drying cycle. The soil specimens are studied for volumetric change measurements before and after the completion of wetting/drying cycles. Dial gauges and pi tape are used to measure the vertical deformations and the diametrical changes respectively. Dial gauge readings are monitored to assess the effectiveness of stabilization with time. The soils were subjected to unconfined compressive strengths at 0, 3 and 14 cycles of wetting/drying. The test is continued until 14 wetting/drying cycles are completed or until the sample fails. Figure 3.5 (a) shows how the specimen is submerged in the water and Figure 3.5 (b) shows the specimen being dried in an oven.



(a) (b)

Figure 3.5 (a) Wetting of Soil Specimen (b) Drying of Soil Specimen

After the desired number of wetting and drying cycles, the soil specimens were subjected to unconfined compressive strength (UCS) as discussed in one of the following sections.

3.3.3.1.2 Leachate Studies

Leachate studies were introduced by McCallister (1990) to address the permanency of chemical stabilization from water percolating through a soil specimen from rainfall and moisture migration. The setup used in the previous research is similar to the one used by McCallister (1990) and Chittoori (2008).

The lime and cement + fly ash treated soil specimens were prepared after the soil sample was cured for 24 hours in a humidity room. The prepared soil specimen was then cured for seven days before subjecting them to leachate studies; the leachate collection setup is shown in Figure 3.6. The cured soil specimen was subjected to moisture flow from a water tank at a constant head. Preliminary tests were conducted to finalize the pressures to be applied to the water flow. These pressures differed from soil to soil as the goal is to complete one leaching cycle in one day. One leaching cycle here is defined as the amount of leachate volume collected that is equal to one soil specimen’s void volume. Specimen void volume can be defined as the total voids/pores (air voids + water voids) present in a compacted specimen. The leachate collected is then studied for calcium concentrations.

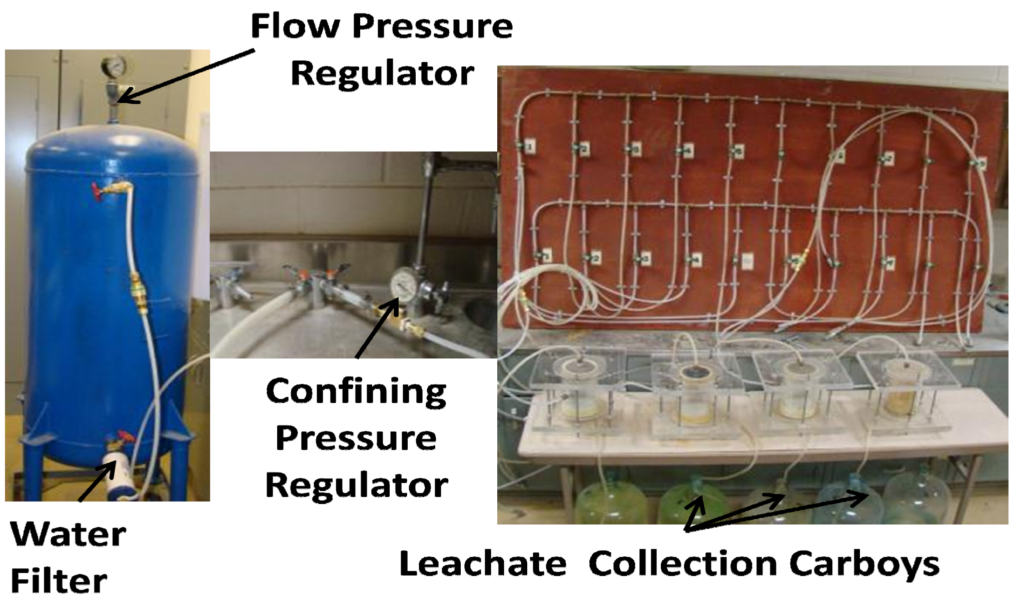


Figure 3.6 Leachate Studies

3.3.3.2 Modified Approach

A new device was developed in this research study. This device combines the wetting/drying and leachate studies into a single test, versus two separate tests. Combining the two tests alleviates the time required for leachate collection. Rather than waiting over 24 hours to reach the pore volume of the sample, it can take as little as 4 or 5 hours. Another advantage to a joint setup is that only one sample is required. Previously, a sample would be prepared for wetting/drying cycles and another sample, with the same properties as the first, is prepared for the leachate studies. This allows for a more efficient and effective use of material and time.

Figure 3.7 and 3.8 shows schematics of the plan view and elevation of the equipment with corresponding dimensions and Figure 3.9 shows the completed combined device.

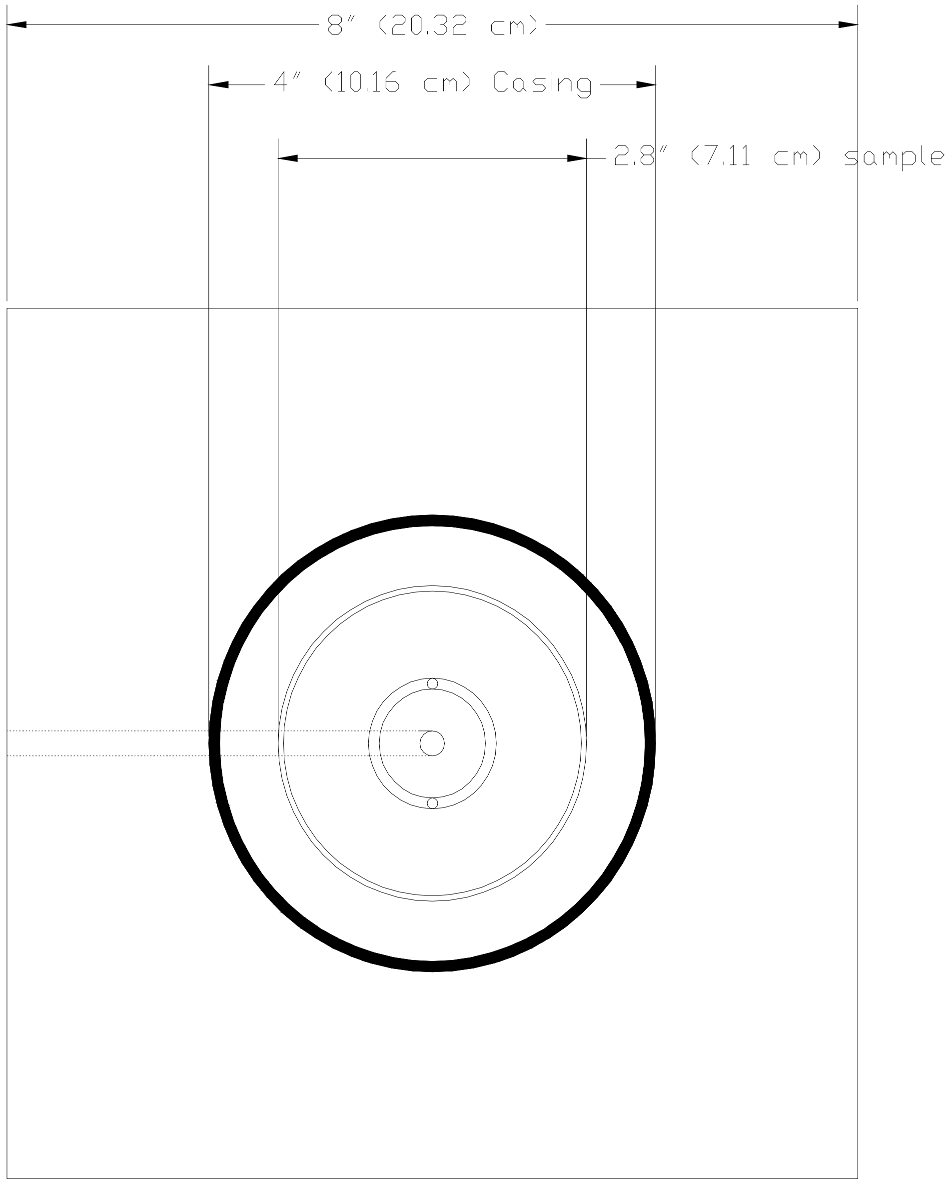


Figure 3.7 Schematic Showing Plan View of the Combined Device

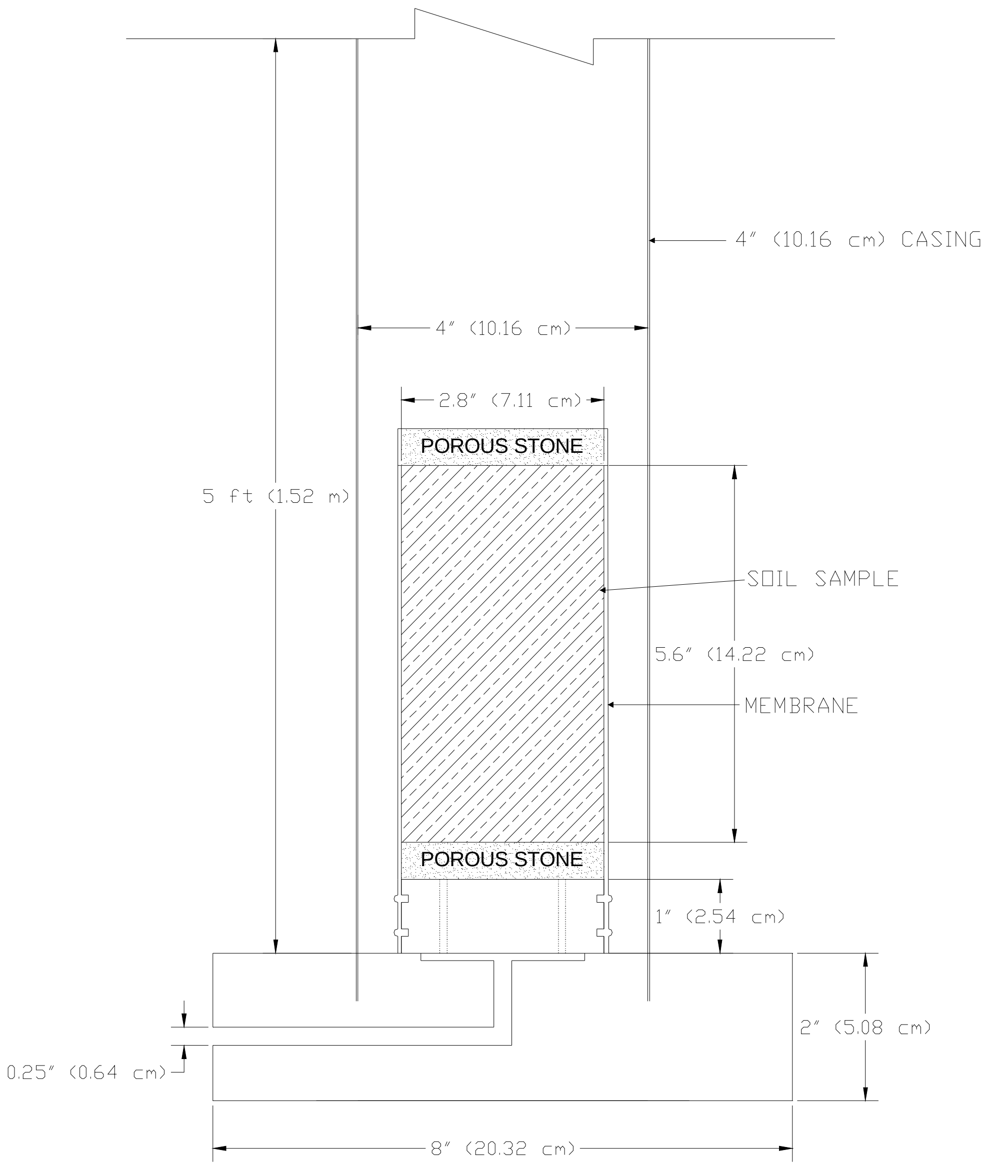


Figure 3.8 Schematic Showing Elevation View of the Combined Device

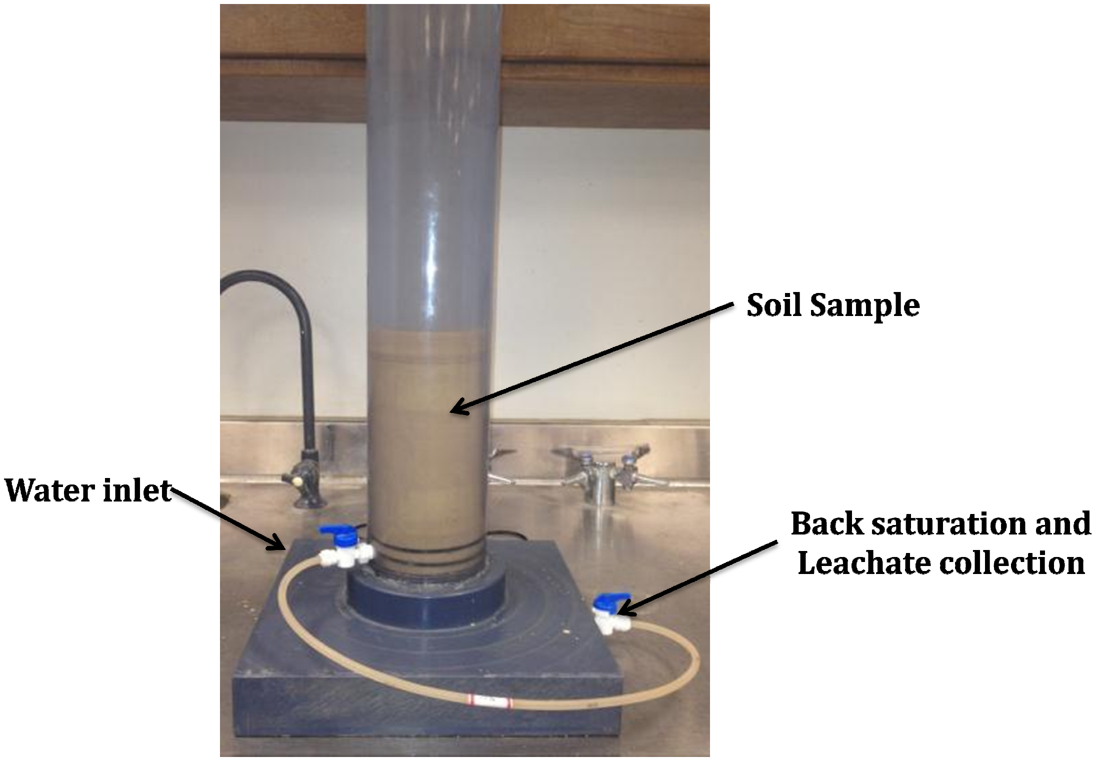


Figure 3.9 Combined Device

Although a new setup was used to conduct the studies, the studies itself are performed in a similar fashion. Samples are still prepared according to the ASTM D 559 method; the prepared soil specimens are cured and then submerged in water for 5 hours and then oven dried at 160ºF for 42 hours to complete one wetting/drying cycle. Volumetric change measurements are recorded both before and after the completion of wetting/drying cycles with the use of dial gauges and pi tape to measure the vertical deformations diametrical changes respectively.

Leachate is collected through the outlet located at the bottom of the base after the specimen has undergone a wetting cycle. Collection occurs after a certain number of wetting/drying cycles are completed. For instance, a three cycle sample will collect leachate on its first and third cycle. A trend is then developed between the collected leachate after calcium concentration tests are performed-more information regarding calcium determination is detailed in the following section.

The soils are then subjected to unconfined compressive strengths at 0, 3 and 14 cycles of wetting/drying. Studies are continued until 14 wetting/drying cycles are completed or until the sample fails.

3.3.4 Calcium Determination by EDTA Method

Leachate collected from each soil specimen is subjected to calcium tests after the completion of the desired number of cycles. A small sample representative, 25 mL, of the collected leachate is taken and placed in a Erlenmeyer flask. The contents of a Calver2 Calcium Indicator pillow packet is poured into the flask and swirled around. If the solution turns blue immediately, no further action is necessary. Whereas, if the solution turns violet upon addition of the Calver2, TitraVer Hardness Titrant is added slowly until the solution turns blue. A flowchart detailing the procedure of determining calcium in a leachate solution is shown in Figure 3.10.

The start point and end point of the titrant is noted. The difference in these numbers provides the amount of titrant required to reach the solutions endpoint. A multiplier is applied to convert the mL to mg/L of Calcium. Furthermore, this number is converted to ppm of stabilizing agent leached out.

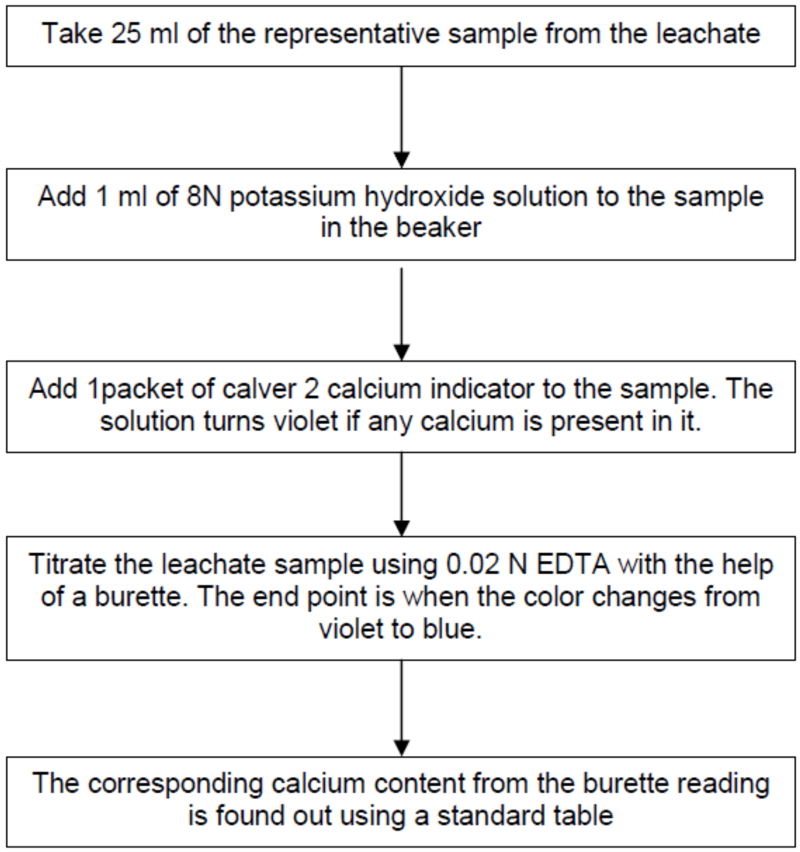
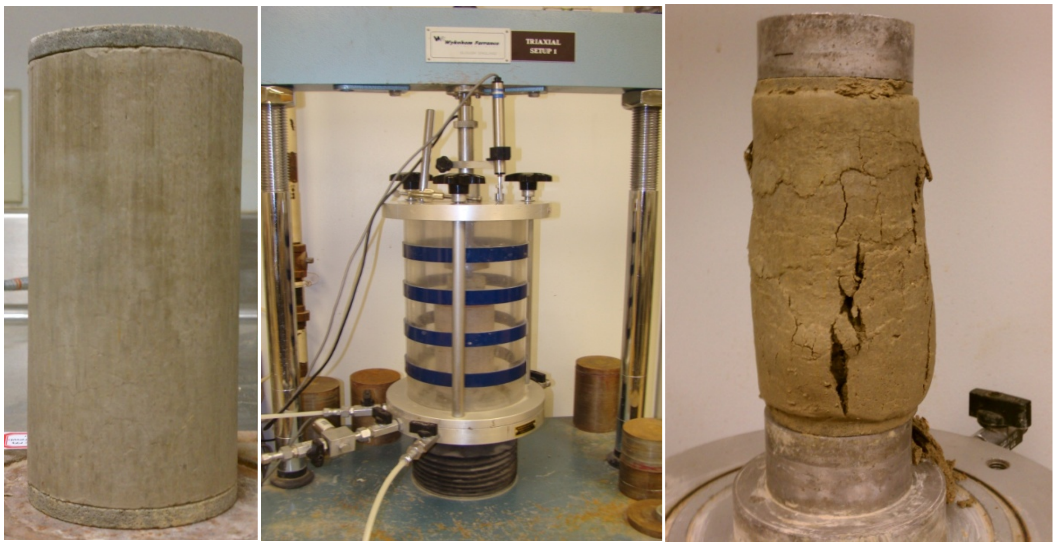


Figure 3.10 Leachate Calcium Concentration Determination Flowchart

3.3.5 Unconfined Compressive Strength Test

Unconfined compressive strength (UCS) tests were carried out on untreated as well as treated soil specimens. All the soil specimens were 5.6 inches (142 mm) in height and 2.8 inches (71 mm) measured diametrically. After the desired number of wetting/drying cycles, the soil specimen is placed on a platform and then raised at a constant strain rate, using the controls of the UCS set up, until it comes in contact with the load cell as shown in the Figure 3.11 (b). Once the specimen is loaded at a constant strain rate of 1.27 mm/sec, and as the load approaches the ultimate load, failure cracks begin to appear on the surface of the soil specimen as shown in Figure 3.11 (c). Deformation and corresponding axial loads of the soil specimen are recorded using the data acquisition system features.



(a) (b) (c)

Figure 3.11 (a) Prepared Soil Sample (b) Test Equipment (c) Failed Specimen

3.4 Summary

In this chapter, test procedures followed in the present research to determine the engineering properties of both control and treated soils are described. Standard and modified durability test procedures, which replicate the moisture fluctuations in the field during summer and rainy seasons, are explained and leachate test procedures, following the simulation of moisture infiltration from rain fall events, are presented. Additionally, the procedure to find the calcium concentrations from a given leachate sample is described in detail with the help of a flow chart.

A comprehensive analysis of durability test results obtained from the above mentioned tests that were conducted on the four selected soils for the long-term performance of stabilized soils is presented in the following chapter.

CHAPTER 4

STABILIZATION DESIGN AND COMBINED DURABILITY STUDIES

4.1 Introduction

This chapter presents the test results and comprehensive analyses of the studies conducted as a part of phase two of the IPL pipeline project. This phase of the study consists of performing stabilization design on the four soils selected based on the phase 1 results presented in Karduri (2011). Stabilization design was attempted using two types of chemical treatments namely lime and cement-fly ash (CFA). The lime stabilization studies used quick lime or Calcium Oxide (CaO) as a standalone additive while CFA stabilization studies used different combinations of cement and fly ash, as stabilization by using cement as a standalone is very expensive while stabilization by using fly ash as a standalone though less expensive requires large amounts of fly ash (usually > 15% by dry weight of soil) due to low calcium content relative to cement and lime. Hence, a combination of cement and fly ash is selected in this research. Both lime and CFA stabilizations were conducted on all four selected soils following the procedures explained in chapter 3. An important part of any stabilization design is to verify the long-term effectiveness of the stabilization. This is especially important in this research as the treated soil will be used as bedding and haunch layers for a pipeline typically designed for 100 year life and any loss in strength of these bedding and haunch layers during this period can damage the pipe and hinder its intended purpose. To address this aspect of the research combined durability studies are conducted as per the procedure outlined in chapter 3.

Durability studies are generally conducted in two stages, stage 1 consists of replicating the volumetric changes that occur due to moisture ingress and digress and this process is imitated by conducting wetting/drying studies in the laboratory as explained in chapter 3. The second stage consists of replicating the rainfall infiltration which can sometimes leach the additive and reduce soil strength; this process is replicated in the laboratory by conducting leachate studies as explained in chapter 3. Typically these two stages are conducted on two separate samples following the procedures explained in chapter 3. However, in this research, rather than using the conventional method where two separate samples are prepared for each stage of durability, a modified approach was developed and implemented. The modified approach uses a combined device; combined meaning that both wetting/drying cycles and leachate collection can be performed on the same soil specimen, thus effectively and efficiently using time and materials.

The standard and modified approaches were compared using B6 soil treated with lime; it can be seen from Figure 4.1 that the modified approach performed well in comparison to the standard approach. Hence the modified approach was adopted for this study.

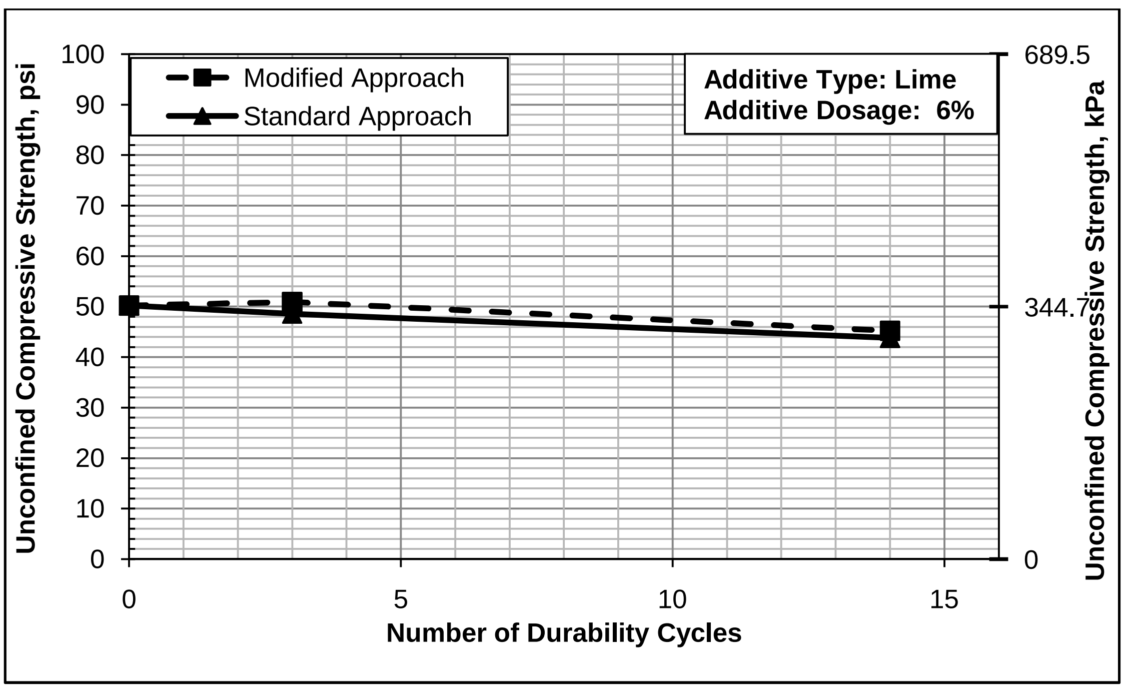


Figure 4.1 Comparison of Standard Approach and Modified Approach with B6 Lim Treated Soil Specimens

Treated soil specimens underwent wetting/drying cycles mainly to simulate the seasonal moisture fluctuations that can occur as the seasons change. Several studies have been performed in the past regarding wetting/drying cycle tests that address the durability issues and performance of stabilizers in arid conditions where moisture fluctuations are likely to occur. For instance, studies conducted by McCallister, 1990; Hoyos, et al. (2005) and Chittoori (2008) were reviewed in order to understand the conventional approach and develop a test protocol to follow that could best replicate field environmental conditions in arid environments such as north Texas. This test procedure was used to study the effectiveness of both chemical treatments and to ensure that they provide durable stabilization under seasonal moisture fluctuations. Details of the test procedures followed in this research study were discussed in Chapter 3.

Leachate collections were completed for the same treated soil specimens, in the same device, to examine the permanency of the additives by observing the leaching of chemical stabilizer through moisture movements. The loss of chemical stabilizers may have serious implications on the durability and sustainability of the chemical treatment. Chemical stabilizers can be lost due to seasonal changes and runoff flow conditions. Previous studies report that the leaching caused by moisture flows in soils result in variations of pH and Calcium ions (McCallister, 1990). Chittoori (2008) addressed the permanency of chemical stabilization due to moisture flows during rainfall events and ground water flows by modifying the size of the soil specimen (6 in. diameter in place of 8 in. diameter) in the test protocol established by McCallister (1990). This test utilizes a flexible wall mold that housed a compacted stabilized soil specimen, which can be seen in Figure 2.12. After reviewing studies conducted by McCallister (1990) and Chittoori (2008), a combined device was designed and developed to decrease the amount of material required for sample preparation and to reduce the time involved in conducting both parts of durability studies individually.

Test results corresponding to the stabilizer mix design for each of the four selected soils, the soils behavior to fluctuations in moisture and temperature before and after the chemical treatments, and the analysis of these results are presented in the following sections.

4.2 Selected Soils and Stabilizer Mix Design

Preliminary tests were conducted on the four selected soils to obtain their gradation curves, maximum dry densities, optimum moisture contents and plasticity indices; the results of these tests are presented in Table 4.1. It can be observed from the table that the soils are low to high compressible soils with plasticity index values ranging from 26 to 62 indicating medium to high expansiveness. These soils, if used in the pipe bedding or haunch regions, can cause excessive swelling pressures in the presence of water and damage the pipe, hence stabilization design was performed for these soils.

Table 4.1 Summary of Basic Soil Tests Conducted

Site Location	Grain Size Analysis				Atterberg's Limits			Soil Classification	Standard Proctor	
	Sieve Analysis		Hydrometer		LL (%)	PL (%)	PI (%)		MDD (pcf)	OMC (%)
	%G	%S	%Si	%C						
B6	0	22	62	16	40	14	26	CL	108.1	16.2
B7	0	12	78	10	82	20	62	CH	95.5	22.8
B8	0	14	66	20	49	15	34	CL	89.8	18.1
B9	0	45	37	18	53	16	37	CH	102.1	19.0

Stabilizer mix design was performed on these soils as per the current TxDOT stabilizer design procedures (Figure 2.1), which are explained in Chapter 2. An iterative procedure was employed where an additive percentage that met the initial strength requirements as per TxDOT standards as explained in chapter 3 was subjected to durability studies to check if it would satisfy the long-term stabilization criterion (as explained in chapter 3). If the current additive percentage did not satisfy the long-term criterion, a new mix design with increased additive percentage was conducted and the durability process is repeated. The additive percentage that satisfied the long-term criterion was finally recommended.

Table 4.2 presents the different stabilizer percentages on each of the soils for both treatment types for all four soils studied in this research.

Table 4.2 Summary of Chemical Stabilizer Type and Dosage for Each Site Location

Site Location	USCS Classification	Plasticity Index (%)	Additive Type	Additive Amount (% by Weight)
B6	CL	26	Lime	6%
			Cement-Fly Ash	3%C-6%FA
				3%C-10%FA
B7	CH	62	Lime	8%
			Cement-Fly Ash	3%C-6%FA
				3%C-10%FA
B8	CL	34	Cement-Fly Ash	3%C-10%FA
B9	CH	37	Cement-Fly Ash	3%C-10%FA

4.3 Cement-Fly Ash Studies

4.3.1 Mix Design

Mix designs for cement-fly ash studies were conducted based on a trial and error procedure as no preliminary tests, similar to Eades and Grimm procedure for lime, is available to determine the required dosages. Specimens were prepared for an initial mix design and then tested for unconfined compressive strength. Once the soil specimen achieved the minimum strength requirements, in this case it is 70 to 150 psi, soil specimens are prepared for durability studies at their respective optimum moisture content (OMC) and maximum dry density (MDD). The OMC and MDD of the soil samples varied for each site location and chemical treatment. Table 4.3 shows the variation of the physical properties of each site location-OMC and MDD.

Table 4.3 Variation of OMC and MDD of Cement-Fly Ash Treated Soil Specimens

Site Location	Additive	OMC (%)	MDD (pcf)
B6	3%Cement+6%Fly Ash	16	110.2
	3%Cement+10%Fly Ash	17	105.6
B7	3%Cement+6%Fly Ash	18	107.0
	3%Cement+10%Fly Ash	18.7	99.8
B8	3%Cement+10%Fly Ash	19.4	100.7
B9	3%Cement+10%Fly Ash	18.5	104.6

4.3.2 Combined Durability Studies

This section presents the results obtained from the durability studies conducted on all four soils using combinations of cement and fly ash as a stabilizer. Each mix design was subjected to 14 durability cycles, except for the ones that failed before 14 cycles. During these cycles the soil samples are monitored for volumetric change by measuring the height and diameter of the sample at the end of the cycle along with the sample weight. The soil samples were tested for unconfined compression strength at 0, 3 and 14 cycles. Also, calcium loss in the soil sample was determined by collecting leachate samples at the end of selected wetting cycle. A leachate sample volume equal to the pore volume of the soil sample is collected to ensure that all the pores are filled with water as explained in chapter 3.

Figure 4.2 and 4.3 present photographs during different durability cycles for untreated and 3% cement-6% fly ash treated B7 soil samples respectively. These photographs are typical of the state of the soil samples as they undergo the durability process. As observed from Figures 4.2 (c) and 4.3 (c), large amounts of volume changes have occurred in the sample and the sample is close to failure. In this case, the cement-fly ash treated samples could last longer (11 cycles of wetting drying) than the untreated soils, which lasted only one cycle.

(a) (b)

(c)

Figure 4.2 Untreated B7 Soil Specimen at (a) Prepared (b) Drying Cycle and (c) Wetting Cycle

(a) (b)

(c)

Figure 4.3 3% Cement-6% Fly Ash Treated B7 Soil Specimen (a) Initial (b) 3 Cycles (c) 11 Cycles

The following sections present the data with respect to the changes in volume, weight, strength and calcium content obtained during the durability studies for each of the four soils studied in this research.

4.3.2.1 Volumetric Strain Changes

Swell and shrink characteristics of clays are best studied when soil specimens are subjected to alternate wetting and drying. Diameter and height changes were recorded before and after the wetting or drying cycles and were measured using a pi-tape or veneer caliper respectively. Volumetric strain changes were based on the changes in both diameter and height. Furthermore, the maximum volumetric strain is a combination of the percent change for wetting and drying of one cycle of durability; this means that the drying (negative) is subtracted from the wetting (positive) to get the total change (wetting-(-drying) = total volumetric strain change).

4.3.2.1.1 B6 Soil

B6 soil has a PI of 26 - a moderately high plasticity. To counteract the plasticity and the expansive nature of the soil, two mix designs (3% cement and 6% fly ash; 3% cement and 10% fly ash) were evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results of both mix designs are presented in Figure 4.4 and 4.5.

The control B6 soil survived for only one cycle of durability with a maximum volumetric strain of 30.21%. To alleviate the expansive nature of this particular site location, an initial mix design (3% cement and 6% fly ash) was tested. B6 soil treated with 3% cement and 6% fly ash survived for 11 cycles of wetting and drying with a maximum volumetric change of 14.85%. Though the volumetric strain of the initial mix design is substantially lower, the total swell and shrink volume magnitudes are still considered problematic. Therefore a second mix design was established to further minimize the swell/shrink potential of the soil; B6 soil treated with 3%

cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum volumetric change of 2.08%.

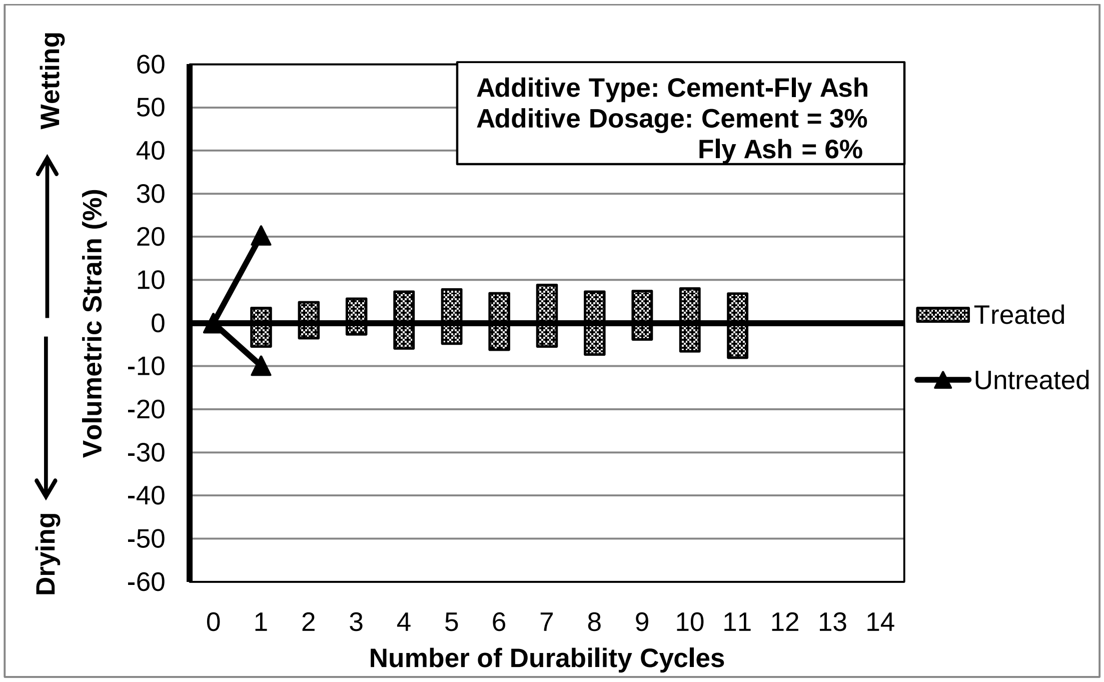


Figure 4.4 Volumetric Strain for 3% Cement and 6% Fly Ash Treated B6 Soil Specimen

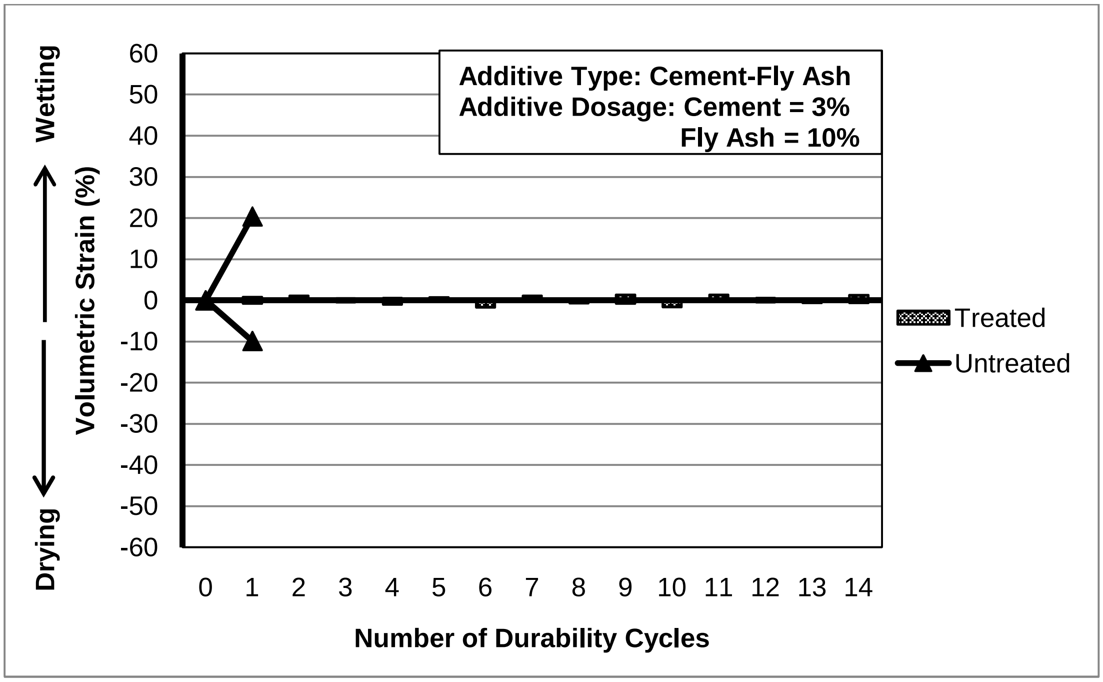


Figure 4.5 Volumetric Strain for 3% Cement and 10% Fly Ash Treated B6 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A considerable decrease in the volumetric strain was noticed for the B6 soil treated with 3% cement and 10% fly ash; the soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 2.08%.

4.3.2.1.2 B7 Soil

B7 soil has a PI of 62 - a very high plasticity. To offset the plasticity and the expansive nature of the soil, two mix designs (3% cement and 6% fly ash; 3% cement and 10% fly ash) were evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results of both mix designs are presented in Figure 4.6 and 4.7.

The control B7 soil survived for only one cycle of durability with a maximum volumetric strain of 75.72%. To improve the expansive nature of this particular site location, an initial mix design (3% cement and 6% fly ash) was tested. B7 soil treated with 3% cement and 6% fly ash survived for 4 cycles of wetting and drying with a maximum volumetric change of 20.67%.

Though the volumetric strain of the initial mix design is substantially lower, the total swell and shrink volume magnitudes are still considered problematic. Therefore a second mix design was established to further minimize the swell/shrink potential of the soil; B7 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum volumetric change of 3.66%.

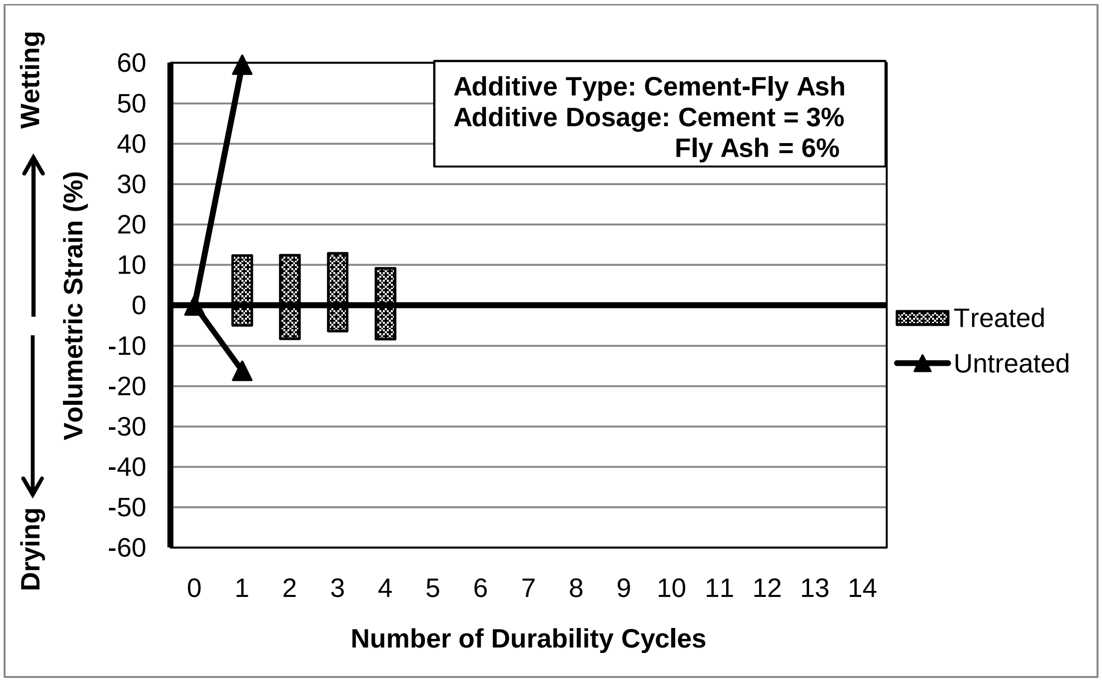


Figure 4.6 Volumetric Strain for 3% Cement and 6% Fly Ash Treated B7 Soil Specimen

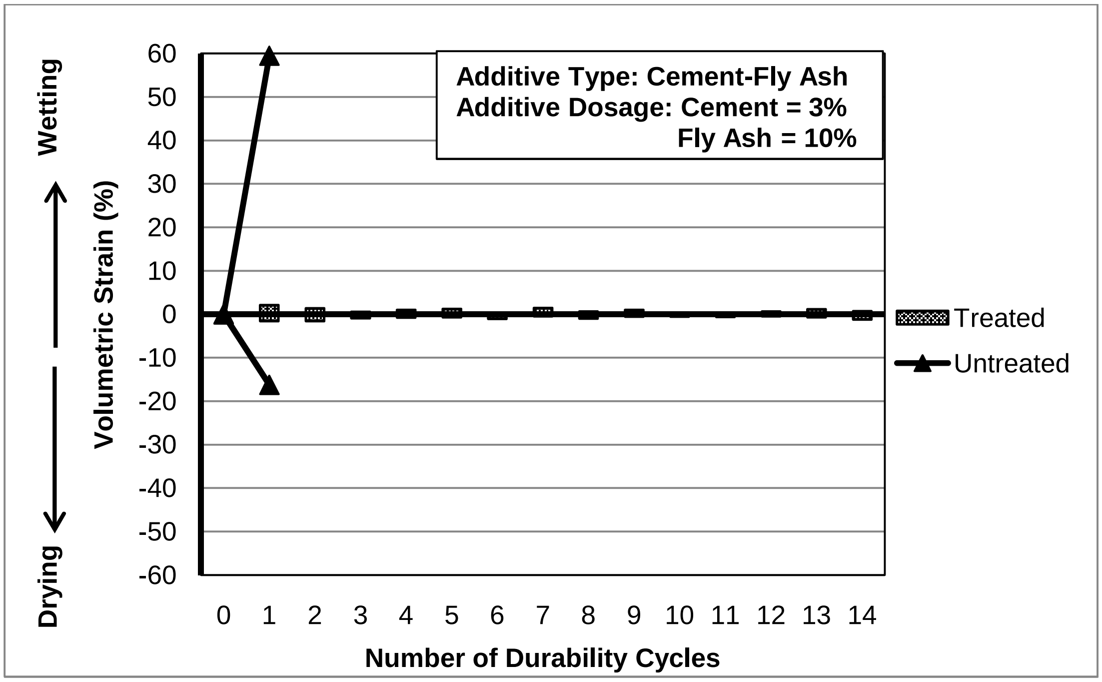


Figure 4.7 Volumetric Strain for 3% Cement and 10% Fly Ash Treated B7 Soil Specimen

Cement-fly ash stabilization proved to be successful on the prepared soil specimen to withstand the durability cycles. A substantial decrease in the volumetric strain was noticed for the B7 soil treated with 3% cement and 10% fly ash; the soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 3.66%.

4.3.2.1.3 B8 Soil

B8 soil has a PI of 34 - a moderately high plasticity. To counterbalance the plasticity and the expansive nature of the soil, 3% cement and 10% fly ash treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results are presented in Figure 4.8.

The control B8 soil survived for only one cycle of durability with a maximum volumetric strain of 73.49%. B8 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum volumetric change of 6.19%.

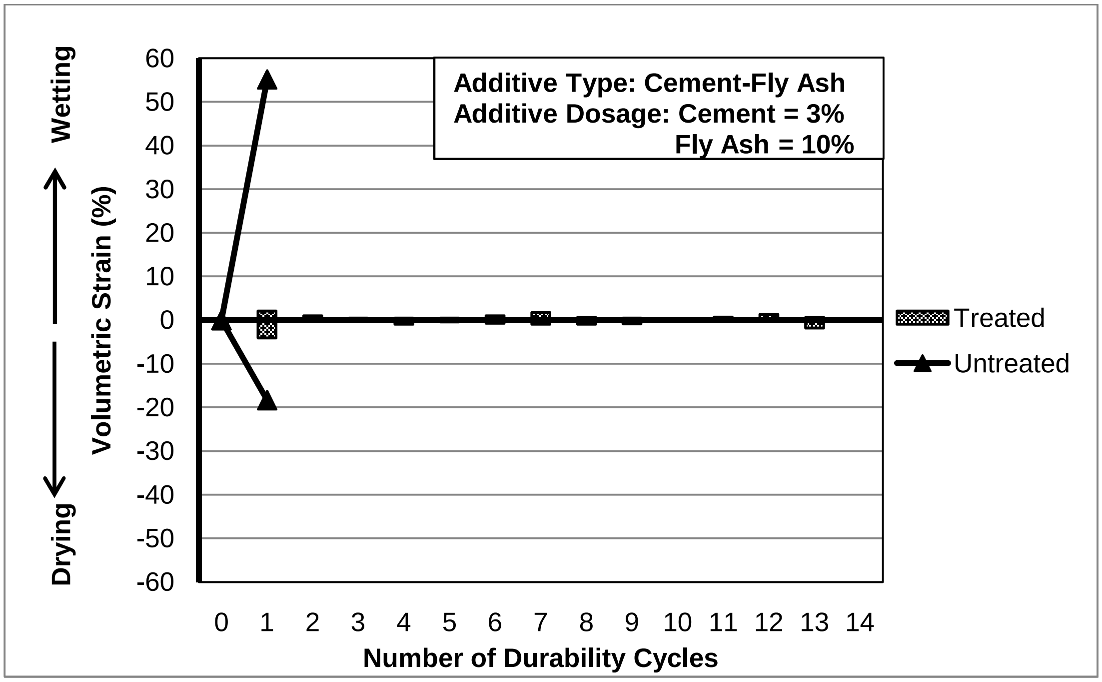


Figure 4.8 Volumetric Strain for 3% Cement and 10% Fly Ash Treated B8 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A substantial decrease in the volumetric strain was noticed for the B8 soil. The cement-fly ash treated soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 6.19%.

4.3.2.1.4 B9 Soil

B9 soil has a PI of 37 - a high plasticity. To counteract the plasticity and the expansive nature of the soil, 3% cement and 10% fly ash treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results are presented in Figure 4.9.

The control B9 soil survived for only one cycle of durability with a maximum volumetric strain of 62.11%. B9 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum volumetric change of 3.15%.

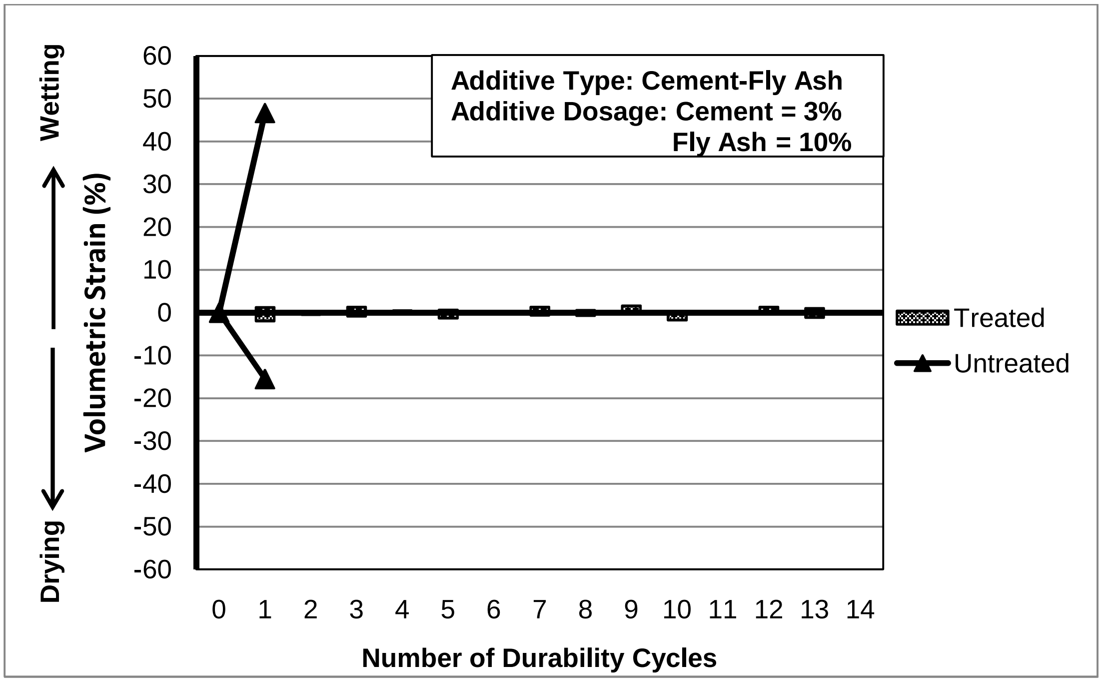


Figure 4.9 Volumetric Strain for 3% Cement and 10% Fly Ash Treated B9 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A significant decrease in the volumetric strain was noticed for the B9 soil. The cement-fly ash treated soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 3.15%.

4.3.2.2 Sample Weight Changes

As previously mentioned, subjecting clay soils to alternate wetting and drying cycles is the best way to study the soil's swell and shrink characteristics. In addition to diameter and height measurements, changes in weight were recorded before and after the wetting or drying cycles and were measured using a weigh scale. Values found as a result of fluctuations in the weight of a sample supplement the volumetric changes with respect to mix design decisions; B6 and B7 soils required a new cement-fly ash mix design to address the high volumetric strain and weight change. Furthermore, the maximum weight change is a combination of the percent change for wetting and drying of one cycle of durability; this means that the drying (negative) is subtracted from the wetting (positive) to get the total change (wetting-(-drying) = total sample weight change).

4.3.2.2.1 B6 Soil

B6 soil has a PI of 26 - a moderately high plasticity. To counteract the plasticity and the expansive nature of the soil, two mix designs (3% cement and 6% fly ash; 3% cement and 10% fly ash) were evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Sample weight changes were recorded; the results of both mix designs are presented in Figure 4.10 and 4.11.

As previously mentioned, the control B6 soil survived for only one cycle of durability with a maximum sample weight change of 38.00%. To alleviate the expansive nature of this particular site location, an initial mix design (3% cement and 6% fly ash) was tested. B6 soil treated with 3% cement and 6% fly ash survived for 11 cycles of wetting and drying with a maximum weight change of 46.34%. The weight change of the initial mix design did not reduce the total swell and shrink volume magnitudes; they are still considered problematic. Therefore a second mix design was established to minimize the swell/shrink potential of the soil; B6 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum weight change of 13.24%.

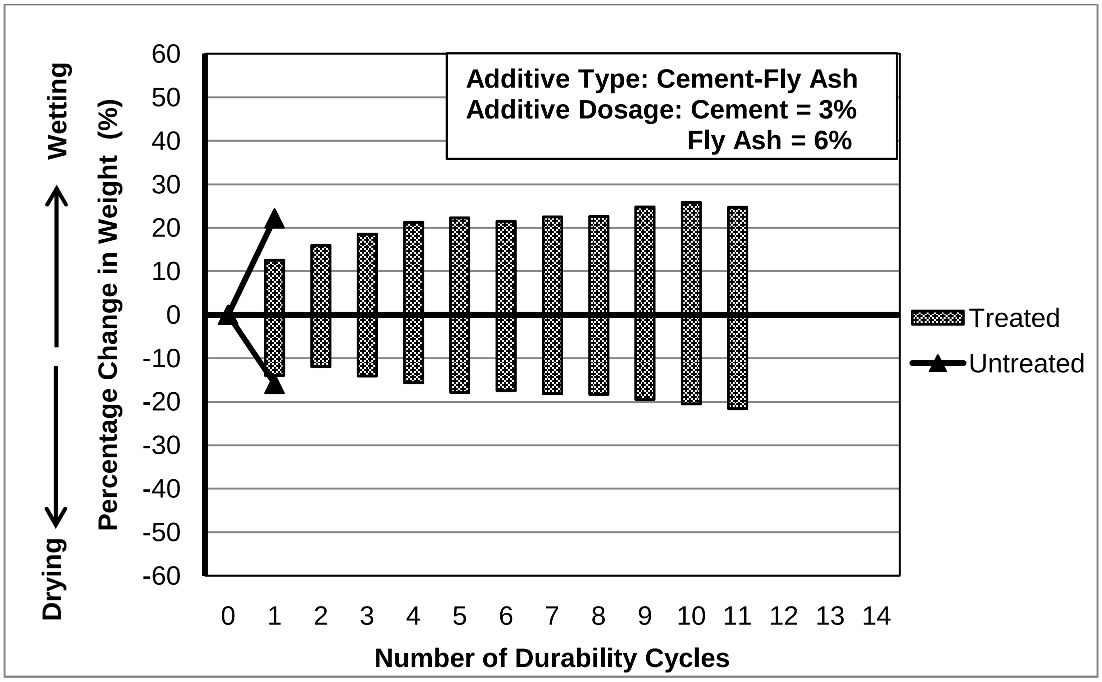


Figure 4.10 Sample Weight Changes for 3% Cement and 6% Fly Ash Treated B6 Soil Specimen

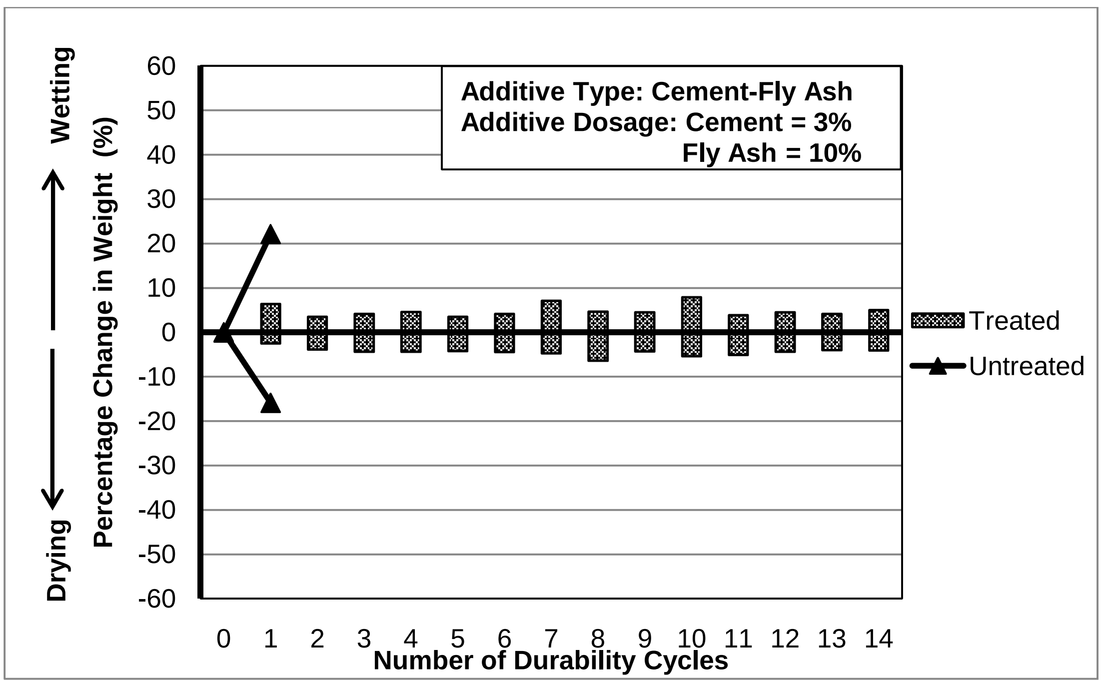


Figure 4.11 Sample Weight Changes for 3% Cement and 10% Fly Ash Treated B6 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A considerable decrease in the weight change was noticed for the B6 soil treated with 3% cement and 10% fly ash; the soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 13.24%.

4.3.2.2.2 B7 Soil

B7 soil has a PI of 62 - a very high plasticity. To offset the plasticity and the expansive nature of the soil, two mix designs (3% cement and 6% fly ash; 3% cement and 10% fly ash) were evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results of both mix designs are presented in Figure 4.12 and 4.13.

As previously mentioned, the control B7 soil survived for only one cycle of durability with a maximum sample weight change of 72.01%. To improve the expansive nature of this particular site location, an initial mix design (3% cement and 6% fly ash) was tested. B7 soil treated with 3% cement and 6% fly ash survived for 4 cycles of wetting and drying with a maximum weight change of 47.33%. Though the sample weight change of the initial mix design is substantially lower, the total swell and shrink volume magnitudes are still considered problematic. Therefore a second mix design was established to further minimize the swell/shrink potential of the soil; B7 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum weight change of 13.52%.

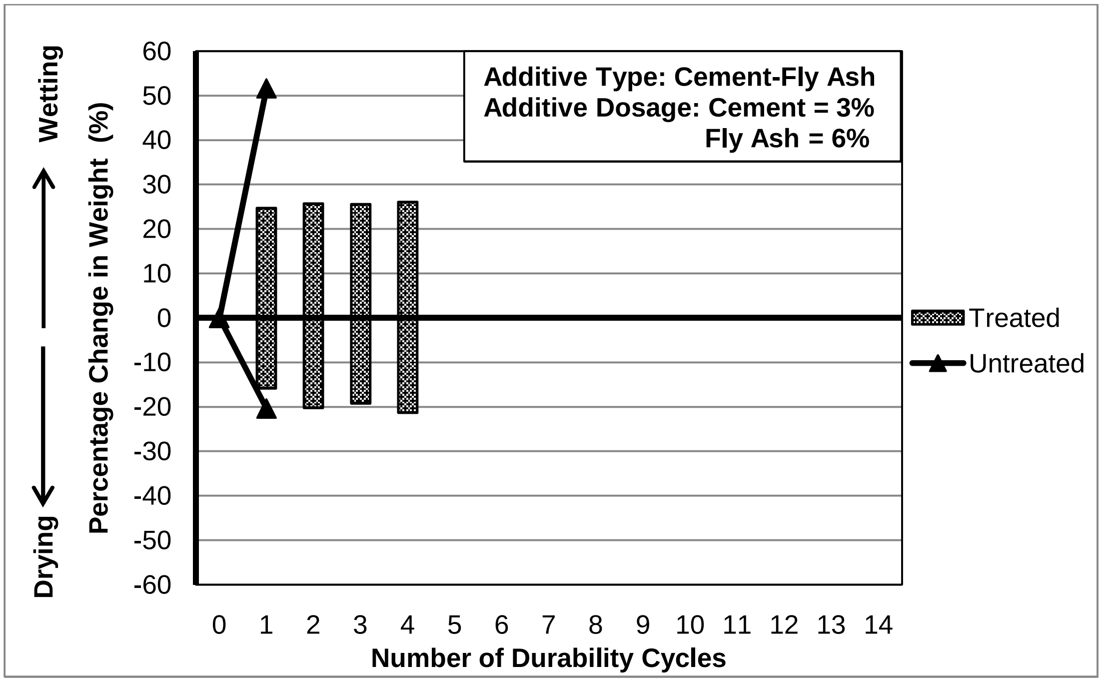


Figure 4.12 Sample Weight Changes for 3% Cement and 6% Fly Ash Treated B7 Soil Specimen

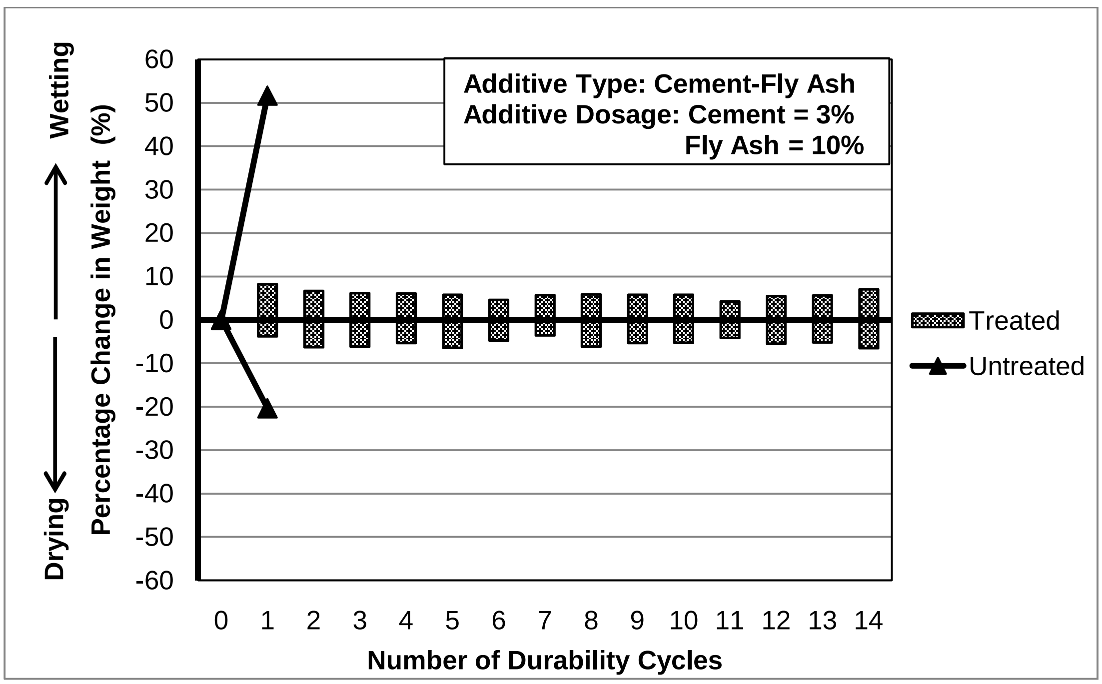


Figure 4.13 Sample Weight Changes for 3% Cement and 10% Fly Ash Treated B7 Soil Specimen

Cement-fly ash stabilization proved to be successful on the prepared soil specimen to withstand the durability cycles. A substantial decrease in the weight change was noticed for the B7 soil. The cement-fly ash treated soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 13.52%.

4.3.2.2.3 B8 Soil

B8 soil has a PI of 34 - a moderately high plasticity. To counterbalance the plasticity and the expansive nature of the soil, 3% cement and 10% fly ash treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Sample weight changes were recorded; the results are presented in Figure 4.14.

The control B8 soil survived for only one cycle of durability with a maximum weight change of 56.02%. B8 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum weight change of 14.70%.

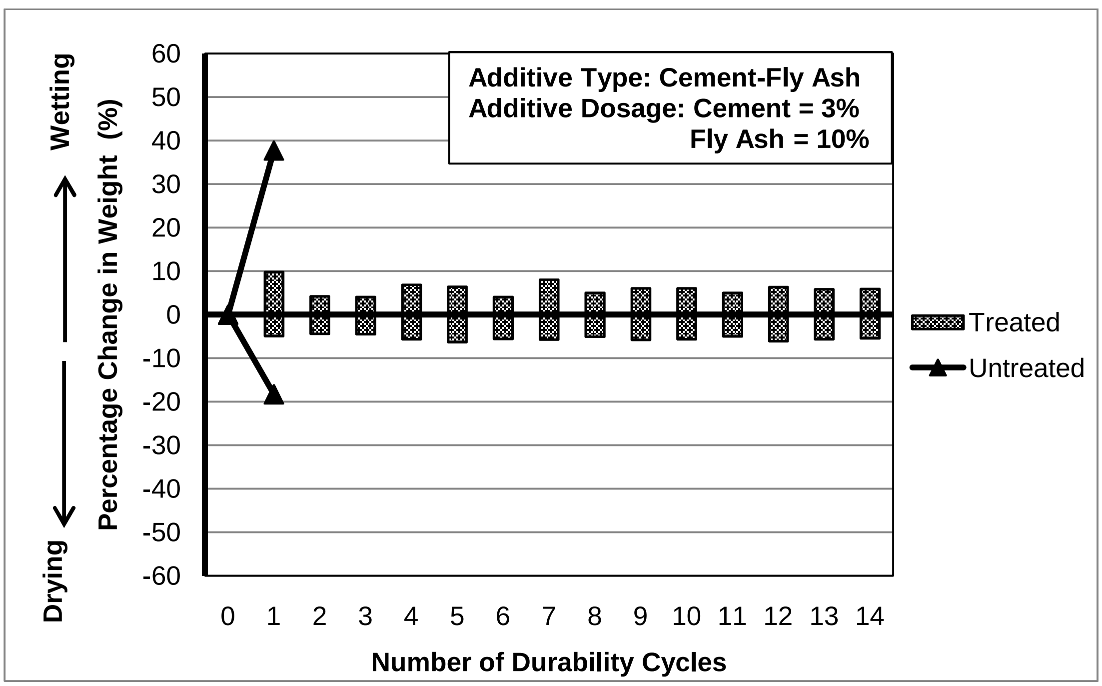


Figure 4.14 Sample Weight Changes for 3% Cement and 10% Fly Ash Treated B8 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A substantial decrease in the weight change was noticed for the B8 soil. The cement-fly ash treated soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 14.70%.

4.3.2.2.4 B9 Soil

B9 soil has a PI of 37 - a high plasticity. To counteract the plasticity and the expansive nature of the soil, 3% cement and 10% fly ash treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Sample weight changes were recorded; the results are presented in Figure 4.15.

The control B9 soil survived for only one cycle of durability with a maximum weight change of 59.18%. B9 soil treated with 3% cement and 10% fly ash survived for 14 cycles of wetting and drying with a maximum weight change of 11.55%.

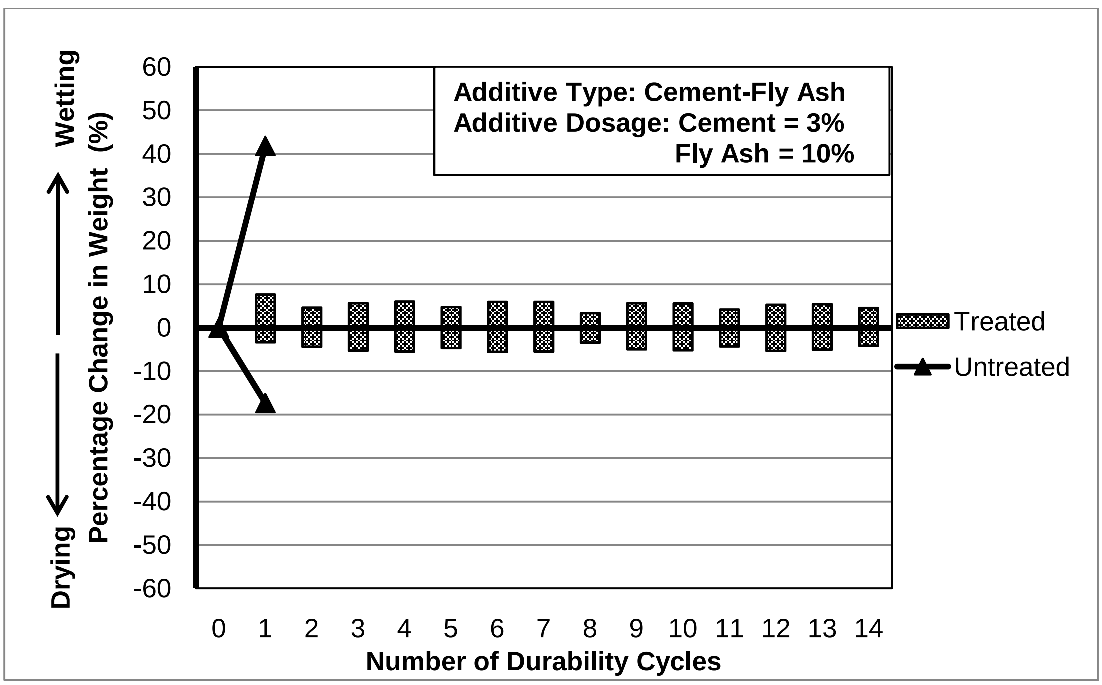


Figure 4.15 Sample Weight Changes for 3% Cement and 10% Fly Ash Treated B9 Soil Specimen

Cement-fly ash stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A significant decrease in the weight change was noticed for the B9 soil. The cement-fly ash treated soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 11.55%.

4.3.2.3 Leachate Calcium Concentration

Leachate samples collected from each of the soil specimens at different cycles of durability were studied for calcium concentrations. One full leachate cycle is defined as the time required to collect one pore volume of leachate through the soil specimen; the time typically varied due to a changing pore volume. The procedure used for determining the calcium concentration of a prepared soil specimen by EDTA was provided in Chapter 3. The concentration of calcium in ppm was determined and plotted against durability cycles to study the variation of calcium leaching out during each cycle. The results obtained from all tests on each site location are presented in Figures 4.16 through 4.19.

B6 soil had a plasticity index (PI) of 26 and was classified as a low compressible clay (CL). The soil was treated with 3% cement-10% fly ash. Figure 4.16 presents the calcium ion concentration changes versus the number of durability cycles of B6 cement-fly ash treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 150 ppm, which reduced to 70 ppm at higher number of cycles. Thus a difference of 80 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

B7 soil had a plasticity index (PI) of 62 and was classified as a high compressible clay (CH). The soil was treated with 3% cement-10% fly ash. Figure 4.17 presents the calcium ion concentration changes versus the number of durability cycles of B7 cement-fly ash treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 150 ppm, which reduced to 95 ppm at higher number of cycles. Thus a difference of 55 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

B8 soil had a plasticity index (PI) of 34 and was classified as a low compressible clay (CL). The soil was treated with 3% cement-10% fly ash. Figure 4.18 presents the calcium ion concentration changes versus the number of durability cycles of B8 cement-fly ash treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 120 ppm, which reduced to 45 ppm at higher number of cycles. Thus a difference of 75 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

B9 soil had a plasticity index (PI) of 37 and was classified as a high compressible clay (CH). The soil was treated with 3% cement-10% fly ash. Figure 4.19 presents the calcium ion concentration changes versus the number of durability cycles of B9 cement-fly ash treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 350 ppm, which reduced to 170 ppm at higher number of cycles. Thus a difference of 180 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

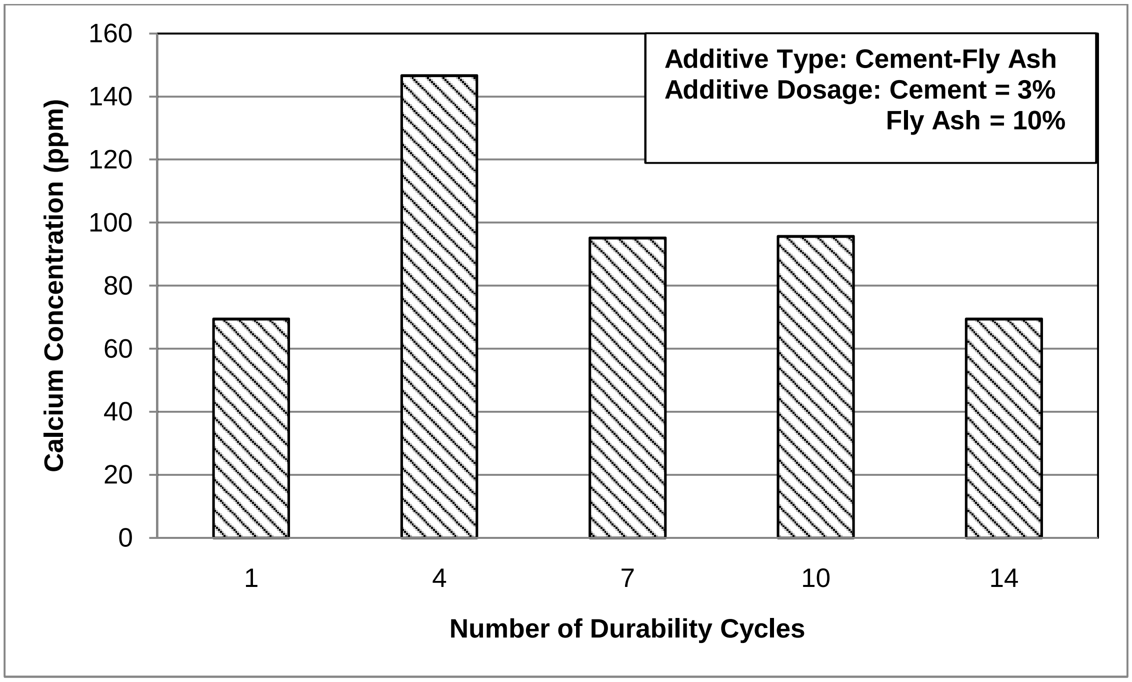


Figure 4.16 Variation of Calcium Concentration for B6 Cement-Fly Ash Treated Soil Specimen

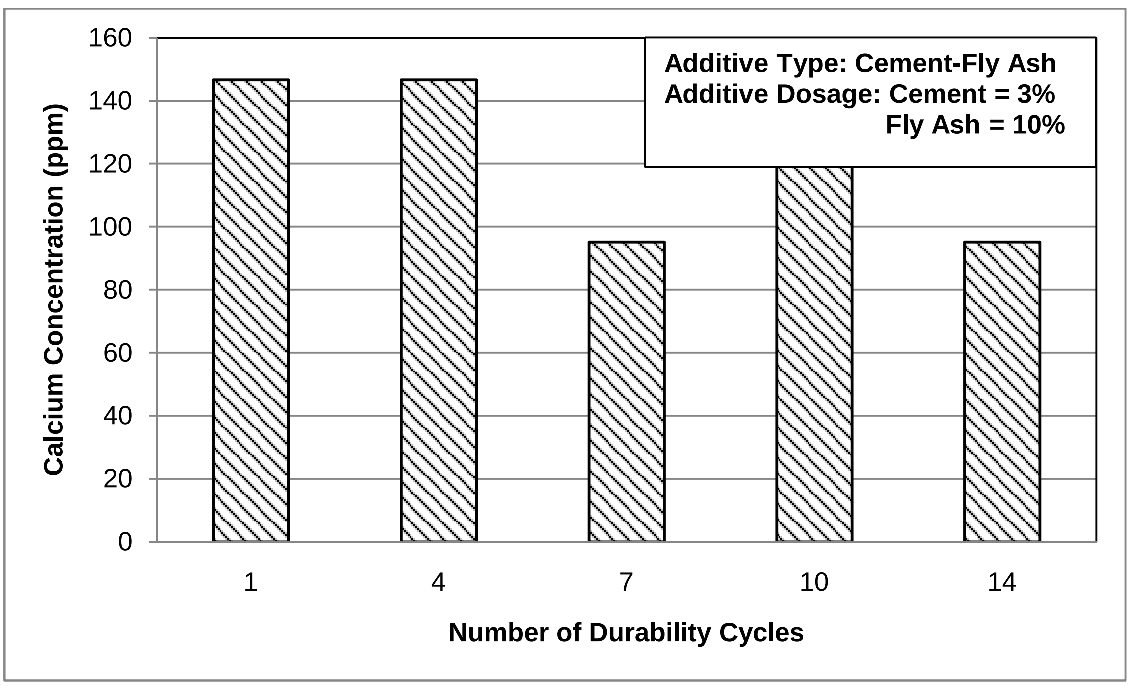


Figure 4.17 Variation of Calcium Concentration for B7 Cement-Fly Ash Treated Soil Specimen

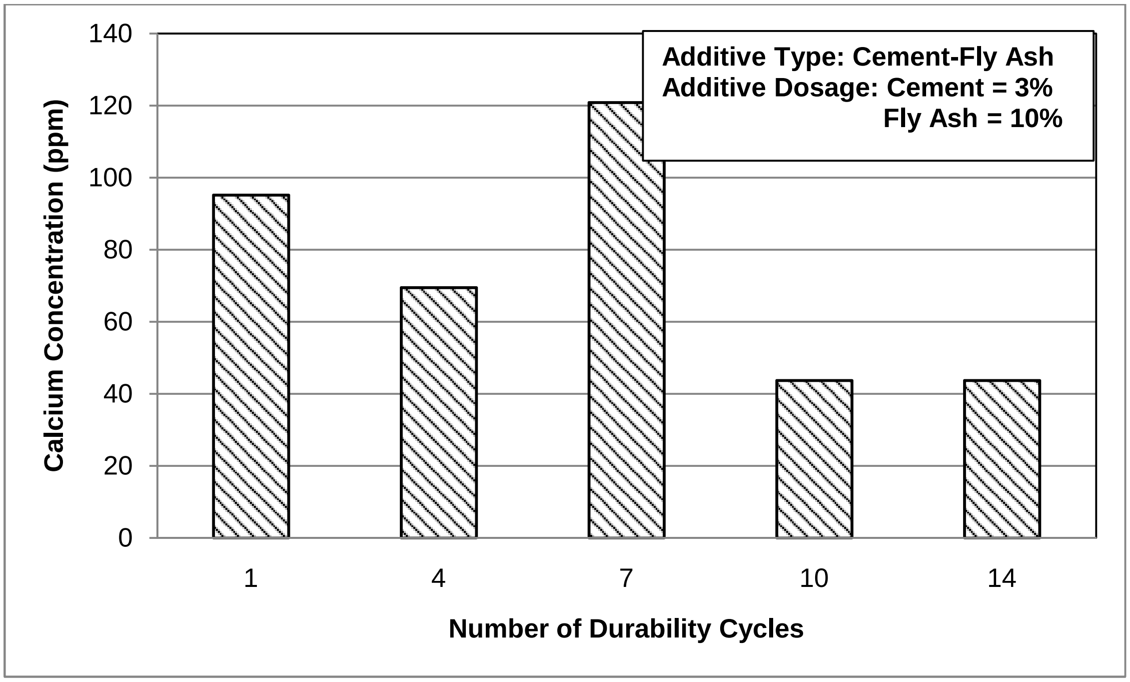


Figure 4.18 Variation of Calcium Concentration for B8 Cement-Fly Ash Treated Soil Specimen

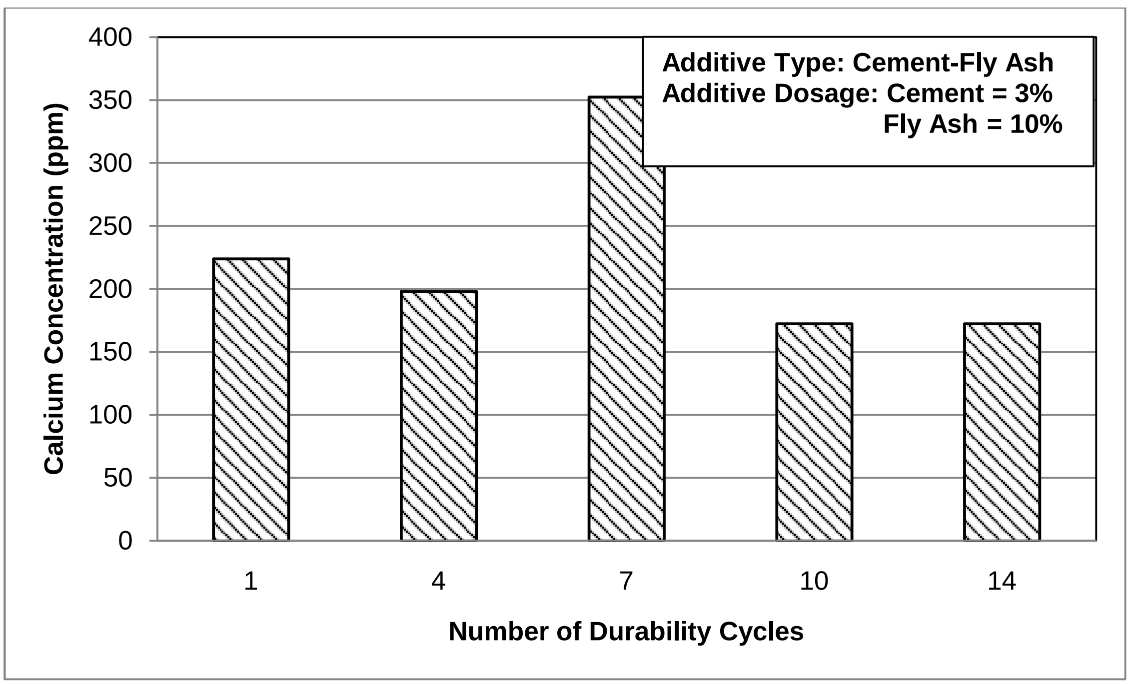


Figure 4.19 Variation of Calcium Concentration for B9 Cement-Fly Ash Treated Soil Specimen

4.3.2.4 Unconfined Compressive Strength (UCS) Test Results

Using the combined device allows a single specimen to be prepared and subjected to both wetting/drying cycles and leachate collection. It is at the completion of the selected wetting/drying cycles and leachate collection that soil specimens were subjected to UCS testing; all specimens were tested immediately after their last wetting cycle – samples were saturated at the time of testing. Graphical representations of the strength values, for both untreated and cement-fly ash treated soil specimens, collected are shown in Figures 4.20 through 4.23 for soils B6, B7, B8, and B9 respectively.

Figure 4.20 presents the variation of unconfined compressive strength with number of durability cycles for B6 cement-fly ash treated soil. The treated soil initially exhibited 105 psi (724 kPa) of UC strength whereas the untreated sample displayed only 23 psi (159 kPa) of strength. This 82 psi (565 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. On the other hand, the treated soil specimen gained strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it doubled in strength when compared to its initial UC strength.

Figure 4.21 presents the variation of unconfined compressive strength with number of durability cycles for B7 cement-fly ash treated soil. The treated soil initially exhibited 102 psi (703 kPa) of UC strength whereas the untreated sample displayed only 27 psi (186 kPa) of strength. This 75 psi (517 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. On the other hand, the treated soil specimen gained strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it gained approximately 18% in strength when compared to its initial UC strength.

Figure 4.22 presents the variation of unconfined compressive strength with number of durability cycles for B8 cement-fly ash treated soil. The treated soil initially exhibited 104 psi (717 kPa) of UC strength whereas the untreated sample displayed only 27 psi (186 kPa) of strength. This 77 psi (531 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. On the other hand, the treated soil specimen gained strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it gained approximately 36% in strength when compared to its initial UC strength.

Figure 4.23 presents the variation of unconfined compressive strength with number of durability cycles for B9 cement-fly ash treated soil. The treated soil initially exhibited 72 psi (496 kPa) of UC strength whereas the untreated sample displayed only 35 psi (241 kPa) of strength. This 37 psi (255 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. On the other hand, the treated soil specimen gained strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it doubled in strength when compared to its initial UC strength.

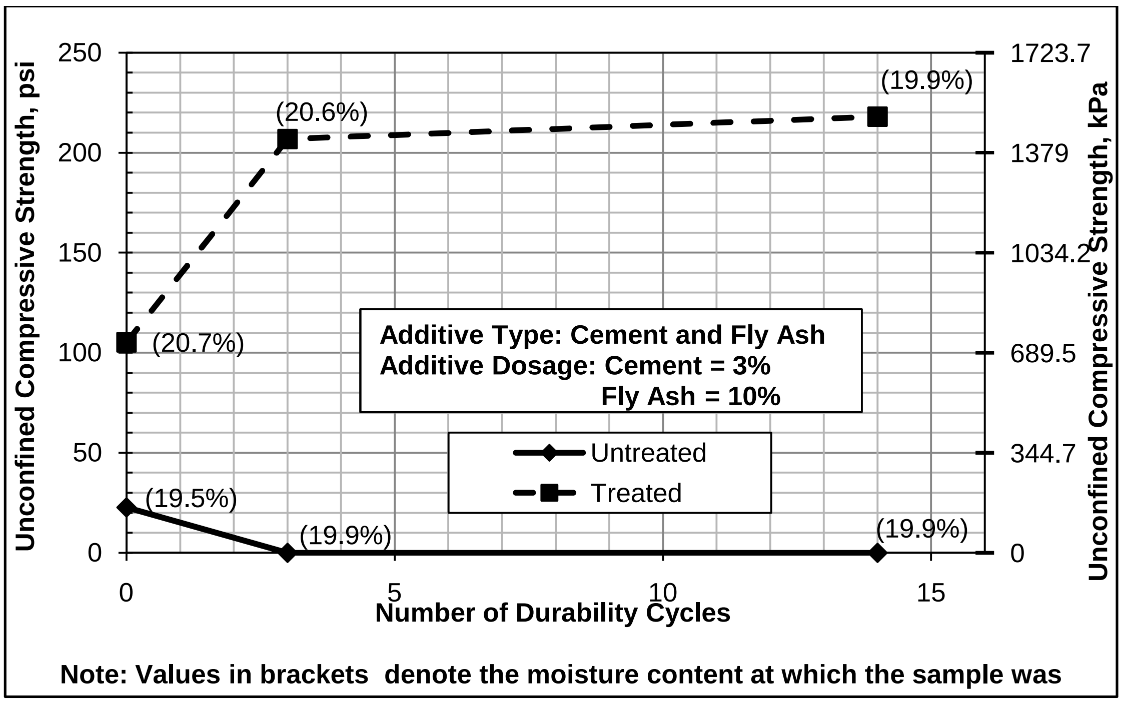


Figure 4.20 Variation of UCS Strength for B6 Cement-Fly Ash Treated Soil Specimen

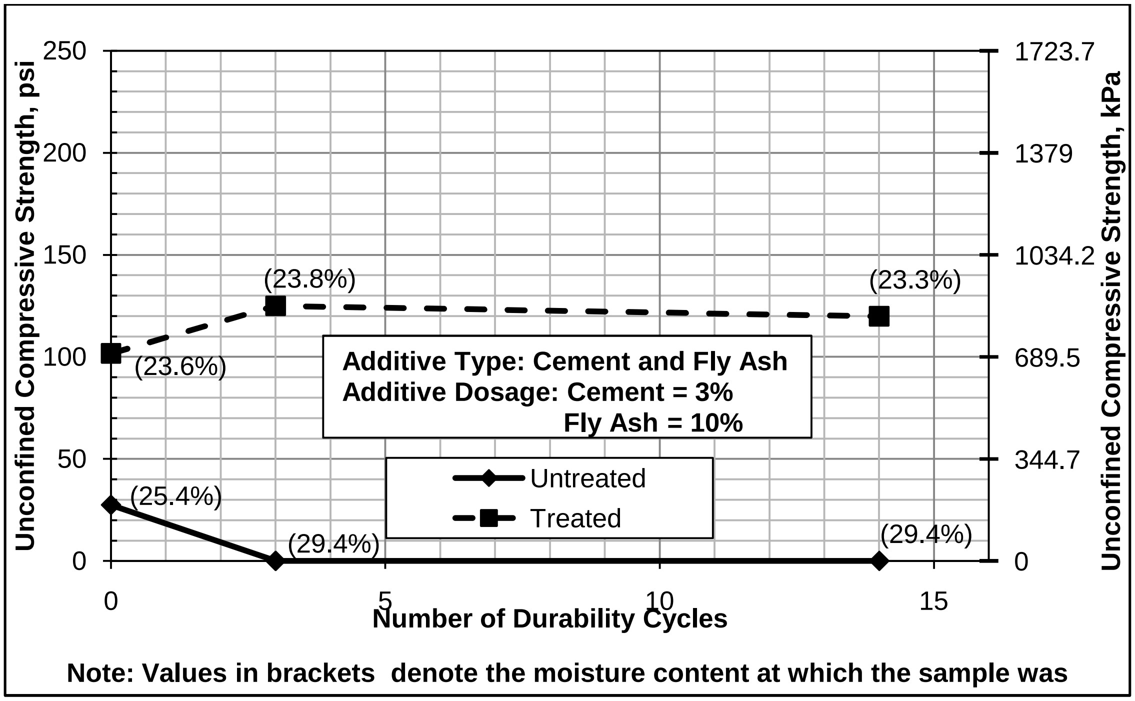


Figure 4.21 Variation of UCS Strength for B7 Cement-Fly Ash Treated Soil Specimen

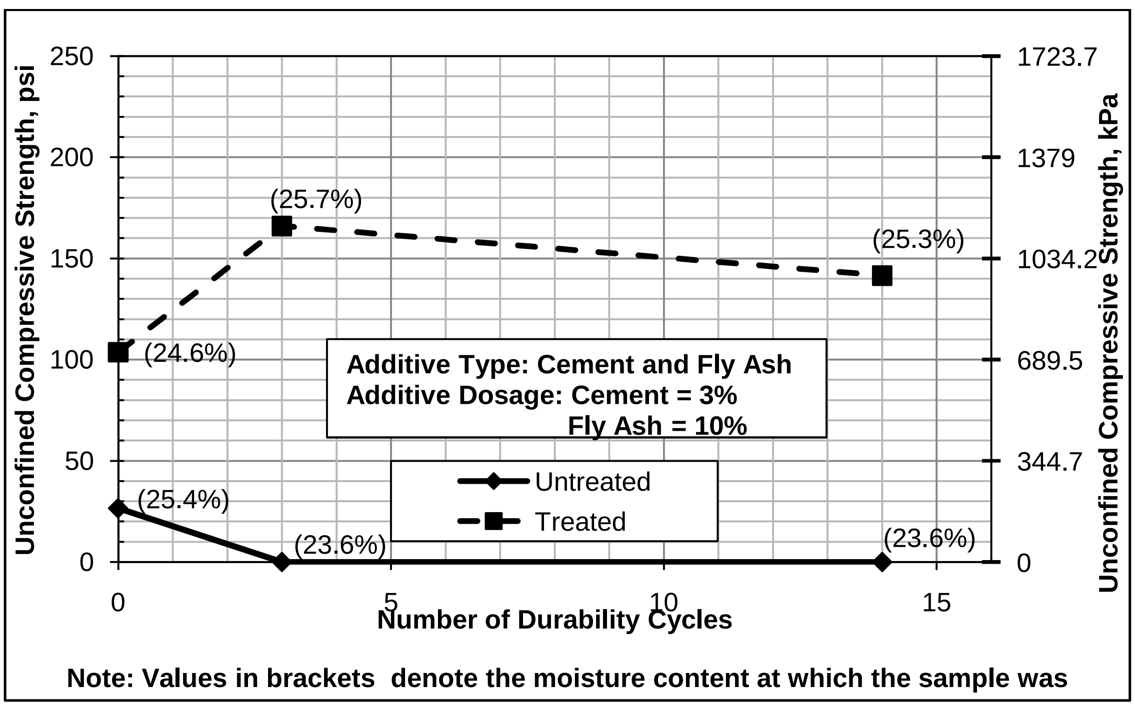


Figure 4.22 Variation of UCS Strength for B8 Cement-Fly Ash Treated Soil Specimen

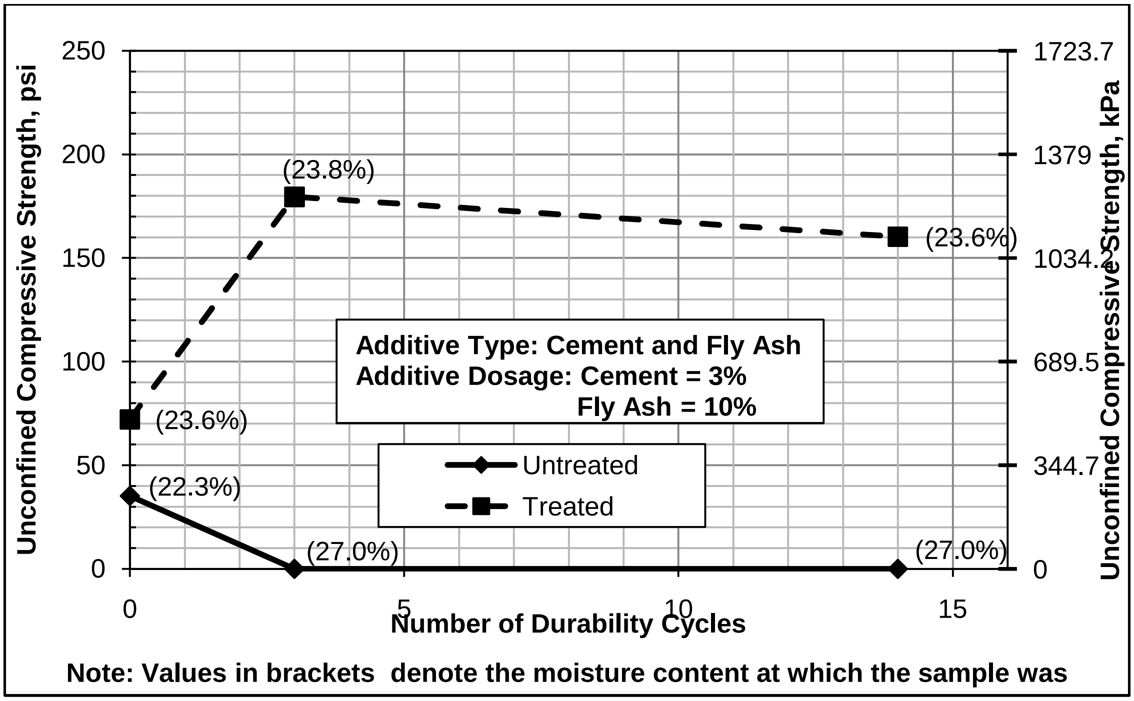


Figure 4.23 Variation of UCS Strength for B9 Cement-Fly Ash Treated Soil Specimen

4.4 Lime Studies

4.4.1 Mix Design

Mix designs for lime studies were conducted in accordance with Tex-121-E method; specifically, the Eades and Grim test was performed to determine the required lime dosages. Details of the procedure are mentioned in Chapter 3. Specimens were prepared for an initial mix design and then tested for unconfined compressive strength. Once the soil specimen achieved the minimum strength requirements, in this case it is 70 to 150 psi, soil specimens are prepared for durability studies at their respective optimum moisture content (OMC) and maximum dry density (MDD).

The OMC and MDD of the soil samples varied for each site location and chemical treatment. Table 4.4 shows the variation of the physical properties of each site location-OMC and MDD.

Table 4.4 Variation of OMC and MDD of Lime Treated Soil Specimens

Site Location	Additive	OMC (%)	MDD (pcf)
B6	6% Lime	19	98.6
B7	8% Lime	24	92.8

4.4.2 Combined Durability Studies

As previously mentioned, there are two components to combined durability testing. The first component of durability studies involves subjecting soil specimens to alternating wetting and drying cycles to replicate variations in moisture and temperature. Whereas the second component of durability studies requires the collection of leachate from all soil specimens to address the permanency of the stabilizer. Details regarding the working procedure for alternating wetting/drying cycles and leachate collection can be found in Chapter 3.

During and after the completion of selected number of wetting/drying cycles on the soil specimens throughout the combined testing, the following properties were recorded: volumetric strain changes, weight changes, calcium content, and strength changes.

4.4.2.1 Volumetric Strain Changes

As previously mentioned, swell and shrink characteristics of clays are best studied when soil specimens are subjected to alternate wetting and drying. Diameter and height changes were recorded before and after the wetting or drying cycles and were measured using a pi-tape or veneer caliper respectively. Maximum volumetric strain is determined based on the percent change for wetting and drying of one cycle of durability; this means that the drying (negative) is subtracted from the wetting (positive) to get the total change (wetting-(-drying) = total volumetric strain change).

4.4.2.1.1 B6 Soil

B6 soil has a PI of 26 - a moderately high plasticity. To counteract the plasticity and the expansive nature of the soil, a 6% lime treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results are presented in Figure 4.24.

The control B6 soil survived for only one cycle of durability with a maximum volumetric strain of 30.21%. B6 soil treated with 6% lime survived for 14 cycles of wetting and drying with a maximum volumetric change of 17.77%.

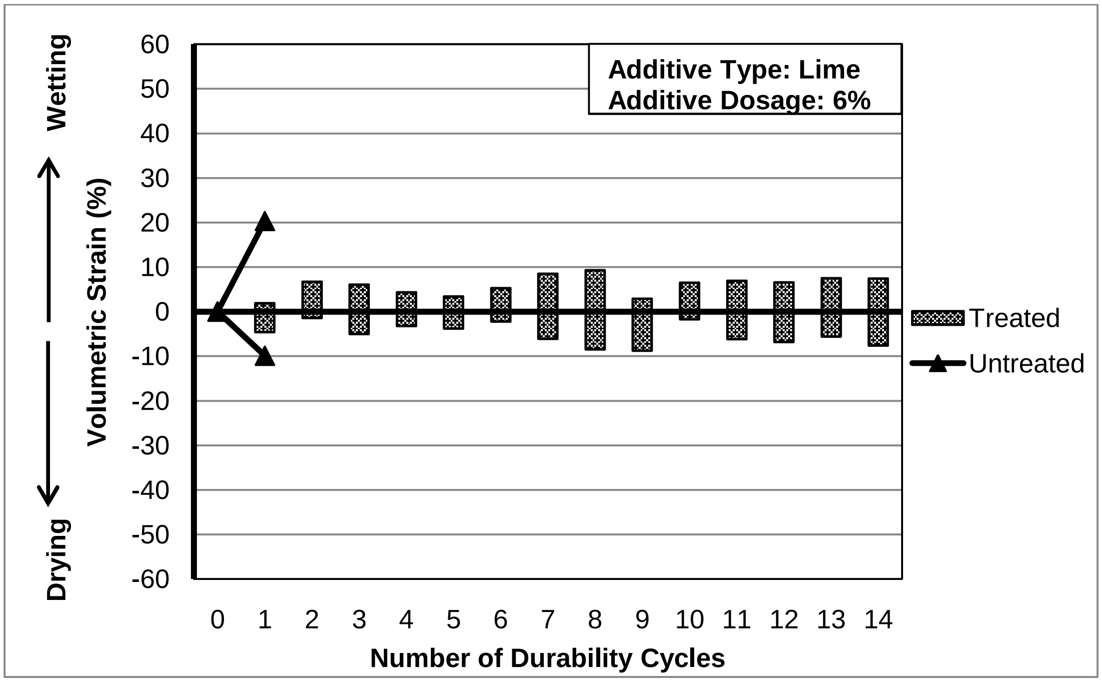


Figure 4.24 Volumetric Strain for 6% LimeTreated B6 Soil Specimen

Lime stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. A considerable decrease in the volumetric strain was noticed for the B6 soil. The lime treated soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 17.77%.

4.4.2.1.2 B7 Soil

B7 soil has a PI of 62 - a very high plasticity. To offset the plasticity and the expansive nature of the soil, an 8% lime treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Volumetric strain changes were recorded; the results are presented in Figure 4.25.

The control B7 soil survived for only one cycle of durability with a maximum volumetric strain of 75.72%. B7 soil treated with 8% lime survived for 14 cycles of wetting and drying with a maximum volumetric change of 11.25%.

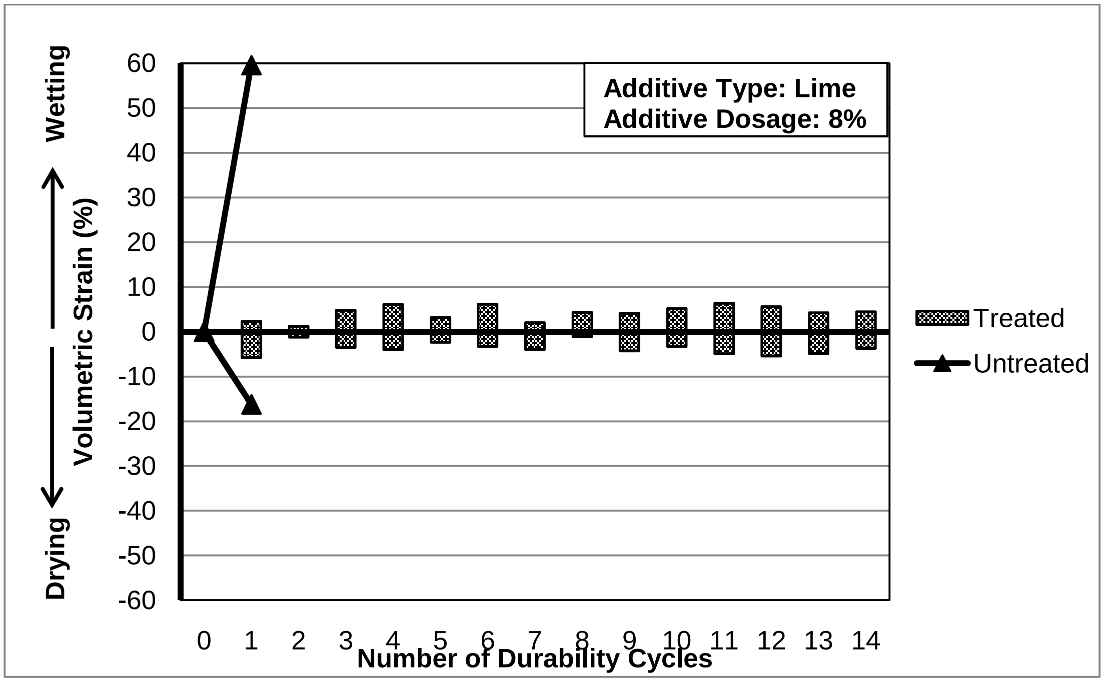


Figure 4.25 Volumetric Strain for 8% LimeTreated B7 Soil Specimen

Lime stabilization proved to be successful on the prepared soil specimen to withstand the durability cycles. A substantial decrease in the volumetric strain was noticed for the B7 soil. The lime treated soil specimen survived for 14 cycles of wetting and drying with a maximum volumetric change of 11.25%.

4.4.2.2 Sample Weight Changes

As previously mentioned, subjecting clay soils to alternate wetting and drying cycles is the best way to study the soil's swell and shrink characteristics. In addition to diameter and height measurements, changes in weight were recorded before and after the wetting or drying cycles and were measured using a weigh scale. Maximum sample weight changes is determined based on the percent change for wetting and drying of one cycle of durability; this means that the drying (negative) is subtracted from the wetting (positive) to get the total change (wetting-(-drying) = total sample weight change).

4.4.2.2.1 B6 Soil

B6 soil has a PI of 26 - a moderately high plasticity. To counteract the plasticity and the expansive nature of the soil, a 6% lime treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Sample weight changes were recorded; the results are presented in Figure 4.26.

The control B6 soil survived for only one cycle of durability with a maximum weight change of 38.00%. B6 soil treated with 6% lime survived for 14 cycles of wetting and drying with a maximum weight change of 62.12%.

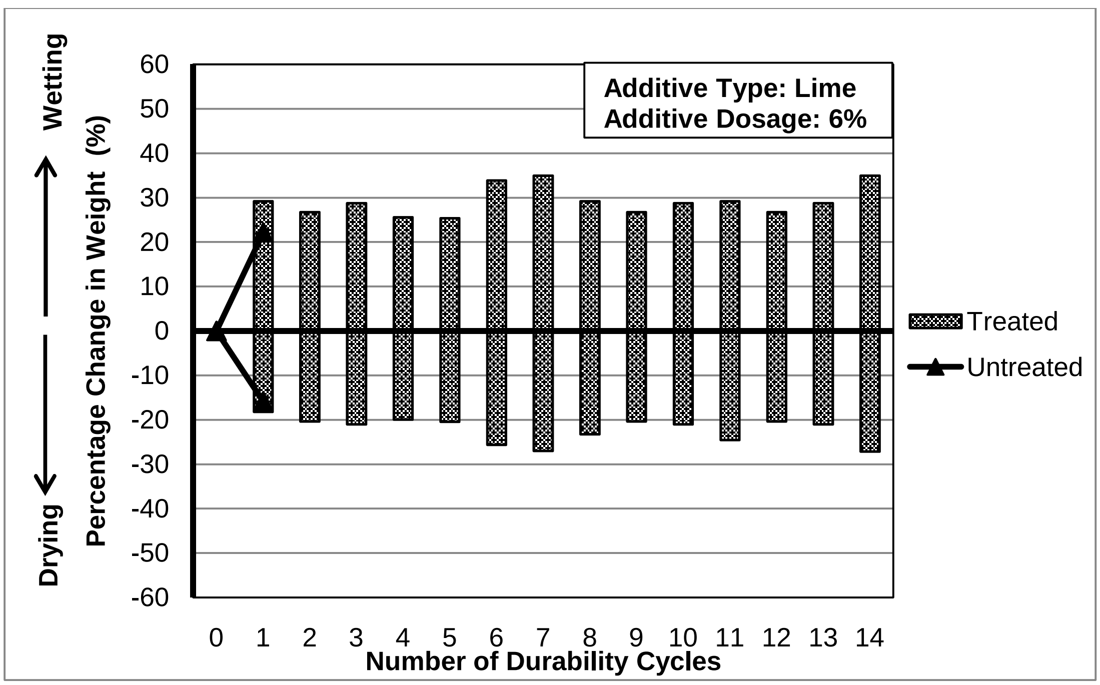


Figure 4.26 Sample Weight Changes for 6% Lime Treated B6 Soil Specimen

Lime stabilization proved to be effective on the prepared soil specimen to withstand the durability cycles. The lime treated soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 62.12%.

4.4.2.2.2 B7 Soil

B7 soil has a PI of 62 - a very high plasticity. To offset the plasticity and the expansive nature of the soil, an 8% lime treatment, by weight of soil, was evaluated. Soil specimens were prepared, cured for 7 days, and subjected to alternate wetting and drying cycles. Sample weight changes were recorded; the results are presented in Figure 4.27.

The control B7 soil survived for only one cycle of durability with a maximum weight change of 72.01%. B7 soil treated with 8% lime survived for 14 cycles of wetting and drying with a maximum weight change of 64.44%.

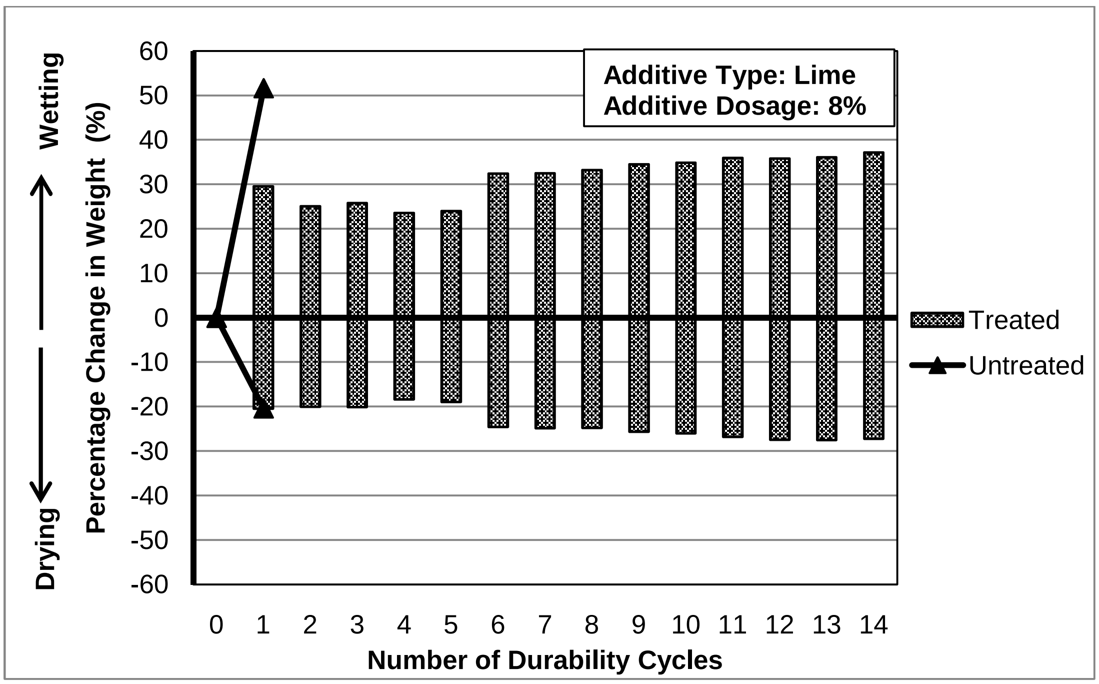


Figure 4.27 Sample Weight Changes for 8% Lime Treated B7 Soil Specimen

Lime stabilization proved to be successful on the prepared soil specimen to withstand the durability cycles. A decrease in the weight change was noticed for the B7 soil. The lime treated soil specimen survived for 14 cycles of wetting and drying with a maximum weight change of 64.44%.

4.4.2.3 Leachate Calcium Concentration

As previously mentioned, leachate samples collected from each of the soil specimens at different cycles were studied for calcium concentrations for one full cycle equivalent to the pore volume of the specimen (air voids + water voids). The procedure used for determining the calcium concentration of a prepared soil specimen by EDTA was provided in Chapter 3. The concentration of calcium in ppm was determined and plotted against durability cycles to study the variation of calcium leaching out during each cycle. The results obtained from all tests on each site location are presented in Figures 4.28 and 4.29.

B6 soil had a plasticity index (PI) of 26 and was classified as a low compressible clay (CL). The soil was treated with 6% lime. Figure 4.28 presents the calcium ion concentration changes versus the number of durability cycles of B6 lime treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 2750 ppm, which reduced to 530 ppm at higher number of cycles. Thus a difference of 2220 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

B7 soil had a plasticity index (PI) of 62 and was classified as a high compressible clay (CH). The soil was treated with 8% lime. Figure 4.29 presents the calcium ion concentration changes versus the number of durability cycles of B7 lime treated soil. It can be observed here that the soil sample remained intact for all 14 cycles of durability. The initial calcium ion concentration leached out was approximately 2380 ppm, which reduced to 380 ppm at higher number of cycles. Thus a difference of 2000 ppm was observed from initial concentration to final concentration of calcium ions. The reduction in calcium ion concentration indicates the possibility of leaching taking place.

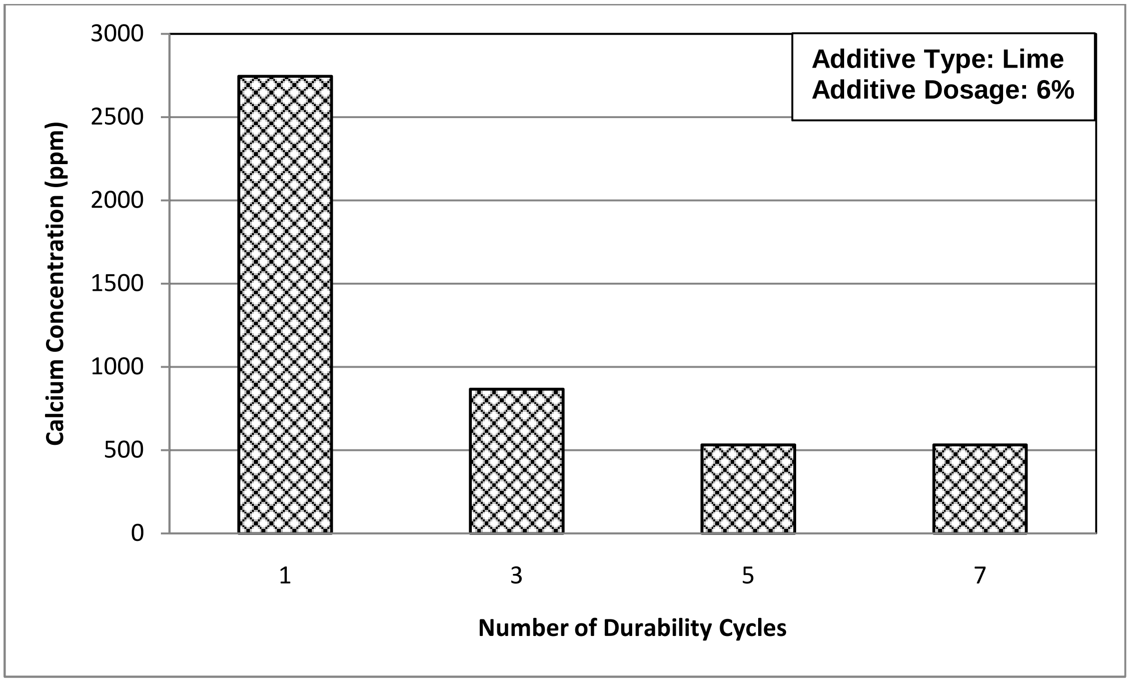


Figure 4.28 Variation of Calcium Concentration for B6 Lime Treated Soil Specimen

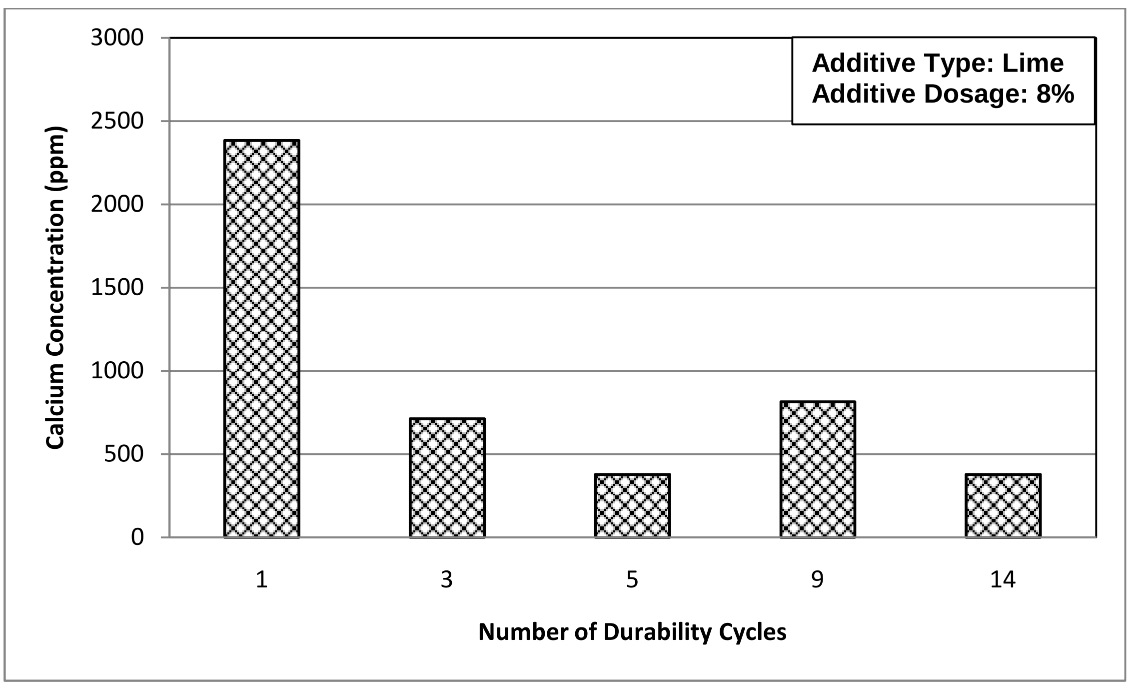


Figure 4.29 Variation of Calcium Concentration for B7 Lime Treated Soil Specimen

4.4.2.4 Unconfined Compressive Strength (UCS) Test Results

A single specimen is prepared and subjected to both wetting/drying cycles and leachate collection for the combined device. At the completion of the selected wetting/drying cycles and leachate collection, the soil specimens were subjected to UCS testing immediately after their last wetting cycle-samples were saturated at the time of testing. Graphical representations of the strength values collected are shown in Figures 4.30 and 4.31 for soils B6 and B7 respectively.

Figure 4.30 presents the variation of unconfined compressive strength with number of durability cycles for B6 lime treated soil. The treated soil initially exhibited 50 psi (345 kPa) of UC strength whereas the untreated sample displayed only 23 psi (159 kPa) of strength. This 27 psi (186 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. The treated soil specimen also lost strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it lost approximately 10% of its strength when compared to its initial UC strength.

Figure 4.31 presents the variation of unconfined compressive strength with number of durability cycles for B7 lime treated soil. The treated soil initially exhibited 78 psi (538 kPa) of UC strength whereas the untreated sample displayed only 27 psi (186 kPa) of strength. This 51 psi (393 kPa) increase in strength is due to the conditions in which the specimens were tested. The untreated soil specimens were tested immediately after preparation – at optimum moisture content, while the treated soil specimens were tested immediately after moisture conditioning – near saturation; the values in the brackets provide the moisture content at which the sample was tested. It can be noted here that the treated specimens were tested at approximately the same moisture content for 0, 3, and 14 cycles. Furthermore, the untreated sample lost all of its strength after 3 durability cycles. The treated soil specimen also lost strength as it underwent a larger number of durability cycles; at the completion of 14 cycles of durability, it lost approximately 15% of its strength when compared to its initial UC strength.

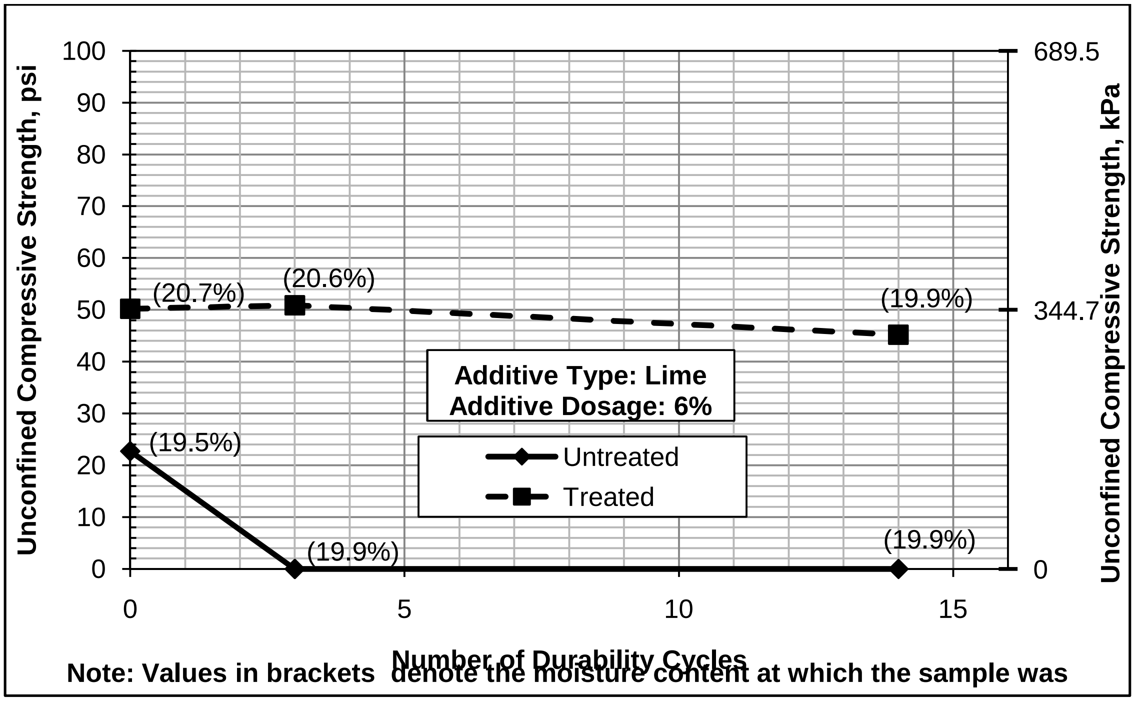


Figure 4.30 Variation of UCS Strength for B6 Lime Treated Soil Specimen

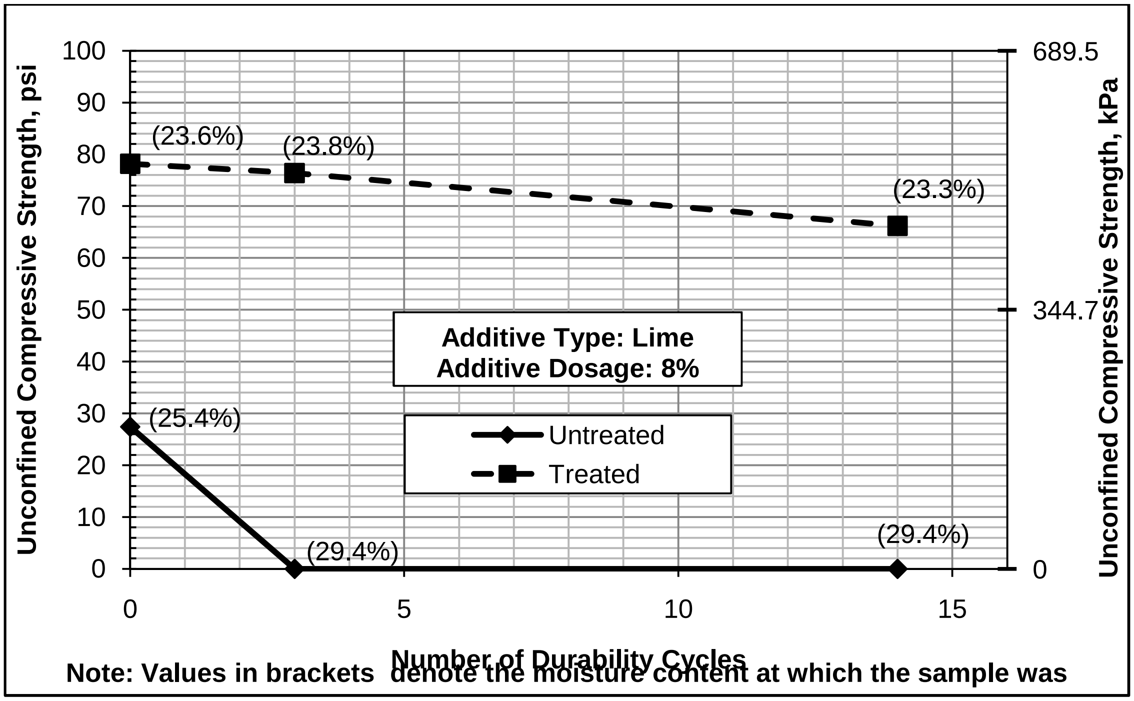


Figure 4.31 Variation of UCS Strength for B7 Lime Treated Soil Specimen

4.5 Analysis of Test Results

Analysis of the above test results is carried out in this section. The effects of additive type and their dosage on the long-term performance and leachability of stabilized expansive clays are addressed.

4.5.1 Effects of Type and Amount of Additive on the Long-Term Performance of Stabilized Soils

To assess the implications made on the long-term performance of stabilized expansive soils, two main factors are considered: type of additive (cement-fly ash and lime) and dosage. Two soils, B6 and B7, were tested with two cement-fly ash mix designs and one lime mix design. These soils were selected for this study based on their plasticity index (PI); B6 has a low PI of 26, whereas B7 has a high PI of 62. Durability results for each soil and additive type have been detailed in the above sections individually; however, the following graphical representations provide a compilation of the results.

Figure 4.32 summarizes the treatments tested on B6 soil. The untreated soil specimen lasted only one cycle of durability with a high volumetric change of 30.21%. To reduce the expansive nature of the soil, both cement-fly ash and lime treated soil specimens were tested for its long-term performance through durability studies. It can be observed from the figure that 6% lime produced a similar volumetric trend to 3% cement-6% fly ash; each of these treatments helped alleviate the expansiveness, yet the reduction was not significant enough. On the other hand, B6 soil treated with 3% cement-10% fly ash proved to be the most effective in significantly reducing the shrink/swell properties of the soil with a maximum volumetric strain of 2.08%.

Figure 4.33 summarizes the treatments tested on B7 soil. The untreated soil specimen lasted only one cycle of durability with a high volumetric change of 75.72%. To reduce the expansive nature of the soil, both cement-fly ash and lime treated soil specimens were tested for its long-term performance through durability studies. It can be observed from the figure that 3% cement-6% fly ash did not last 14 cycles of durability as the treated soil specimen failed after 4 cycles. Furthermore, the 8% lime treated soil specimen produced a similar volumetric trend to 3% cement-10% fly ash, yet the lime treated soil did not achieve the same substantial reduction in the volumetric strain. B6 soil treated with 3% cement-10% fly ash proved to be the most effective in significantly reducing the shrink/swell properties of the soil with a maximum volumetric strain of 3.66%.

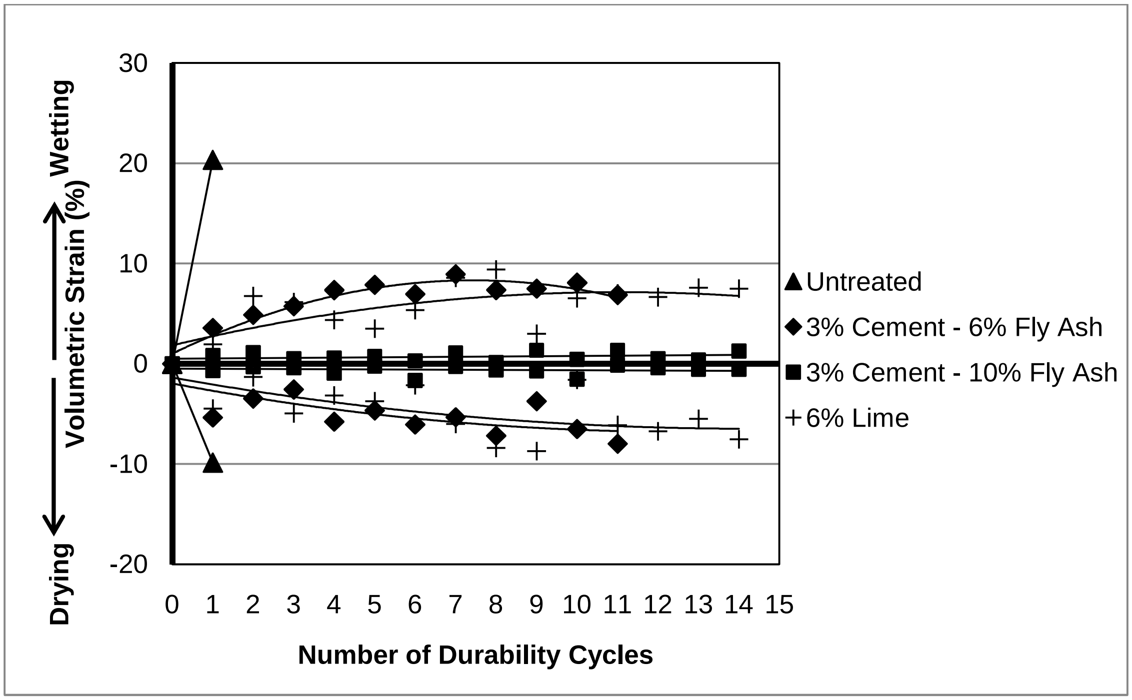


Figure 4.32 Summary of Volumetric Strains for B6 Treated Soils

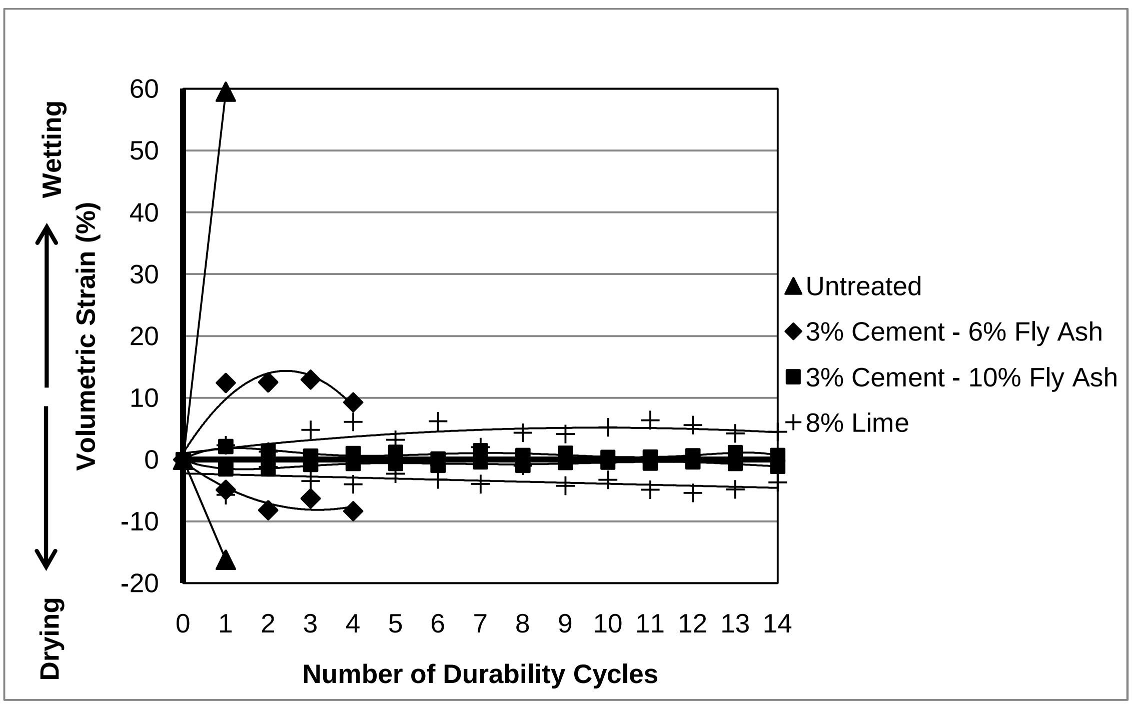


Figure 4.33 Summary of Volumetric Strains for B7 Treated Soils

Table 4.5 further summarizes and compares the effect of the type of additive used on the durability and long-term performance of the stabilization under seasonal variations and volumetric changes due to these fluctuations in moisture. From the table, it can be observed that the 3% Cement-6% Fly Ash failed prior to reaching 14 cycles. This premature failure, for both B6 and B7, is attributed to low additive dosages used for stabilization. Hence, a new cement-fly ash mix design (3% cement-10% fly ash) was developed in which combined durability studies were carried out on. Both 3% cement-10% fly ash and lime treatments lasted the full 14 cycles of durability for both site locations despite the large difference between their plasticity index (PI).

Table 4.5 Comparison of B6 and B7 Volumetric Results Between Additive Types

Site Location	Type and Amount of Additive	# of Cycles Survived	% Retained Strength	Max Volumetric Change (%)
B6 (PI=26)	None	1	0	30.21
	3% Cement-6% Fly Ash	11	-	14.85
	3% Cement-10% Fly Ash	14	100	2.08
	6% Lime	14	90	17.77
B7 (PI=62)	None	1	0	75.72
	3% Cement-6% Fly Ash	4	-	20.67
	3% Cement-10% Fly Ash	14	100	3.66
	8% Lime	14	85	11.25

4.5.2 Effects of Type and Amount of Additive on the Leachability of Stabilized Soils

To assess the implications made on the leachability of stabilized expansive soils, two main treatments are considered: 3% cement-10% fly ash and respective lime treatments. Two soils, B6 and B7, were tested for calcium ion concentrations with respect to the above mentioned treatments. These soils were selected for this study based on their plasticity index (PI); B6 has a low PI of 26, whereas B7 has a high PI of 62. Durability results for each soil and additive type have been detailed in the above sections individually; however, the following graphical representations provide a compilation of the results.

Figure 4.34 summarizes the calcium ion concentrations for B6 soil treated with 3% cement-10% fly ash and 6% lime. It can be observed from the figure that the leachate collected from lime treated soil specimens contained higher amounts calcium ions whereas the calcium ion concentration of leachate collected from cement-fly ash treated soil specimens were relatively low. Both treatments experienced a reduction in calcium ion concentration, meaning the chemical treatments were leaching out.

Figure 4.35 summarizes the calcium ion concentrations for B7 soil treated with 3% cement-10% fly ash and 8% lime. It can be observed from the figure that the leachate collected from lime treated soil specimens contained higher amounts calcium ions whereas the calcium ion concentration of leachate collected from cement-fly ash treated soil specimens were relatively low. Both treatments experienced a reduction in calcium ion concentration, meaning the chemical treatments were leaching out.

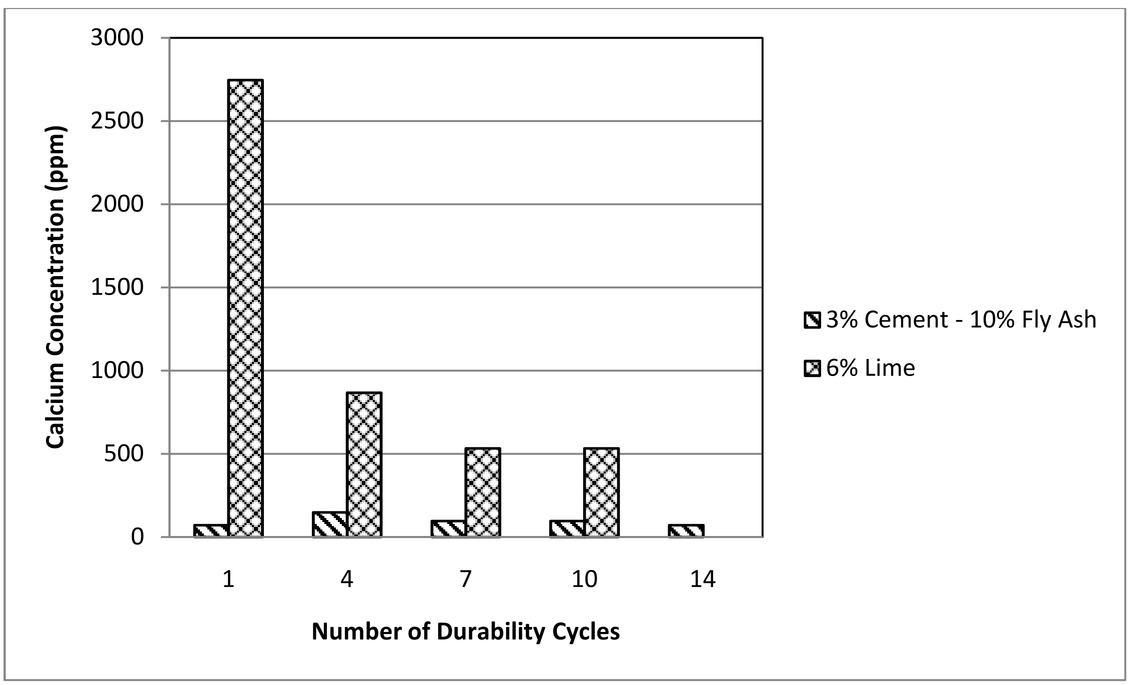


Figure 4.34 Summary of Calcium Concetrations for B6 Treated Soils

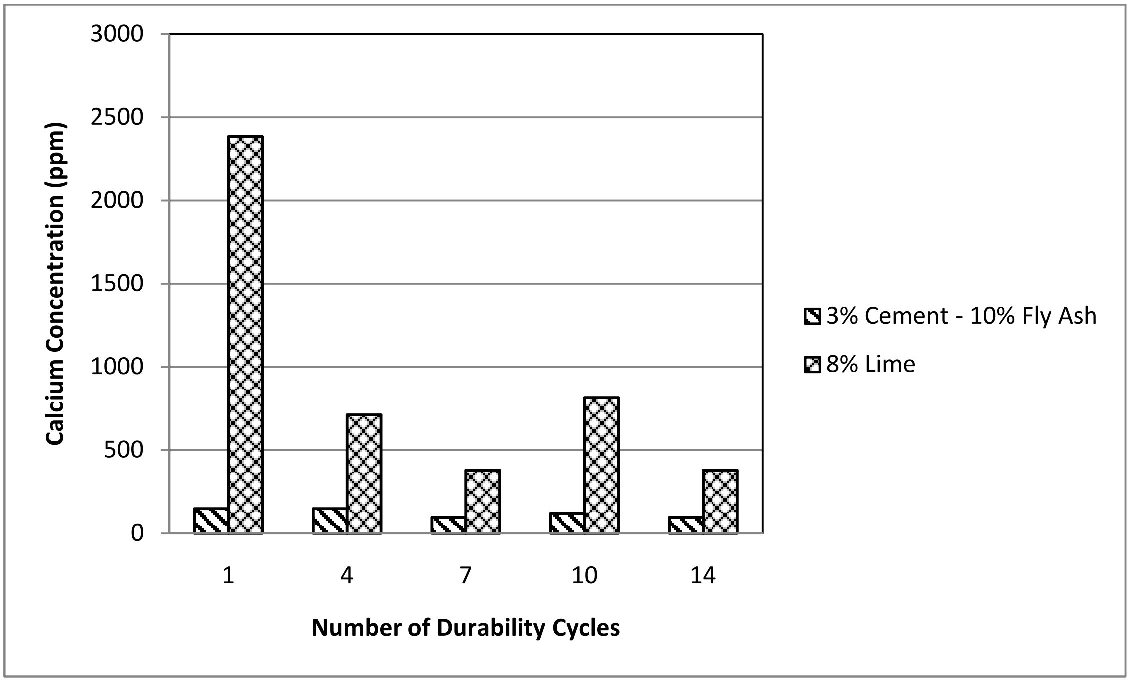


Figure 4.35 Summary of Calcium Concetrations for B7 Treated Soils

Table 4.6 further summarizes and compares the effect of the type of additive used on the leachability of the stabilization under seasonal variations and volumetric changes due to these fluctuations in moisture. From the table, it can be observed that the 3% cement-10% fly ash had lower concentrations of calcium ions when compared to leachates collected from lime treated soil specimens. Additionally, the percent additive leached for 3% cement-10% fly ash is minimal in comparison to that of lime. A reduction in calcium ion concentration is noticeable among both chemical treatments; lime treated soil specimens experienced a higher reduction than cement-fly ash treated soil specimens. Lime treated samples experience a large reduction in calcium concentration because not all of the free lime present has participated in the reaction; therefore the free lime leaches out after the first cycle. Previous studies have indicated a similar trend in the reduction of calcium ion concentration.

Table 4.6 Comparison of B6 and B7 Leachate Results Between Additive Types

Site Location	Type and Amount of Additive	# of Cycles Survived	% Retained Strength*	Reduction in Calcium Ion Concentration (ppm)	% Additive Leached*
B6 (PI=26)	3% Cement-10% Fly Ash	14	100	80	0.54
	6% Lime	14	90	2220	1.3
B7 (PI=62)	3% Cement-10% Fly Ash	14	100	55	0.39
	8% Lime	14	85	2000	0.82

*At the completion of 14 cycles of durability

4.6 Summary and Findings

A total of four soils were selected for studying the long-term performance of stabilized expansive soils by conducting a combined durability test. Combined durability tests incorporate both wetting/drying cycles and leachate cycles into a single device; a single sample undergoes both components simultaneously, thus using material and time effectively and efficiently. Details regarding the combined durability device and testing procedure are presented in Chapter 3.

Results of the combined durability tests that were conducted on prepared untreated and treated soil specimens have been presented here. Volumetric strains and sample weight changes were collected over the course of alternating wetting and drying cycles with a pi tape, veneer caliper, and weigh scale. Additionally, leachate samples were collected at select cycles and tested for calcium concentration; in other words, the leachate samples were tested for the amount of chemical stabilizer leached out.

The effect of the type and amount of additive on the long-term performance of stabilized expansive soils was studied in this research. It has been observed that 3% cement-6% fly ash did not last the full 14 cycles of durability for both B6 and B7 soils. On the other hand, 3% cement-10% fly ash and lime treated specimens proved to significantly alleviate the shrink/swell characteristics of these soils.

On the other hand, the leachability of the chemical additives is more pronounced for lime treated soil specimens. There were relatively larger amounts of calcium ion concentration in leachates collected from lime treated soil specimens when compared to leachates collected from cement-fly ash treated soil specimens. Both chemical treatments experienced a reduction in calcium concentrations, thus proving the leaching of chemicals yet the percent of additive leached are minimal and the strengths of the samples are well maintained over the course of 14 cycles of durability. Lime treated soil specimens experienced a greater percent of additive leached – anywhere from 10-16%. On the other hand, cement-fly ash treated soil samples observed minimal loss of additive – less than 1%.

Based on the above mentioned, the combined device proved to be an integral solution for conducting durability studies, primarily due to the effective and efficient use of materials and time. It accurately depicts moisture fluctuations that occur in arid climates such as north Texas when compared to conventional testing and procedures used by McCallister (1990), Hoyos (2005), and Chittoori (2008) as detailed in Chapter 2.

CHAPTER 5

SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary and Conclusions

Expansive soils have been a major concern for many years now. Their shrink/swell characteristics have deteriorated many overlying structures, such as roads, low rise housing and public buildings primarily due to the presence of clay minerals like Montmorillonite. Due to the concern of constructing on problematic soils, stabilization has become a topic of interest primarily in order to reduce the construction and maintenance costs of any and all civil infrastructure. Chemical stabilization, in particular, has been practiced for decades to improve the performance of base and subgrade materials to address the expansive nature of soils.

Extensive research was documented with respect to the engineering properties and the durability of various types of stabilized soils. A recent previous research study presented details on clay mineralogy, durability studies and leachate studies. Methodology for different experiments including CEC, durability studies and calcium determination from the leachate has been presented. This study primarily focused on one stabilizer type and its dosage. Hence, new studies are needed to understand the effectiveness of stabilization types on various types of soils.

In this research an attempt is made to design and develop a device that combines both stages of durability – alternating wetting/drying cycles and leachate collection – to address the long-term performance and permanency of stabilized soils. Stage 1, wetting/drying studies, focused on replicating the volumetric changes that occur due to moisture ingress and digress. Whereas stage 2, leachate collection, focused on replicating the rainfall infiltration that can sometimes leach the additive and reduce soil strength. Both of these stages play an instrumental role in the development of the combined device.

The first task in this study was to identify and select the most problematic soils for testing. A total of four natural expansive soils were selected from different locations along the pipe alignment in the IPL pipeline project. Basic soil tests were conducted prior to conducting mix designs for lime and cement-fly ash treatments; these tests include: grain size analysis, Atterberg's limits, soil classification, and standard proctor compaction. Mix designs were estimated for each treatment using methods carried out in previous studies. As no test protocol is available for cement-fly ash stabilization, previous studies and an iterative approach were used to determine the appropriate amount of each additive was necessary to stabilize the soil. For lime treatment, Tex-121-E method provides details on the Eades and Grim method, which determines the minimum amount of lime stabilizer required based on the pH criterion.

The second task comprised of treating the selected soils with the mix designs initially established and studying them for durability studies. Prepared soil specimens were subjected to alternating wetting/drying cycles and leachate collection studies to evaluate the long-term performance and the permanency of the chemical treatment method used. Additionally, unconfined compressive strength tests were conducted after 3, 7 and 14 cycles of durability to address the strength changes due to both rainfall ingress and digress as well as additive leaching.

The following are conclusions derived from the analysis of test results:

1. 3% cement-6% fly ash was not an adequate treatment dosage for B6 (CL) and B7 (CH) soils as they did not last the full 14 cycles of durability.
2. All soils, from four borehole locations, were stabilized effectively with 3% cement-10% fly ash as the treated soils completed 14 cycles of durability and maintained their strength.
3. Volumetric swell and shrinkage strains of B6 and B7 reduced considerably when treated with cement-fly ash, whereas lime treated samples did not see the same large

reduction in volume. B6 and B7 3% cement-10% fly ash samples survived 14 cycles of durability with a maximum volumetric change of 2.08% and 3.66% respectively.

4. B8 (CL) and B9 (CH) soils experienced a reduction in volumetric strain when treated with 3% cement-10% fly ash, yet it was between 10% and 15%. This is still high for soil reuse; further testing may be required to find an additional alternative to alleviating the remaining swell/shrink characteristics of these two site locations.
5. The retained strengths after 14 cycles of durability are higher for cement-fly ash treated soils than lime treated soils. This proves the pre-established fact that soils partially treated with cement have higher initial strength than the lime treated soils.
6. The percent leaching of chemical additive in short term leachate studies is small but can be considerable if the original stabilizer dosage used is less than 4. Overall, this study clearly showed that leaching may not be highly problematic in the initial years if the treatment dosages are high (6% or higher).
7. Overall, combining wetting/drying cycles with leachate collection in a single device proved to be acceptable in comparison to the conventional methods detailed in McCallister (1990) and Chittoori (2008).

All these findings have provided valuable data that is used in the next sections on proposed recommendations

5.2 Proposed Recommendations and Further Studies

From this study, it is recommended that the long-term performance of stabilized soils due to ingress and digress of moisture and the permanency of stabilizer be tested using the modified device that combines both stages of durability. The combined device proved to be adequate in comparison to conventional methods of testing. Similar test results can be achieved without the possibility of differing properties in the soil specimens for separate testing. Additionally time and material is saved using a device that can conduct both tests.

Although previous studies have shown similar results when tested with the conventional methods, further testing is recommended with both the conventional and combined methods for soils with similar PI. These additional tests will help further understand the similarities in the modified (combined) approach and the conventional methods.

Table 5.1 presents a summary of the treatments recommended for implementation for the IPL project. The primary criteria for choosing a chemical treatment for the four selected soils are that the maximum volumetric strain be less than 10% and that strength is retained over 14 cycles of durability. It can be observed that all treatments recommended are 3% cement-10% fly ash. The maximum volumetric strain for B6 and B7 was greatly reduced when treated with 3% cement-10% fly ash; the values were well below the 10% cutoff mark. On the other hand, B8 and B9 experienced maximum volumetric strains above the cutoff mark – closer to 15%, yet they still provide the strength required for the IPL project.

Although the combined device is comparable to conventional test methods, it is important to conduct further studies to better understand its implications on soils with varying PI.

Table 5.1 Summary of Recommended Chemical Treatments for IPL Project

Site Location	PI	Soil Classification	Recommended Chemical Treatment	# of Cycles Survived	% Retained Strength*	% Additive Leached*
B6	26	CL	3% Cement-10% Fly Ash	14	100	0.54
B7	62	CH	3% Cement-10% Fly Ash	14	100	0.39
B8	34	CL	3% Cement-10% Fly Ash	14	100	0.53
B9	37	CH	3% Cement-10% Fly Ash	14	100	1.22

*At the completion of 14 cycles of durability

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BIOGRAPHICAL INFORMATION

Priya Pravin Lad was born in Naperville, Illinois on the 6th of August 1989. She graduated from the University of Texas at Arlington (UTA), Arlington, Texas with a Bachelor of Science in Civil Engineering in December 2010. As a part of the Fast-Track program, within the department at UTA, she pursued a Master of Science in Geotechnical Engineering in Spring 2011. At UTA, she performed research on the combined durability device with stabilized expansive soils under the guidance of Professor Anand J. Puppala and successfully defended her thesis in April 2012.