DURABILITY STUDIES ON STABILIZATION EFFECTIVENESS OF SOILS CONTAINING DIFFERENT FRACTIONS OF MONTMORILLONITE

by

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To my Mom, Dad and Bunty

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ABSTRACT

DURABILITY STUDIES ON STABILIZATION EFFECTIVENESS OF

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OF MONTMORILLONITE

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Stabilization of clays with additives such as lime and cement has been practiced for several years and worked well in improving the subgrades. The stabilizer design based on PI and gradation of the soil was widely followed. Though this practice is used widely, there were cases where the treated subgrades exhibited premature failures. Many cases were reported, where the treated subgrade experienced failures due to loss of stabilizer over a time period, or a stabilizer being ineffective in certain soils. The design methods need to be examined by incorporating clay mineralogy and durability of the treatment studies.

An experimental study was conducted here on four soils having different mineralogical characteristics. The soils were studied with two types of stabilizers (lime and cement). The first task is to assess the long term durability of stabilized expansive clays with distinct clay mineralogy by subjecting them to wetting/drying studies. This study replicates moisture fluctuations occurring during seasonal variations. Volumetric strain and unconfined compressive strength of the soil specimens were monitored at select cycles during wetting/drying cycles. The second task is to study the soil specimens under severe rainfall conditions which can be replicated in the lab with the help of Leachate apparatus. Leachate coming out from the soil specimens was studied for calcium concentrations and pH variations during select cycles. Also the final strength retained in the soil specimen is found after leaching for 14 cycles. Calcium concentrations, pH and cation exchange capacities of soil specimens at select cycles were monitored.

Durability test results were analyzed to understand the importance of mineral Montmorillonite in clays on their stabilization process. Results revealed that there is considerable effect of mineral Montmorillonite on the stabilization effectiveness of clays where an increase in the percent amounts of this mineral resulted in the poor performance of stabilized soils during durability studies. Leaching of stabilizer was small and hence did not influence the treated soil strength. This research paves way for future research studies to increase the accuracy of selecting a stabilizer by the inclusion of clay mineralogy and durability aspects in the stabilizer design methods.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Expansive soils pose a serious threat to the stability of structures built on them. Replacement of the problematic soils is a tedious and costly process, instead stabilization with additives proved to be effective. Hence, the modification of engineering properties of expansive soils has become very important to geotechnical engineers. This modification can be achieved with the help of chemical stabilization. Stabilization of such non-ideal soils requires proper study on the stabilization effectiveness, when treated with a chemical stabilizer.

Lime and cement stabilization have been used consistently for improving expansive clays and in increasing the life of the structure above the soil. This stabilizing technique is widely used in the construction of roads, airports, embankments, or canal linings by intimate mixing with clay subgrades to improve workability, strength, swelling characteristics, and bearing capacity. Since the properties of soil–lime mixtures and soil-cement mixtures depend upon the mineralogy of the clay soil, and the type and period of curing, the method and quality of construction and the proper amount of additive to be used should be investigated before the application of the soil-additive mixture technique. The recent approach followed by the department of transportation's (DOT's) in the selection of stabilizer is mainly based up on the soil PI and gradation characteristics. However, several states have had problems with subgrade failure due to a loss of stabilizer over time, or a stabilizer being ineffective in some soils while other soils with the same index properties respond well to that stabilizer (Little et al., 2000).

This necessitated a research to study the relationship between the additive dosage and the mineralogy of the clays and stabilizer dosages for a given type of treatment.

1.2 Objective

The objective of this research is to select the problematic soils showing different percents of Montmorillonite and stabilize them using the standard stabilization procedures. In the present research four soils were selected having different mineralogical contents. The second objective of this research is to bridge a relationship between the mineralogy of the soil and the dosage of stabilizer. In order to achieve this, durability and leachate experiments were conducted on the soils which are stabilized chemically with different dosages of additives.

All the selected soil specimens have been treated with additives as per the TxDOT's stabilizer design methods Tex 120-E (Cement as additive) and Tex 121-E (Lime as additive).

Lime stabilization develops because of base-exchange and cementation processes between clay particle and lime. The primary effect of small lime additions (2% to 8%) is to decrease significantly the liquid limit, plasticity index, maximum dry density, and swelling pressure, and to increase the optimum water content, strength, and durability of expansive clays (Glendinning, 1996). Cement stabilization enhances soil properties from the cementitious bonds between the calcium silicate and aluminate hydration products of cement and the soil particles. The action of the cement had considerable effect on the swelling reduction and strength of the soil (Van der Kerkhof, 2001). The basic strategy of cement stabilization is to reduce the liquid limit, plasticity index, permeability and swelling potential.

The mineralogy of the soils was identified and found that the mineral Montmorillonite showed considerable effect on the stabilizing potential of the soil. Previous research done by

Chittoori (2008) showed that the soils having high Montmorillonite contents seized to show any stabilizing effect when treated with standard stabilizer dosage (lime and cement). This research studies the effect of stabilizer dosage on the Montmorillonite dominant soils.

The soils were assessed for the effects of clay minerals on the long-term durability of stabilized expansive clays by conducting wetting/drying (W/D) studies replicating moisture fluctuations expected during summer and winter seasons in the field. The long-term performance of stabilized expansive soils was studied by conducting wetting/drying studies. The unconfined compressive strengths of the samples at select cycles were determined to see the effect of seasonal changes on the strength. The test methodologies are presented in detail in chapter 3. An accelerated curing method, which was developed to save time and proved to be effective (Chittoori, 2008), was followed in this study for curing and moisture conditioning of the treated soil specimens.

A second task was implemented in order to study the effect of rainfall infiltration on the soil sample. The Leachate apparatus which is a laboratory model of replicating the field rainfall infiltration was used to study the long term performance of stabilized soils. The apparatus was explained in detail in chapter 3. Leachate fluid samples coming out of the soil samples were collected after 3, 5, 7 and 14 cycles to study the chemical changes occurring due to leaching of the additive.

1.3 Organization and summary

Chapter 2 presents the recent advances in the mineralogy of the clay detailing about mineral Montmorillonite in particular. The literature available for clay mineral identification of a soil is presented in detail. The recent advances in chemical stabilization are discussed.

Previous research on the durability studies followed by the leachate studies was presented in this chapter.

Chapter 3 gives a detailed explanation of the test procedures used in the current research. The procedures for curing the soil specimens followed by wetting and drying cycle of the samples were given in detail. Leachate apparatus, the equipment used for extracting the leachate out of the soil specimen was explained in detail along with the working procedure. The test procedures used for the determining of CEC and calcium concentrations is given in detail.

Chapter 4 summarizes the results obtained from the durability tests conducted on the untreated and treated clay specimens. Tests results from UCS conducted on the soil specimens after 3, 7, 14 and 21 cycles of wetting/drying were presented. Volumetric strain of the soil samples was monitored during durability tests.

The effects of the dominating mineral Montmorillonite on the stabilizing ability of the clay for different lime dosages were studied in detail in chapter 5. The amount of calcium coming out of the soil sample is found out at select leachate cycles. pH of the leachate was monitored at select cycles.

Summary and conclusions derived from the test results and the effect of the minerals on the stabilizing ability of the clay specimens are presented in chapter 6.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In the common geotechnical engineering practice, the soils at a particular site are not ideal to support structures and in some cases expansive nature of these soils pose several problems to structures. Having different mineral compositions in soils may cause heave instability for the structures built above. Swelling and shrinking characteristics of the clay minerals present in the soils are responsible for the damages caused to the pavements and other structures built on them. These expansive soils are found in abundance in semi-arid regions of tropical and temperate climatic zones, where annual evapo-transpiration exceeds precipitation (Jones and Holtz, 1973). In the United States, damage from swelling soils annually causes a greater economic loss than the damage caused by floods, hurricanes, tornadoes, and earthquakes (Jones and Holtz, 1973).

The first part of this chapter covers the current literature review on clay mineralogy and the main focus will be on mineral Montmorillonite. Then the recent advances in chemical stabilization were reviewed and discussed. Then the durability issues with respect to chemical stabilization of expansive clays are discussed.

2.2 Clay Mineralogy

In nature clayey soils exists with different clay mineral compositions which in turn show variation in these soils with respect to how they behave. Clay minerals in soils belong to a family known as phyllosilicates or layered silicates. Clay minerals occur in small particle sizes and their unit cells ordinarily have a residual negative charge. The different clay mineral groups are characterized by the stacking arrangements of alumina and silica sheets (Mitchell and Soga, 2005). Clay minerals contain continuous two-dimensional tetrahedral sheets of composition Si_2O_5, Al_2O_5 and Be_2O_5. The tetrahedral sheets are linked in the unit structure to octahedral sheets, or to groups of coordinated cations, or individual cations. (Bailey, 1980)

As stated before, mineralogy of a soil controls its size, shape, physical and chemical properties. Based on the mineralogy, the particle size of soil varies from very large cobbles and gravel to very fine silts and clays (Mitchell and Soga, 2005). The common clay minerals usually found in soils are Kaolinite, Illite and Montmorillonite. Kaolinite is a common phyllosilicate mineral in subgrades and is most abundant in soils of warm moist climates. The expansiveness is less evident in this mineral. Illite is known to exhibit moderate swelling. Figure 2.1 presents different types of minerals and their structures.

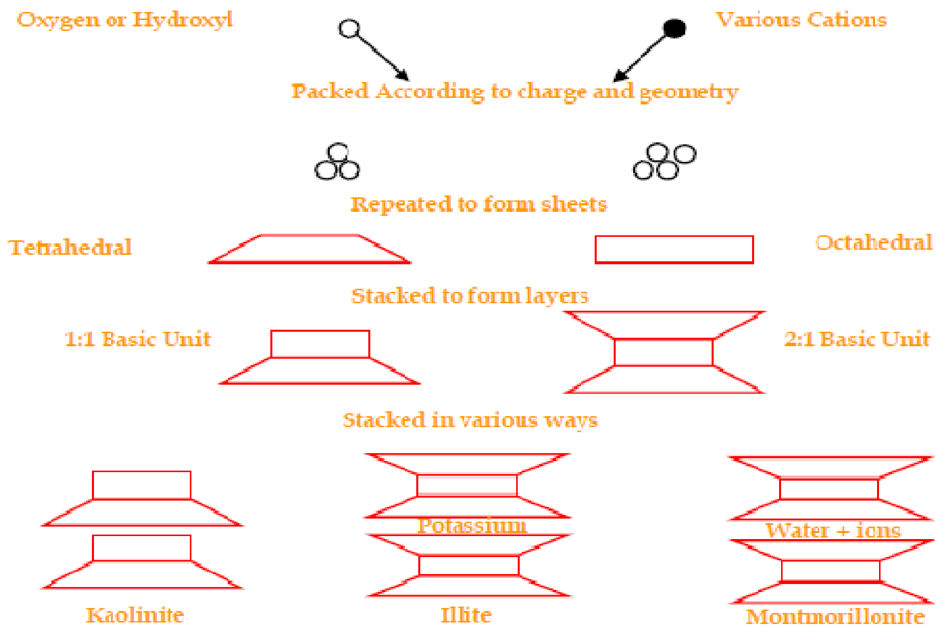


Figure 2.1: Figure showing the mineral structures of dominant clay minerals (Chittoori, 2008)

Montmorillonite is a member belonging to the Smectite group which includes other dioctahedral minerals such as Beidellite, and Nontronite, and the trioctahedral minerals Hectorite (Li-rich), Saponite (Mg-rich), and Sauconite (Zn-rich). Smectites commonly result from the weathering of basic rocks. The basic structural unit is a layer consisting of two inward-pointing tetrahedral sheets with a central alumina octahedral sheet. The bonds between layers are weak, allowing water and other molecules to enter between the layers causing expansion (Grim, 1953). These minerals are in small size and are concentrated in the fine clay fraction of soils. The alkaline environment and lack of leaching favor the formation of Montmorillonite (Smectite group) minerals in the soils (Abduljauwad, 1993). Smectites are known for their capacity to absorb large quantities of water and decrease the strength of the soil. The negative charge of Smectites and their expansive nature cause them to be extremely reactive in soil environments. Some soils exhibit same characteristics but different mineralogical contents which in turn lead to behavior differences (Teresa et.al 2004). The identification of any clay mineral is indirectly detected by tests such as cation exchange capacity (CEC), specific surface area (SSA) and total potassium (TP).

Because of the small particle size and interlayer expansion, Montmorillonite has high specific surface area values ranging from 600 m^2/g to 800 m^2/g. The range of CEC values for smectites is given by Borchardt (1989) as 47 to 162 meq/g. The structure of the mineral Montmorillonite is as shown in Figure 2.2

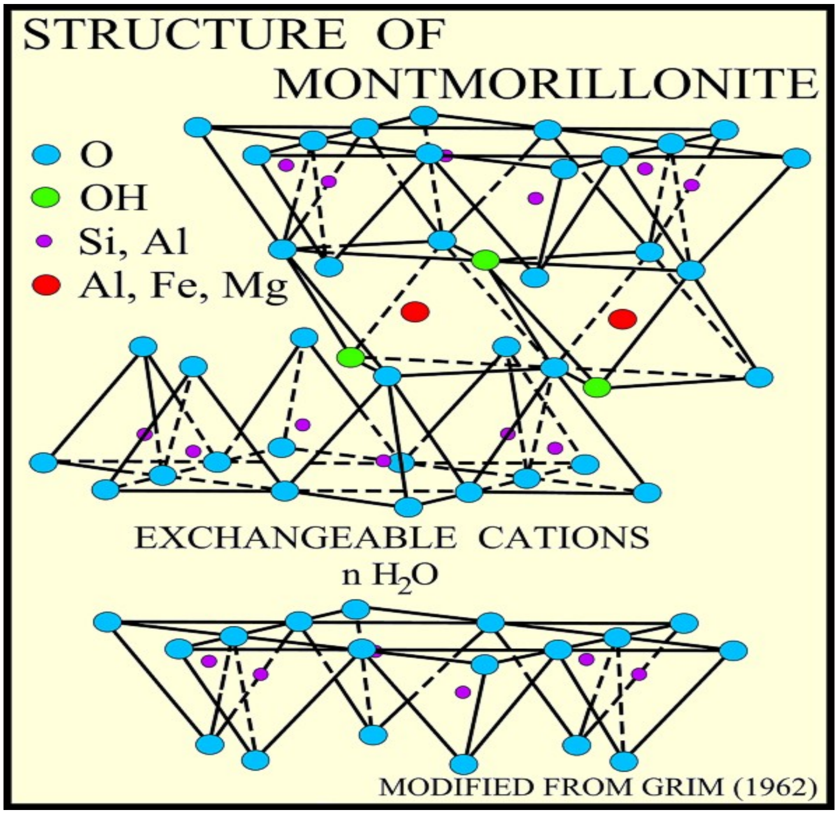


Figure 2.2: Mineral structure of Montmorillonite

(Source: http://serc.carleton.edu/images/NAGTWorkshops/mineralogy/montmorillonite_structure.jpg)

Procedures such as vibrational spectroscopy, thermal analysis, atomic absorption spectrometry and X-ray diffraction have been developed for qualitative identification of such minerals (Whittig and Allardice, 1986). Quantification of the clay minerals obtained with the help of properties such as CEC, SSA and TP were given much importance in the current research. In the previous research done by Chittoori (2008) the soil mineral percentages were identified based on the measurement of these properties.

2.3 Soil Stabilization

Soil stabilization proved to be an efficient and economical way of treating the non-ideal soils. Besides reducing the construction and maintenance costs, stabilization often improves the performance of base and sub-base materials of a pavement system enhancing riding comforts to the travelers. The properties that are altered by stabilization are shear strength, modulus, durability, stability and resistance to moisture. Extensive research was documented with regard to the engineering properties, reliability and durability of various types of stabilized materials (Tayabji et al., 1982 and Puppala et al., 2006). Petry and Armstrong (1989) stated that it was economical to perform initial stabilizations than performing remedial treatments later on with existing structures around.

Generally, the soil quality improvements through stabilization can be achieved through:

1. Reduction of plasticity index or swelling potential, and
2. Increase in durability and strength

The steps involved in the stabilization design are presented as follows.

2.3.1 Soil Exploration

Material sampling and testing is critical and is required to characterize material and physical properties that can affect the performance of the pavement structure. Field reconnaissance is crucial in order to know the conditions of the underlying strata that affect the performance of the pavement structure and treated layers.

2.3.2 Soil selection

The flow charts for the selection of base and subgrade materials and their testing followed by the TxDOT were given below in Figures 2.3 and 2.4.

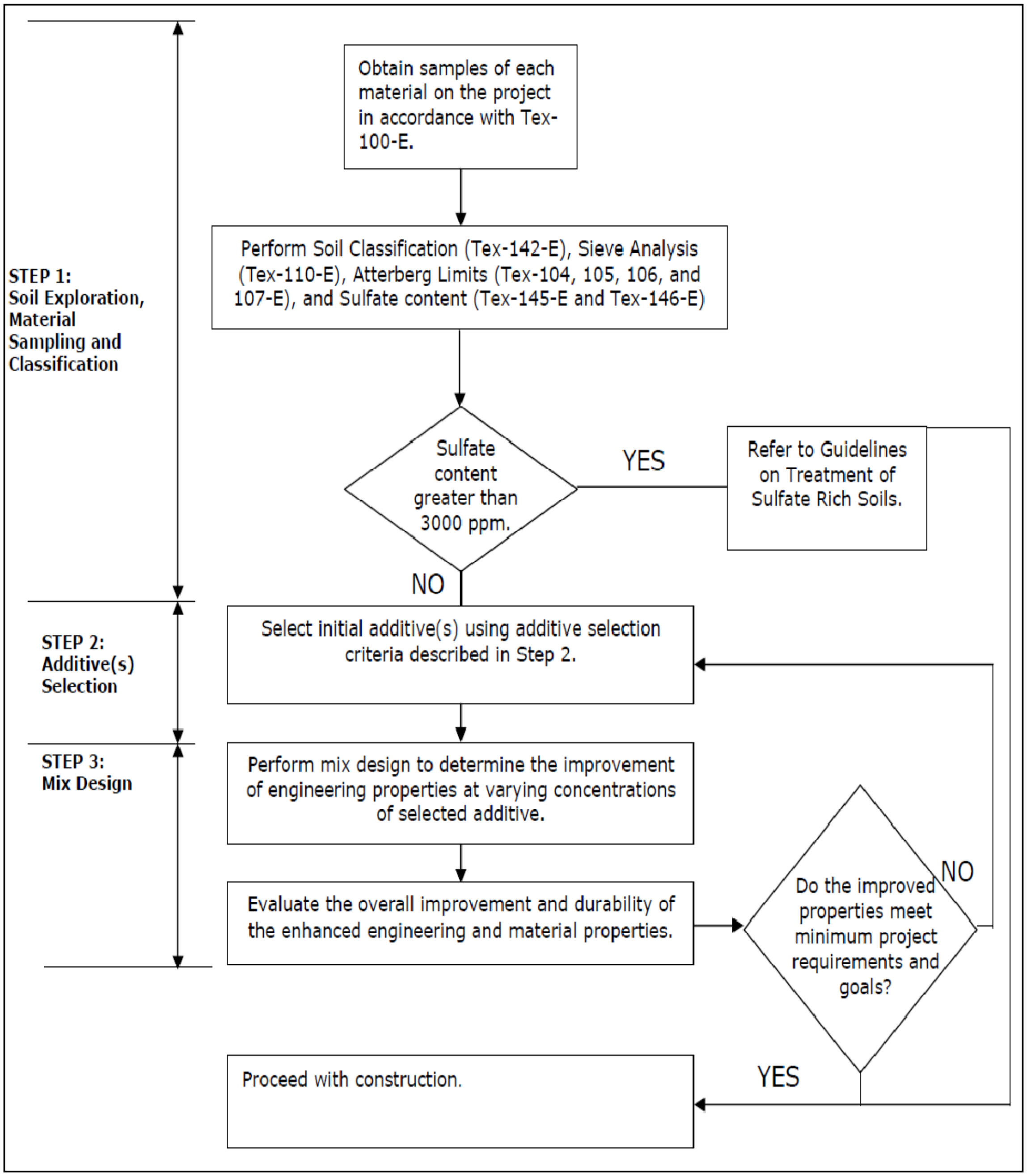


Figure 2.3: Flow chart for Subgrade soil treatment (TxDOT Guidelines)

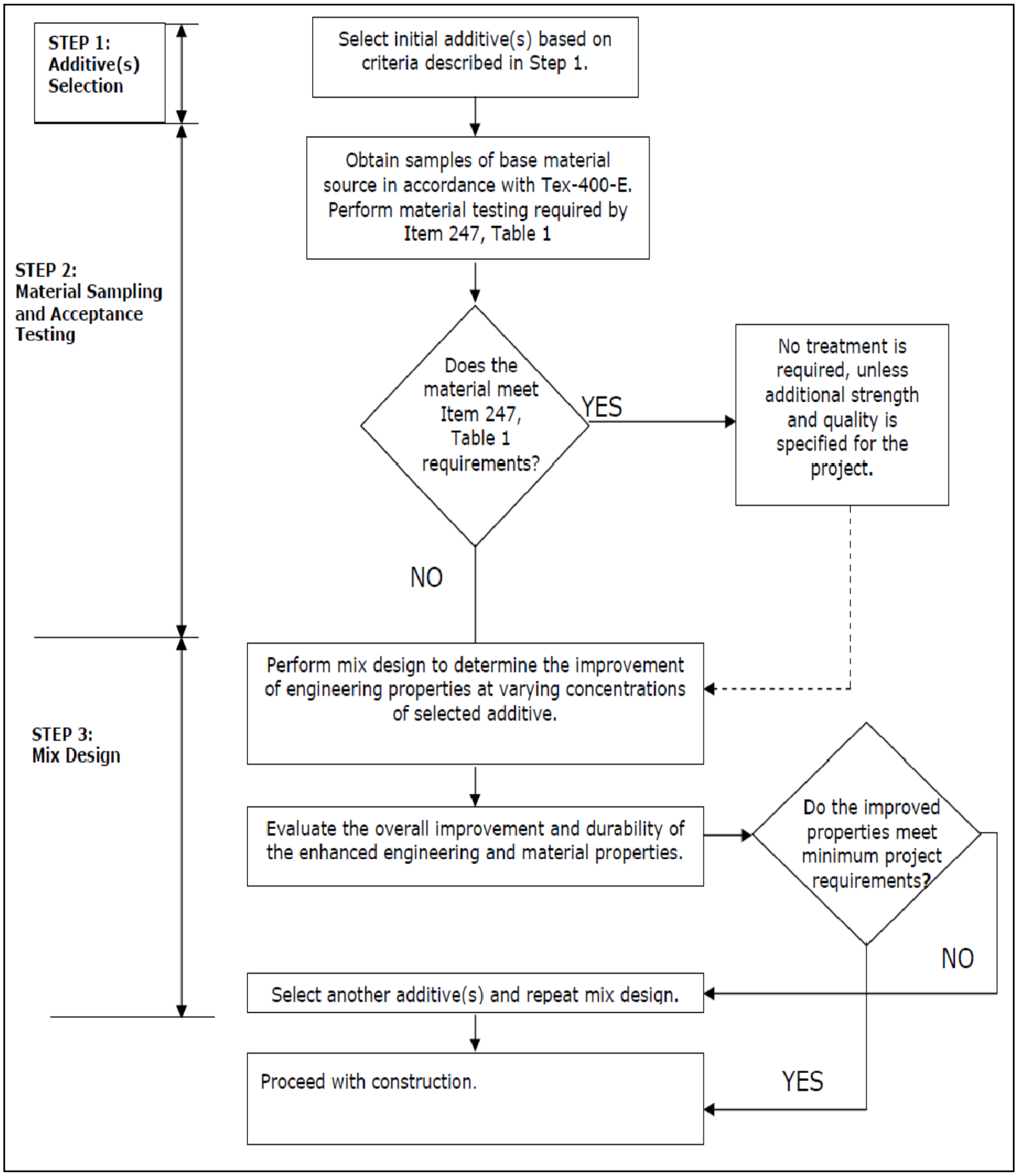


Figure 2.4: Flow chart for Base soil treatment (TxDOT Guidelines)

2.3.3 Additive selection

The selection and determination of the percentage of additives depend upon the soil classification and the degree of improvement in soil quality desired. In general, smaller amounts of additives are required to alter soil properties, such as gradation, workability, and plasticity. In order to improve the strength and durability of the soil efficiently the selection of type of stabilizer and optimum amount of dosage are of primary importance. In the current practice of soil stabilization selection of chemical additives is based on the plasticity index (PI) property and gradation of the soil (Wanyan et al., 2008). In order to select an appropriate additive the following factors have to be considered.

1. Soil mineralogy
2. Soil Classification
3. Desired goal for achievement of engineering and material properties (modulus and swell)
4. Mechanism of additives
5. Design life
6. Environmental conditions
7. Cost of the project

The Texas department of transportation (TxDOT) agency has provided a few design charts of stabilization design based on the physical properties of the soil. Both Figures 2.5 and 2.6 presents the stabilization selection steps for screening the chemicals for treating subgrade and base materials, respectively.

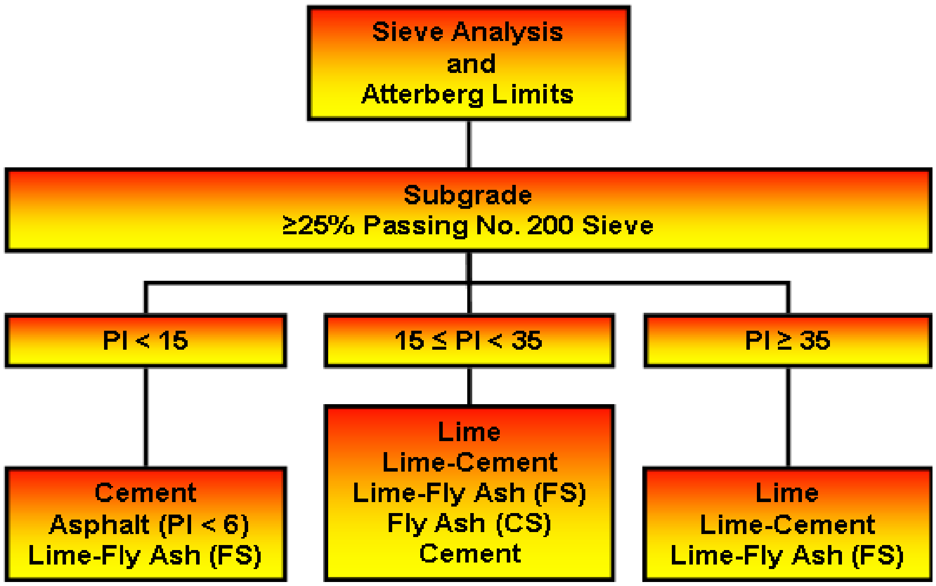


Figure 2.5: Additive selection criteria for subgrade material using soil classification (TxDOTguidelines)

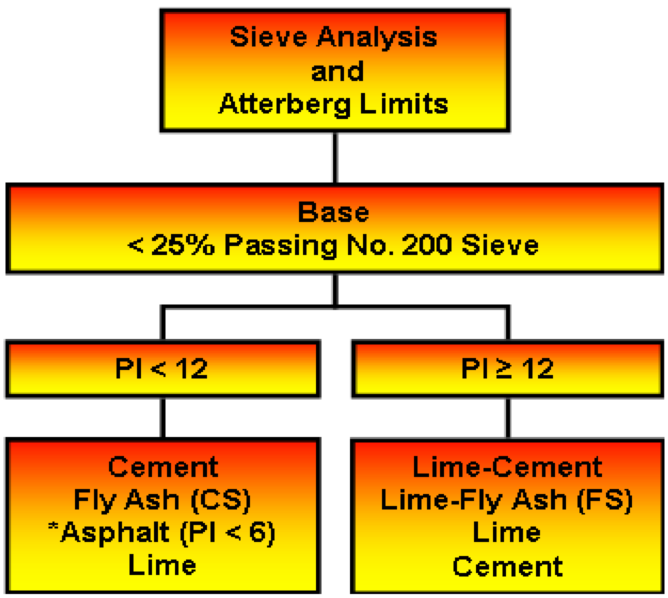


Figure 2.6: Additive selection criteria for base material using soil classification (TxDOTguidelines)

2.3.4 Selection of additive dosage

The procedure to get the adequate dosage of stabilizer is given in Tex-120-E for cement stabilization and in Tex-121-E for lime stabilization. TxDOT guidelines for estimating the dosage of stabilizer for cement is founded on the basis of unconfined compressive strength after moisture conditioning of the soil specimen in the laboratory. The amount of lime necessary to stabilize the soil is based on the pH method. This method, also known as the “Eades-Grim” test (Eades and Grim, 1966), is 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 reactions at this pH level. The lowest percentage of lime in a soil that produces a laboratory pH of 12.4 is hence treated as the minimum percentage for stabilizing the soil. A series of soil specimens with various lime percentages ranging from 0 to 10% are tested in the laboratory to determine the required amount of lime. In the research done by Bell (1996), three most frequently occurring minerals namely Kaolinite, Montmorillonite and Quartz were subjected to a series of tests such as X-Ray diffraction (XRD), Scanning electron microscope (SEM) and PI. Results showed that, with the addition of lime, the plasticity of Montmorillonite was reduced considerably. Also, all the minerals showed an increase in the moisture content and a decrease in plasticity when treated with lime. They also found that the optimum addition of lime needed for soil stabilization is between 1% and 3%, while other researchers (Wanyan et al., 2008) suggested the use of lime between 2% and 8% lime by weight. Generally, hydrated lime of 3% to 8% by weight is added to the top soil layer for stabilization (Nelson and Miller, 1992).

2.3.5 Compaction of treated soils

Static compaction is an efficient way of preparing the soil specimens, when compared to dynamic compaction method due to less possibilities of layering (Bahar et al, 2004). Though the dry density of the soil sample produced from dynamic compaction is high, static compaction is equally adopted to replicate field compaction conditions.

2.3.6 Current Status

Soil stabilization with lime and cement is an effective and economical way of stabilizing expansive clays (Al-Rawas et.al, 2005).

2.3.6.1 Lime stabilization

The findings from the previous studies show that when lime is added to clay soils in the presence of water, reactions including cation exchange, flocculation and pozzolanic reaction will take place. In the research conducted by Ninov and Donchev (2008) the pozzolanic reactions are noted to be taken place between lime and clay minerals and these treatments are studied in detail by using XRD and SEM methods. They found out that the strength gained in the first 6 months is due to the initially formed and hardened gelatin products of pozzolanic reactions involving the clay minerals. The phase changes of the calcium hydrosilicates takes place at longer storage time periods and leads to higher compressive strength values. Also, the studies reported in the literature showed that the addition of lime increased the optimum water content, shrinkage limit and strength, and reduced the swelling potential, liquid limit, plasticity index and maximum dry density of the soil.

The selection of the percentage of lime as an additive is usually based on the consistency limits, pH levels, and strength tests (Kezdi, 1979). In the process of application of lime in soil, an increase in the concentration of OH^- ions will increase the pH level, resulting in dissolved alumina and silica in the clay fraction (Thompson, 1968). The released alumina and silica interact with calcium ions from lime to produce two cementing agents of pozzolanic reaction. Those cementing agents are called Calcium Silicate Hydrate (CSH) {$3CaO \cdot 2SiO_2 \cdot 3H_2O$} and Calcium Aluminate Hydrate (CAH) {$3CaO \cdot Al_2O_3 \cdot Ca\ (OH)_2) \cdot 12H_2O$}, respectively, which cause cohesive soils to become more workable and less plastic. Narasimha Rao (1993) used both XRD and SEM techniques to successfully identify the formation of the compounds such as Calcium Aluminate Hydrate and Calcium Silicate Hydrate when the soil is treated with lime.

The stabilization process by the lime columns is controlled mainly by the lime migration. It is thus widely reported that lime migrates from the lime piles or columns and reacts with the surrounding soil resulting in stabilization of soil (Rogers and Glendinning 1997).

Rajasekaran et. al. (1997) conducted a series of mineralogical experiments to study the improvement in strength and durability of lime stabilized weak marine clays. X-ray diffraction (XRD) and Scanning Electron Microscope (SEM) were used to investigate the micro changes occurring at particulate level due to the addition of lime. The XRD patterns revealed the formations of pozzolanic products like calcium silicate hydrate and calcium aluminate hydrate. The formation of these compounds helps in binding the particles together and results in overall improved behavior of soil. SEM studies revealed that the soil system having porous media and aggregate formation helps in higher strength and stability. Also, it was found that the presence of sea water had no effect in the formation of CSH and CAH compounds.

When lime is added to the soil, the first reaction occurring is the replacement of the exchangeable ions by the calcium provided by the lime. The cation exchange is the first step to help in stabilization when a soil is stabilized chemically (Choquette et.al, 1987). In the research conducted by Choquette et. al. (1987) four soil samples were selected from different locations near Quebec and were subjected to a series of mineralogical tests using scanning electron microscope and X-ray diffraction. The properties of these soils were given in the Table 2.1

Table 2.1: Properties of the four soil samples (Choquette et.al. 1987)

Soil\Property	**% < 2μ**	**CEC (meq/100g)**	**PI**
Buckingham	42	16.8	30
St.Etienne	31	11.4	14
Jonquiere	43	14.8	22
St-Hyacinthe	66	21.4	31

Each soil specimen has been tested with three types of limes (hydrated, quick and ground limestone) and five water contents. The mixes were prepared in accordance with ASTM D 3551-76 method and compacted. The gain in soil strength with time in the treated soil sample is attributed due to the continuous formation of the products such as CAH and CSH (observed by the scanning electron microscope). The formation of these products is little initially, but after 300 days of stabilization the products are sufficient to provide maximum strength to the sample. All the samples were subjected to X-ray diffraction and scanning electron microscope to study the mineralogical properties of the soils. The soils were tested for shear strengths as shown in Figures 2.7 and 2.8.

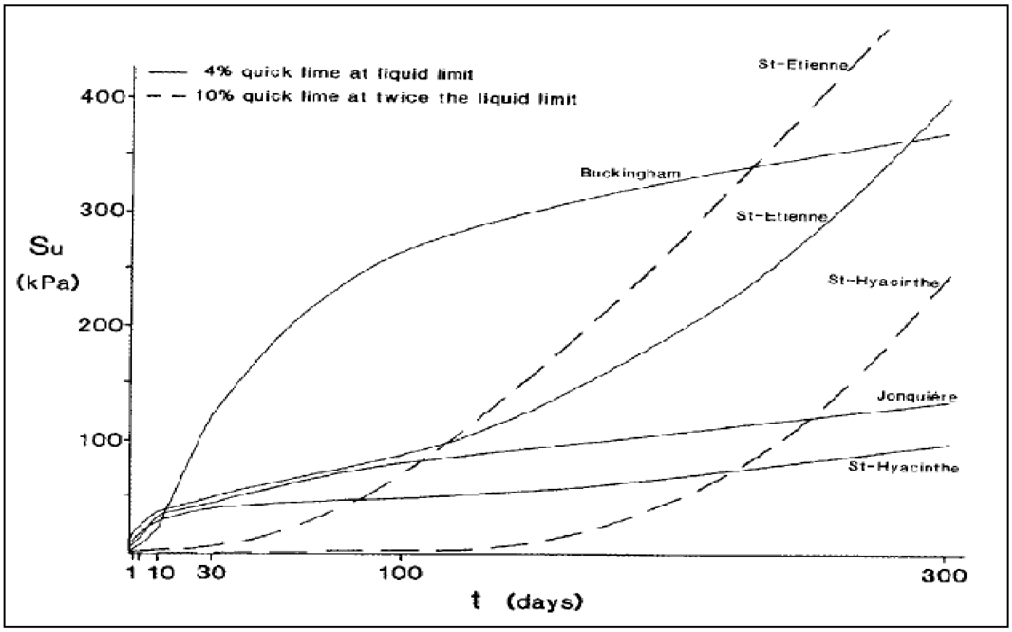


Figure 2.7: Strength of four soils treated with 4% lime as a function of curing time (Choquette et.al. 1987)

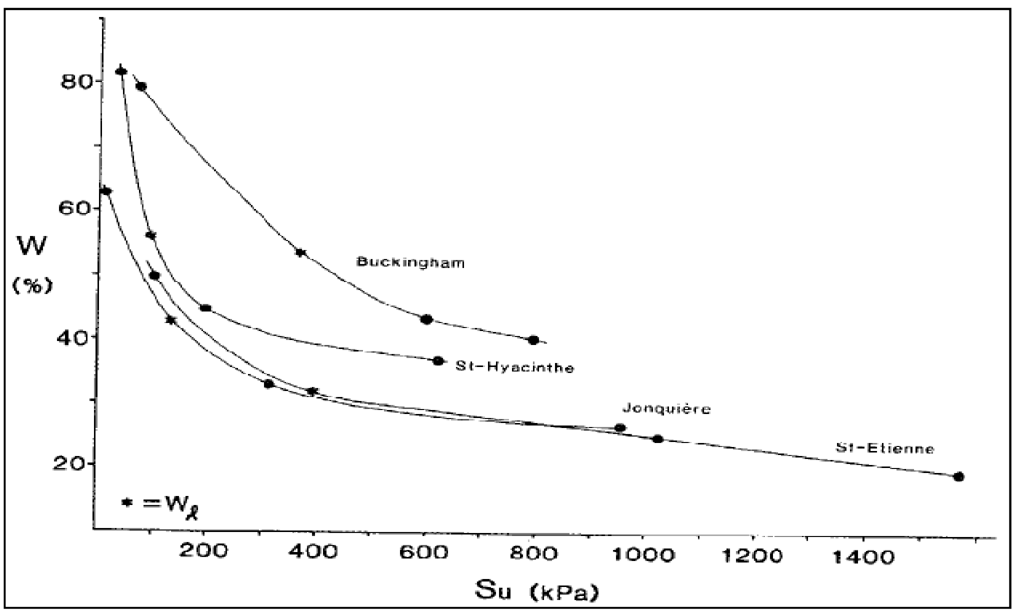


Figure 2.8: Strength after 300 days of curing for four soils treated with 4% lime as a function of water content (choquette et.al. 1987)

On the basis of clay mineral content of the soils, Choquette et al. (1987) came up with the order for best potential for lime stabilization, which is St-Hyacinthe, Buckingham, St-Etienne and Jonquiere. There were several other explanations for providing the hierarchy of the stabilized soil but the authors reveal that the potential for lime stabilization on the basis of clay mineralogy is of primary imporance.

Marshall and Frank (2007) studied the durability of cement stabilized expansive subgrade by pretreatment with lime. They found that lime treatment increased resistance to degradation of strength upon saturation.

In the research done by Mathew and Rao (1997) the effect of lime columns on the surrounding soil was studied in detail. The diffusion of lime in to the surrounding soil was confirmed by the increase in pH. Figure 2.9 presents the variation of cation exchange capacities of the soil surrounding lime columns at different time periods.

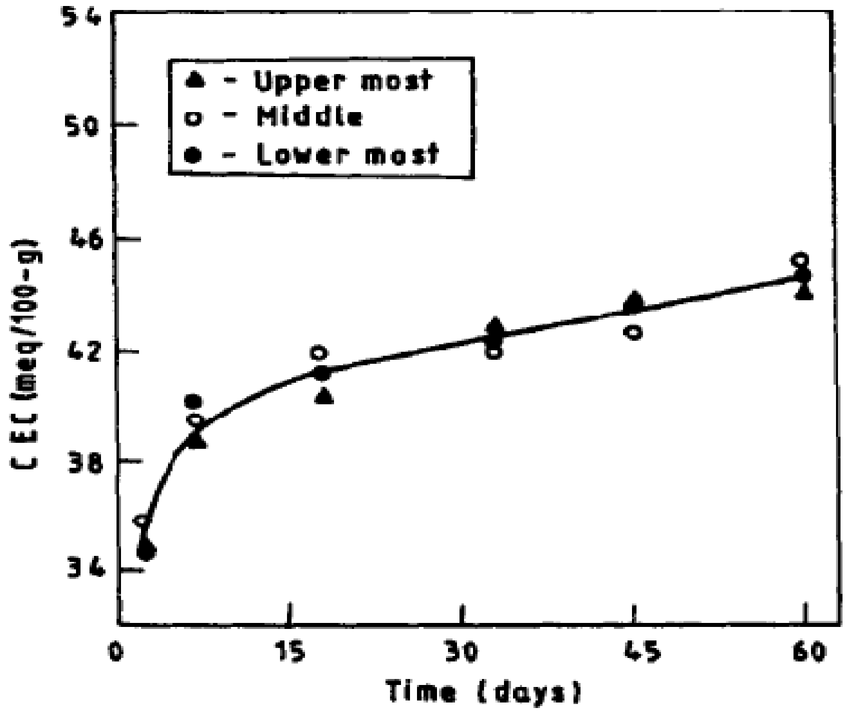


Figure 2.9: Variation of CEC with time in lime stabilized soils (Matthew and Rao, 1997)

This research proved that lime stabilization increases the pH as well as the cation exchange capacity of the soils.

In another research performed by Basma and Tuncer (1991) the effect of lime on the volume change and compressibility of expansive clays has been studied. It was found that, with increasing lime content, reduction in compression and rebound indices was achieved. Also, increasing lime content and curing time decreased primary consolidation and increased immediate settlement.

2.3.6.2 Cement stabilization

The cementing action of Portland cement with clay is similar to that of lime (Croft, 1967). Cement in soil stabilization increases the strength of the mixture and makes the soil structure brittle. In clay soils, the chemical reaction of cement and soil is responsible for soil property improvement. The interaction between the lime and clay minerals play an essential role in terms of the soil cement interaction process. The mechanism of the latter will be similar to that of a lime–clay interaction, as previously addressed (Yong et al., 1996 and Aiban et al., 2006). Raymond et.al (2006) conducted several experiments on lime/cement stabilized marl soils. The results of this study indicate that the very common method of studying soil stabilization focuses attention on mechanical aspects of soil performance and is not capable of evaluating the failures and instability of stabilized marl.

In another research conducted by Stavridakis (2004), an effective measure was developed to restrict the swelling of cement treated soil when soaked in water. Soil specimens were studied for UCS and swell pressure tests. A relationship between final adsorbed water content and UCS was postulated. Finally, it was found out that higher amount of cement dosages helps in the improvements of UCS strength, stiffness and durability of the clay sample.

2.4 Durability studies

Durability studies are conducted on the soil specimens to replicate the field climatic conditions in the laboratory in a short time frame. The procedure to replicate the field moisture and temperature fluctuations is achieved by subjecting the soil sample to wetting and drying cycles according to ASTM D 559 method. Two similar specimens of each soil/additive combinations are prepared at the optimum moisture content. The lime-treated soil specimens are prepared after mellowing for 12 hours, 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 48 hours according to the standards.

Rao et al. (2001) conducted a study to assess the long-term performance of stabilized black cotton soils. In the research done by Rao et al., lime was used in the stabilization of black cotton soils and found out that the effect of lime stabilization is partially lost after four cycles of wetting and drying cycles. The increased clay content has considerable effect on the Plasticity Index and swelling potential of the soils. Figure 2.10 shows the variation of swelling potential for different lime treated black cotton soil specimens.

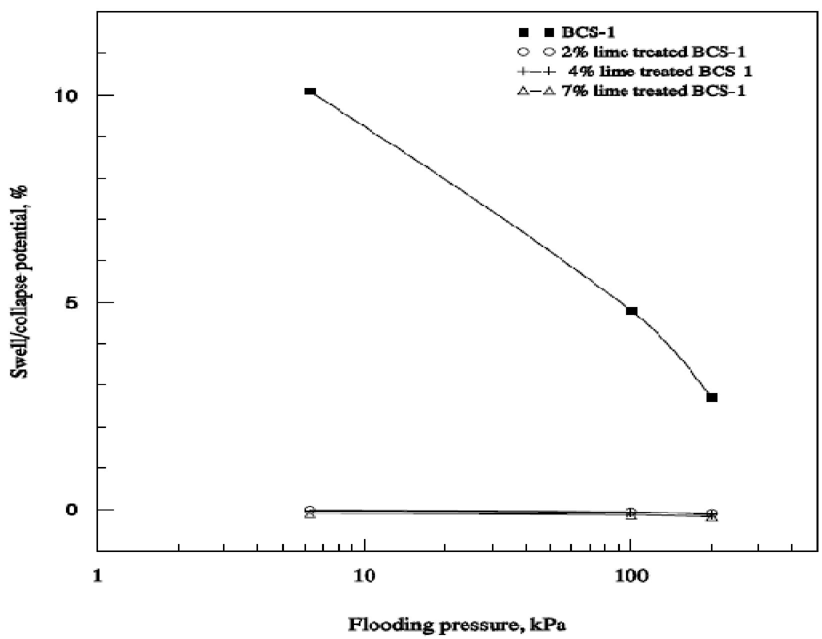


Figure 2.10: Effect of lime on swelling pressure of black cotton soils (Rao et.al., 2001)

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 2.11.

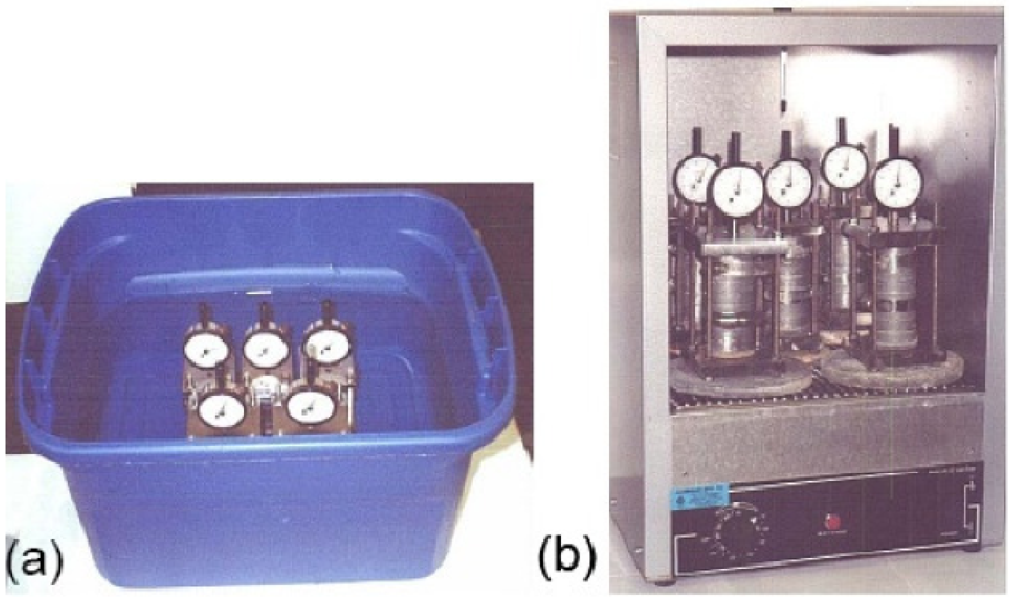


Figure 2.11: (a) Wet and (b) Dry cycles by Hoyos et al. (2005)

In the research conducted by Young and Ouhadi (2007), the cause of failures in the lime treated and cement treated marl soils were studied. A set of phisio-chemical and mechanical experiments such as specific surface area (SSA), X-Ray Diffraction and california bearing ratio (CBR) were conducted to study the nature of natural and stabilized marl soils. Results from XRD and SSA studies showed that the formation of mineral Ettringite helps in increasing the swelling potential of the marl soil. Figure 2.12 shows the variation of PI with increase in lime dosage. Figure 2.13 shows the presence of mineral Ettringite in the treated marl soils.

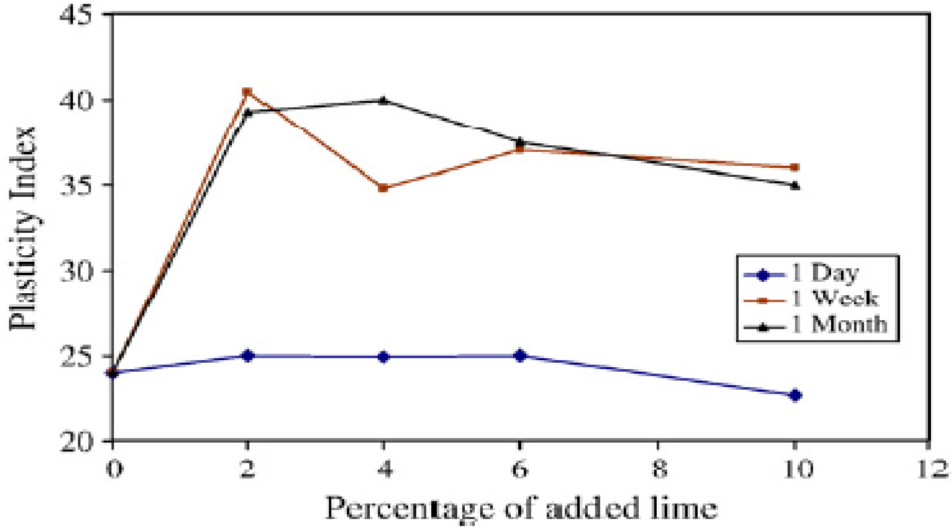


Figure 2.12: Showing the variation of PI with lime dosages (Yong and ouhadi, 2007)

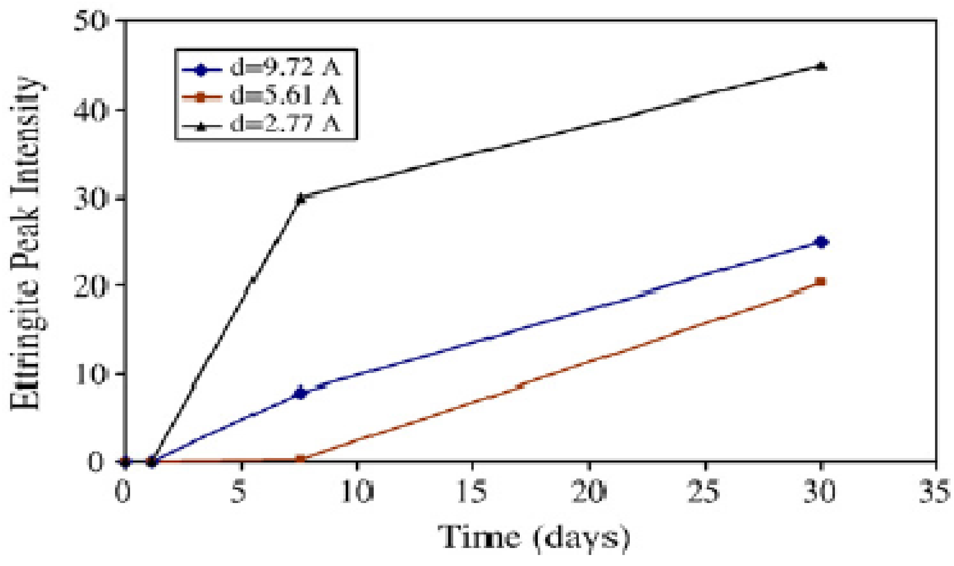


Figure 2.13: Variation of Ettringite peak intensiity in lime stabilized marl (Yong and ouhadi, 2007)

2.4.1 Study by Chittoori (2008)

Chittoori, (2008) conducted experimental investigations on soils having different percentages of Illite, Montmorillonite and Kaolinite. The soils were sampled from different regions in Texas and were highly expansive. The soils shown in Table 2.2 were subjected to accelerated curing since it was proved that accelerated curing produces better results in a short period of time to the standard curing test given by ASTM. The specimens were subjected to durability studies by alternating wetting and drying. Both volumetric changes and strength loss were monitored and presented for all the soil samples at various cycles.

2.4.1.1 Soil I (Pharr-A)

This soil comprises of 50% Montmorillonite, 25% Kaolinite and 25% Illite. The soil had a plasticity index of 45 and was classified as high compressible fat clay. Based on the PI design procedures (Tex 120 E for Cement and Tex 121 E for Lime) the soil was stabilized with 4% lime and 4% cement.

Figure 2.14 demonstrates the variation of UCS strengths of this soil with wetting/drying cycles. Both the untreated and treated conditions are depicted. The untreated specimens failed after 2 cycles whereas the treated specimens survived for 4 cycles of wetting/drying. It can be observed that the soil specimen did not survive 21 cycles of wetting and drying. Figure 2.15 presents the volumetric strain of the treated and untreated specimens of Pharr-A with wetting/drying cycles.

The maximum volumetric strain exhibited by the untreated soil was around 60% for 1 cycle of wetting and drying where as when treated with 4% lime restricted the strain to 30% for 4 cycles of wetting and drying.

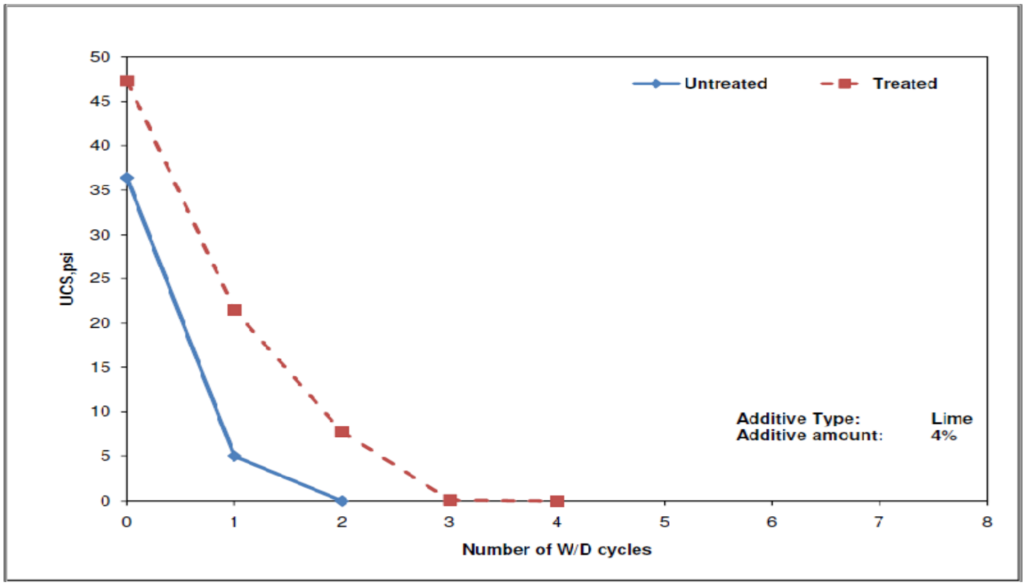


Figure 2.14: UCS strengths of Pharr-A specimen at different w/d cycles (Chittoori, 2008)

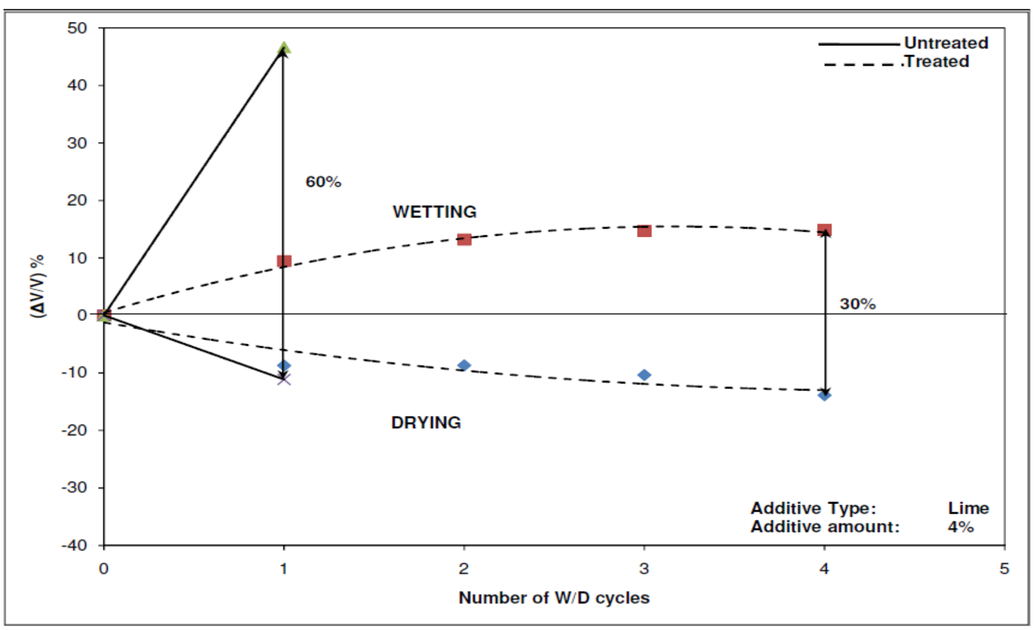


Figure 2.15: Volumetric change of Pharr-A specimen with W/D cycles (Chittoori, 2008)

Though the volumetric change was reduced to 30% the stabilized soil was still considered as problematic as it is not within the threshold limit of 5% volumetric strain.

Similar studies were conducted on Pharr-A soil specimen when treated with 4% cement. The specimen did not last all 21 cycles of wetting and drying. The soil specimen exhibited a maximum volumetric strain of 31% when treated with 4% cement. Both the treatments (lime and cement) could not result in durable treatments of the soils that lasted all 21 test cycles. This revealed that these soils when treated with lime or cement exhibit problems with time.

2.4.1.2 Soil II (Pharr-B)

Experiments conducted on the Pharr B soil specimen revealed that the mineralogical contents of this soil as 20% Montmorillonite, 50% Kaolinite and 30% Illite. The soil had a PI of 37 and was classified as a highly compressible clay (CH). The soils were stabilized with 3% lime and 3% cement, (design procedures based on PI) and the durability and strength of the stabilized soils were studied in detail. Figure 2.16 presents the variation of UCS strengths with wetting/drying cycles when the Pharr-B soil specimen was stabilized with 3% lime and with 0% lime (untreated).

The untreated sample failed after 2 cycles where as the treated sample collapsed after 8 cycles of wetting/drying. The specimen did not last for 21 cycles of wetting and drying. The maximum volumetric strain exhibited by the untreated soil was around 26% for 1 cycle of wetting and drying where as when treated with 3% lime restricted the strain to 18% for 8 cycles of wetting and drying. Though the volumetric change was reduced to 18% the stabilized soil was still considered as problematic. Figure 2.16 presents the variation of UCS results with wetting/drying cycles for lime treated M20 soils.

Similar studies were conducted when Pharr-B soil specimen when treated with 3% cement. The treated soil specimen survived until 15 cycles of wetting/drying. The maximum volumetric strain exhibited by treated soil specimen was 13% for 14 cycles of wetting and drying.

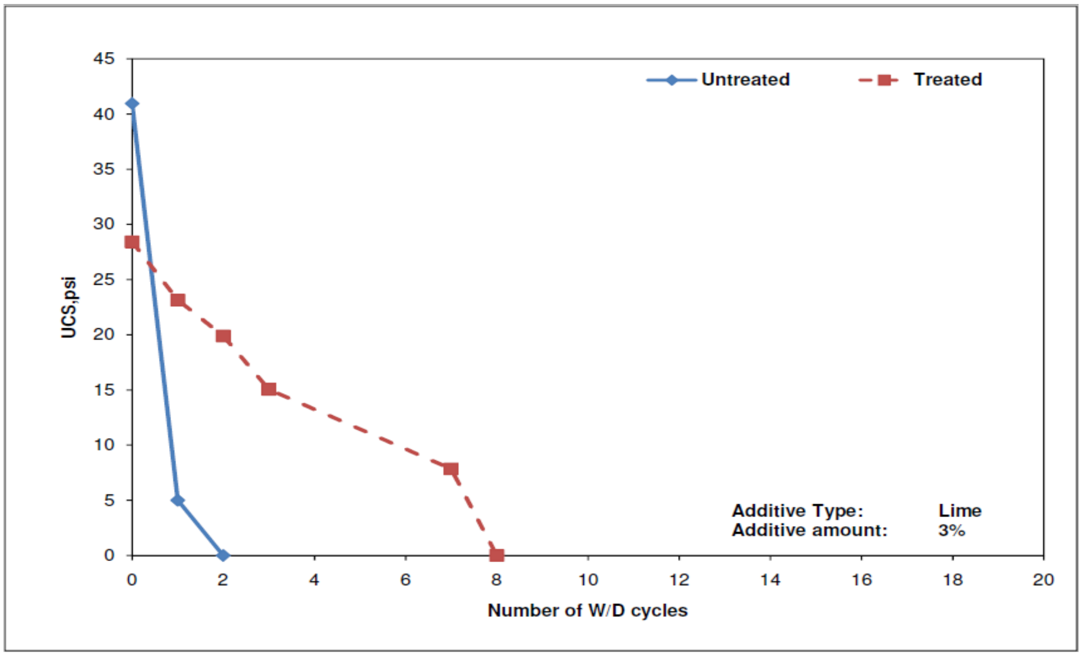


Figure 2.16: UCS strengths of Pharr-B specimen (3%lime) at different Wetting/Drying cycles (Chittoori, 2008)

Both the treatments (lime and cement) could not last for all the 21 cycles. This revealed that these soils when treated with lime or cement in low dosages exhibits premature cracking on the pavement after few years of service due to the loss of the effect of chemical treatment in the treated subgrade layers.

2.4.1.3 Soil III (Austin)

Mineralogical tests conducted on this specimen revealed the contents of the soil as 40% Montmorillonite, 35% Kaolinite and 25% Illite. The high Montmorillonite percentage and a PI close to 34 shows that the soil was highly expansive. The soil was treated with 6% lime suggested by the design charts which are based on PI. Figure 2.17 demonstrates the variation of UCS strengths with wetting/drying cycles when the Austin soil specimen was stabilized with 6% lime. The untreated specimen failed after 2 cycles where as the treated specimen collapsed after 12 cycles of wetting/drying. The treatment with lime did not last for all the 21 cycles.

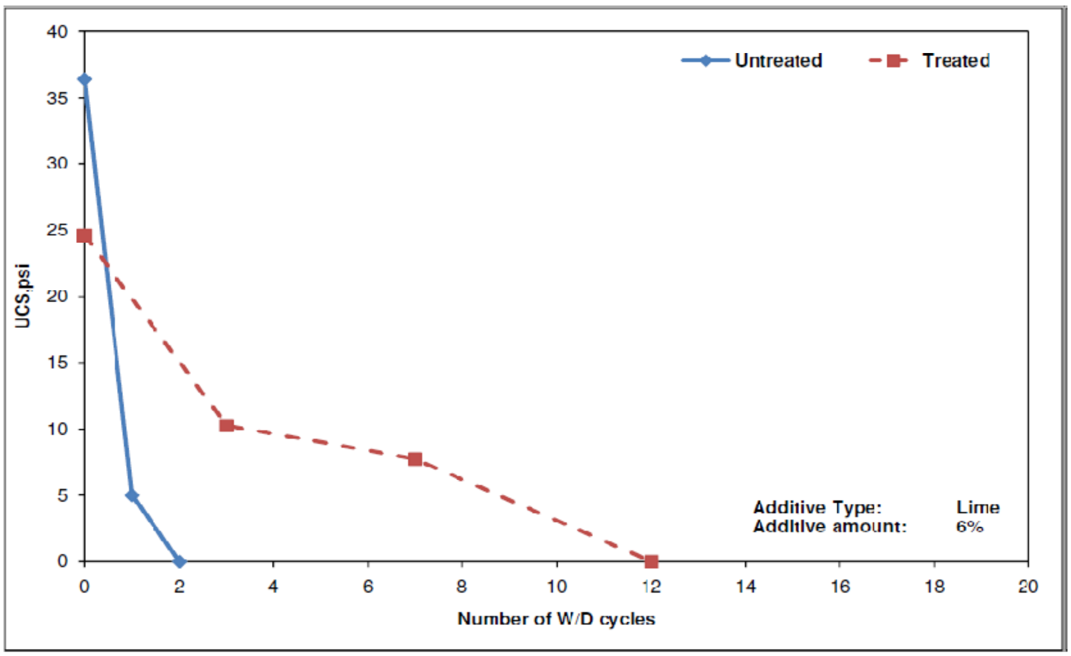


Figure 2.17:UCS strengths of Austin soil specimen at different cycles (Chittoori, 2008)

The maximum volumetric strain exhibited by the untreated soil was around 50% for 1 cycle of wetting and drying where as when treated with 6% lime survived 12 cycles of wetting and drying with a strain of 15%. Though the volumetric change was reduced to 15% the stabilized soil was still considered as problematic as it is not within the threshold limit of 5% the volumetric strain. This showed that these soils when treated with low dosages of lime exhibits premature cracking on the pavement after few years of service due to the loss of the effect of chemical treatment in the treated subgrade layers.

2.4.1.4 Soil IV (Fort Worth)

The soil consists of 60% Montmorillonite, 24% Kaolinite and 16% Illite minerals. The plasticity index of the soil is 32 and is classified as high compressible clay (CH). In accordance with the design charts based on PI the soil sample was stabilized with 6% lime and was studied for durability and strength.

Figure 2.18 displays the variation of UCS strengths with wetting/drying cycles when the Fort Worth sample was stabilized with 6% lime and with 0% lime (untreated). The untreated specimen failed after 1 cycle where as the treated sample collapsed after 11 cycles of wetting/drying. The treatment with lime did not last for all the 21 cycles.

This showed that these soils when treated with low dosages of lime exhibits premature cracking on the pavement after few years of service due to the loss of the effect of chemical treatment in the treated subgrade layers

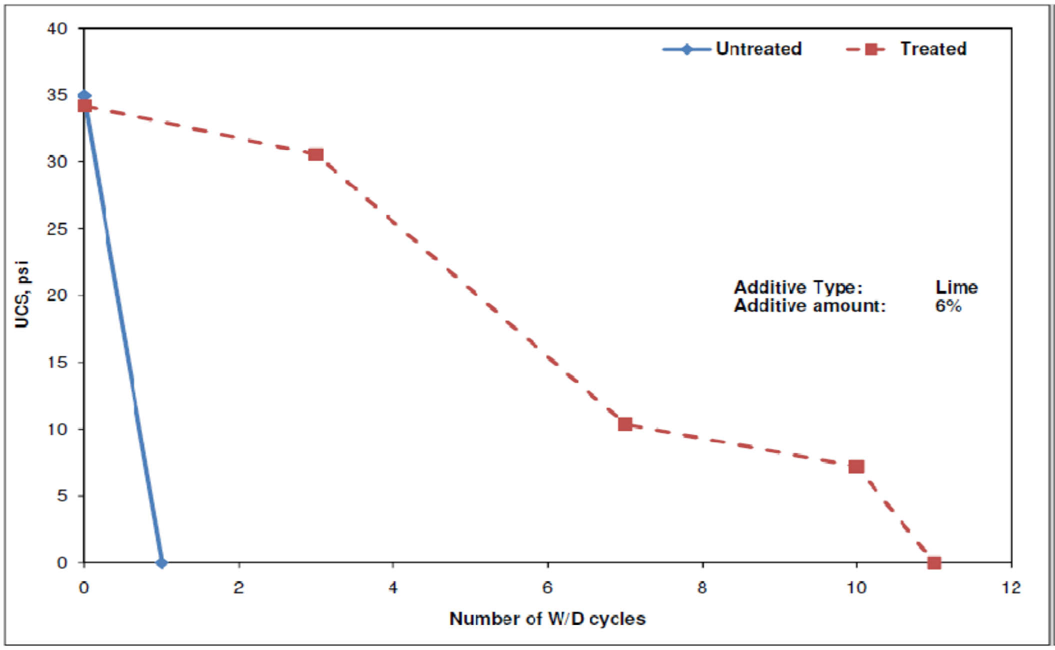


Figure 2.18: UCS strengths of Fort Worth specimen at different Wetting/Drying cycles (Chittoori, 2008)

Table 2.2 presents the number of cycles survived by both untreated and treated soil specimens having different contents of mineral Montmorillonite. All the soils have failed before 21 cycles of wetting and drying. Failure of the soil specimens is defined when the sample attained a residual strength of zero during wetting/drying cycles. Since these soil samples have failed before 21 cycles of wetting and drying, the stabilization method used in the present research for this soil was deemed not effective.

Table 2.2: Number of survivable cycles of each 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 of soil

Leachability of the soil sample is a parameter used to measure the permanency of the stabilizer on the soil. 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. In the research conducted by Thompson (1968) the direct influence of leaching on the properties of soil such as soil pH, percentage base saturation and calcium/magnesium ratio is predominant. He also 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.

Yong et al. (1985) showed that the leaching has considerable influence on the strength of the soil specimen. Yong et.al (1985), conducted studies on soils specimens that are leached with distilled water to study the effect of leaching on strength and found that the strength of the soil sample decreased when leached.

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 confinement of the soil sample will be higher than the pressure of the water which is sent through the soil sample. The leachate coming out of the soil sample is collected and is tested for calcium and pH studies. This experiment simulates a field condition of a soil subjected to leachate after some time period. Chittoori (2008) conducted calcium leaching studies on the four soil samples with various leachate cycles

Figure 2.19 shows the leachate apparatus used by McCallister (1990) and Chittoori (2008). Table 2.3 presents the variation of the calcium concentrations after 14 leachate cycles.

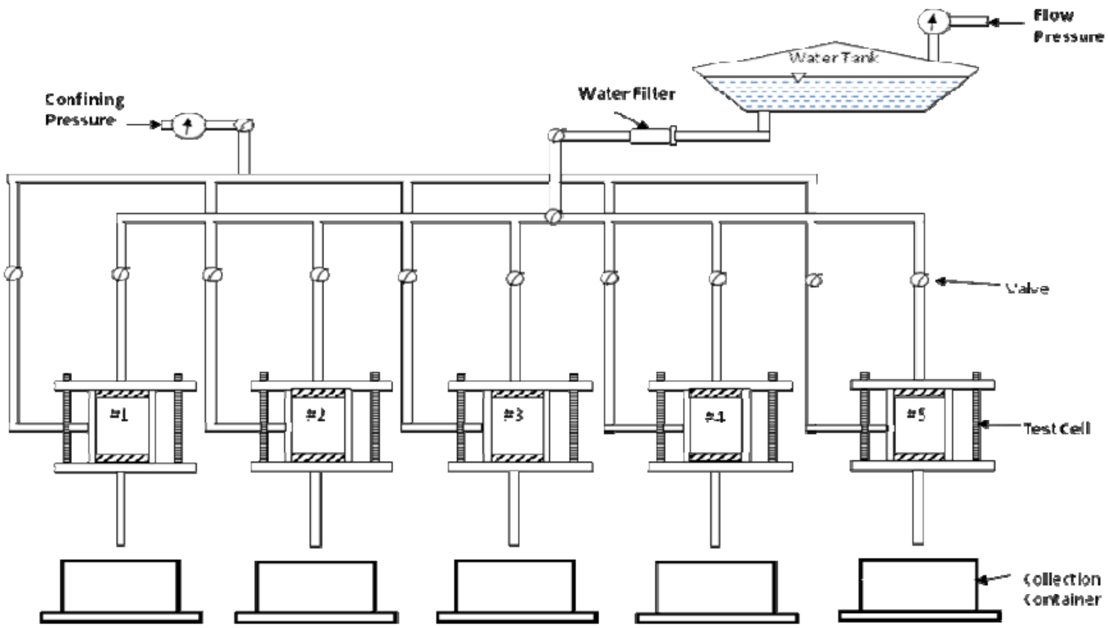


Figure 2.17: Schematic of the leachate apparatus used by Chittoori, (2008)

Table 2.3: Calcium concentrations of different 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
Pharr A	4% Cement	310	200	14
Pharr B	4% Lime	200	200	14
Pharr B	4% Cement	420	400	14
Austin	6% Lime	720	340	14
Fort Worth	6% Lime	560	400	14

Each cycle was calculated on the basis of one pore volume of the leachate flushed through the soil sample. All the treated soil samples were tested for the percent calcium coming out of the specimen, which in turn will explain the probable loss of stabilizer. The procedural steps for the calculation of pore volume and determination of calcium coming out of a soil sample are given in chapter 3.

2.6 Summary

This chapter reviewed the research conducted on expansive soils and their mineralogy. Previous literature cited on mineral Montmorillonite is presented in this chapter. Research conducted on the cation exchange capacity of soils is discussed. Then the current stabilization procedures followed by the Texas department of transportation were summarized. Previous research conducted by Chittoori (2008) was presented in detail to address the stabilization effectiveness when design procedures based on PI were used for Montmorillonite dominant soils. Finally, the issues with respect to the loss of stabilizer and the durability were covered. In the next chapter detailed test procedures for the different methods followed in the current research were presented.

CHAPTER 3

EXPERIMENTAL METHODOLOGY

3.1 Introduction

The research work is executed in two phases. The first phase constitutes the identification of the soils and their Montmorillonite (MM) content. Several soils with different amounts of MM were selected for this phase. Montmorillonite, a mineral from the Smectite group has high swelling potential and is reckoned to be the major mineral in mitigating the stabilization process when present at certain levels. As a result, due consideration was given in selecting the soil specimens having different percentages of MM. The selected soils were then subjected to durability tests and the engineering behavioral changes occurring within the specimen were studied in detail.

The second phase comprised of testing the stabilized select soils for durability investigations, by subjecting the compacted and cured soil specimens to various cycles of wetting and drying. The soil samples were also tested for potential leaching of the stabilizer from water infiltration. Leachate apparatus was designed and used to replicate moisture infiltration in the field from rainfall events.

In this chapter, detailed information on different test procedures followed and equipment used for simulating the field moisture fluctuations are presented. Figure 3.1 explains the experimental methodology followed in the current research.

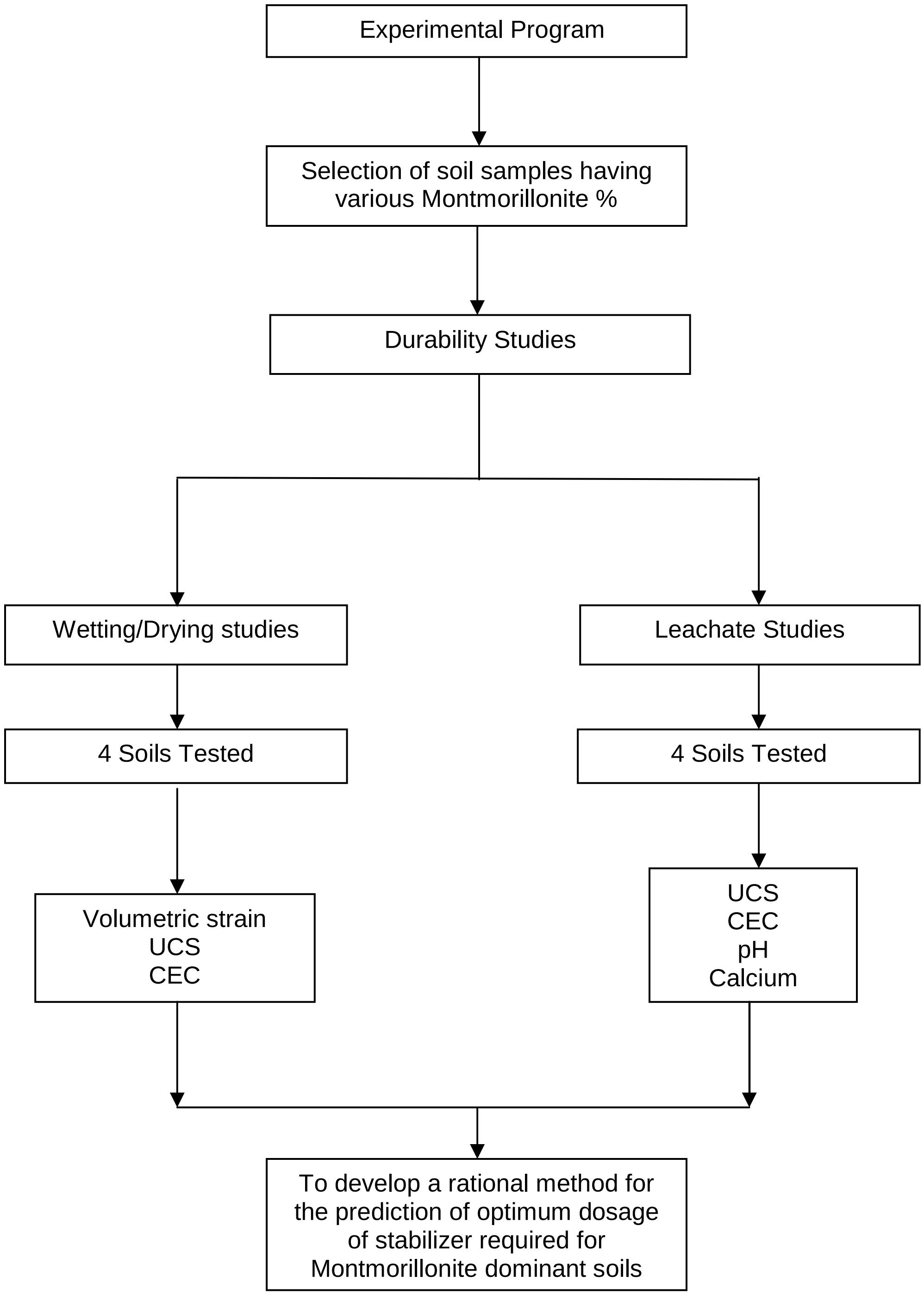


Figure 3.1: Flow chart detailing the experimental methodology adopted in the current research

3.2 Tests conducted on untreated soils

3.2.1 Soil selection and preliminary tests

A total of four soils collected from different regions of Texas were selected for this study. In a previous study conducted by Chittoori (2008) at UTA, four soil types namely Pharr-A, Pharr-B, Austin and Fort Worth (all soils named after the place from which they were extracted) were collected and tested for durability tests.

The soils were subjected to preliminary tests in order to determine their index properties. As per Tex-110-E method, sieve analysis test was conducted to obtain the grain-size distribution of all four soils. Sieve analysis provides the percent amount of various size fraction of the soil including percent fines. The distribution of particle size of the soil retained on No.200 sieve is determined by sieve analysis, while the same for the portion passing through No.200 sieve is determined by the hydrometer analysis. The distribution of the grain sizes in test materials finer than 0.0075 mm was determined using TxDOT procedure Tex-110-E. Table 3.1 shows the percentage of soil passing the No.200 sieve for all the four soils.

Test procedures to obtain the maximum dry density and optimum moisture content using proctor compaction test were explained in the following sections.

3.2.2 Standard Proctor compaction tests

Standard Proctor compaction tests were conducted on all soils to determine the optimum moisture content and dry unit weight of the soils in the present research program. 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 due to low volume of voids. Tex-114-E procedure was followed to determine the optimum moisture content and maximum dry density of the control as well as treated soil specimens.

3.2.3 Atterberg limits

Upon addition of water, the state of soil changes from dry, semi-solid, plastic and finally to liquid limit states. The water content at the boundaries of these states are known as shrinkage (SL), plastic (PL) and liquid (LL) limits, respectively (Lambe and Whitman, 2000). Also known as Atterberg limits, the above mentioned soil properties are essential to correlate the shrink-swell potential of the soils to their respective plasticity indices. LL is known as the water content at which the soil flows and PL is determined as the water content at which the soil starts crumbling when rolled into a 1/8-inch diameter thread. The numerical difference between LL and PL is known as plasticity index (PI) and characterizes the plasticity nature of the soil. Representative soil specimens from different locations as mentioned before were subjected to Atterberg limit tests to determine LL and PL following Tex-104-E and Tex-105-E, respectively. Table 3.1 explains the index properties of the control soils from the four site locations.

Table 3.1: Soil classification and plasticity chart

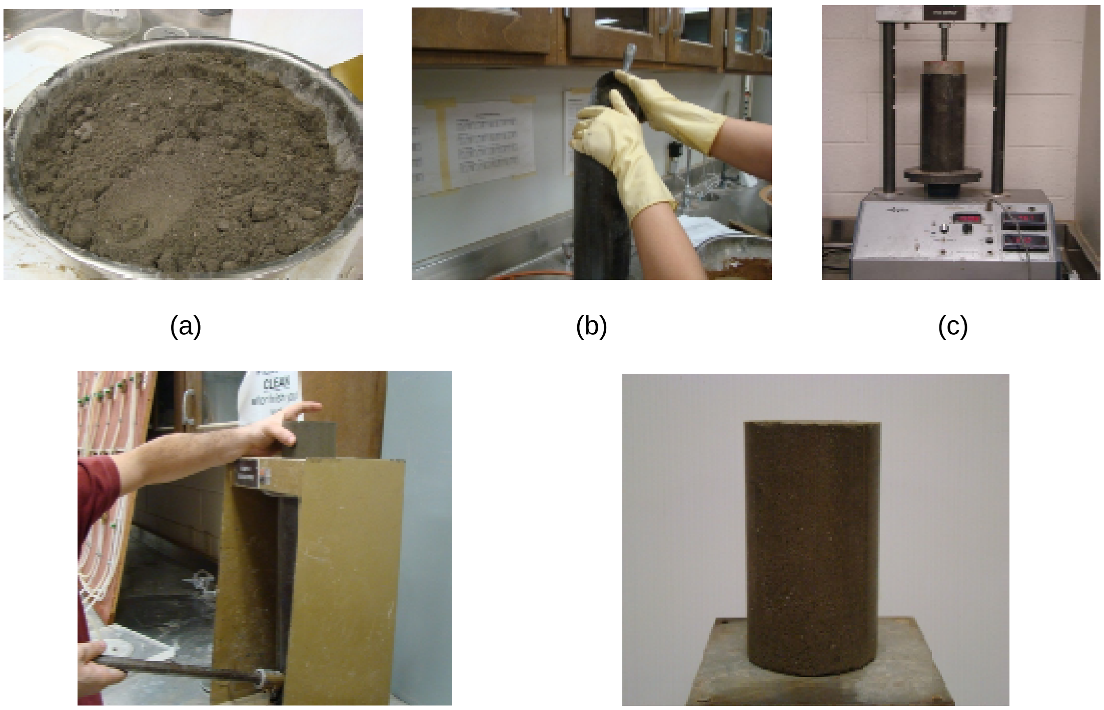
Soil	% Passing No. 200 sieve	LL	PL	PI	USCS classification
Pharr A	98	67	22	45	CH
Pharr B	97	56	19	37	CH
Austin	95	51	17	34	CH
Fort Worth	89	61	29	32	CH

3.2.4 Specimen preparation

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 given below:

1. The amount of material required to make a soil specimen is calculated on the basis of the desired dry density, degree of compaction and optimum moisture content.
2. A metal mould used to prepare the specimen is cleaned and is lubricated for free 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 gets compacted as force is applied on the top surface and is finished when the top of the block flush with in 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 extracted from the mould with the help of a hydraulic jack.

Detail procedural steps are shown in Figure 3.2.



(a) (b) (c)

(d) (e)

Figure 3.2: Showing sample preparation procedure (a) Prepared soil mixture (b) Soil filled in to the mould (c) Soil is being compacted (d) Extraction of soil sample using a hydraulic jack (e) Extracted soil specimen

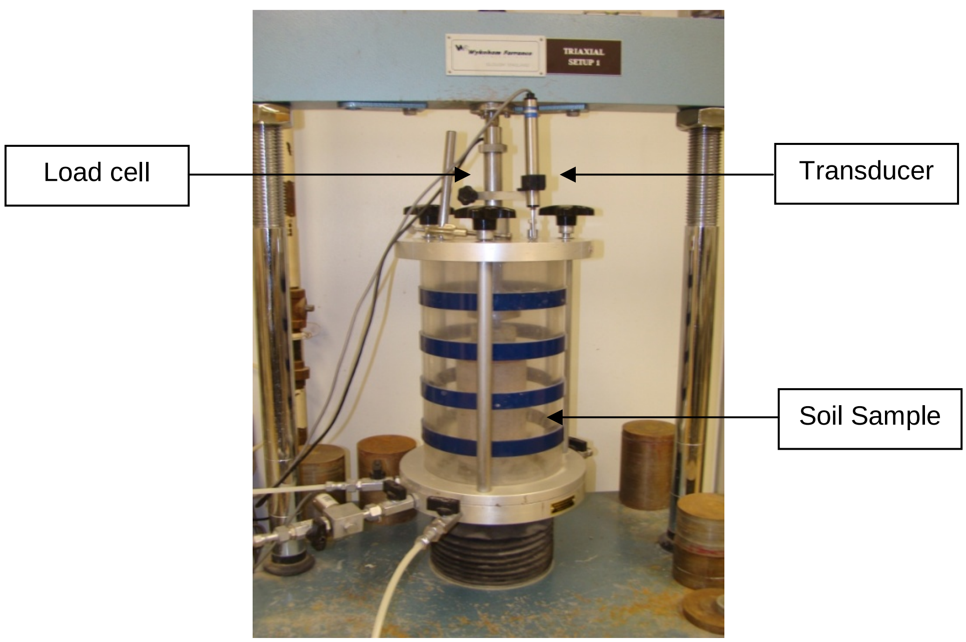
3.2.5 Strength tests

Unconfined compressive strength (UCS) tests were carried out on untreated as well as cured soil specimens. All the soil specimens were 6 inches (150 mm) in height and 4 inches (100 mm) measured diametrically. The soil specimen after desired number of wetting/drying cycles 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 load cell as shown in the Figure 3.3(c). Once the specimen is loaded at a constant strain rate, and as the load approaches the ultimate load, failure cracks would begin to appear on the surface of the soil specimen as shown in Figure

3.3(b). Both deformation and corresponding axial loads on the soil specimen were recorded using the data acquisition system features.

(a)

(b)



(c)

Figure 3.3: (a) showing the prepared soil sample (b) showing the the failed specimen (c) test equipment

Figure 3.3 (a) presents the Austin soil sample to be tested for strength after desired number of wetting and drying cycles. Figure 3.3 (b) shows the sample when it reached its limit strength. Figure 3.3(c) shows the unconfined compressive strength testing unit used.

Strength tests were conducted after the completion of desired number of wetting and drying cycles. Figure 3.4 shows the variation of load and axial strain for the Pharr-A soil specimen under the UCS test.

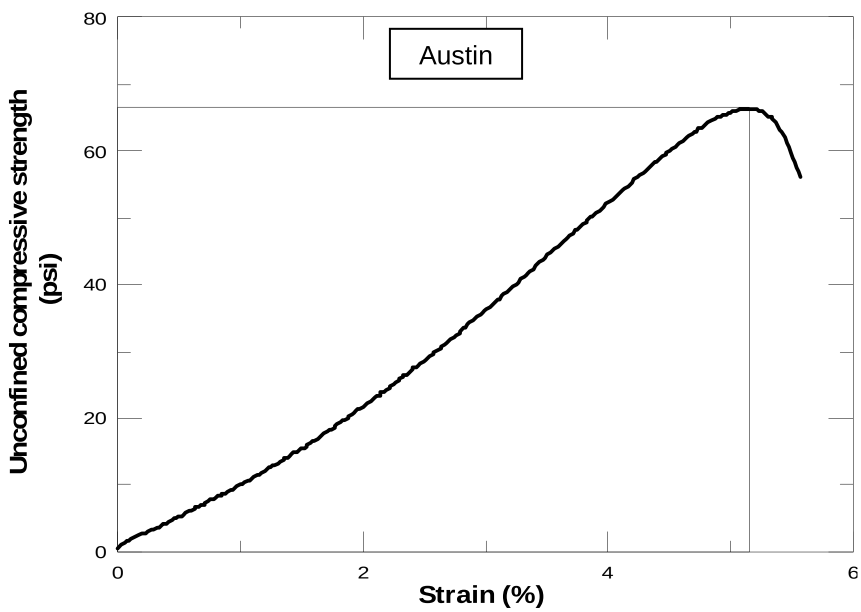


Figure 3.4: Stress strain plot for Austin soil specimen after 3 cycles of wetting and drying

The specimen is subjected to its limit load at 68 Psi with a strain of 5.2%. The soil sample failed after reaching its limit strength as shown in Figure 3.3(b).

3.2.6 Cation exchange capacity

The cation exchange capacity (CEC) of a soil is defined as the ability of the soil to exchange free cations available at the exchangeable locations. Cation exchange capacity is the measure of the net negative charge on the soil particles resulting from isomorphous substitution and broken bonds at the boundaries. The CEC was measured in meq/100g (milliequivalents of cations per 100 gram of soil particles) or cmolc/kg (centimoles of charge per kilogram of dry soil) (Terzaghi et al, 1996). The CEC represents the expansive nature of the soil specimen. For example, a specimen with high CEC value indicates the high expansive nature of the soil due to the presence of mineral Montmorillonite, whereas low CEC value indicates the presence of minerals like Kaolinite and Illite. One of the earliest methods proposed by Chapman (1965) was used in the current research. The method involves addition of a saturation solution and then removal of the adsorbed cations using an extracting solution as given in the Figure 3.6

The saturating solution used in the current research is ammonium acetate (NH_4OAc). The soil sample is mixed with the saturating solution and allowed to stand for a period of 16 hours. This step is to ensure all the exchange locations are occupied by the NH_4^+ ions. The solution is then filtered through a Buchner funnel and washed with 5 additions of 25 ml NH_4OAc each. The step exposes all the cations replaced by the NH_4^+ ions. Excess NH_4OAc was removed by the addition of 8 different 10ml additions of 2-Propanol. The CEC of the soil sample is known if the amount of ammonium ions is determined. This can be obtained by washing the sample with 8 different 25 mL additions of 1M potassium chloride (KCl) solution. Figure 3.5 shows the apparatus used for the determination of CEC.

(a) (b)

Figure 3.5: (a) apparatus used and (b) spectrophotometer for the determination of cation exchange capacity (CEC)

Though potassium ion (K^+) has similar electro negativity it has higher molecular weight and has the ability to substitute the $NH4^+$ ion. The concentration of $NH4^+$ in the KCl extract gives the CEC of the soil. The detailed step by step procedure of the test is given in the flowchart shown in Figure 3.6

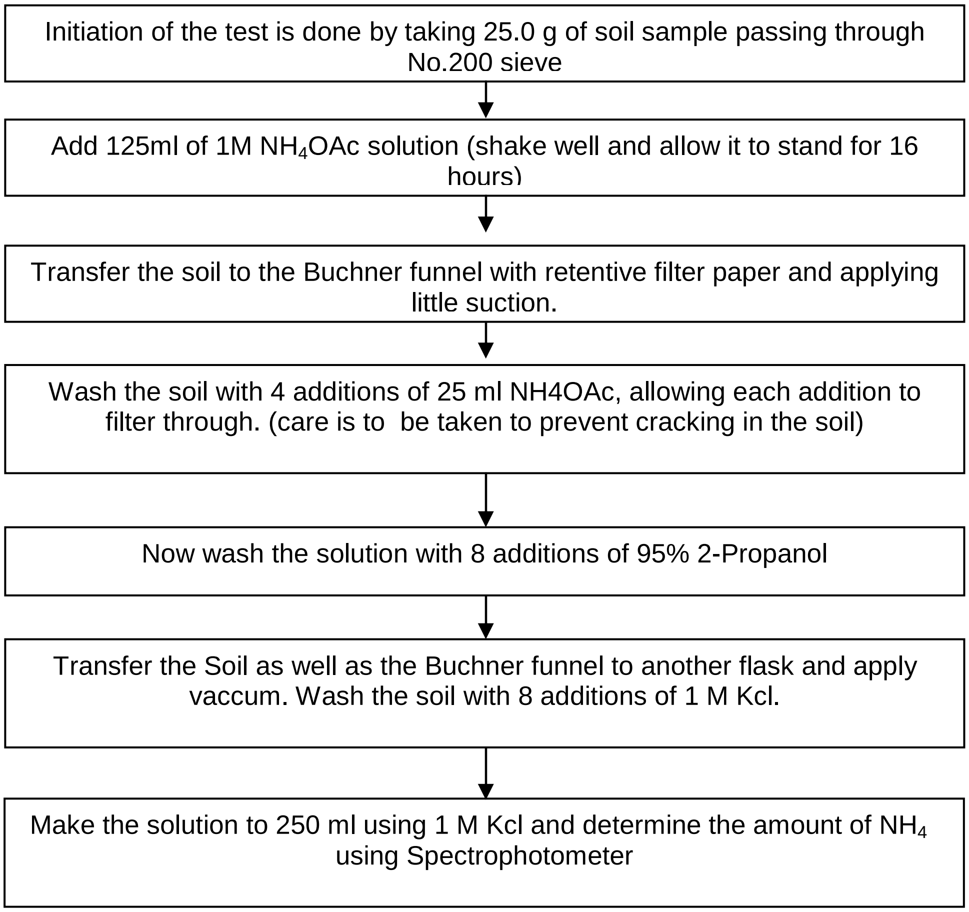


Figure 3.6: Showing the procedural flow chart to determine the CEC of a soil

3.3 Tests conducted on treated soils

3.3.1 Stabilizer mix design

The major objective of the stabilizer mix design was to determine the optimum dosage of stabilizer by evaluating engineering properties of soil with various dosages of stabilizer.

The importance of mix design is reflected in the following areas:

1. Establishing optimum dosage of stabilizer
2. Reducing cracking and other types of premature failures

3. Optimization of engineering properties to the design standards.

A detailed step by step procedure is followed to obtain the optimum additive content for the selected soils is shown below

3.3.1.1 Selection of stabilizing agent

As described in the previous chapter, TxDOT follows the stabilization chart based on PI for the selection of additive dosage.

3.3.1.2 Determination of the dosage of stabilizing agent

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 CO_2 is added to these mixtures. The samples are then shaken in an Eberbach shaker for 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. Typical plot used for calculation of optimum lime dosage is given in Figure 3.7

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 before. The soil specimen was ready for testing after it is cured.

Accelerated curing was adopted as this approach has facilitated a quick testing of these treated soils (Chittoori, 2008). In this method, initially the soil specimens were subjected to drying by placing it in an oven heated at 104^{o} F for 48 hours. The dried soil specimen was then subjected to back saturation for a period of 24 hours. All the soil specimens were subjected to curing before being studied for durability and leachate studies.

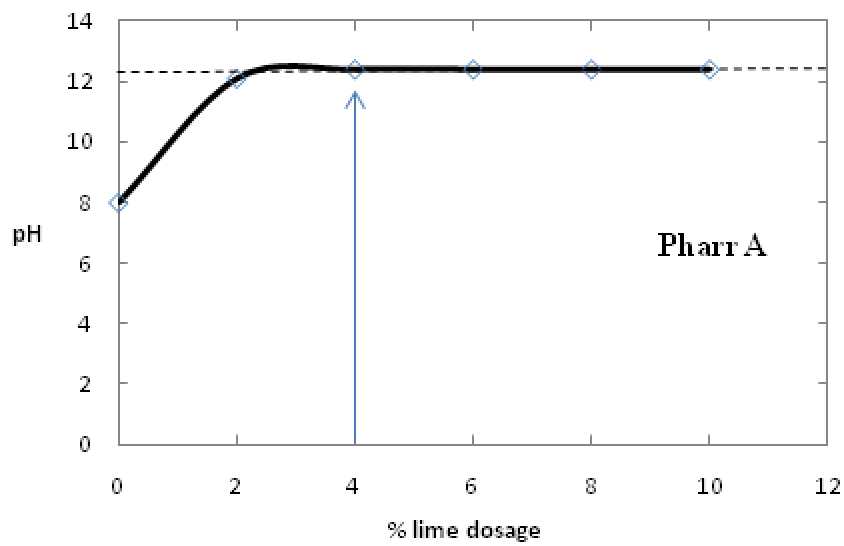


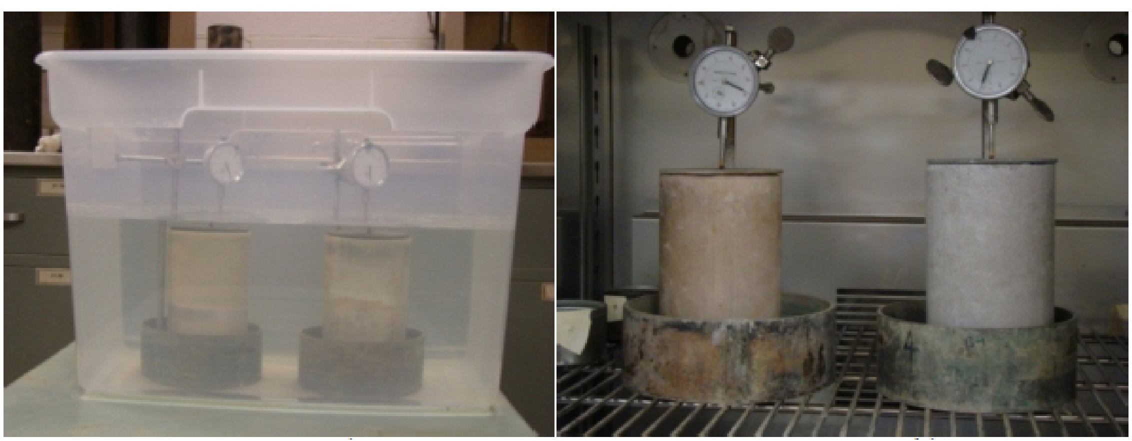
Figure 3.7: Plot showing the variation of pH with Lime dosage for Pharr A specimen

3.3.2 Durability Tests

Durability studies are conducted by subjecting the soil specimens to alternative wetting and drying processes. ASTM D 559 method is the standard method often used for these wet-dry cycle investigations. During these cycles, the volumetric strain, strength and stiffness are studied. Identification of these properties helps us in studying how the soil responds to the stabilizing agent and its dosage. The following section explains the test procedure.

3.3.2.1 Wetting and Drying

The wetting and drying of soil specimens were carried out on the basis of ASTM D 559. The method simulates both wetting and drying conditions close to field conditions within a short period of time. Three dimensional deformations of the soil specimens are allowed in this test. 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. The measurements of the vertical deformations are done by using dial gauges on the top and the diametrical changes by pi tape. The soils were subjected to unconfined compressive strengths at 0, 3, 7, 14 and 21 cycles of wetting/drying. The test is continued till 21 wetting/drying cycles or till the sample fails. Figure 3.8(a) shows how the specimen test apparatus was submerged in the water and Figure 3.8 (b) showing the specimen being dried in an oven.



(a) (b)

Figure 3.8: (a) Showing wetting of soil specimen and (b) drying of soil specimen

The soil specimens were submerged for a period of 5 hours to complete one wetting cycle. Similarly the soil specimens were transferred to an oven as shown in the Figure 3.8(b) and were subjected to a temperature of 160ºF for a period of 42 hours to complete one drying cycle. Together they constitute one cycle of wetting and drying. Dial gauge readings are monitored to assess the effectiveness of stabilization with time.

After desired number of wetting and drying cycles, the soil specimens were subjected to unconfined compressive strength (UCS), CEC and 3-D volumetric strain tests as discussed before.

3.3.3 Leachate studies

This test was introduced by McCallister (1990) to address the permanency of chemical stabilization from water percolating through the soil specimen from rainfall and moisture migration. The setup used in the current research is similar to the one used by McCallister (1990) and Chittoori (2008).

The lime and cement 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 cured soil specimen was subjected to moisture flow from a water tank at a constant head. A few 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.

3.3.3.1 Calculation of void ratio

Void ratio determines the amount of pore volume present in the soil specimen. The amount of leachate coming out of the specimen could be determined if the total pore volume is calculated. Details of the calculations are presented in Figure3.9.

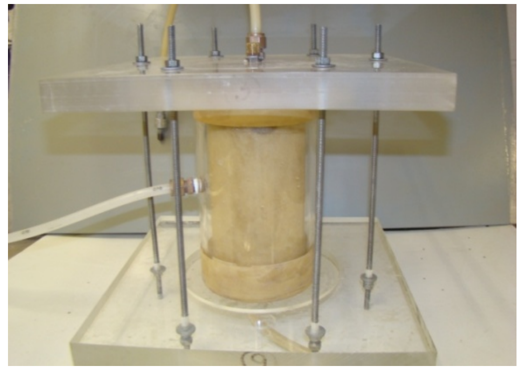
Dry unit weight (γ_d)	= 90 pcf
Unit Weight of water (γ_w)	= 62.4 pcf
Specific gravity (G_s)	= 2.7
Height of the sample (h)	= 6.5 in
Diameter of the sample (d)	= 4 in
Total volume $V = \frac{\pi d^2 h}{4}$	= 1340 ml
Void ratio $e = \frac{\gamma_w}{\gamma_d} G_s - 1$	= 0.89
Volume of solids $V_s = \frac{1}{1+e} * V$	= 715 ml

Figure 3.9:Showing the steps for the calculation of pore volume of Pharr-A soil

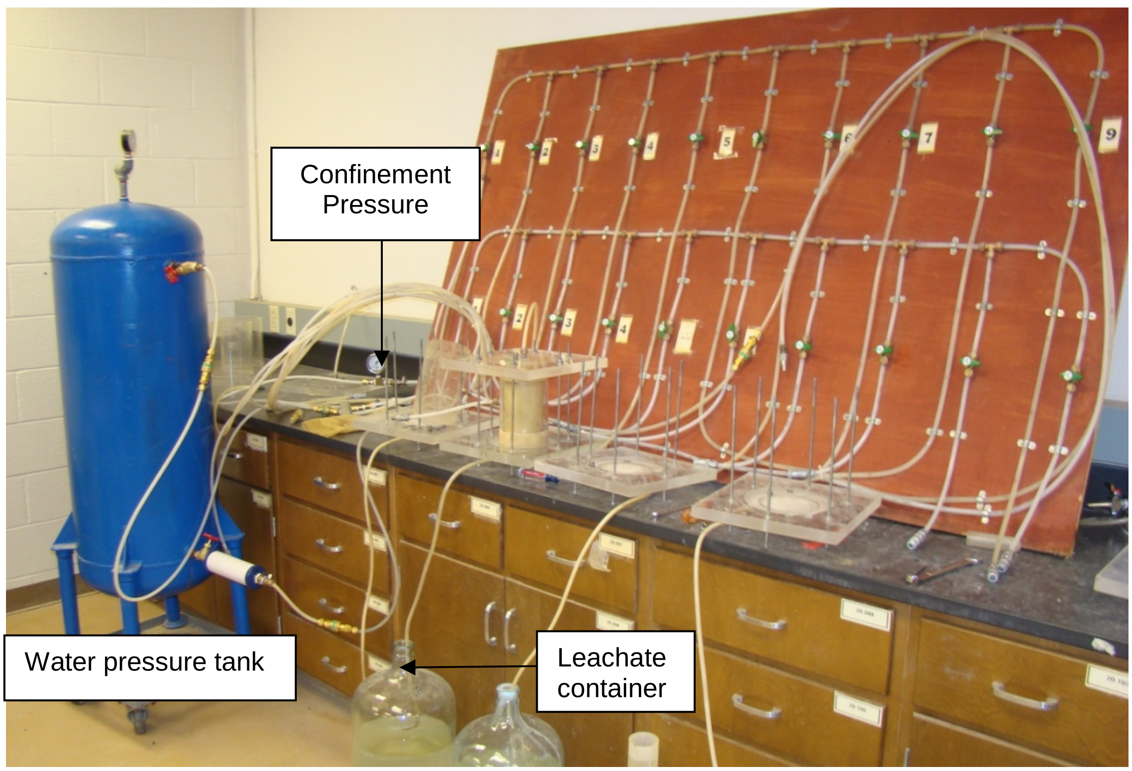
One leaching cycle here is defined as the amount of leachate volume collected that is equal to one soil specimen's void volume. The cured soil specimens were placed in the sample cells as shown in the Figure 3.10 (a) and a confinement pressure greater than the water head is applied from the sides to the soil specimen. The main purpose of this confinement is to restrict the water from percolating through the sides of the specimen. The confinement and water pressures differed from soil to soil as the ultimate goal is to complete one leaching cycle in one day. Figure 3.10 presents the working of a leachate apparatus.

In Figure 3.10 (a) a soil sample confined by the leachate cell with a help of an elastic membrane is presented. Later that cell is fixed at the top and bottom with the help of plates shown in the Figure 3.10 (b). The setup is then brought to a place where confinement from the external air valve and flow pressure from the tank as shown in Figure 3.10(c) could be given. From beneath the cell an opening is provided to collect the leachate coming out from the sample. The leachate collected is then studied for calcium concentrations. After the completion of the test the soil specimens were subjected to strength, calcium and pH tests as detailed above.

(a)



(b)



(c)

Figure 3.10: (a) soil sample in the Leachate cell (b) Top and bottom fixed by plates and (c) Leachate apparatus

During the test, moisture is allowed to percolate through the soil specimen which results in Leachate and collected at the bottom. Leachate tests were conducted on several identically prepared and cured soil specimens. The specimens were collected after 3, 5, 7, 11, and 14 cycles of leaching. Leachate sample collected in the container was tested for the amount of calcium present after the completion of required number of leachate cycles.

pH of the soil samples was monitored at select cycles for soil specimens subjected to leachate studies. The pH of the soils was determined by Tex-128-E procedure.

3.3.3.2 Determination of Calcium by EDTA

The leachate from soil is collected in a container and subjected to calcium tests after the completion of desired number of cycles. A small sample representative of the collected leachate is taken and then studied for calcium concentrations.

The concentration of the calcium obtained from the leachate of a soil could be found out by using the multiplier factors given in the Table 3.2. To convert from mg/L as $CaCO_3$ to mg/L as Ca a multiplying factor of 0.4 was used in the calculation.

Table 3.2: Showing the multipliers for different ranges of sample volumes taken

Range (mg/L as $CaCO_3$)	**Soil Volume (ml)**	**Hardness titrant concentration**	**Multiplier**
0-500	50	0.02 N	20
400-1000	25	0.02 N	40
1000-2500	10	0.02 N	100

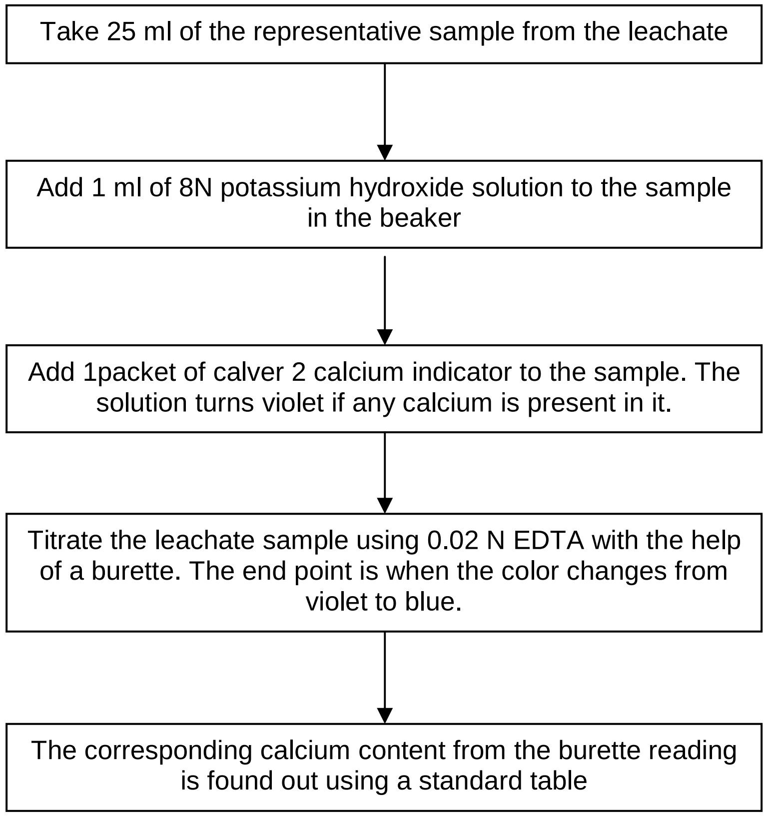


Figure 3.2: Flowchart for the determination of calcium concentration of the leachate

3.4 Summary

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

The test procedure for the determination of cation exchange capacities of the soil samples is given in detail with the help of a flow chart. The next two chapters present the results obtained from the above mentioned tests that were conducted on the four soil samples selected for this study.

CHAPTER 4

DURABILITY STUDIES

4.1 Introduction

This chapter provides a comprehensive analysis of the test results conducted on four selected soils to determine the effects of Montmorillonite mineralogical contents on the stabilizing ability of the soils with different Montmorillonite content. Two types of chemical treatments, lime and cement stabilization methods are examined in this research. The treated soil samples were studied for durability by subjecting them to alternate wetting and drying studies. Wetting/drying studies were conducted mainly to simulate the seasonal moisture fluctuations that might occur during different seasons. The three dimensional volumetric strains in swell and shrinkage conditions and unconfined compressive strengths (UCS) were monitored for the soil samples during these durability studies. The next phase of testing comprises of testing the same type of treated soil samples by subjecting them to leachate studies and the results will be discussed in the next chapter.

An attempt was made to review the studies conducted by Hoyos et al. (2005) and Chittoori (2008), to come up with a test procedure that simulates exact field conditions in arid environments such as North Texas. All the above mentioned experiments were carried out in order to come up with a way of correlating soil mineralogy with stabilization effectiveness. The physical properties of the selected soil samples were determined and classified according to the USCS method. Table 4.1 presents the gradation properties as well as the classification of the four selected soil samples.

Table 4.1: Physical properties of soil samples

Soil	Gradation percentage				USCS classification
	Gravel	**Sand**	**Silt**	**Clay**	
Pharr-A	0	2	39	59	CH*
Pharr-B	0	3	55	42	CH*
Austin	0	5	38	57	CH*
Fort Worth	0	11	37	52	CH*

CH* - Highly compressible clay

All the selected soils were classified as high compressible clays under UCSC soil classification.

4.2 Mineralogical content of clays

The soils collected from different parts of Texas were studied for mineralogy by previous research conducted by Chittoori et al. (2008). Mineralogical contents for the four selected soil samples were presented in Table 4.2. Separate notation was used in the current research to address these soil samples as shown in Table 4.2.

Table 4.2: Table showing the mineralogical compositions of the clays (Chittoori et al. 2008)

Soil	PI	MM* (%)	Illite (%)	Kaolinite (%)	Notation
Pharr B	37	20	30	50	M20
Austin	34	40	25	35	M40
Pharr A	45	50	25	25	M50
Fort Worth	32	60	16	24	M60

Note: MM*-Mineral Montmorillonite

Table 4.2 provides information about the mineralogical contents of the clay samples. Soil sample M60 has the highest MM content and moderate PI amongst the other samples. It can be resolved from the above table that mineralogical content of the clays has no effect on the PI of the clay sample. Montmorillonite is the dominant mineral in M40, M50 and M60 and is least present in M20 where as Kaolinite claims the dominance in soil M20.

All the soil specimens showed some form of failures when stabilized with additives on the basis of standard design charts. The information on stabilizer mix design and failure of soil specimens was presented in chapter 2. In the present research much effort was given to study the soil samples in detail and find the causes for instability among these soils.

The properties of soil samples varied with different lime and cement additive dosages. Table 4.3 shows the variation of physical properties of soil such a maximum dry densities and optimum moisture contents.

Table 4.3: Showing variation of physical properties with additives for different soils

Soil	Additive	OMC* (%)	MDD** (lb/ft^3)
M20	Control	24.7	94
	6% lime	28	89
	8% lime	29	87
	6% cement	28.5	89
M40	Control	20.5	106.2
	8% lime	21	95
	3% cement	21.5	99
	6% cement	21	96
M50	Control	31	83.3
	6% lime	31.5	77.8
	8% lime	32.5	76
	3% cement	32	77
	6% cement	32.5	76
M60	Control	24	91.5
	8% lime	25.5	90
	3% cement	24.5	90
	6% cement	25	89

* - Optimum moisture content
**- Maximum dry density

The soil specimens were prepared for testing at their respective optimum moisture contents and maximum dry densities.

4.3 Wetting/drying studies

Durability studies were conducted on the soil specimens to study the stabilizer effectiveness on the long term performance of the treated soil samples. As discussed before, the soils were subjected to alternate wetting and drying to simulate field conditions in the laboratory. Details on how the soils behaved to the variations in moisture and temperature were given in this chapter followed by the analysis of test results.

Soil specimens were studied for durability by subjecting the soil samples for alternate wetting and drying cycles. The working procedure of this test is best described in chapter 3. Volumetric strain changes, strength and CEC were the properties studied on these soil specimens after the completion of selected number of wetting/drying cycles.

4.3.1 Volumetric studies

Swell and shrink characteristics of the clays are best studied when subjected to alternate wetting and drying. The measurement of 3-D swell and shrink of the soil specimens is achieved by taking readings before and after the wetting or drying cycles.

(1) M20 Soil

M20 soil has a PI of 37 and the dominant mineral being Kaolinite. The cured soil specimens are subjected to alternate wetting and drying cycles. The soil specimens were tested for two dosages of lime (6% and 8%) and two dosages of cement (3% and 6%). Soil specimens treated with 6% and 8% lime were studied for volumetric strain changes and the test results are presented in Figure 4.1 and Figure 4.2.

The control M20 soil survived for only two cycles of durability with a maximum volumetric strain of 26%. M20 soil treated with 6% lime survived for 14 cycles of wetting and drying with a maximum volumetric change of 12%.

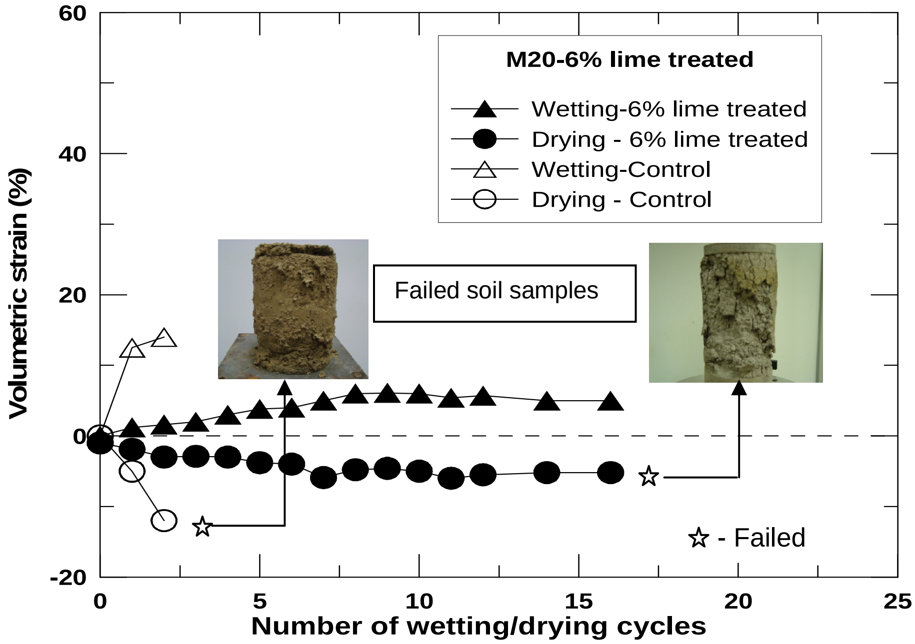


Figure 4.1: Variation of volumetric strain with w/d cycles for M20 treated with 6% lime

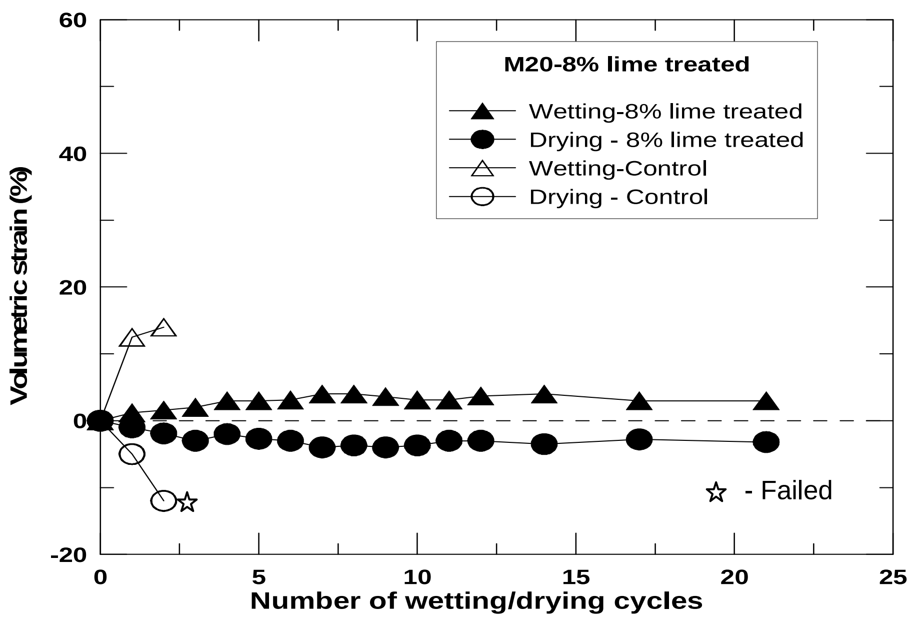


Figure 4.2: Variation of volumetric strain with w/d cycles for M20 treated with 8% lime

Lime stabilization helped the soil specimen to withstand the durability cycles and also there is considerable decrease in the volumetric strain of the M20 soil. M20 soil treated with 8% lime survived for 21 cycles of wetting and drying with a maximum volumetric change of 6%.

The stabilization effectiveness of cement on the M20 soil was studied when the soil was treated with two cement dosages. The soils treated with 3% and 6% cement and were studied for durability studies. Figure 4.3 details the volumetric strain of M20 soil when treated with 3% cement whereas Figure 4.4 details the volumetric strain of M20 soil when treated with 6% cement.

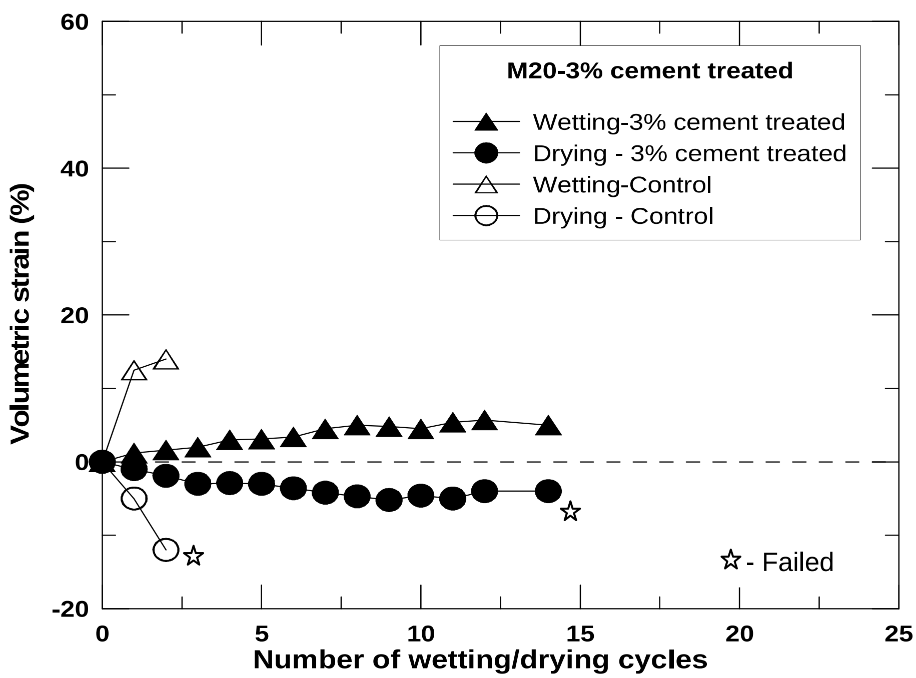


Figure 4.3: Variation of volumetric strain with w/d cycles for M20 treated with 3% cement

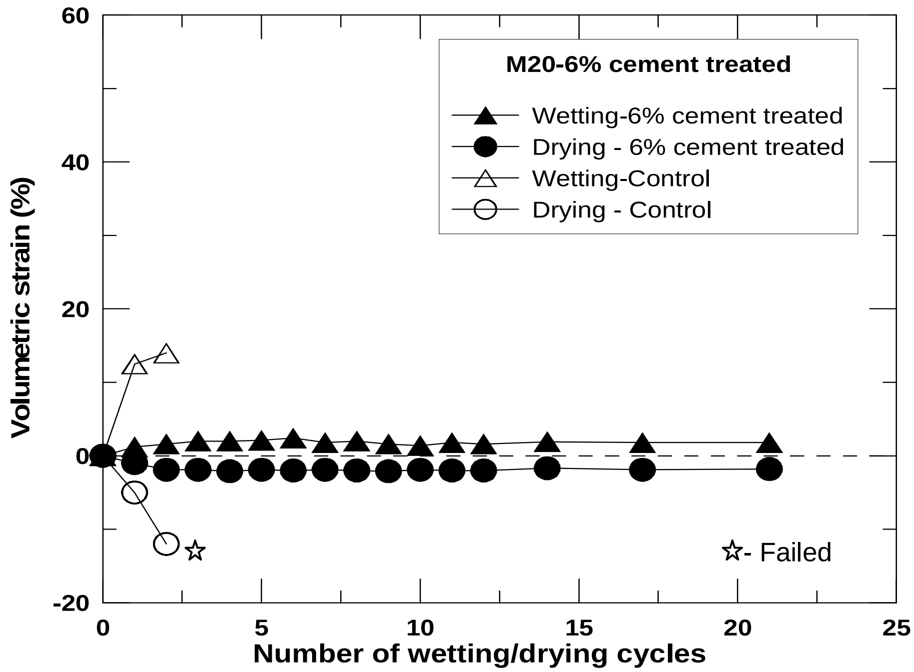


Figure 4.4: Variation of volumetric strain with w/d cycles for M20 treated with 6% cement

M20 soil treated with 3% cement survived for 14 durability cycles with a maximum volumetric strain of 10%. M20 soil when treated with 6% cement survived for 21 cycles of wetting and drying with a maximum volumetric strain of 4%.

(2) M40 Soil

M40 Soil has a PI of 34 and the dominant mineral being Montmorillonite. The cured soil specimens were subjected to alternate wetting and drying cycles. This soil was tested for one dosage of lime (8%) and two dosages of cement (3% and 6%). Soils were treated with 8% lime and were studied for volumetric changes as shown in Figure 4.5

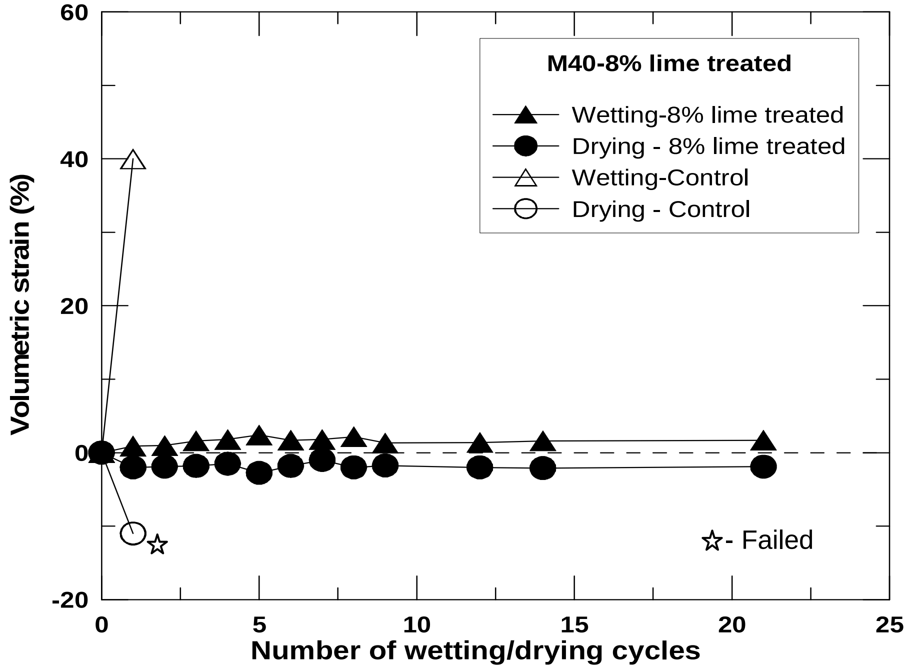


Figure 4.5: Variation of volumetric strain with w/d cycles for M40 treated with 8% lime

The control M40 soil survived for one durability cycle with a total volumetric strain of 52%. M40 soil sample treated with 8% lime survived for 21 cycles of wetting and drying with a final maximum volumetric strain of 6%.

The M40 soil was then treated with 3% and 6% cement. The variation of volumetric strain with durability cycles of a soil sample treated with 3% cement was shown in Figure 4.6 and the same with 6% cement treatment was shown in Figure 4.7.

M40 soil showed considerable changes in volumetric strain when stabilized with 3% cement but the soil sample failed after 12 cycles of wetting/drying. The maximum volumetric strain of this sample was 10%. The M40 soil treated with 6% cement survived for 21 cycles of durability with a maximum volumetric strain of 4%.

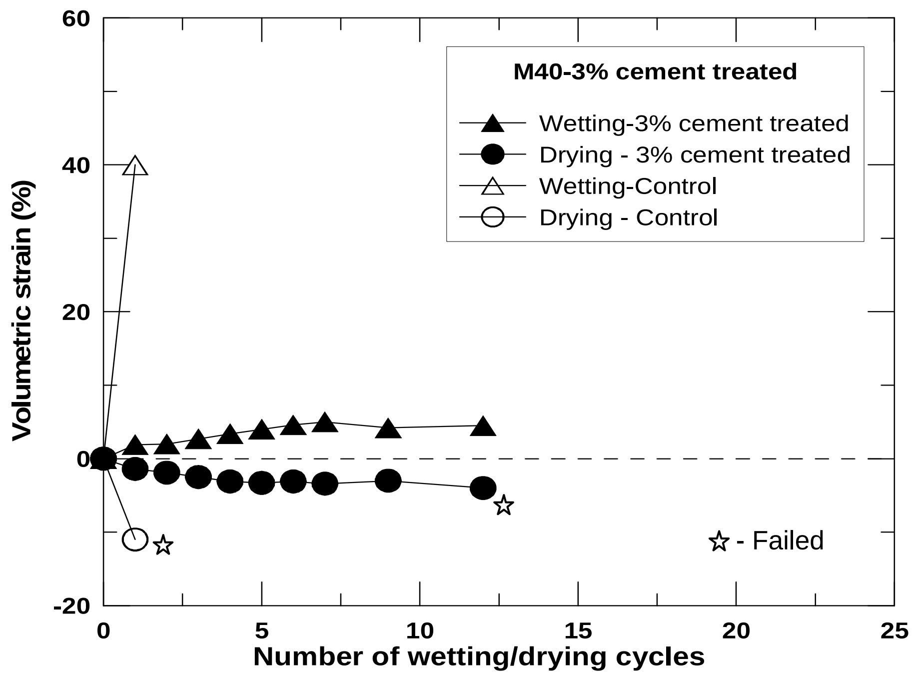


Figure 4.6: Variation of volumetric strain with w/d cycles for M40 treated with 3% cement

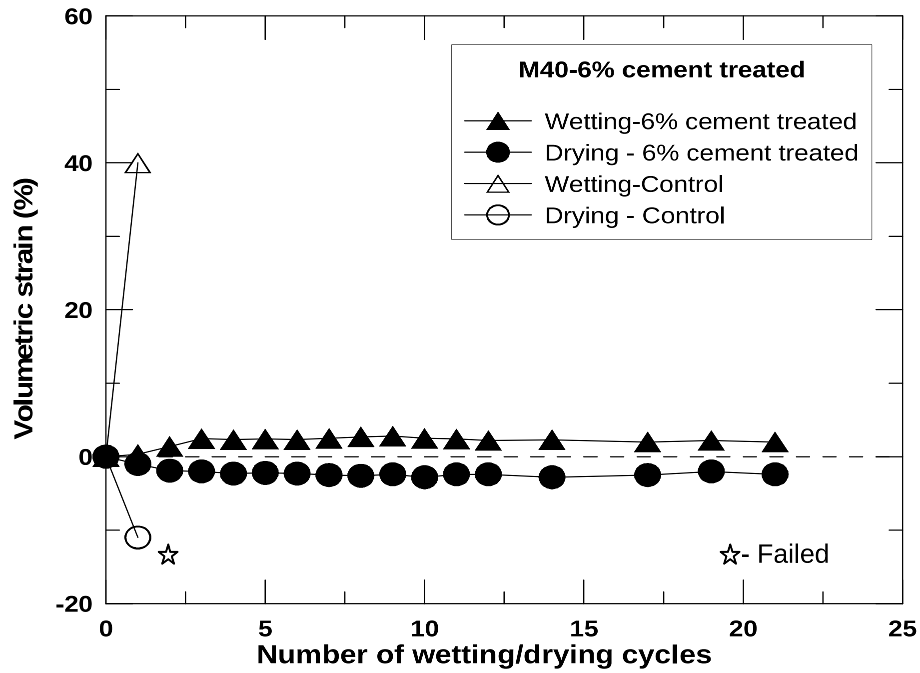


Figure 4.7: Variation of volumetric strain with w/d cycles for M40 treated with 6% cement

(3) M50 Soil

The M50 soil has a PI of 47 and 50% MM mineral. M50 soil was tested with two lime dosages (6% and 8%) and two cement dosages (3% and 6%). The volumetric strain of soil specimen stabilized with 6% lime is shown in Figure 4.8. Similarly volumetric strain of soil specimen stabilized with 8% lime is shown in Figure 4.9.

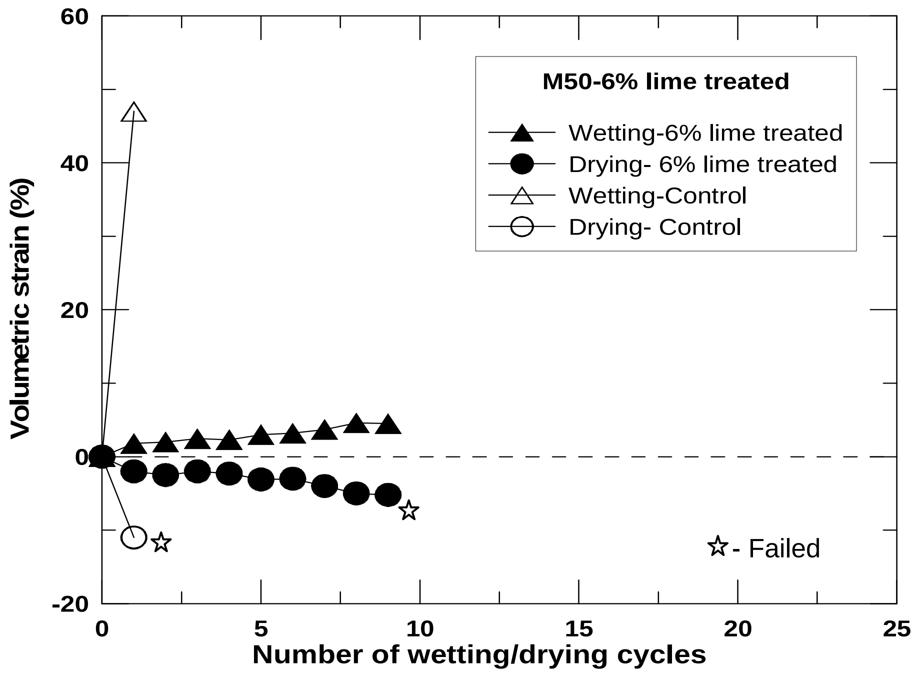


Figure 4.8: Variation of volumetric strain with w/d cycles for M50 treated with 6% lime

The control soil specimens of M50 soil sustained one durability cycle with a volumetric strain of 58%. M50 soil treated with 6% lime experienced a maximum volumetric strain of 9% and survived for 9 durability cycles.

Similarly M50 soil treated with 8% lime survived for 14 cycles of durability with a maximum volumetric strain of 7%. Both the additive dosages are deemed ineffective to stabilize the soil specimen.

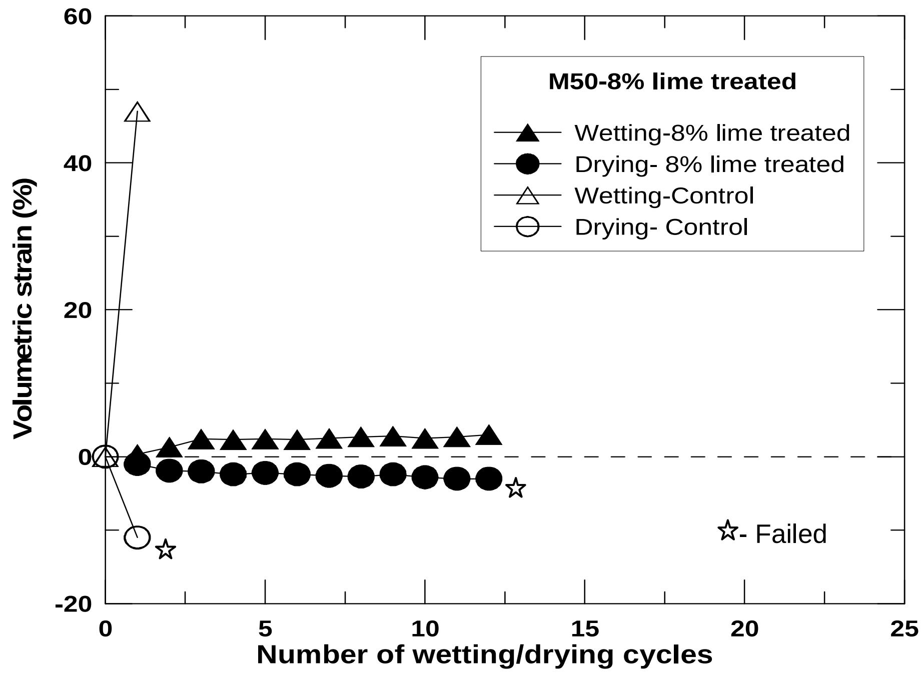


Figure 4.9: Variation of volumetric strain with w/d cycles for M50 treated with 8% lime

The M50 soil specimen was then treated with 3% and 6% cement dosages to study the stabilization effectiveness. Variation of volumetric strain with wetting/drying cycles of M50 soil sample treated with 3% cement was given in Figure 4.10.

Similarly the variation of volumetric strain with durability cycles when treated with 6% cement was given in Figure 4.11.

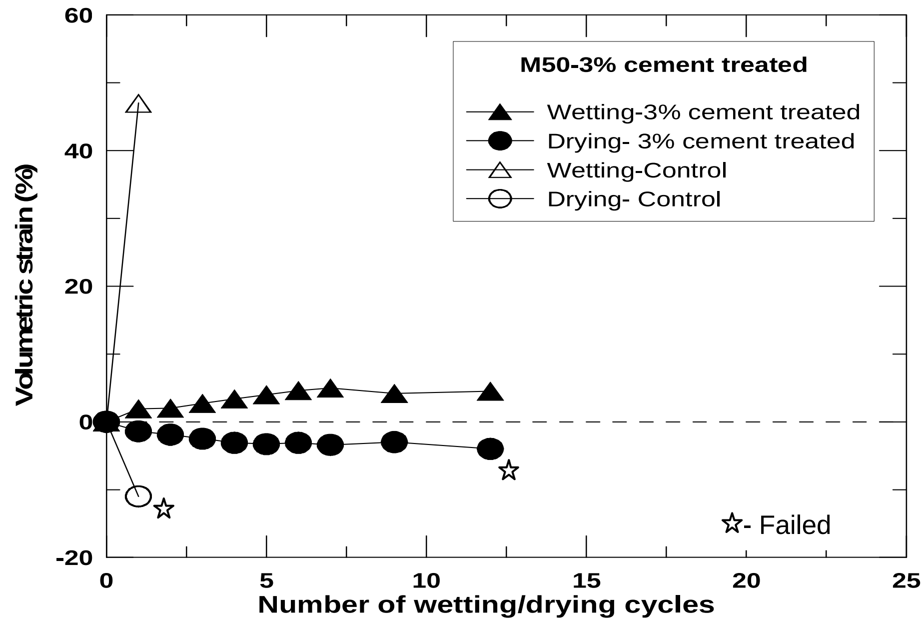


Figure 4.10:Variation of volumetric strain with w/d cycles for M50 treated with 3% cement

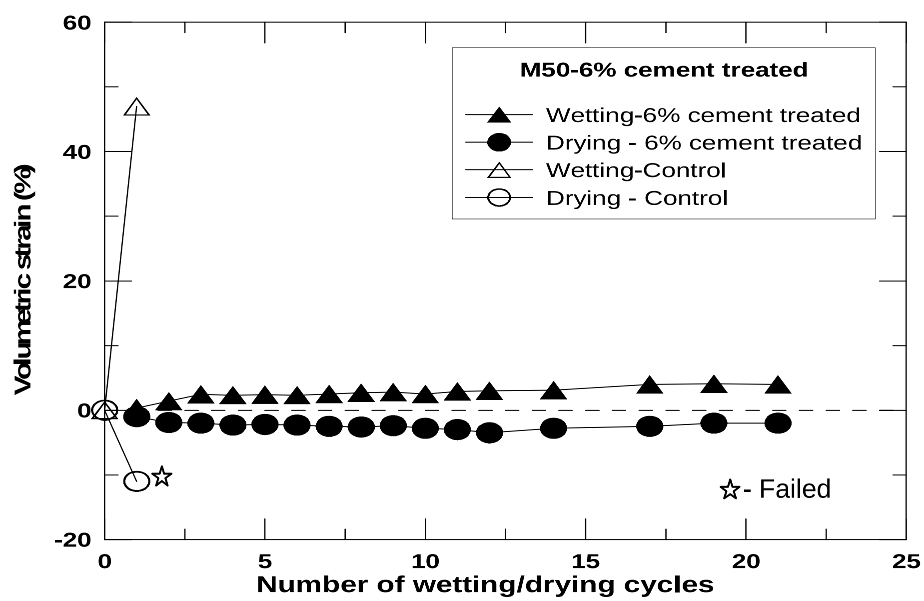


Figure 4.11: Variation of volumetric strain with w/d cycles for M50 treated with 6% cement

(4) M60 Soil

M60 soil has a PI of 32 and the dominating mineral is Montmorillonite (60%). This soil was tested for one dosage of lime (8%) and two dosages of cement (3% and 6%) to study the stabilization effectiveness.

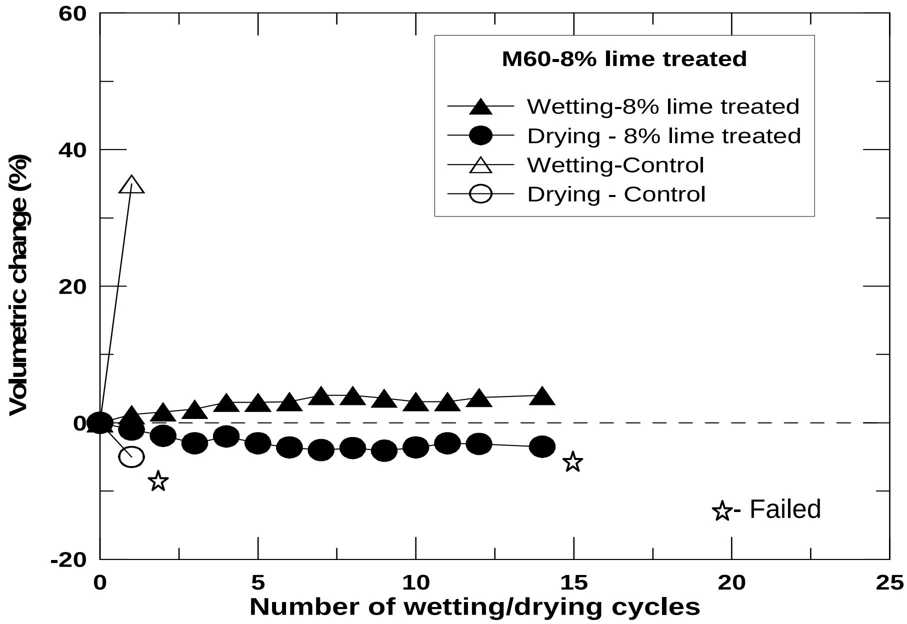


Figure 4.12:Variation of volumetric strain with w/d cycles for M60 treated with 8% lime

The control soil specimen underwent a maximum volumetric change of 42% and survived for one cycle of wetting/drying. The lime treated soil specimen survived for 14 cycles of wetting/drying with a maximum volumetric change of 8%. The soil was stabilized to a certain extent but did not reach the threshold limiting value of 5%. Studies were conducted on M60 soil samples stabilized with 3% and 6% cements and their volumetric strains are shown Figures 4.13 and 4.14, respectively.

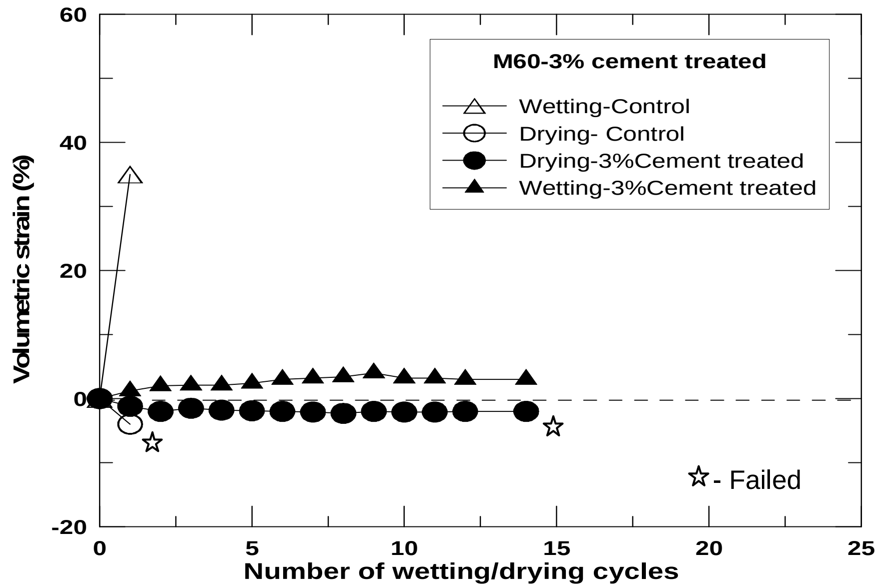


Figure 4.13: Variation of volumetric strain with w/d cycles for M60 treated with 3% cement

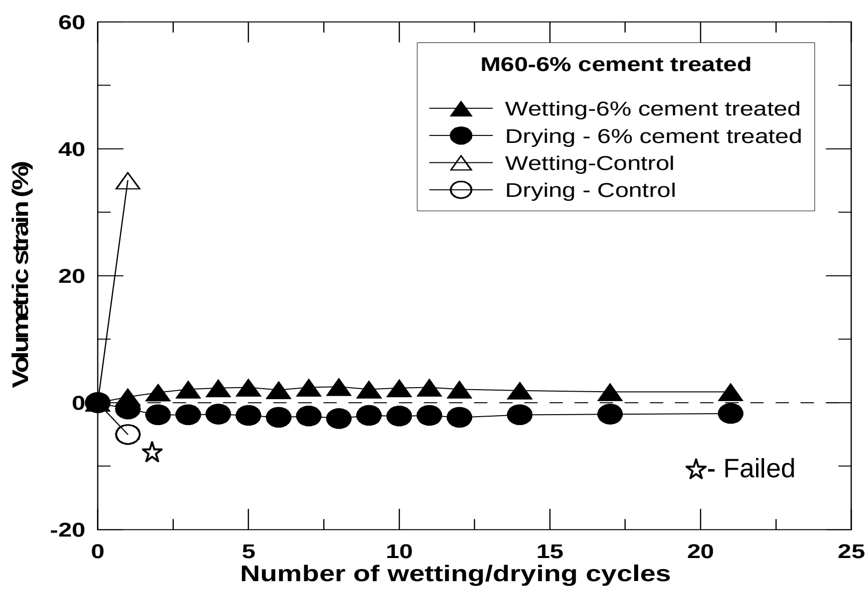
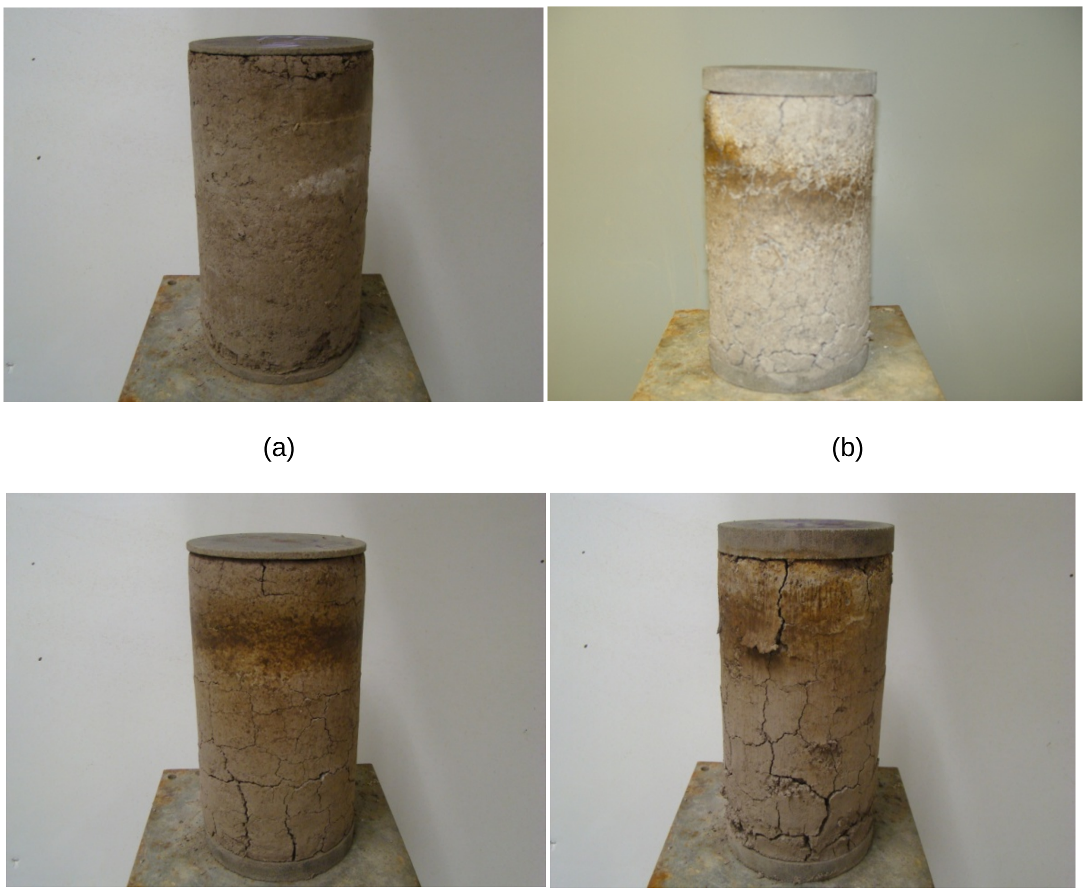


Figure 4.14: Variation of volumetric strain with w/d cycles for M60 treated with 6% cement

The soil specimen treated with 3% cement survived for 14 cycles of wetting/drying with a maximum volumetric strain of 11%. The soil sample is improved to a certain extent but not stabilized effectively. When the soil sample is treated with 6% cement the soil sample survived for 21 cycles of wetting/drying with a maximum volumetric strain of 5%. Below shown are the pictures of the soil samples at selected durability cycles.



(a) (b) (c) (d)

Figure 4.15: M20 soil specimen (8% lime treated) at (a) 0 cycles (b) 3cycles (c) 14cycles and (d) 21 cycles

(a)

(b)

(c)

(d)

Figure 4.16: M40 soil specimen (6% cement treated) at (a) 0 cycles (b) 3cycles (c) 14cycles and (d) 21 cycles

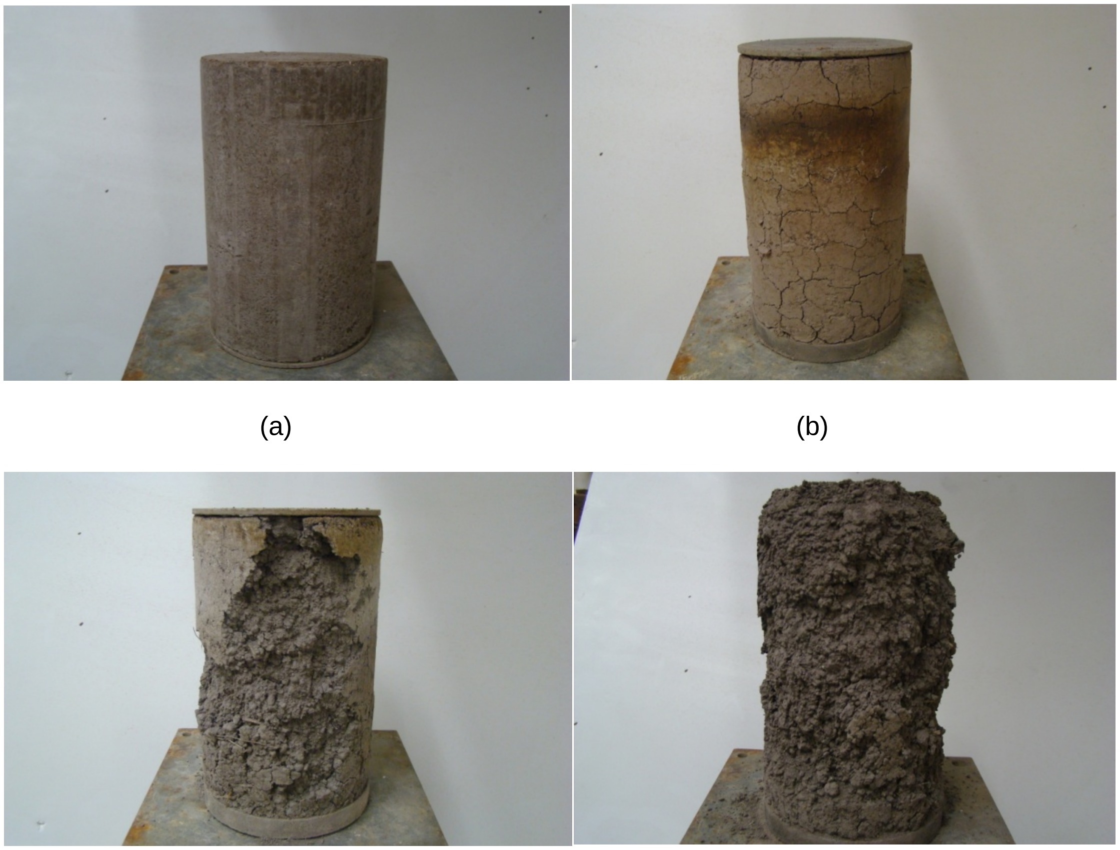
(a)

(b)

(c)

(d)

Figure 4.17: M50 soil specimen (6% cement treated) at (a) 0 cycles (b) 3cycles (c) 14 cycles and (d) 21 cycles



(a) (b)

(c) (d)

Figure 4.18: M60 soil specimen (8% lime treated) at (a) 0 cycles (b) 3cycles (c) 14cycles and (d) 21 cycles

4.3.2 Unconfined compressive strength (UCS) Test results

Soil specimens have been subjected to UCS test after selected wetting/drying cycles. The treated soil samples showed an increase in the UCS strength with increase in dosage of additive. The soil samples were tested for both lime and cement treatments.

(1) M20 Soil

M20 soil specimen was studied for two lime dosages (6% and 8%) and two cement dosages (3% and 6%). Below shown Figure 4.19 explains the variation of UCS values of M20 soil when treated with lime. Control M20 soil showed a maximum strength of 40 psi at 0 cycles. Previous study done by Chittoori (2008) with 3% lime was also included in this plot to study the variation of strength with other lime dosages. The maximum strength the soil exhibited was 130 psi with 8% lime dosage. Similarly the M20 specimens were subjected to cement treatment to study the soil stability.

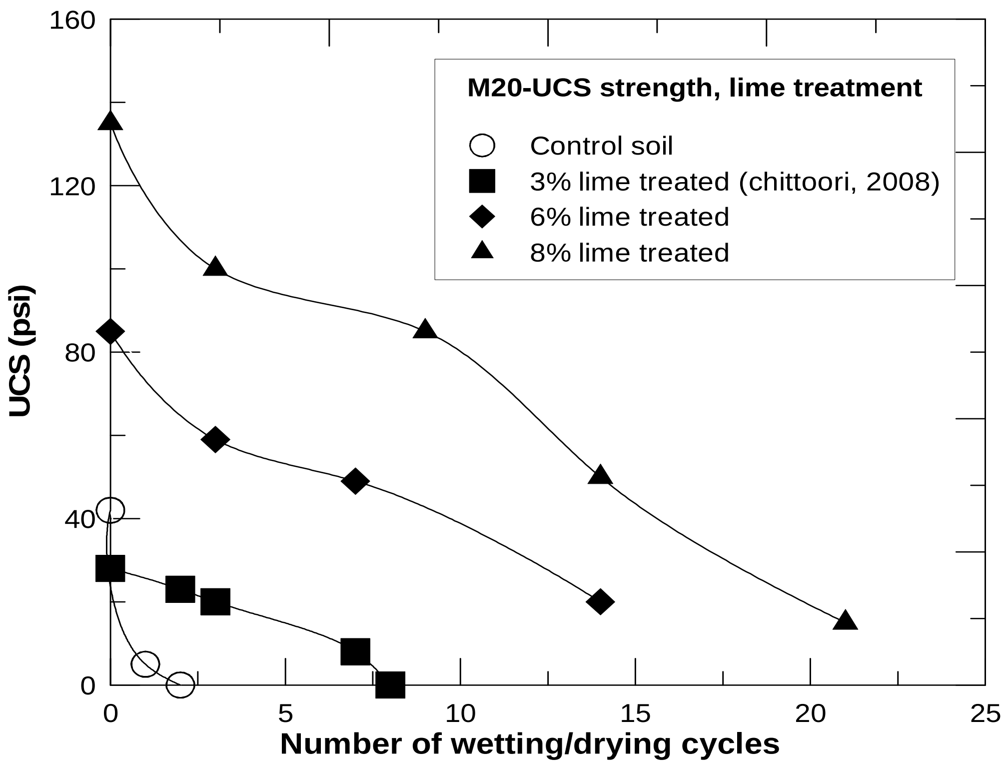


Figure 4.19: Variation of UCS strengths with wetting/drying cycles of lime treated M20 soil

The variation of UCS values with durability cycles for M20 soil specimens treated with cement were shown in Figure 4.20.

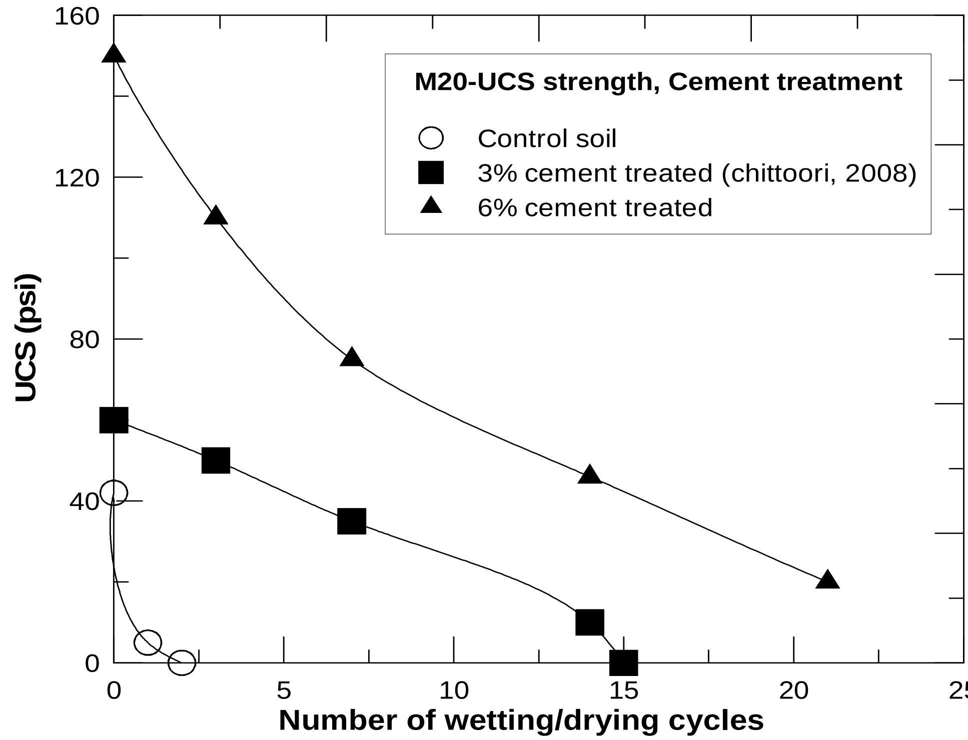


Figure 4.20: Variation of UCS strengths with wetting/drying cycles of cement treated M20 soil

(2) M40 soil

The variation of the strength of the M40 soil treated with different additives is studied in detail. The M40 soil was treated with 8% lime dosage and 3% and 6% cement dosages. The control soil exhibited an initial strength of 38 psi. The plot of 6% lime dosage was previously presented by Chittoori, (2008) which failed to stabilize the M40 soil. Figures 4.21 and 4.22 present the M40 soil test results with lime and cement treatments, respectively. M40 soil when treated with 3% and 6% cement survived for 14 and 21 cycles in the wetting/drying studies.

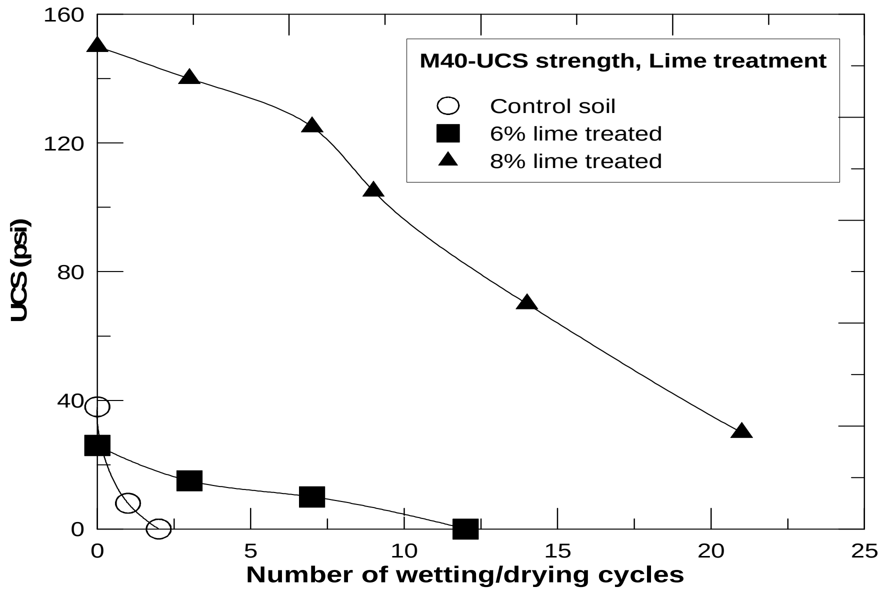


Figure 4.21: Variation of UCS strengths with wetting/drying cycles of lime treated M40 soil

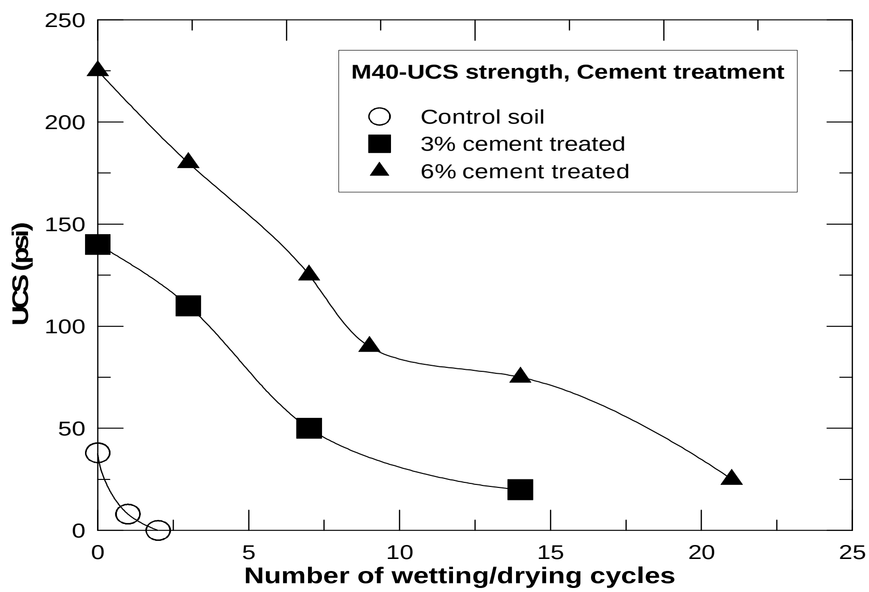


Figure 4.22: Variation of UCS strengths with wetting/drying cycles of cement treated M40 soil

(3) M50 Soil

Strength tests were conducted on M50 soil by treating it with two dosages of lime (6% and 8%) and two dosages of cement (3% and 6%). The control soil exhibited a maximum strength of 35psi at 0 cycles. The soil specimens showed an increase in UCS strength with increase in additive dosage but the number of cycles the soil survived does not meet the stabilization requirements.

The variation of UCS strength with wetting/drying cycles when the M50 soil specimen is treated with lime is plotted in Figure 4.23.

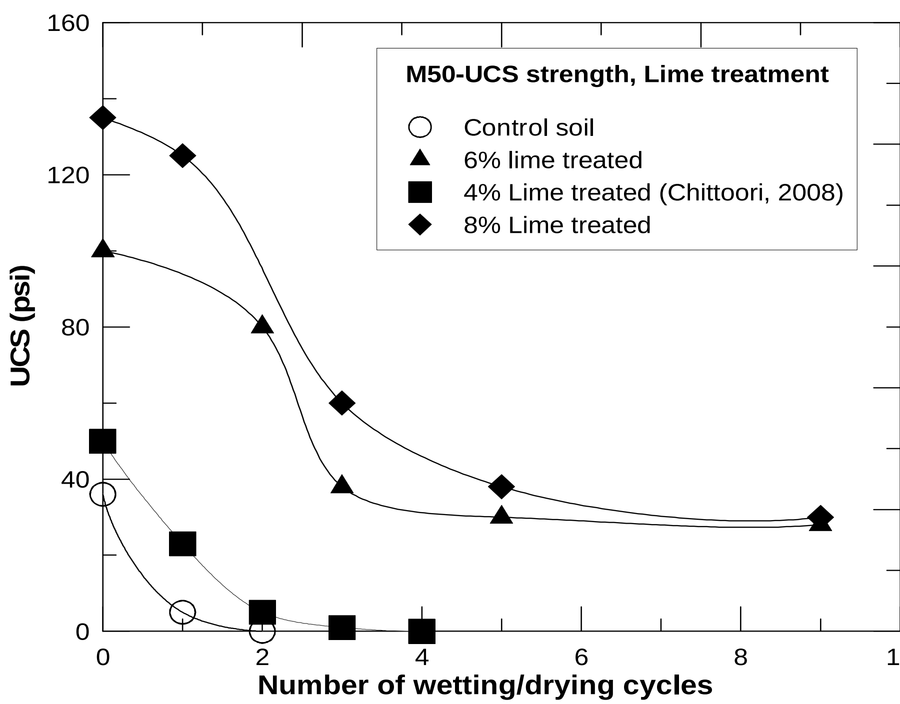


Figure 4.23: Variation of UCS strengths with wetting/drying cycles of lime treated soil M50.

The results of soil M50 when treated with cement were presented in Figure 4.24. The soil sample survived 21 cycles of durability when treated with 6% cement.

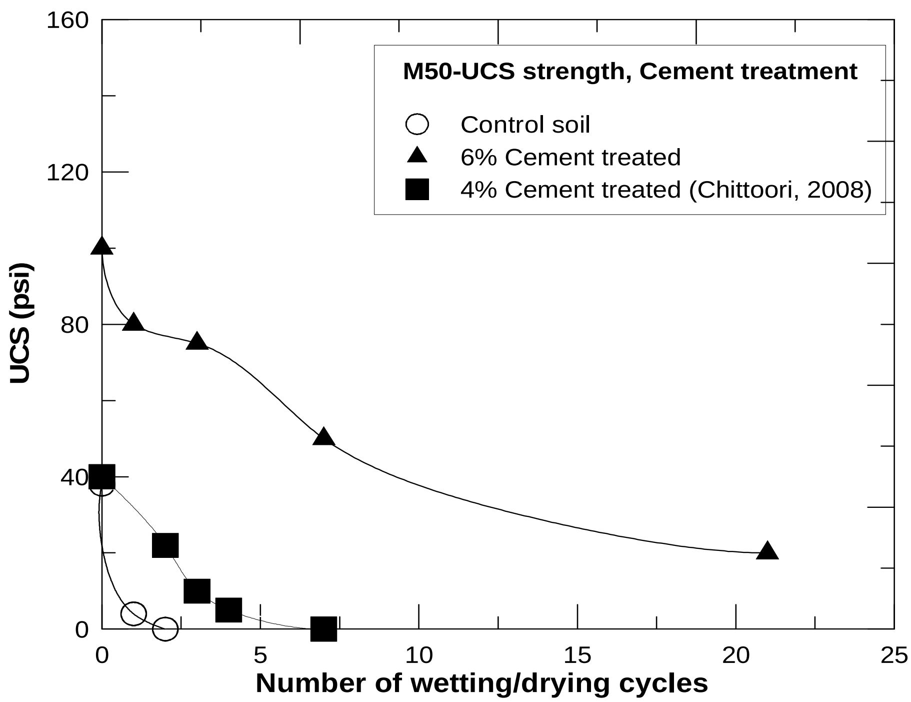


Figure 4.24: Variation of UCS strengths with wetting/drying cycles of cement treated M50 soil

(4) M60 soil

M60 soil treated with one lime dosage (8%) and two dosages of cement (3% and 6%) was subjected to durability studies. The control soil sample exhibited a maximum strength of 35 psi at 0 cycles. The same soil treated with 6% lime additive experienced premature failures. The variation of UCS test results with wetting/drying cycles for lime treated M60 soil was presented in Figure 4.25. The soil specimens subjected to cement treatment were studied for UCS strength variation with wetting/drying cycles as shown in Figure 4.26.

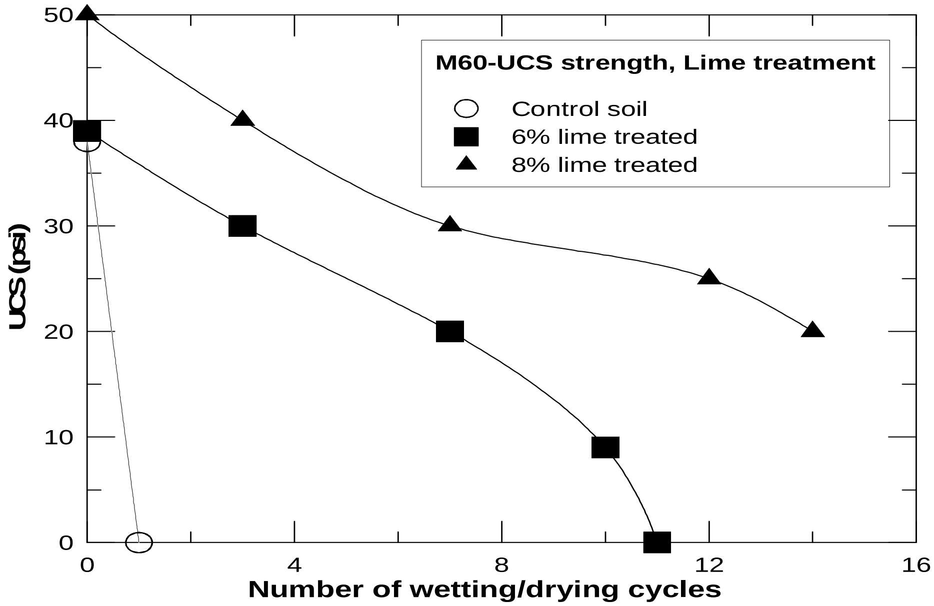


Figure 4.25: Variation of UCS strengths with wetting/drying cycles of lime treated M60 soil

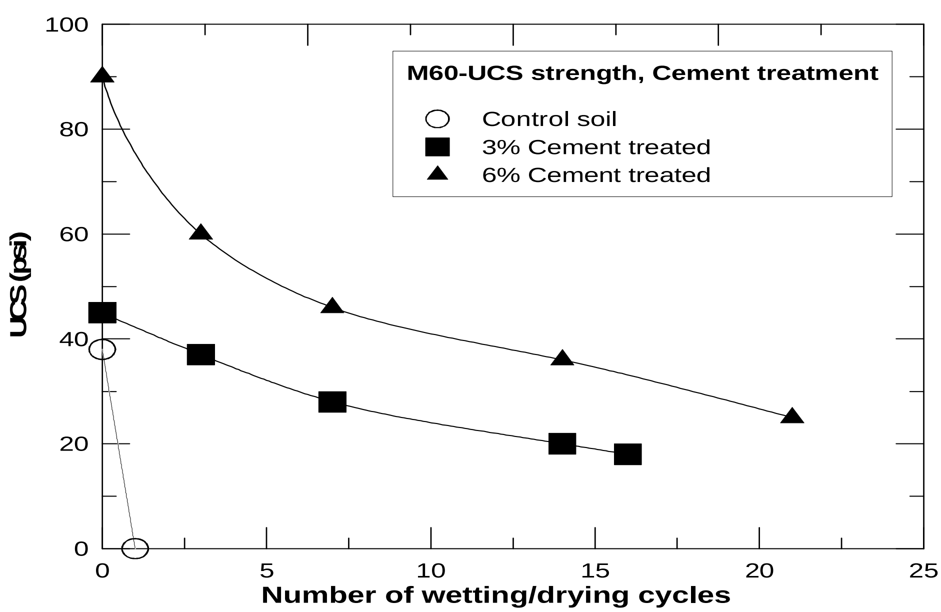


Figure 4.26: Variation of UCS strengths with wetting/drying cycles of cement treated M60 soil

4.3.3 Cation exchange capacity (CEC)

All soil samples were subjected to durability studies and CEC were measured at different cycles during the durability studies. The variation of cation exchange capacities (CEC) of soils at the respective cycles was examined. The soil specimens after UCS tests were preserved in a moisture room and tested for CEC as per the procedure explained in chapter 3.

The variation of CEC for different soil samples treated with lime and cement are shown in Figure 4.27 and Figure 4.28. The CEC was studied for 8% lime and 6% cement treated soils. With wetting/drying cycles the soil specimens show a slight increase in CEC values.

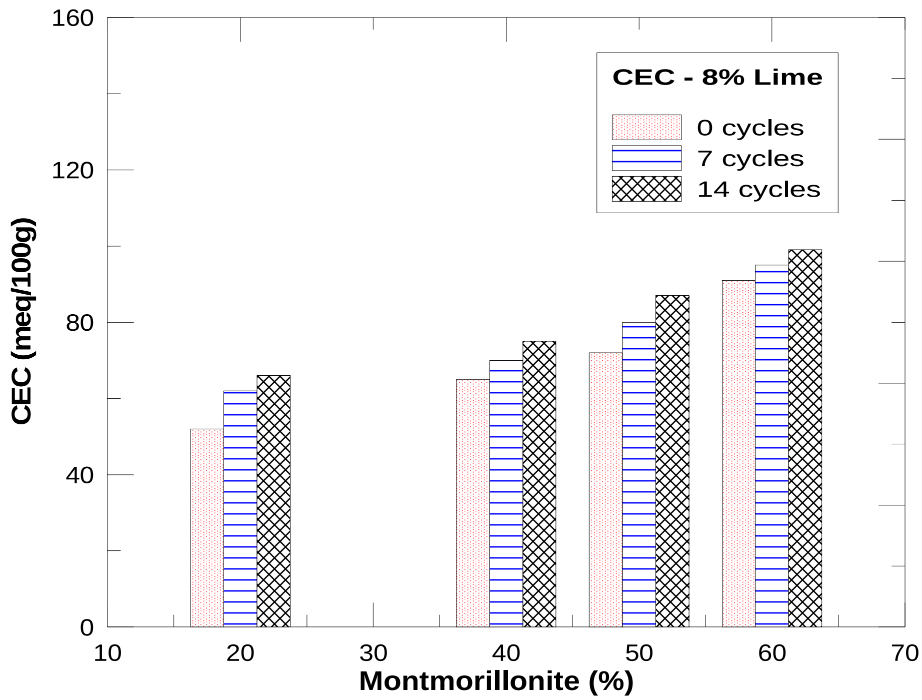


Figure 4.27: Variation of CEC with durability cycles for different soils when treated with 8% lime

Similarly, Figure 4.28 details the variation of CEC with durability cycles for soils treated with cement and having different Montmorillonite contents. There was a stable increase in the CEC with durability cycles.

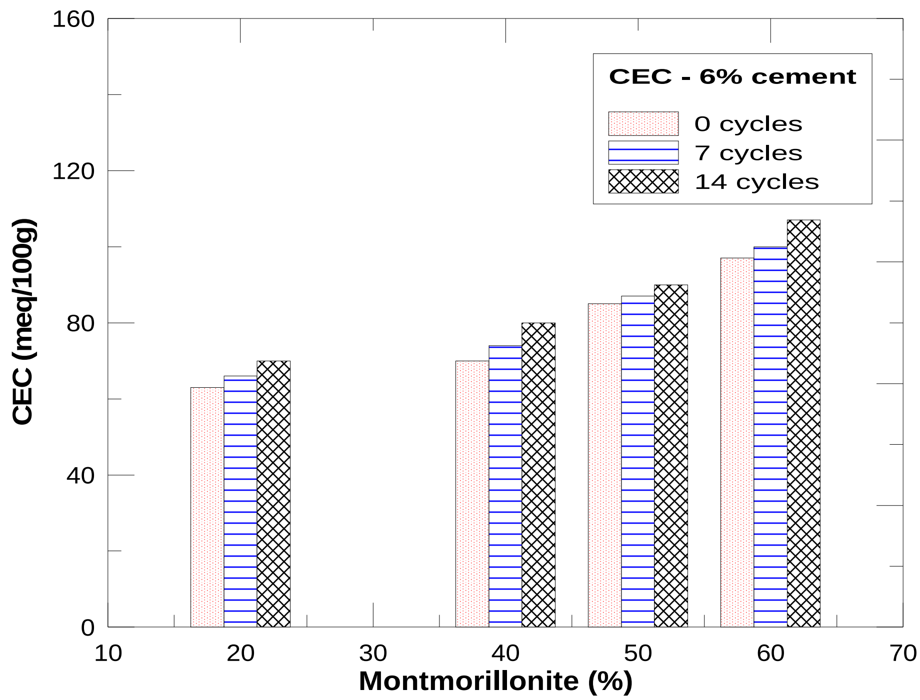


Figure 4.28: Variation of CEC with durability cycles for different soils when treated with 6% cement

From the plots it can be concluded that the variation of CEC for cement treated soil specimens are sligtly higher than that of lime treated soil specimens with durability cycles. The variation is higher for high Montmorillonite rich soils.

4.4 Analysis of test results

Analysis of the test results are carried out and presented in the following section. The effects of mineral Montmorillonite, type of additive and additive dosages on the long-term durability of treated soil samples are studied in the following sections.

4.4.1 Effect of mineralogy

Montmorillonite mineral has considerable effect on the premature failing of the soil specimens. The soil specimens when treated with small amounts of stabilizers did not show any improvement in the durability. Higher dosages of lime (8%) and cement (6%) stabilized all the tested soils. Table 4.3 presents the survivability results of the soil specimens treated with lime and cement.

The study conducted on different parameters that affect the stabilization effectiveness of the Montmorillonite dominant soils is presented. The variations of UCS with Montmorillonite contents, lime and cement dosages and the effect of mineral on the soils are studied in detail.

4.4.1.1 UCS versus Montmorillonite

The variation of UCS strengths with lime and cement dosages for different Montmorillonite soils are given in Figures 4.29 and 4.30. This study was conducted at 0 cycles of durability.

It can be concluded from the figures that the UCS results of the soil sample showed a constant trend initially and dropped when the Montmorillonite percentage is more than 50. This shows that soils having high Montmorillonite content are difficult to stabilize. The UCS results for soil M40 were much higher than soil M20. The reason for this change in the trend could be the excessive amounts of mineral Kaolinite (50%) in soil M20. Figure 4.29 presents the variation of UCS results with Montmorillonite percentage for soil specimens treated with lime

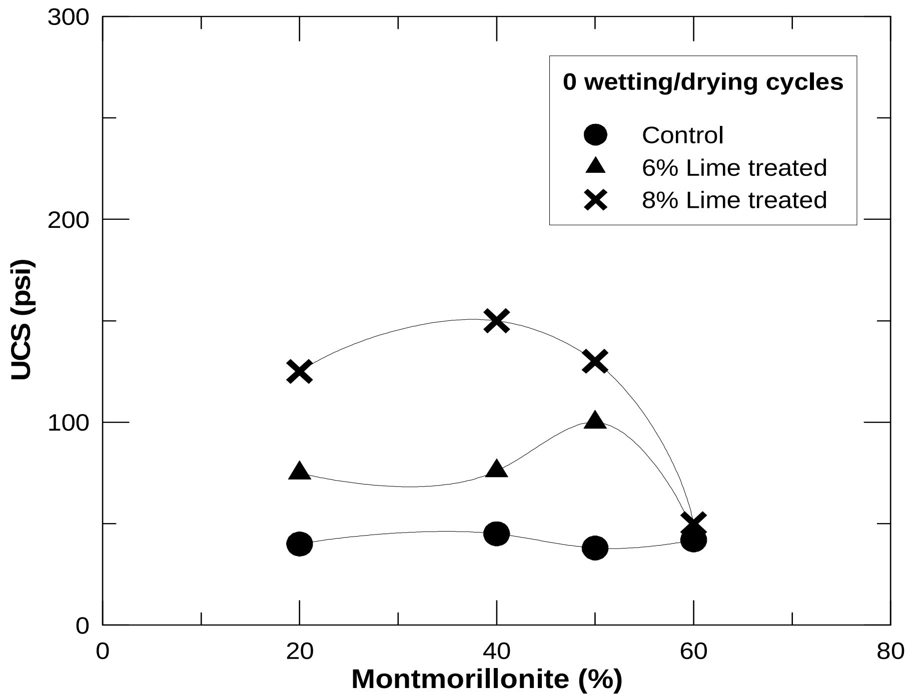


Figure 4.29: Variation of UCS strength (at 0 w/d cycles) for different soils at 2 dosages of lime (6% and 8%)

Figure 4.31 presents the results obtained from both lime and cement treated soil samples. Table 4.4 presents the number of cycles survived by each soil sample and its corresponding residual strength.

Table 4.4: Survivability of soil samples with durability cycles

Soils	Dominating mineral	Stabilizer	No. of cycles the sample survived	Residual strength (psi)
M20	Kaolinite	3% Lime	8	0
		6% Lime	14	0
		8% Lime	21*	20
		3% Cement	14	0
		6% Cement	21*	25
M40	Montmorillonite	6% Lime	12	0
		8% Lime	21*	25
		3% Cement	14	0
		6% Cement	21*	30
M50	Montmorillonite	4% Lime	4	0
		6% Lime	9	30
		8% Lime	9	35
		3% Cement	9	0
		6% Cement	21*	0
M60	Montmorillonite	6% Lime	11	0
		8% Lime	14	20
		3% Cement	17	15
		6% Cement	21*	20

* - Sample still intact

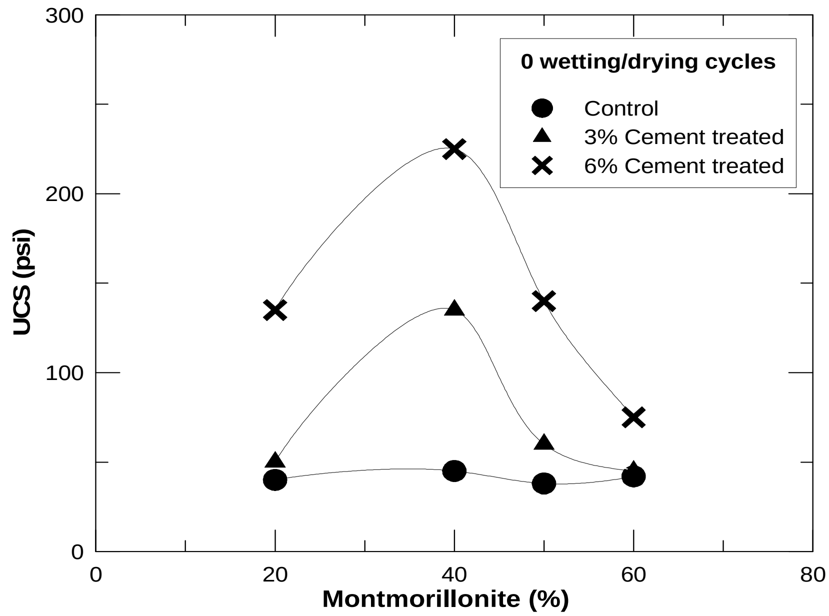


Figure 4.30: Variation of UCS strength (at 0 w/d cycles) for different soils at 2 cement dosages

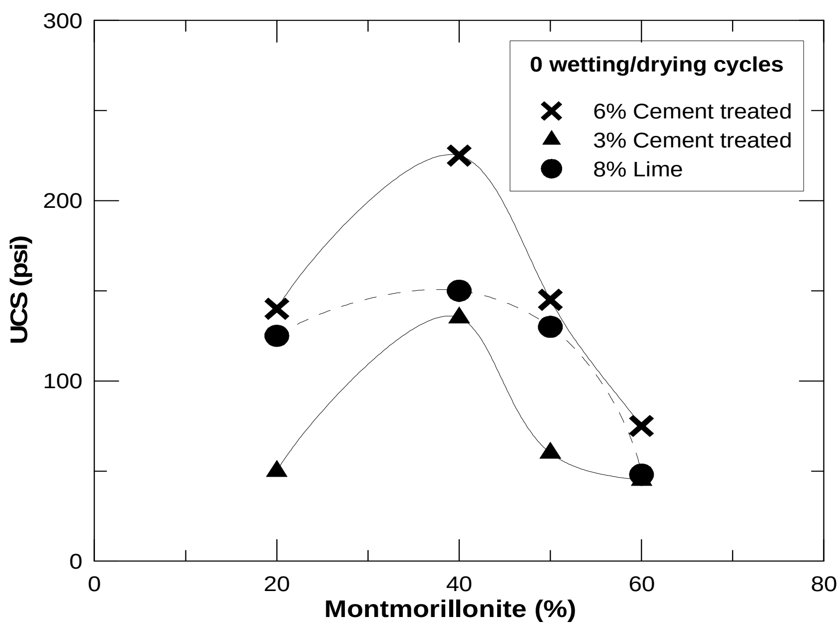


Figure 4.31: Comparison between lime and cement treated soil samples at 0 cycles

From the above presented data it can be concluded that with increase in Montmorillonite content in the soil specimen the UCS value decreases. This plot compares the UCS values of lime (8%) and cement (3% and 6%) treated soils. The soil specimens treated with cement exhibited a maximum UCS strength when compared to lime treated soils. Among all soils tested, the Austin soil (M40) shows a maximum UCS value when treated with stabilizers.

4.4.1.2 Effect of MM content

Montmorillonite is a highly expansive mineral when compared to Kaolinite, but the percentage of the mineral present in the soil sample plays an important role in the stabilization process. The number of cycles of durability survived by different soils with different mineralogies was determined. Figure 4.32 presents the number of cycles of durability survived versus Montmorillonite dominant soils at different chemical additive dosages.

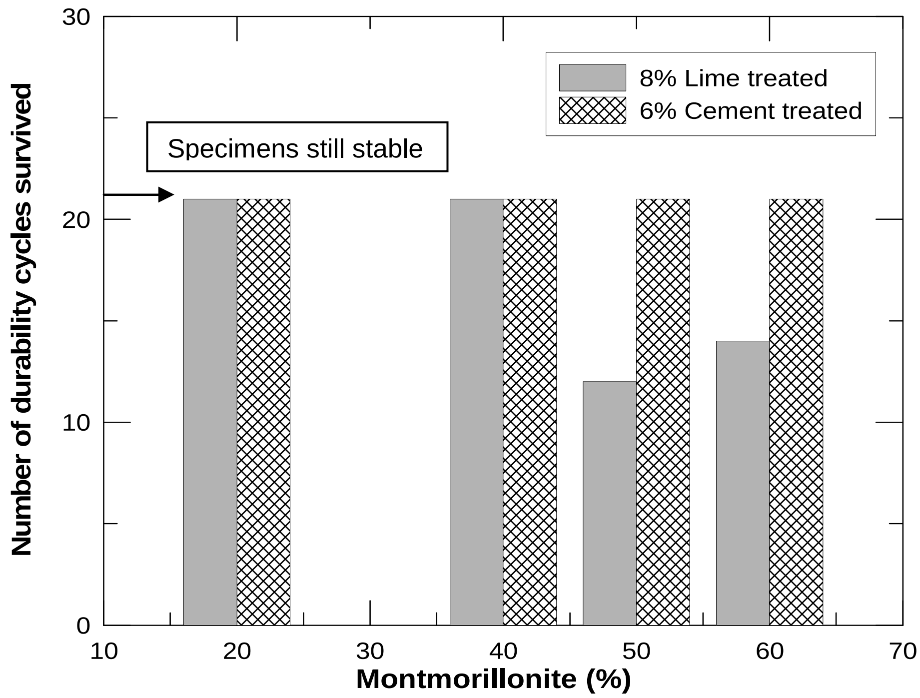


Figure 4.32: No of cycles survived by MM soil specimens at different additive dosages

Figure 4.32 shows the effect of stabilizers with mineral contents. Lime does not act as an effective stabilizer when the Montmorillonite content is above 50%. The Kaolinite dominant soils like M20 were stabilized effectively with 8% lime and 6% cement dosages, whereas for Montmorillonite dominant soils like M60 6% cement is needed to make the soil specimen survive for 21 cycles of durability. Figure 4.33 presents the number of durability cycles survived by Kaolinite dominant soils when treated with different dosages of additives.

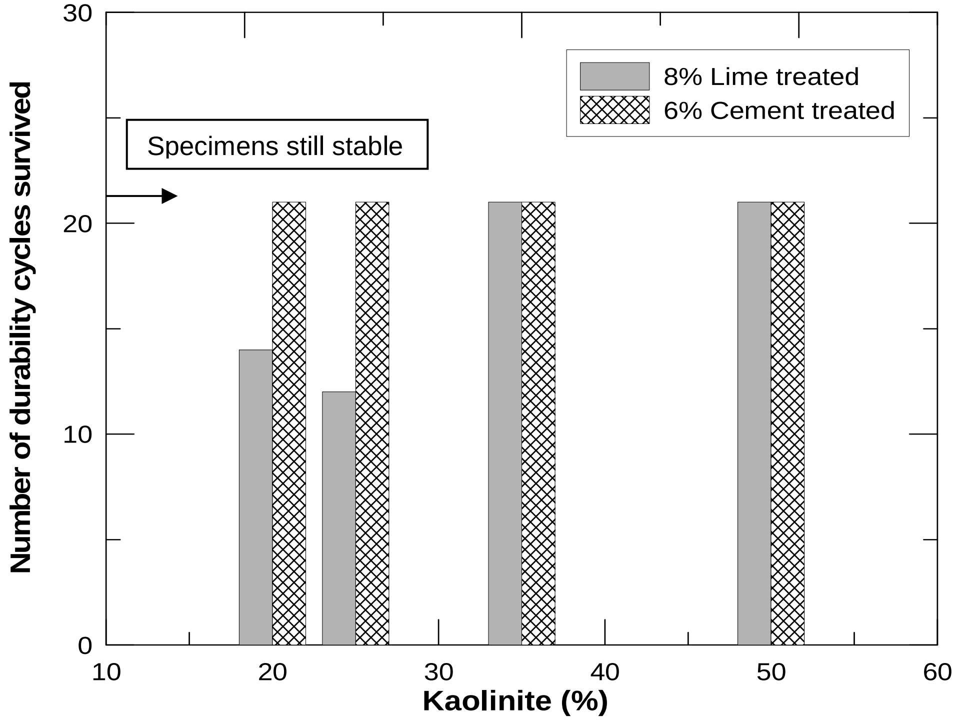


Figure 4.33: Number of cycles survived by Kaolinite soil specimens at different additive dosages

The soils were effectively stabilized at high contents of Kaolinite. This shows that high amounts of mineral Kaolinite has no influence on the durability cycles.

4.4.1.3 Effect of stabilizer

Chemical additive dosages play an important role in stabilizing expansive clays, hence it is appropriate to study both lime and cement treatments on the soil samples. The Montmorillonite soils have failed when the soils were stabilized according to the design standards. Figures 4.34 and 4.35 present the variation of UCS results with different dosages of additive at 3 durability cycles for the soil samples. Both the figures show that the UCS values increase with dosage where as the highest strength is exhibited by cement treated soil samples.

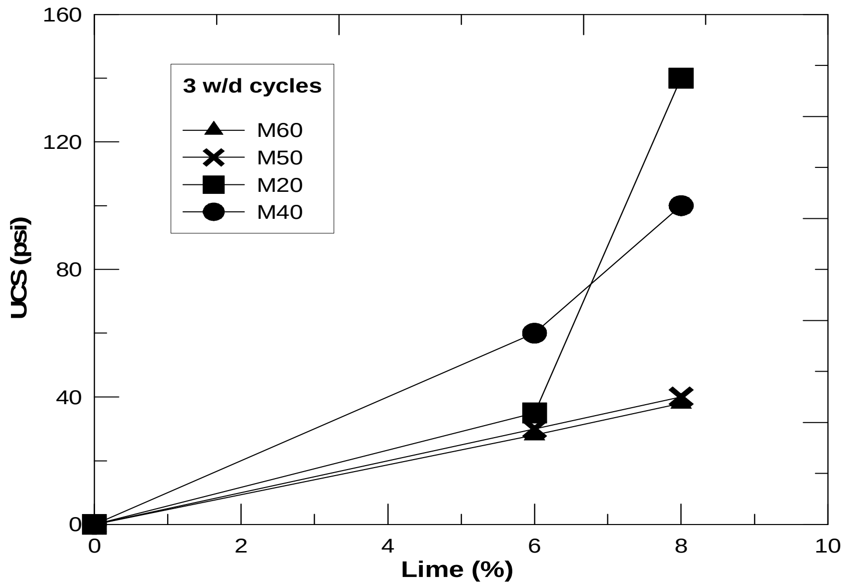


Figure 4.34: UCS response of lime treated soil specimens at 3 w/d cycles

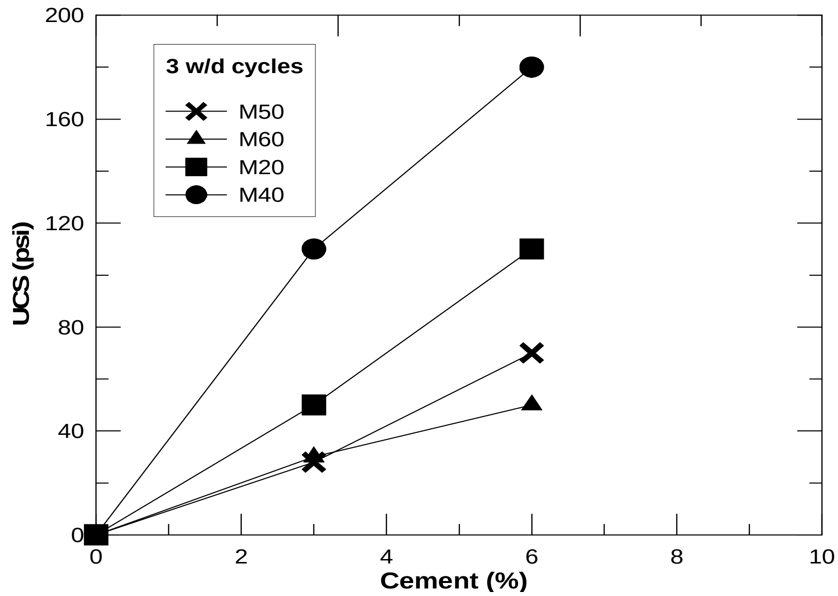


Figure 4.35: UCS response of cement treated soil specimens at 3 w/d cycles

Figure 4.34 presents the variation of UCS results at 3 durability cycles when treated with lime. The soils dominant with mineral Montmorillonite did not show considerable increase in the UCS results with lime treatment. Similarly the UCS results for soil specimens treated with cement showed considerable increase in trend as shown in Figure 4.35.

4.5 Summary

A total of four soils having different mineralogical content were studied in the present research by treating them with two stabilizers (lime and cement). The effect of mineralogy on the long-term performance of stabilized expansive soils was studied and found out that the soils having high mineral contents show less resistance to failure when stabililzed. Both volumetric strain and unconfined compressive strength were measured at various cycles of wetting/drying. The volumetric strain for the soils was effectively reduced when the stabilizer dosage increased. The soil samples survived 21 durability cycles with less than 5% volumetric strain were M20 (at 8% lime and 6% cement), M40 (8% lime and 6% cement), M50 (6% cement) and M60 (at 6 % cement). This shows that 6% cement is an effective additive and can be applied to all soils having different Montmorillonite contents.

The cation exchange capacities of the soil specimens were studied after selected durability cycles. It has been found that the CEC values for Montmorillonite dominant soils show an increasing trend with durability cycles when stabilized with lime and cement. The next chapter presents the test results obtained from the leachate studies.

CHAPTER 5

LEACHATE STUDIES

5.1 Introduction

Leachate studies were conducted on all the soil specimens. The main objective of this study is to address the permanency of the stabilizer on the long term durability of both lime and cement treated soil sample containing different amounts of Montmorillonite content. The leachate collected from the soil specimens was studied for pH and calcium concentrations for selected cycles. The soil samples were studied for leachability according to the procedures discussed in chapter 3. The leachate coming out of the soil sample was studied for pH and calcium concentrations. The soil sample after leached for 14 cycles was tested for residual UCS test, calcium at select cycles, pH at select cycles and CEC. Details of the test results were given as follows.

5.2 pH test results

The leachate coming out of the soil sample was tested for pH test, and the variation of pH with leachate cycles is studied and presented. The variation of pH with leachate cycles for M20 soil when stabilized with 6% lime and 6% cement was presented in Figure 4.29. Similar studies were conducted on all the other soil specimens when stabilized with lime and cement to study the variation of pH with leachate cycles. The cement treated soil specimens showed slightly higher pH than that of lime treated soil specimens. Figures 4.30, 4.31 and 4.32 present the variation of pH results with leachate cycles for M40, M50 and M60, soils respectively.

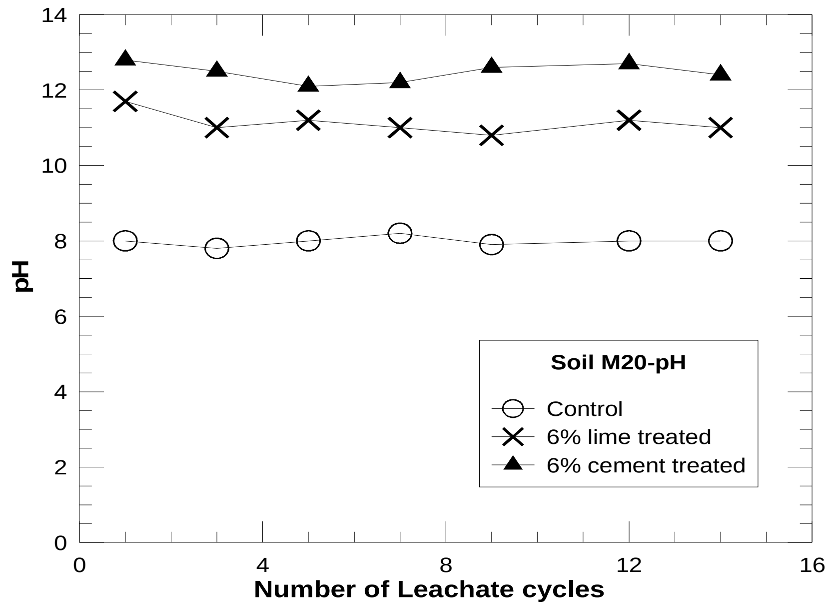


Figure 5.1: Variaion of pH with leachate cycles for M20 soil

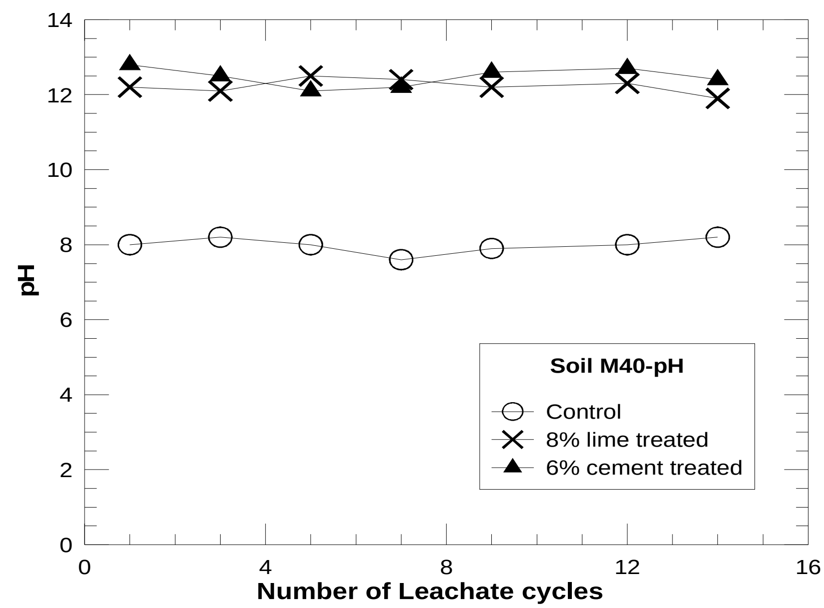


Figure 5.2: Variaion of pH with leachate cycles for M40 soil

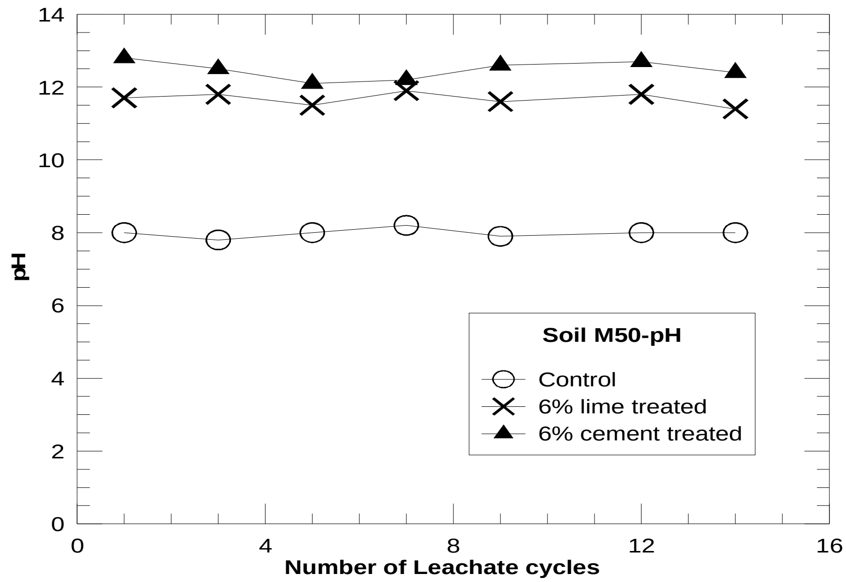


Figure 5.3: Variaion of pH with leachate cycles for M50 soil

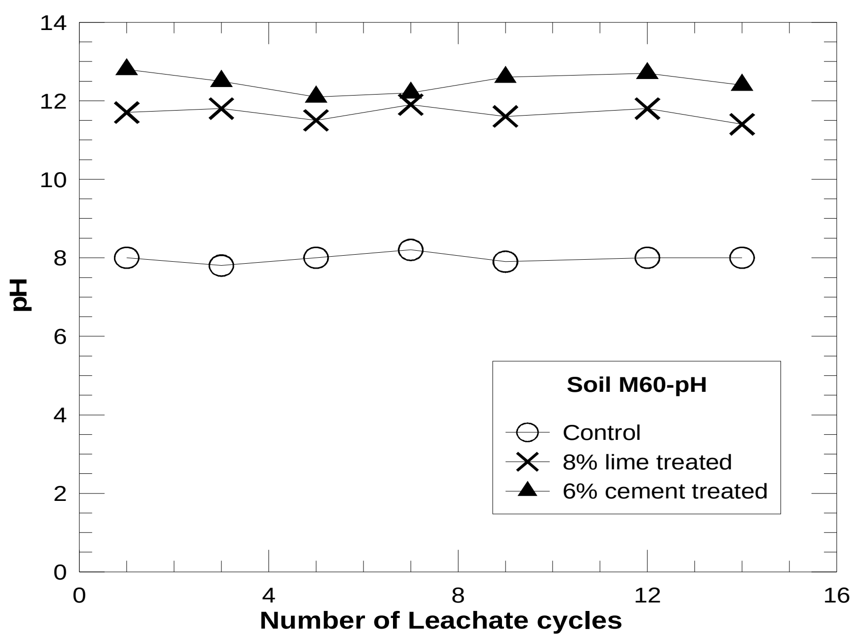


Figure 5.4: Variaion of pH with leachate cycles for M60 soil

5.3 Calcium studies

Leachate samples collected from the soil specimens at different cycles were studied for calcium concentrations. The procedure for the determination of calcium by EDTA was given in detail in chapter 3. The concentration of calcium in ppm was determined and plotted against leachate cycles to study the variation of calcium leaching out during each cycle. Figure 5.5 presents the variation of calcium concentrations with leachate cycles for M20 soil.

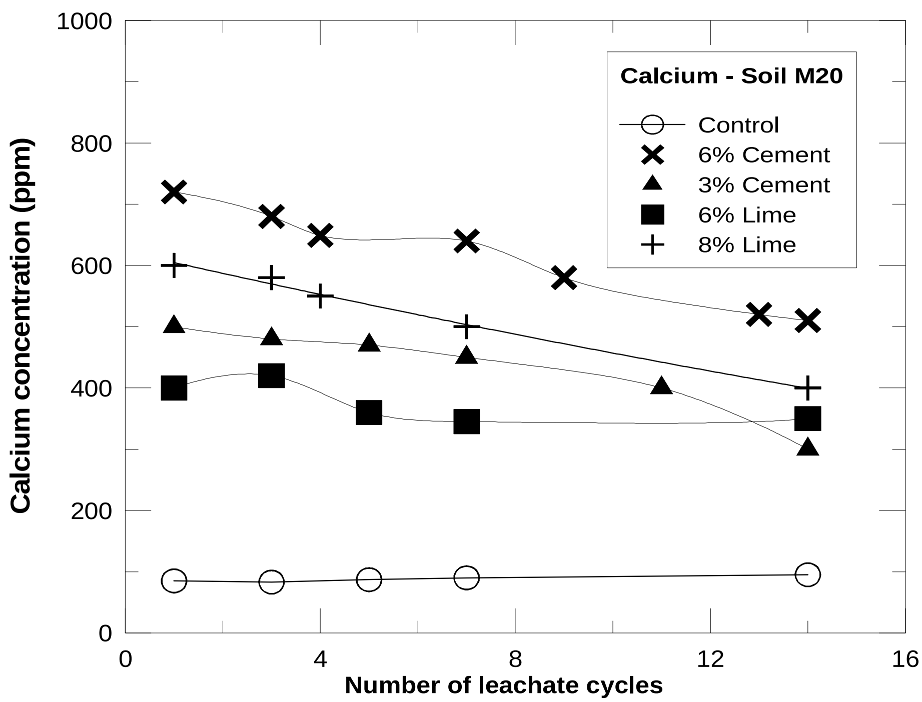


Figure 5.5: Variation of Calcium concentrations with leachate cycles for M20 soil

The M20 soil when treated with different additives showed a decreasing trend in calcium concentrations with different leachate cycles. Figures 5.6, 5.7 and 5.8 present the values of calcium concentrations with leachate cycles for M40, M50 and M60 soils respectively.

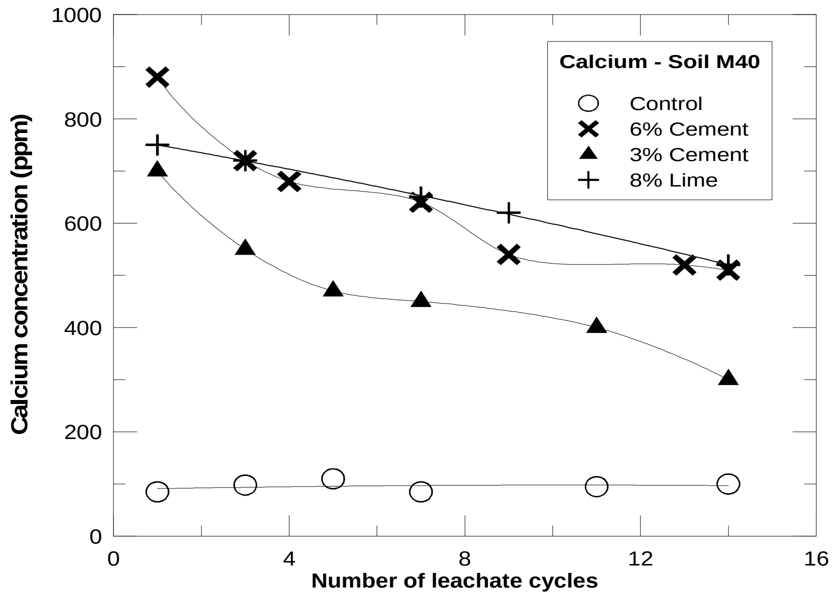


Figure 5.6: Variation of Calcium concentrations with leachate cycles for M40 soil

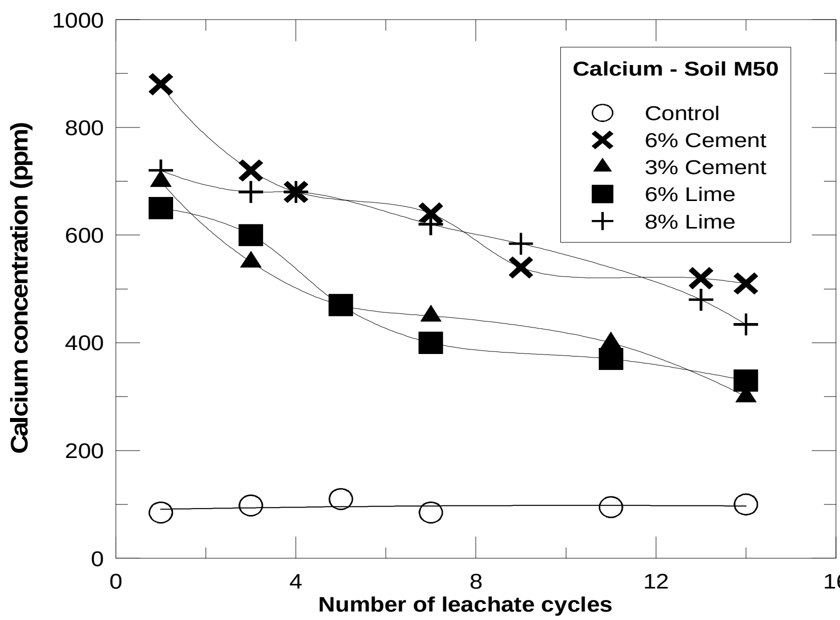


Figure 5.7: Variation of Calcium concentrations with leachate cycles for M50 soil

Soil sample M40 had shown a decreasing trend in calcium concentrations when treated with 3%, 6% cement and 8% lime. The soil M50 showed similar trend when stabilized with lime and cement.

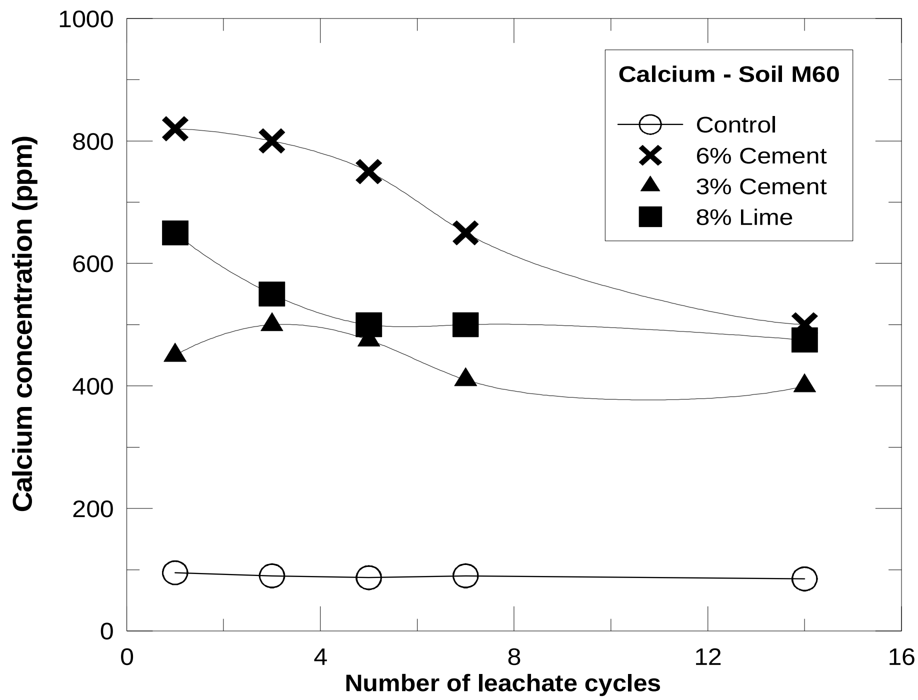


Figure 5.8: Variation of Calcium concentrations with leachate cycles for M60 soil

Above plot presents the trend of calcium concentrations in the leachate collected from soil M60 when treated with lime and cement.

Detail study on the percentage lime/cement leached out from all the soil specimens was conducted and presented in Table 5.1.

5.4 Cation Exchange Capacity

Cation exchange capacities of the soil specimens subjected to leachate cycles were studied before and after 14 cycles of leachate. The variation of CEC with 14 cycles of leachate for different soil specimens was presented in the Figures 5.9 and 5.10 below. The CEC values for soil sample M20 is constant and showed a decreasing trend for all other soils.

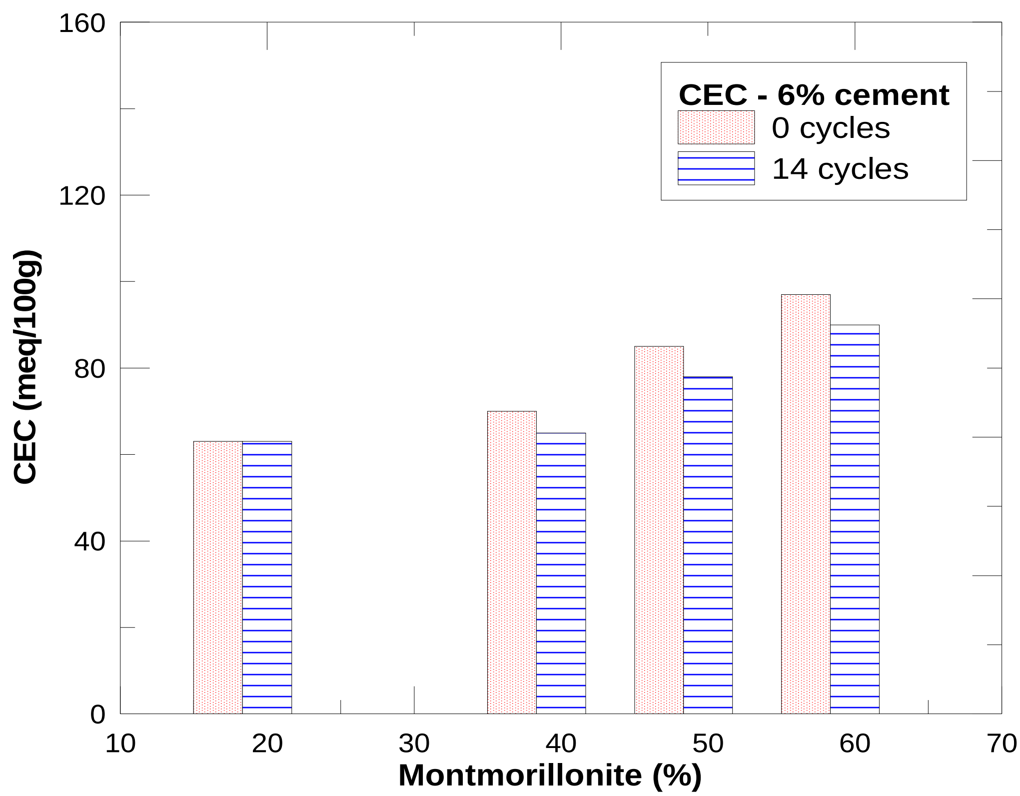


Figure 5.9: Variation of CEC with MM content for 8% lime treated soils

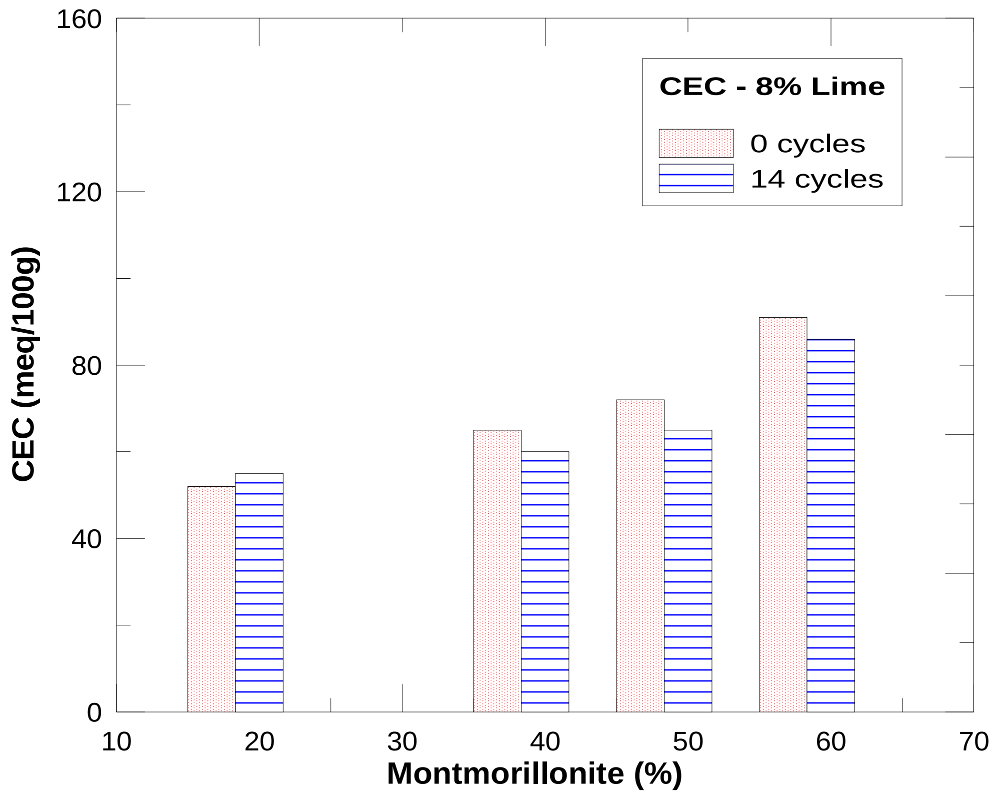


Figure 5.10: Variation of CEC with MM content for 6% cement treated soils

5.5 Analysis of Test Results

The amount of lime leached out of different soil samples was as shown in Table 5.1. The soil specimens after 14 leachate cycles were subjected to unconfined compressive strength test to test the residual strength in the soil specimen.

Table 5.1: Showing the retained properties of soils after 14 leachate cycles

Soil	Additive	Average calcium concentration (ppm)	% of lime/cement leached out after 14 cycles	% strength retained after 14 cycles
M20	6% Lime	375	0.75	88
	8% Lime	526	0.98	95
	3%Cement	217	0.43	90
	6% Cement	614	0.91	97
M40	6% Lime	435	0.40	99
	8% Lime	652	0.80	97
	3% Cement	478	0.41	98
	6% Cement	641	0.58	97
M50	6% Lime	478	0.88	96
	8% Lime	641	1.15	98
	3% Cement	470	0.43	97
	6% Cement	599	0.83	99
M60	6% Lime	430	0.31	97
	8% Lime	535	0.68	98
	3% Cement	447	0.70	96
	6% Cement	704	0.83	98

From Table 5.1 it can be inferred that the soil strength from leachate cycles is unaffected. The percentage of lime leached out from the soil specimen was less than 1% for all the soil specimens. This outcome rules out the reason that the soil samples are not effectively stabilized due to loss of stabilizer.

5.6 Field infiltration rate

The field infiltration rate was calculated to determine the number of years under actual field conditions replicated in the laboratory. According to the rainfall data given by Texas precipitation records the average annual rainfall for the state of Texas is 30 in. per year. Out of this total rainfall, only 35% is assumed to infiltrate into sub-soils. This number is very conservative and is considered to make a safe estimate of the number of years replicated in the infiltration studies in the laboratory conditions. The detailed procedure is given in the Figure 5.11.

From the infiltration capacity and time of infiltration the field infiltration capacity for a soil specimen can be calculated as shown in Figure 5.11. For most of the soil specimens the number of years replicated in the field was 4 to 5 years for 14 cycles of leachability. This states that the soil sample which had undergone 14 cycles of leachate in laboratory is equal to a representative soil sample in field experiencing rainfall infiltration for 5 years.

Calculation of Field Infiltration:

Average annual rainfall in Texas (AAR) = 30 in.

Approximate % infiltration %I = 35%

Rainwater in-filtered per year I_{field} = AAR * I = 10.5 in.

Calculation of Laboratory Infiltration:

Cross sectional area of soil specimen (A) = 81 cm^2

Volume of water infiltrated in one day (I_1) = 610 ml

Volume of water infiltrated in 14 days (I) = I_1 *14 = I_{14} = 8540 cm^3

Conversion of volume to head of water $I_{Lab} = \frac{I_{14}}{A}$ = 41.5 in.

Number of years replicated in years = $n = \frac{I_{Lab}}{I_{Field}}$ = 4 years

Figure 5.11: Calculation of number of years replicated in the field

5.7 Summary of test results

During leachate studies the concentrations of calcium and pH were monitored at selected number of cycles. A decreasing trend of CEC is found when the soils are subjected to 14 cycles of leachate. The pH of the leachate increased with increase in additive dosage and remained constant with durability cycles. It has been found out that the concentration of calcium leached was a little higher in cement treated than lime treated soils. This experiment also proves that the loss of stabilizer from the soil after 14 cycles of leachate is small compared to the initial percent amount used. The strength loss from the leachate cycles for all the soils specimens is very low. Hence it can be concluded that the reason for the ineffectiveness of stabilization for Montmorillonite dominant soils is not due to stabilizer loss.

CHAPTER 6

SUMMARY AND CONCLUSIONS

6.1 Summary

Stabilization of expansive clays with lime and cement has been widely accepted and used to improve their properties. When the problematic soils are treated with chemical stabilizers, the properties of the soils are improved, which in turn enhances riding comforts to the travelers. However, the stabilization effectiveness is not always same for all soils and this arises several issues with respect to stabilization design as the procedure established based on PI alone is not sufficient. Soils with similar PI values will behave differently due to the presence of different fractions of clay minerals. Another important reason is the lack of sufficient understanding of the chemical interactions between the stabilizer and the soils containing various fractions of MM mineral.

A recent previous research study documented a few details on clay mineralogy, durability studies and leachate studies. Methodology for different experiments including CEC, durability studies and calcium determination from leachate has been presented. This study only focused one stabilizer type and its dosage. Hence, new studies are needed to understand effectiveness of stabilization types on various types of soils with varying amounts of MM fraction. This has been the main research objective of the present investigation.

The first part of the research consisted of identification and selection of soils having different mineralogical contents. A total of four soils have been selected from different parts of Texas for this study and mineralogical characteristics are known by the experiments conducted by previous study. Four soils with varying fractions of MM were considered as control soils for this research. The second part comprises of treating the select soils with different stabilizer dosages and studying them for wetting/drying type durability test and leachate tests. Due to the frequent use in the field of ground improvement, only lime and cement treatments were considered in this research.

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

a) Soils with high percentage of Montmorillonite showed poor engineering properties when stabilized with low dosages of lime and cement stabilizer.

b) M20 soil (Pharr-B) was stabilized effectively with 8% lime and 6% cement. M40 soil (Austin) was also effectively stabilized with 8% lime and 6% cement. Similarly, M50 and M60 soils are stabilized effectively with 6% cement However, these two soils did not perform well in durability studies with high amounts of lime treatments.

c) The volumetric strains of soil samples reduced considerably when treated with higher dosages of additives. Cement treated soils also showed considerable reduction in volumetric strains. M20, M40, M50 and M60 soil samples survived for 21 cycles of durability with a maximum volumetric change less than 5% when treated with 6% cement.

d) The CEC of soils treated with additives slightly increased with durability cycles. This proves that the soils exchange capacity increases with seasonal changes.

e) Soils subjected to 14 leachate cycles (without allowing volume change) did not show strength reduction, while the CEC values were reduced considerably in

Montmorillonite dominant soils. This shows that the leachability of treated clays of different MM fraction is similar to other soils with different clay minerals.

f) The retained strengths after 14 cycles of leachate are higher for cement than lime treated soils.

g) Overall, stabilization charts based on soil PI and gradation are deemed incomplete without the inclusion of soil mineralogy. This is because soils with high fractions of MM performed poorly with the stabilizer design in particular the lime treatment. High dosages of cement and higher dosages of lime (more than 8% used in this research) should be considered for soils with high fractions of MM.

6.2 Proposed recommendations

From the study, it is recommended that soil stabilization based on current practices based on PI and gradation of soil is insufficient for selecting an effective stabilizer. As soils having same PI act differently to stabilizers, due consideration is to be given to include clay mineralogy in the stabilization charts. As proposed by Chittoori (2008), a set of simple procedures like CEC, specific surface area (SSA) and total potassium (TP) can be utilized for the determination of mineralogy in the soil rather than using costly equipment such as XRD and SEM. Figure 5.1 presents the proposed changes in the stabilization chart used by TxDOT for the selection of additives for subgrades.

6.3 Future recommendations

The current research assumes that clay fraction is made up of Montmorillonite, Illite and Kaolinite. However other non clay minerals like quarts, feldspar which are present in the soil should be included in the future studies. The soils have a very close PI range in the present research, hence testing of soils possessing a diverse range of PI could help better understanding of the MM-PI relationship in the future. Also, research should be conducted on how to design a versitile setup that can perform both wetting/drying cycles and leachate cycles to provide better replication of the field.

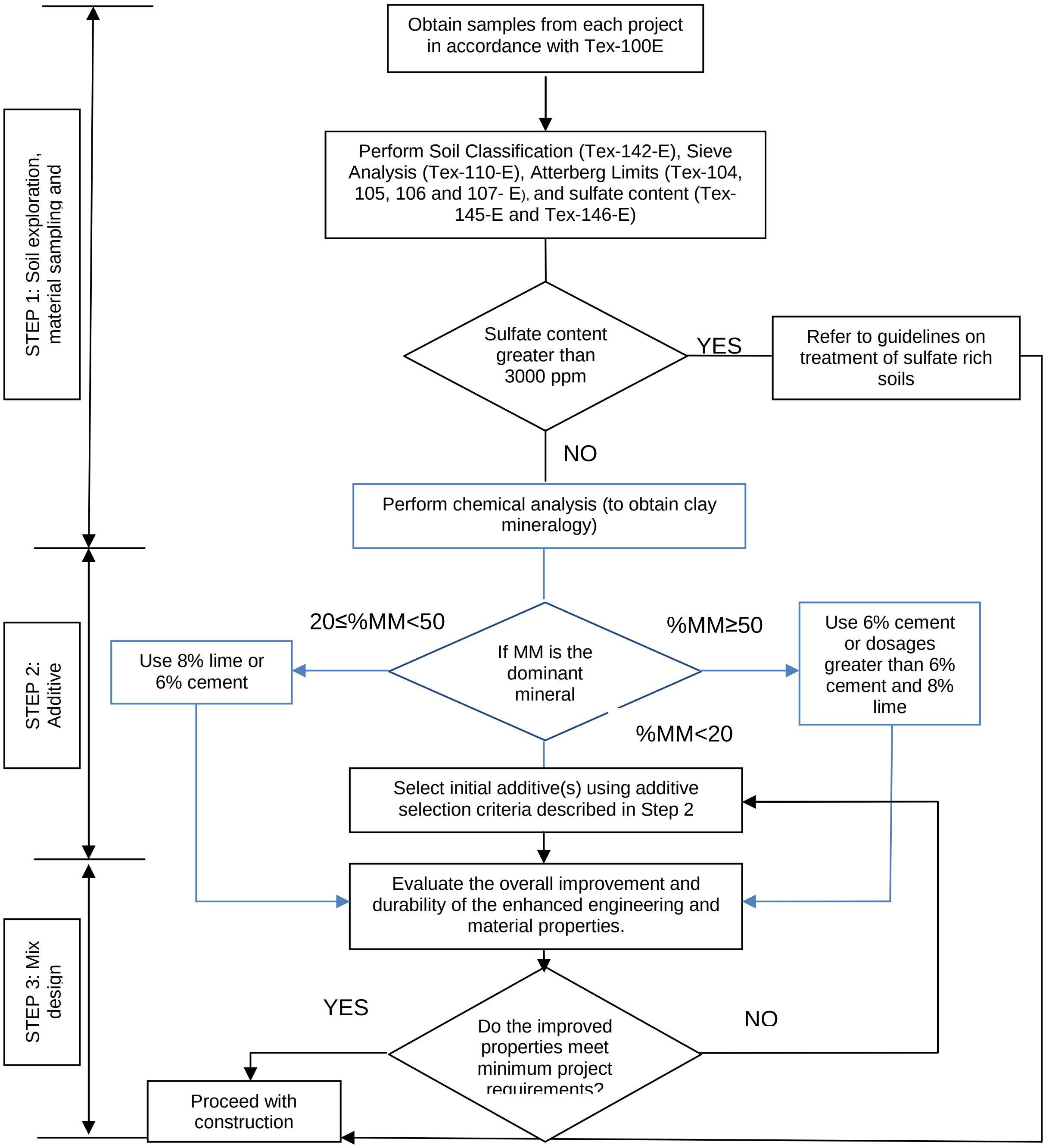


Figure 6.1:Proposed guidelines for subgrade soil treatment

REFERENCES

Abduljauwad, S.N., (1993). “Treatment of calcareous expansive clays”. Fly Ash for Soil Improvement,Geotechnical Special Publication, ASCE, 36, pp. 100–115.

Aiban, S.A., Al-Ahmadi, H.M., Asi, I.M., Siddique, Z.U., Al-Amoudi, O.S.B., (2006). “Effect of geotextile and cement on the performance of sabkha subgrade”. Building and Environment 41 (6), pp. 807–820.

Al-Rawas,A.A.,Hago, A.W.,Al-Sarmi,H., (2005). “Effect of lime, cement and saroj (artificial pozzolan) on the swelling potential of an expansive soil from Oman”. Building and Environment 40, pp. 681–687.

Bahar. R, Benazzoug. M, Kenai. S (2004). “Performance of compacted cement stabilized soil”. Cement & Concrete Composites 26 (2004) 811–820.

Bailey. S. W. (1980). “Summary of recommendations of AIPEA nomenclature committee on clay minerals”. American Mineralogist, 65, 1-7.

Basma, A.A and Tuncer E.R. (1991). “Effect of lime on volume change and compressibility of expansive clays”. Transportation Research Record, 1295.

Bell FG. (1996). “Lime stabilization of clay minerals and soils”. Engineering Geology;42:223–37.

Borchardt, G. (1989), “Smectites”, In J.B. Dixon and S.B. Weed, eds., Minerals in Soil Environments, 2nd ed., Madison, WI: Soil Science Society of America.

Chapman, H. D., (1965). “Cation-exchange capacity” In: C. A. Black ed., Methods of soil analysis - Chemical and microbiological properties, Agronomy 9, 891-901.

Chittoori, B. C. S. (2008). “Clay Minerology effects on long term performance of Chemically treated Expansive clays”, Thesis submitted to the department of civil engineering, The University of Texas at Arlington, Texas in partial fulfillment of the doctorial degree.

Choquette. M, Andreberube. M and Locat. J. (1987) “Mineralogical and Microtextural changes associated with lime stabilization of marine clays from eastern Canada” Applied clay science, 2, 215-232.

Croft, J.B., 1967. The influence of soil mineralogical composition on cement stabilization. Geotechnique 17, 119–135.

Eades, J. L. and Grim, R. E. (1966). “A Quick Test to Determine Lime Requirements for Soil Stabilization.” *Highway Research Record 139*, HRB, National Research Council, Washington D.C., 61-72.

Grim, R. E., (1953). “Clay Mineralogy.” Mc Graw Hill Book Company, New York.

Hoyos, L.R., Laikram, A., and Puppala, A.J (2005). “Assessment of Seasonal Effects on Engineering Behavior of Chemically Treated Sulfate Rich Expansive Clay.” *Proc., GEOPROB2005: International Conference on Problematic Soils*, 25-27.

Jones, D.E. and Holtz, W.G., 1973.“Expansive soils-the hidden disaster,” *Civil Engineering*, ASCE, 43, pp. 49–51.

Kezdi, A., 1979. Stabilized Earth Roads. Elsevier Scientific Publishing Company, Amsterdam.

Little, D. N., Males, E. H., Prusinski, J.R. and Stewart, B. (2000). “Cementitious Stabilization.” *79th Millennium Rep. Series*, Transportation Research Board.

Mathew K.P. and Narasimha Rao. N., (1997) “Effect of lime on Cation exchange capacity of Marine clay” Journal of Geotechnical and Geo-environmental engineering, 183.

Marshall, A. B. and Frank, P. A. (2007). “Extending durability of lime modified clay subgrades with cement stabilization.” Geotechnical Special Publication, Proceedings of Sessions of Geo-Denver Soil Improvement, 172.

McCallister, L.D. (1990). “The Effects of Leaching on Lime-Treated Expansive Clay.” Thesis submitted to The University of Texas at Arlington, Arlington, Texas, in partial fulfillment for the doctorate degree.

Mitchell, J.K. and Soga, K. (2005). “Fundamentals of Soil Behavior” John Wiley & Sons, New York.

Narasimha Rao, S., Subba Rao, K. V. and Rajasekaran, G. (1993). “Microstructure Studies of Lime Treated Marine Clays.” Proc. 12th International Conference on *Offshore Mechanics and Arctic Engineering*, 1, 425-431.

Nelson J.D. and Miller D.J. 1992. *Expansive soils, problems and practice in foundation and pavement engineering*, John Wiley and Sons Inc., New York.

Ninov J. and Donchev I., (2008) “Lime stabilization of clay from the ‘Mirkovo’ deposit Part I: Kinetics and mechanism of the process” Journal of Thermal Analysis and Calorimetry, Vol. 91 2, 487–490

Petry, T. M. and Armstrong, J. C. (1989). “Stabilization of Expansive Soils.” *Transportation Research Record*, 1219, 103-112.

Puppala, A. J., Punthutaecha, K. and Vanapalli, S. K. (2006). "Soil-water characteristic curves of stabilized expansive soils." Journal of Geotechnical and Geoenvironmental Engineering, 132 (6), 736-751.

Rajasekaran G., Murali T.K., and Srinivasaraghavan R., (1997) “Fabric and Mineralogical studies on lime treated marine clays” Ocean engineering, Vol 24 No.3 pp. 227-234.

Rao, S.M., Reddy, B.V.V. and Muttharam, M. (2001). “The impact of cyclic wetting and drying on the swelling behavior of stabilized expansive soils.” *Engineering Geology*, 60 (4), 223-233.

Rogers, C.D.F and Glendinning, S. (1997), "Stabilisation of Shallow Slope Failures Using Lime Piles", Transportation Research Record 1589, TRB, Washington DC, USA, p.83-91.

Stavridakis E. I. (2005), “Evaluation of engineering and cement–stabilization parameters of clayey–sand mixtures under soaked conditions” Geotechnical and Geological Engineering (2005) 23: 635–655.

Tayabji, S. D., Nussbaum, P. J. and Ciolko, A. T. (1982). “Evaluation of Heavily Loaded Cement-Stabilized Bases.” *Transportation Research Record*, TRB, National Research Council, Washington, D.C., 839, 6-11.

Teresa López Lara, Hernández J.B. Zaragosa, Cajun C. López. (2004) “Mineralogical characterization of stabilized soils” Electronic journal of Geotechnical engineering, V 9F.

Thompson, M.R., 1968. “Lime stabilization of soils for highway purposes” Final Summary Rep. Civil Engineering Studies, Highway Series No.25, Illinois Cooperative Highway Research Program, Project IHR-76, 26 pp.

Wanyan, Y., Abdallah, I., Sabnis, A. and Nazarian, S. (2008). “An Expert System for Design of Low-Volume Roads on High-Plasticity Clay Subgrade.” TxDOT Research Report 0-5430-1, The University of Texas at El Paso, El Paso, Texas.

Whittig, L. D. and Allardice, W. R. (1986). “X-Ray diffraction techniques.”, In A.Klute, (ed.,) Methods of Soil Analysis, Part 1—Physical and Mineralogical Methods, 2nd ed., *American Society of Agronomy*, Madison, Wisconsin, 331-362.

Yong, R.N., Ouhadi, V.R., Mohamed, A.M.O., (1996). Physiochemical evaluation of failure of stabilized marl soil. 49th Canadian Geotechnical Conference Frontiers in Geotechnology, vol. 2, pp. 769–776.

Yong, R.N., Ouhadi, V.R., (2007) “Experimental study on instability of bases on natural and lime/cement stabilized clayey soils” Applied clay science, 35, 238-249.

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