

EFFECTS OF CALCIUM-BASED TREATMENT ON ORGANIC SOIL BEHAVIOR

by

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To my Mom, Dad, Vikram and Vivek

## ACKNOWLEDGEMENTS

Civil engineering discipline always had challenges regarding the behaviors of materials in different environments. To better serve the demands and face the challenges encountered in the evolution of civil engineering field it is vital to incorporate science and technology from other fields. “Stabilization Effects of Organic Rich Soils” is one such a project which required application of knowledge from various discipline including soil mechanics, chemistry, and engineering geology.

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July 11, 2008

## ABSTRACT

### EFFECTS OF CALCIUM BASED TREATMENT ON ORGANIC SOIL BEHAVIOR

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Organic soils are found in many places around the world. Organic soils undergo large secondary settlements depending on the amount of organic matter present in the soil. Organic soil is a mixture of finely divided particles of organic matter, in some instances visible fragments of partly decayed vegetable matter and shells are also present in the organic matter. In order to reduce the secondary settlements caused by organic matter, soil is treated with different stabilizing agents. The difficulties associated with organic soils arise when they are treated with cement or lime stabilizers, as organic matter inhibits cementitious reactions responsible for strength gain. There is a need to understand the fundamentals behind the chemical reactions contributing to the changes in geotechnical properties of stabilized organic soil beds.

Subsequently, 12 soil samples are obtained from 6 locations. The locations include Abilene, Austin, Beaumont, Bryan (Huntsville and College Station), Corpus Christi for research. Laboratory experiments were conducted on the control soil and treated samples (lime and cement). These experiments are conducted to measure the properties like vertical free swell strain, linear shrinkage strain and unconfined compressive strength at different intervals. This improvement factor is also affected due to the presence of organic content. Particularly,

unconfined compressive strength of some soils decreased after 56 days of treatment. This may be due to the presence of organics and humic acid in the soil. However, a detailed analysis with increased curing time and preparation of artificial samples with known organic content and humic acid may give better insight into the behavior and strength gain properties of soils due to stabilization.

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CHAPTER 1  
INTRODUCTION  
1.1 Introduction

Organic soils are found in many places around the world. Organic soils undergo large secondary settlements depending on the amount of organic matter present in the soil (Terzaghi et al., 1996). Organic soil is a mixture of finely divided particles of organic matter, in some instances visible fragments of partly decayed vegetable matter and shells are also present in the organic matter (Terzaghi et al., 1996).

In order to reduce the secondary settlements caused by organic matter, soil is treated with different stabilizing agents. The difficulties associated with organic soils arise when they are treated with cement or lime stabilizers, as organic matter inhibits cementitious reactions responsible for strength gain. There is a need to understand the fundamentals behind the chemical reactions contributing to the changes in geotechnical properties of stabilized organic soil beds (Hampton and Edil, 1998).

In the past few years, Texas Department of Transportation (TxDOT) has been experiencing difficulties in stabilizing the organic rich subgrade soils with calcium based additives. When the soils containing organic matter less than one percent, desired improvement is never achieved or the improvement disappears over time. However, in other parts of Texas, soils containing organic matter more than 3 percent have been successfully stabilized. These conflicting results raise several uncertainties with respect to organic matter in subgrades including laboratory and field characterization and problematic levels at which chemical treatments can be deemed ineffective. Therefore, this research thesis concentrates on the problems associated with stabilization of organic rich soils, by using optimum lime and cement content.

## 1.2 Research Objective

The main objective of this research is to address the problems associated with the stabilization of organic rich soils with calcium based stabilizers. Then study the effect of calcium based stabilizers on the organics present in soil. The amendment effects are explained as a function of organic matter present in the soil. Unconfined compressive strength, 1-D free swell, bar shrinkage, and secondary settlement properties are explained as a function of organic content. However, unconfined compressive strength is explained with respect to time. In order to address these problems a systematic research study is planned with the following objectives:

- To perform a comprehensive literature review on classification of organic soils, procedures used for stabilization of organic soils, and the reactions taking place after the soil is stabilized.
- To perform a survey in Texas, on the problems of pavements due to organic soils.
- To perform a series of basic and engineering laboratory tests on control and treated soils with lime and cement. The soils are sampled from districts like Abilene, Austin, Beaumont, Bryan, and Corpus Christie in Texas.
- To analyze the experimental data measured from laboratory tests performed on all control soils and treated soils with cement and lime. Then, to assess the suitability of stabilizers for organic soils.
- To summarize the research conclusions and suggest some future recommendations.

## 1.3 Research Overview

The present thesis report is organized in six chapters:

- Chapter 1 provides the introduction, research significance, research objectives, and report organization of the research.
- Chapter 2 presents the literature review on classification of organic soils, procedures used for stabilization of organic soils, and the reactions taking place after the soil is stabilized.

- Chapter 3 provides the survey analysis on the problems due to the stabilization of organic soils in Texas.
- Chapter 4 provides the information pertaining to series of basic and engineering laboratory tests on control and treated soils with lime and cement. The soils are sampled from districts like Abilene, Austin, Beaumont, Bryan, and Corpus Christie in Texas.
- Chapter 5 provides the analysis of experimental data measured from laboratory tests performed on all control soils and treated soils with cement and lime. Then, to assess the suitability of stabilizers for organic soils.
- Chapter 6 provides the summary of research conclusions and suggests some future recommendations.

In the last section, the references related to literature review and experimental procedures are presented and finally the appendices are included.

## CHAPTER 2

### OVERVIEW OF LITERATURE

#### 2.1 Introduction

In the past few years, Texas Department of Transportation (TxDOT) has been experiencing difficulties in stabilizing the organic rich subgrade soils with calcium based additives. When the soils containing organic matter less than one percent, desired improvement are never achieved or the improvement disappears over the time. However, in other parts of Texas, soils containing organic matter more than 3 percent have been successfully stabilized. These conflicting results raise several problems with respect to organic matter in subgrades including laboratory and field characterization and problematic levels at which chemical treatments can be deemed ineffective.

In order to address these problems a systematic research study is planned with the following objectives:

- To analyze the different organic soils and find the organic content levels that are deleterious to calcium based stabilizer treatments.
- To study the concentrations of organic matter required for deleterious reactions and assess if these are same in different regions of the state.
- To study the effects of organic matter on the engineering properties of treated subgrade layers

As a part of this research, a comprehensive review of the literature has been carried out to understand various types of organic soils and effects of organic content on engineering properties of soils, and interactions among organic content, chemical stabilizers such as lime and cements and soil types. This literature review is presented in this technical memorandum and it

discusses organic soils, classification and their properties in Sections 2.2 through 2.5. The methods available for determining the organic content is also presented.

Section 2.6 deals with the characteristics of organic matter; while the interactions of organic matter with soils are presented in Section 2.7. Section 2.8 describes the effects of organic matter on engineering properties of soil. The reaction of organic matter with lime, and cement are covered in Section 2.9. Different methods to stabilize organic soils are discussed in Section 2.10.

### 2.2 Geological origin of organic soils

According to Larsson (1996), sulphide rich silts (usually called as svartmocka) and sediments rich in calcium carbonates (marl and diatomaceous soils) are also termed as organic soils. Larsson (1996) noted that organic matter in soils originates from living plants, animals and organisms. Especially, marine animals and plants contribute a major amount for the formation of organic material in the soil. During the transformation processes of plants, organic products such as peat and coal are created.

The transformation of plants and animals into organic soils predominantly through bacterial activity, and this process is intensified by hot climate, suitable humidity and exposure to oxygen in the air as shown schematically in Figure 2.1. Furthermore, the formation of peats occurs in the areas with humid areas of the temperate climate zones, and accumulates wherever the climate is favorable, irrespective of altitude or latitude. Figure 2.2 presents the abundance of organic soils across the United States of America. It can be seen that the occurrence/abundance of organic soils are found to be high in the state of Texas.

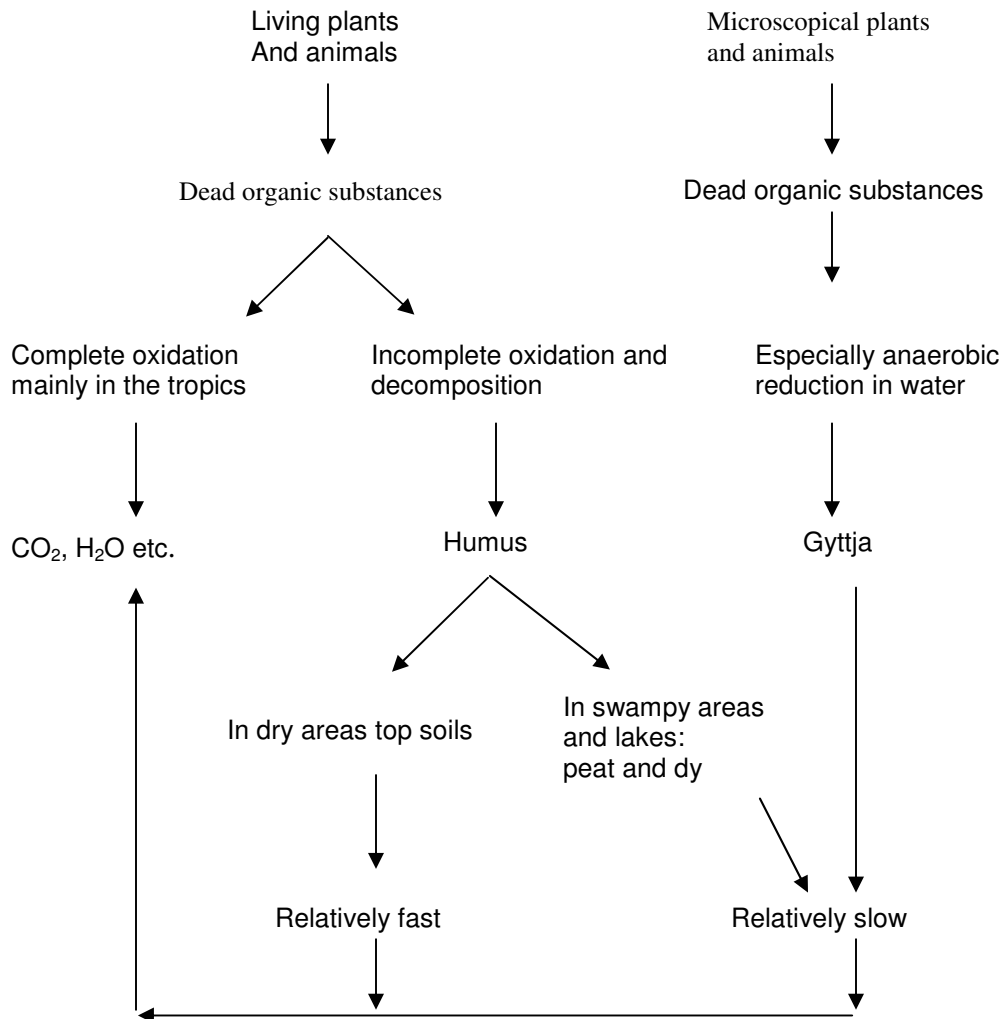


Figure 2.1 Schematic Processes During Decomposition of Biogenic Matter (Hallden, 1961).

The development of soils in Texas is extremely diverse and is directly related to the composition of the rocks on which they are produced. There are four key factors that control the fragmentation and decay of rocks into soil generation. These are: properties of the parent rocks, climate, presence or absence of soil and vegetation, and length of exposure (Press and Siever, 2001).

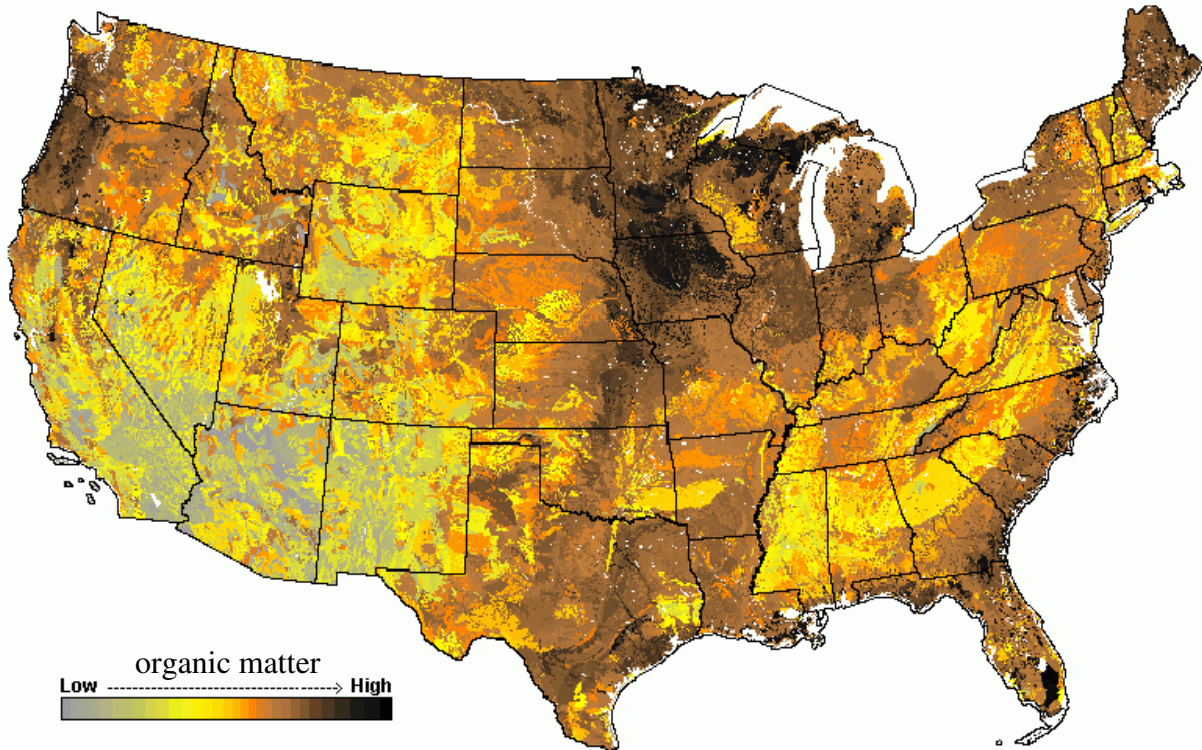


Figure 2.2 Intensity of Organic Soil Deposits Across the United States of America. ( Source : A New High-Resolution National Map of Vegetation Ecoregions Produced by William W. Hargrove and Robert J. Luxmoore) ([www.unl.edu/.../Soil Organic Matter Content.htm](http://www.unl.edu/.../Soil_Organic_Matter_Content.htm))

The composition and texture (i.e. grain size and orientation of crystals) of the parent rocks are important in soil formation because different minerals weather at different rates and the texture affects their susceptibility to cracking and fragmentation. A tombstone composed of limestone will alter more quickly than the granite one and in a few years the lettering may become illegible on the limestone tombstone, but the lettering on the granite tombstone will still be fresh.

The climate (rainfall and temperature) has a profound impact on soil generation. Using the tombstone analogy again, a limestone tombstone in southeast Texas will decompose more rapidly than a limestone tombstone in west Texas of the same age. Climate and living organisms strongly affect chemical breakdown of rocks. A hot and humid climate encourages growth of organisms, but cold, dry climates impede organism growth and chemical alteration of the rocks.

The presence of preexisting soil will increase the rate of alteration of the rock. Once soil starts to form, it works to weather the rock more rapidly. It retains rainwater, and it hosts a variety of vegetation, bacteria, and other organisms which all combine to create an environment that promotes



mineral alteration and/or dissolution.

Time is the last element in soil formation. A tombstone composed of limestone that is 100 years old in a graveyard in southeast Texas will be badly weathered, but a limestone tombstone that is 10 years old in that same graveyard will still be relatively unblemished. Therefore, the longer a rock is exposed to a certain climate, the more weathered it will become.

Because climate strongly influences weathering, it has a profound impact on the characteristics of the soil formed on any given parent rock. Figure 2.3 shows how soil scientists have characterized soils in general. There are generally three horizons designated by A, B, and C, with the O horizon only developed in temperate climates. The thickness and/or presence of each horizon will vary in different climates. For example, the A horizon will lie directly on the C horizon in wet, tropical climates. There are no O or B horizons because the organic matter is quickly oxidized and recycled into the vegetation. In temperate climates, there is a better developed B horizon and there can be a pronounced O horizon. In arid climates, there is a small A horizon and a large B horizon with no O horizon.

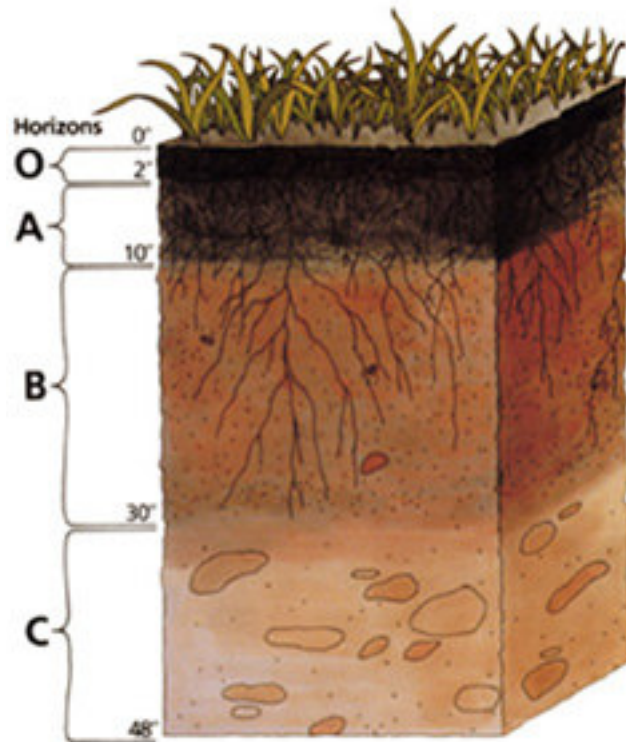


Figure 2.3 A Typical Soil Profile for a Temperate Climate

The O horizon is dominated by undecomposed or partially decomposed organic material (less than half of the weight is mineral matter). An O horizon may be at the surface or any depth beneath the surface if it has been buried. A horizon is composed mostly of clay and insoluble minerals like quartz in a soil that has formed over a long period of time. Soluble minerals have been leached from this layer. Beneath the A horizon is the B horizon, where there is little organic matter. Soluble minerals and iron oxides have accumulated in small pods, lenses, and coatings in this layer. The C horizon is the lowest layer and is slightly altered bedrock (parent material) fragments that have been broken and weathered, mixed with clay from chemical alteration.

Vegetation is also controlled to a large extent by the geology. The map on the left side of Figure 2.4 was assembled by Benjamin Tharp in 1939; it breaks the state up in different regions based on differences in the vegetation. Geologists often identify different rock units based upon the dominant vegetation growing in the area. For example, Spanish oak characterizes the Walnut Springs limestone; an open stand of cedar, the Glenrose; liveoak and cedar, the Edwards (Tharp, 1939). The rock types illustrated in the geologic map on the right side of Figure 2.4 shows a good correlation with the vegetation zones of Tharp (1939).

The vegetation will impact the type of organic matter in a soil. Wardwell et al. (1983) explain that an important constituent in OM decomposition is lignin which varies widely from one species to another. The amount of organic matter in a soil is influenced by several factors. Jenny (1941) arranged the importance of the soil forming factors as follows:

Climate > vegetation > topography = parent material (rock formations) > age

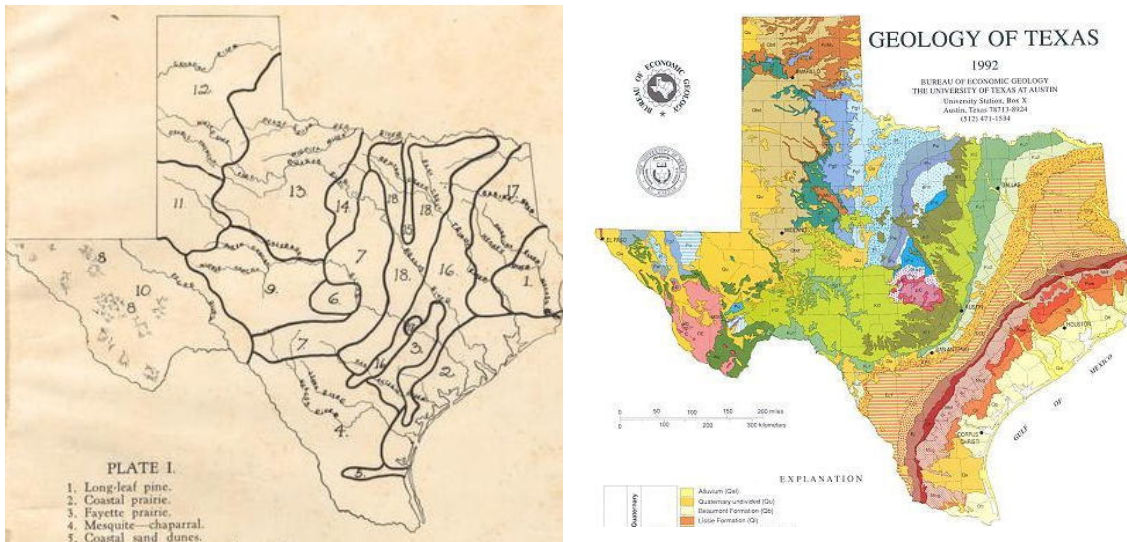


Figure 2.4 Vegetational regions of Texas showing how Vegetation [left] varies with Geology [right] (vegetation map from Tharp, 1939; geologic map from the Bureau of Economic Geology 1992)

The concentration of organic matter in undisturbed soils varies. The following generalizations on the organic matter concentrations are presented based on the research conducted by Jenny (1941):

- Grassland soils have higher organic matter than forest soils.
- High PI soils have higher organic matter than low PI soils.
- Poorly drained soils have higher organic matter than well-drained soils.
- Lowland soils have more organic matter than upland soils.
- Organic matter increases as precipitation increases.
- Organic matter decreases as temperature increases.

In residual soils, organic matter is the most abundant in the surface horizons (Mitchell and Saga, 2005). The size of organic particles range down to 0.1  $\mu\text{m}$  and their specific properties alter greatly depending upon the parent material, climate and stage of decomposition (Mitchell and Saga, 2005).

### 2.3 Types of organic soils and their classification

In Civil Engineering nomenclature, a soil is said to be an organic if it has a sufficient organic content to affect the engineering properties of the material but does not have the spongy structure of peat or muck (Schmidt, 1965). The significance of organic content rich soils has been recognized in different disciplines such as geotechnical engineering, transportation engineering,

geology, soil science and agronomy. Though the relevance is widely diversified from discipline to discipline, the Geotechnical Engineering deals with the engineering properties of soil such as secondary consolidation effects, shear strength parameters and the hydraulic conductivity of organic soils.

Geotechnical engineers categorize the organic soils as one of the problematic soils because of their high compressibility and moisture content (Mitchell & Soga, 2005). Transportation area also addresses the occurrence of settlements after the pavement construction on organic soils (Mitchell & Soga, 2005). Agronomy and Soil Science deal with the composition of organic materials such as ammonia, phosphorous and the degradable matter of plants and animals for the production of crops (Mitchell & Soga, 2005).

As discussed above, the importance of organic rich soils are different from each discipline and hence one finds various definitions of the organic soil in the literature. Organic soils are composed of plant and animal remains that have accumulated, in varying stages of decomposition, in an environment that does not allow decay of the materials to take place rapidly (Caldwell, 1977). An organic soil can be defined as a soil containing 174 gm or more of organic carbon per kilogram of the soil having mineral fraction of clay more than 500 gm and it is 116 gm if the soil containing no clay fraction in the case of saturated soil condition. In unsaturated condition, if the soil having organic carbon of 203 gm or more per kilogram of soil, then the soil is said to be organic (Emission of green house gases in the United States-2003, 2004). The soil is considered to be organic if the half of the 80 cm depth of the top soil (upper crest) has the organic material or the organic material of any thickness resting on the rock or the remnant material apertures being filled with the organic materials (Soil Taxonomy, 2006). Maximum number of soils have predominant amount of mineral material with horizons of organic matter present in it (Soil taxonomy, 2006).

The organic soils are classified using two different classification systems known as 'Von Post system' and 'Radforth system' (Landva et al., 1983). Von Post system is used to classify soils as per their horticultural, agricultural and forestry requirements whereas Radforth system is used to classify the organic soil as per geotechnical engineering field related application. The

Radforth classification system is applicable only to soils with 80% or higher organic content. These systems use organic content, fiber content, type of botanical matter, degree of decomposition and other attributes for classification purposes.

Vonpost classified the peat based on the degree of humification. He had given a scale from H<sub>1</sub> to H<sub>10</sub> based on the decomposition, plant structure, content of amorphous material, material extruded on squeezing (passing between fingers). The classification of above system is shown in the Table 2.1.

Table 2.1 Degree of humification according to Vonpost (1924) (Hartlen & Wolski, 1996)

Degree of Humification	Decomposition	Plant structure	Content of amorphous material	Material extruded on Squeezing	Nature of residue
H <sub>1</sub>	None	Easily identified	None	Clear, Colourless Water	
H <sub>2</sub>	In significant	Easily identified	None	Yellowish Water	
H <sub>3</sub>	Very slight	Still identifiable	Slight	Brown, Muddy water, No peat	Not pasty
H <sub>4</sub>	Slight	Not easily identified	Some	Dark brown. Muddy water, no peat	Some what pasty
H <sub>5</sub>	Moderate	Recognizable, But vague	Considerable	Muddy water and Some peat	Strongly pasty
H <sub>6</sub>	Moderately Strong	Indistinct	Considerable	About one third of peat squeezed out, water Dark brown	Fibers and roots more resistant to Decomposition
H <sub>7</sub>	Strong	Faintly recognizable	High	About one half of peat squeezed out; any water very dark brown	
H <sub>8</sub>	Very strong	Very indistinct	High	About two third of peatsqueezed out; also some pasty water	
H <sub>9</sub>	Nearly complete	Almost unrecognisable		Nearly all the peat squeezed out as a fairly uniform peat	
H <sub>10</sub>	Complete	Not discernible		All the peat passes Between the fingers No free water visible	

Radforth (1969) classified the peat based on structure of peat rather than its botanical origin. Moreover, Radforth approach makes it better for estimating the mechanical properties of peat soils. In this classification, peat was divided into three main categories including amorphous granular, fine fibrous and coarse fibrous as per the character of structure. Furthermore, these were further categorized based on woody and non-woody characteristics as presented in Table 2.2.

Table 2.2 Classification of peat (Radforth, 1969), (Hartlen & Wolski, 1996)

Predominant characteristic	category	Name
Amorphous-granular	1	Amorphous-granular peat
	2	Non-woody, fine fibrous peat
	3	Amorphous-granular peat containing non woody fine fibers
	4	Amorphous-granular peat containing woody fine fibers
	5	Peat, predominantly amorphous-granular containing non woody fine fibers, held in a woody, fine fibrous frame work
	6	Peat, predominantly amorphous granular containing woody fine fibers, held in a woody, coarse fibrous frame work
	7	Alternate layering of non woody, fine fibrous peat and amorphous granular peat containing non woody fine fibers
Fine fibrous	8	Non woody fine fibrous peat containing a mound of coarse fibers
	9	Woody, fine fibrous peat held in a woody, coarse-fibrous frame work
	10	Woody particles held in non-woody, fine fibrous peat
Coarse fibrous	11	Woody and non woody particles held in fine fibrous peat
	12	Woody coarse fibrous peat
	13	Coarse fibers criss crossing fine fibrous peat
	14	Non woody and woody fine fibrous held in a coarse fibrous frame work
	15	Woody mesh of fibers and particles enclosing amorphous granular peat containing fine fibers
	16	Woody coarse fibrous peat containing scattered woody chunks
	17	Mesh of closely applied logs and roots enclosing woody coarse fibrous peat with wood chunks

According to ASTM standard classification, a soil is said to be an organic or muck if the organic content is less than 75% by dry mass of the soil, otherwise it is called as a peat. In

contrary, the International Peat Society (IPS) classifies the soil as organic if the organic content is less than 20%; otherwise the soil is called as a peat. Nevertheless, the Unified Soil Classification System (USCS) classifies the soil based on its liquid limit. If the liquid limit of any soil after oven drying at 105 – 110 °C is less than 75% of its liquid limit value before oven drying is said to be an organic soil. In this soil classification system organic soils are generally divided into two groups. They are OL (organic silts and organic silty clays with low plasticity) and OH (organic clays with medium to high plasticity, organic silts).

The classification of organic soils on the basis of organic content is described in the Table 2.3. The majority constituent of the organic soil is peat. Organic soils which are not peat are categorized as carbonaceous or mineral sediments, depending on their total ash content in the Organic Sediments Research Center (OSRC) system (Andrejko et al, 1983). However, the comparison of the OSRC system with some other presently accepted systems are shown in the Table 2.4.

Table 2.3 Guiding values for the Classification of Soils on the Basis of Organic content (Karls0n and Hansbo, 1981)

Soil group	Organic content in weight % of dry material	Examples of designations
Low organic soils	2-6	Gyttja bearing clay Dy bearing silt Humus bearing, clayey sand
Medium organic soils	6-20	Clayey gyttja Silty dy Humus rich sand
High organic soils	>20	Gyttja, Dy, Peat Humus rich top soil

Table 2.4 Comparison of Classification of Organic Soils (Andrejko et al., 1983)

		OSRC SYSTEM	JARETT SYSTEM	DAVIS (1946)	U.S.S.R SYSTEM	LGS SYSTEM		
ASH CONTENT (%)	0	PEAT	LOW ASH	PEAT	PEAT	PEAT	0	ASH CONTENT (%)
			MEDIUM ASH				10	
	10		HIGH ASH				20	
	20	CARBONACEOUS SEDIMENT	LOW ASH	PEATY	PEAT	PEATY MUCK	30	
	30						HIGH ASH	
	40		CLAYEY SILTY/SANDY/GRAVELLY	MUCK	NON PEAT	50		
	50					CLAYEY MUCK	60	
	60						CLAY	
	70		ORGANIC	80				
	80			MINERAL SEDIMENT	ORGANIC CLAY OR SILT	MINERAL SOIL	NON PEAT	
	90	100						
	100						100	

The following subsections provide descriptions of different types of organic soils as per Geotechnical classification.

### 2.3.1 Peat

Many coastal and marine scientists had mistakenly referred peat as salty marsh sediment; horticulturists referred them as moss plants which make up the peat and peat itself is an interchangeable term (for example, peat moss versus moss peat), which ended the exact meaning of the peat in total confusion (Andrejko et al, 1983). However, the organic sediments research center (OSRC) at the University of South Carolina defined it as the soil having 25% or less inorganic material on dry weight basis (Andrejko et al, 1983). It has 75% or more of organic matter which is least decomposable. Peat symbolizes the incorporation of partially decomposed and disintegrated plant remains, which are preserved under high water content and incomplete



aeration conditions. Moreover, peats are accumulated if the rate of decay is slower than the rate of addition (Bell, 2000).

Peat is utilized to large extent in the fields of horticulture and agriculture, especially; they are used in the North America as much or soil enhancer for growth medium in potted plants or as bagged sheets to increase the growth of winter vegetables. It is also used as a fuel in the United States by direct combustion, gasification, peat pelletization or by changing into other synthetic fuels such as methanol (Andrejko et al, 1983). Figure 2.5 depicts the typical picture of a peat soil.

### 2.3.2 Mucky Peat

Mucky peat (Hemic) is an intermediate material between the more decomposed sapric material and the less decomposed fibric material. Because of its less decomposable nature, parts of plant in that organic material are identifiable to some extent. According to Gunaratne et al. (1998); as mentioned in Mitsch and Gosselink (2000), mucky peat is defined as the soil containing the organic matter between 5-10%.



Figure 2.5 Typical Pictorial View of a Peat Soil ([www.news.cornell.edu/releases/Feb02/microbial](http://www.news.cornell.edu/releases/Feb02/microbial))

### 2.3.3 Muck

According to OSRC classification system for peats and organic sediments muck is used for describing sub peat and variety of soils and sediments in the range of 26-85% ashes (Andrejko et al, 1983). Muck is a well decomposed soil organic material (USDA, 1975). However, American geological institute defines it as dark in color having high percentage of decomposed organic matter (American geological institute, 1962). The typical mucky organic soil can be viewed in Figure 2.6. Materials like Farmyard dung, manure, decaying vegetable matter are some of the examples of peat (American geological institute, 1962). If the material is decomposed sufficiently, unable to identify the plant materials is called as the muck (Shaw et al, 1956). It has the least amount of plant fiber, highest bulk density, and low water content at the saturation of organic soil material.

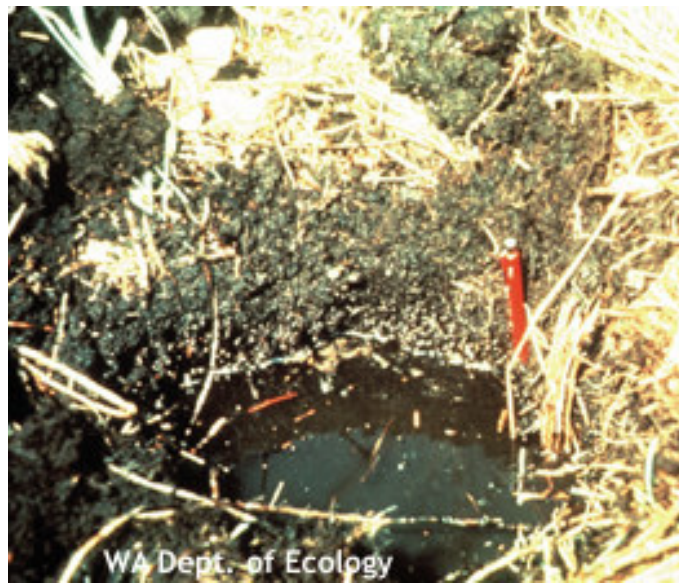


Figure 2.6 Typical Pictorial view of a Mucky Organic Soil ([www.dnr.wa.gov/.../recognizing/soils.html](http://www.dnr.wa.gov/.../recognizing/soils.html))

### 2.3.4 Peat lands

The peat itself acts as a reservoir of holding the water above the ground water level and the water associated with such peat lands is acidic, these are termed as peat lands or bogs (Bell, 2000). The peat lands or bogs are formed where there is know significant inflow or out flow of the water (Mittsch & Gosselink, 2000).The areas where peat accumulates are also called as peat

lands or bogs. Peat bog is a naturally water logged area, which can be used as a fuel when it is dried (Feehan et al, 1997).

Bog lands are nutrient poor wet lands comprised of animals and plants. Bogs are generally formed where the dampness and stagnant water is dominant (Hamond, 1981). The basic difference between the fens and bogs of the peat lands; fens receive the water from the surrounding watersheds, inflowing streams, groundwater and also by precipitation where as bogs receive the water only from precipitation (Mittsch & Gosselink, 2000). According to Mittsch and Gosselink (2000), bogs are classified into four types with respect to the land scape development. They are,

- 1) Raised bogs are peat deposits, raised above the groundwater level and receive the major inputs of nutrients from precipitation. Raised bogs are generally assumed to be disconnected from the ground water and fed only by the precipitation only.
- 2) String bogs are the long, narrow of the higher peat hummocks (strings) and form ridges perpendicular to the slope of peat land and separated by deep pools.
- 3) Paalsa bogs are generally the large plateaus of bog underlain by frozen peat and silt (20-100 meters in breadth and length and three meters high).
- 4) Blanket bogs are peat literally to the “blanket” and this advance on slopes up to eighteen percent; extremes of twenty five percent are also found in the western Ireland.

#### 2.4 Field and laboratory tests for organic soils

The laboratory test methods used for the determination of organic content in the soil are Ignition test method, Thermogravimetric analysis, and Allison’s method. Franklin et al. (1973) reported these procedures which are described in the following sections.

##### *2.4.1 Ignition test method*

Ignition test method is the most commonly used approach in geotechnical engineering for the determination of organic content in soils. Ignition test procedure includes the burning of the soil sample until it reaches a constant weight in a high temperature oven, and taking weight loss as a measure of organic content. However, one limitation in this test is the loss of surface hydration water from clay minerals. This water is normally retained in drying at 105°C and it is

also the standard drying temperature for water content determination. However, it may be lost at higher temperatures depending upon the type of mineral. van Olphen (1963) and Lambe (1951) noted that most absorbed water in the clayey particles is lost in the temperature range of 100° to 300°C as shown by the differential thermal analysis (DTA) data.

On the other hand, smectites, micas, chlorites and mixed layer minerals loose their water at rather high temperatures ranging from 250°C to 400°C as reported by the Warshaw and Roy (1961). Lambe and Martin (1956) conclude organic contents determined by ignition loss and chemical analyses agree quite well if the non organic portions of the soil are not decomposed by the heat and do not contain significant amount of adsorbed water. Usually, these problems occur with the soils containing the minerals such as carbonates that are decomposed by heat and montmorillonite, which has large amount of adsorbed moisture.

#### *2.4.2 Thermogravimetric analysis method*

Schnitzer et al. (1959) used another test method called as Thermogravimetric analysis to determine the organic content of the soils. In this method, weight loss is obtained as the function of temperature to distinguish, due to different constituents during the ignition test. These differences in the results of ignition tests on samples 1, 2, and 3, using a laboratory muffle furnace are shown in the Figure 2.7.

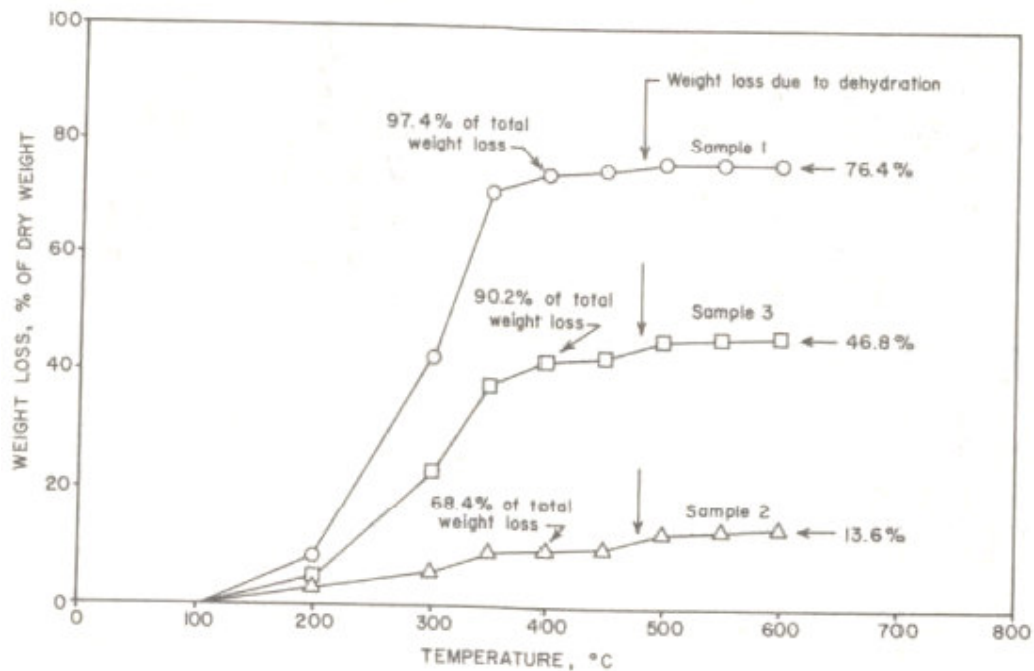


Figure 2.7 Weight loss versus Temperature Curves (Franklin et al., 1973)

In this test, sample is first dried at 105°C and then the sample is burned until it reaches constant weight. Usually, it is done by raising 50°C increments up to 600°C and held at each point until constant weight of the sample is reached. From the graph as shown in the Figure 2.18, 90% of the weight loss was occurred during a temperature of 400°C. Moreover, between 400°C and 450°C very little change had occurred, while in between 450°C and 500°C additional losses had occurred probably due to the result of water losses.

Keeling (1962) demonstrated burning at 375°C for 16 hours in the number of samples of clay removed the 90% of carbonaceous sediments without loss of structural water, and Arman (1969) concluded combustion at 450°C for a period of 5 hours produced the more accurate results.

#### 2.4.3 Chemical methods

Chemical methods are more reliable than ignition tests for the calculation of organic content determination, but they are time consuming (Franklin et al, 1973). The use of hydrogen peroxide as an oxidizing agent followed by oven drying at 105°C to determine the weight loss due

to oxidation has been suggested (Franklin et al, 1973). However, Holtz and Krizek (1970) reported that it offered some problems but concluded it could be used in caution.

Organic matter can also be detected by treating the soil with a 15% hydrogen peroxide solution. In this method, hydrogen peroxide reacts with organic matter to give vigorous effervescence (Kunze & Dixon, 1986).

On the other hand, Allison (1960) developed a new chemical method and was later modified by Grass and Lemert (1971). In this test, a sample of 1g to 2g is digested in a mixture of potassium dichromate with concentrated sulfuric and phosphoric acids. Then, organic content can be determined from the weight of carbondioxide evolved (Franklin et al, 1973).

#### 2.4.4 Empirical relationships between specific gravity and organic content

In this method, the specific gravity of the soil specimen is determined and the organic content is then determined from the graph shown in Figure 2.8. The specific gravity,  $\rho_s$  of the sample is usually determined by boiling the dry, pulverized sample with distilled sample in a pyknometer or volume bottle and weighing the bottle after cooling and adding distilled water up to the volume mark. Especially for organic soils, the water is exchanged for kerosene and the boiling by heating is exchanged for treatment with vacuum. After finding out all the masses, the specific gravity of the organic soil can be determined using the following relation.

$$\rho_s = \frac{m_s \times \rho_f}{[(m_s - m_1) + m_2]} \dots\dots\dots$$

(Eq.1)

Where

$m_s$  = mass of solid material

$m_1$  = mass of bottle, fluid and soil

$m_2$  = mass of bottle filled only with fluid at that particular temperature

$\rho_f$  = specific gravity of fluid at that particular temperature

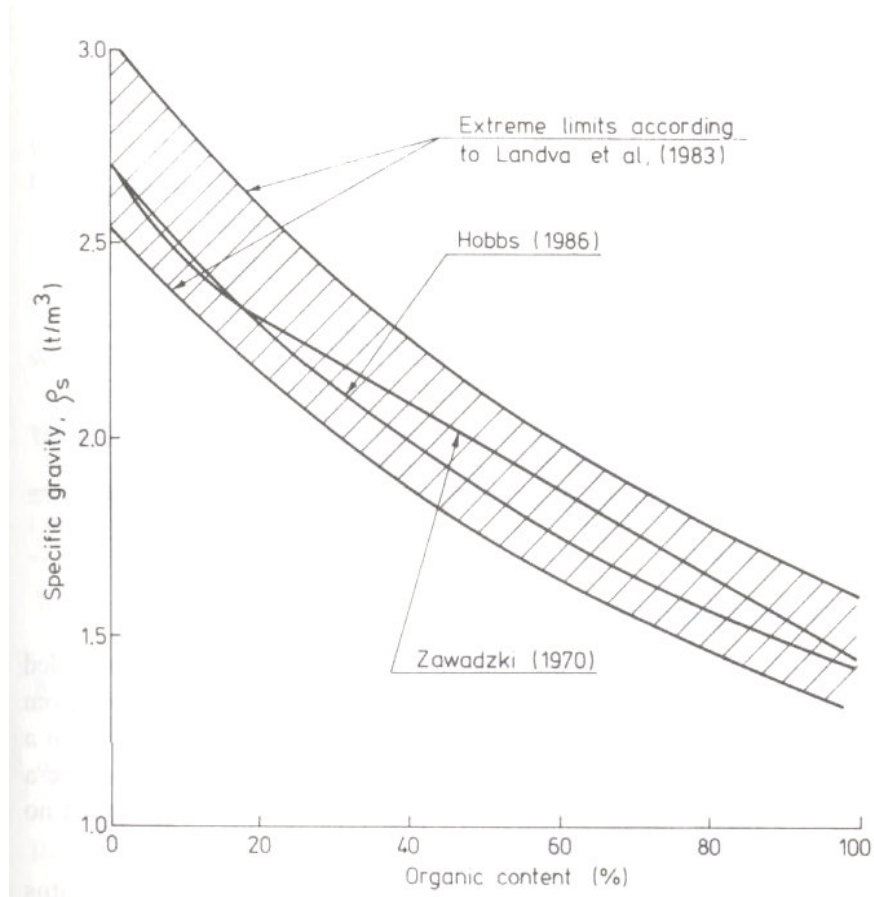


Figure 2.8 Specific gravity versus Organic content (Lechowicz et al., 1996)

Once the specific gravity of the specimen is obtained, the organic content of the soil is estimated from the empirical relationship between the organic content and specific gravity as proposed by Lechowicz et al. (1996) through a graphical relationship as shown in Figure 2.9. One can also use the following empirical relationship proposed by Hobbs (1986) to find the organic content in the soil.

$$\rho_s = 3.8 / (0.013 (\text{Organic content}) + 1.4 ) \quad \dots\dots\dots$$

(Eq.2)

**2.4.5 Calorimetric method**

In calcareous soils, another method called as calorimetric method is used for the determination of organic content in the soil. The test procedure was presented by Larsson et al. (1987). In this test, a dry pulverized sample is mixed with the potassium dichromate solution in a retort. Organic matter is wet combusted by adding the concentrated sulphuric acid to it.

Consequently, by oxidation of the organic carbon with dichromate, the oxidation of the fluid changes from orange to green. Subsequently, a simple but reliable measurement of the organic carbon content is obtained by measuring the intensity of green colour, which is obtained by oxidation, with a calorimeter supplied with a filter for wavelengths close to 620nm. The given calorimeter is calibrated for with known amounts of organic carbon as shown in Figure 2.9. However, the main source of error in this test is the relatively small amount of sample in each test and the conversion factor used to convert organic content from organic carbon may vary to some extent (Lechowicz et al., 1996). Usually, the organic matter is considered to contain 58% of organic carbon.

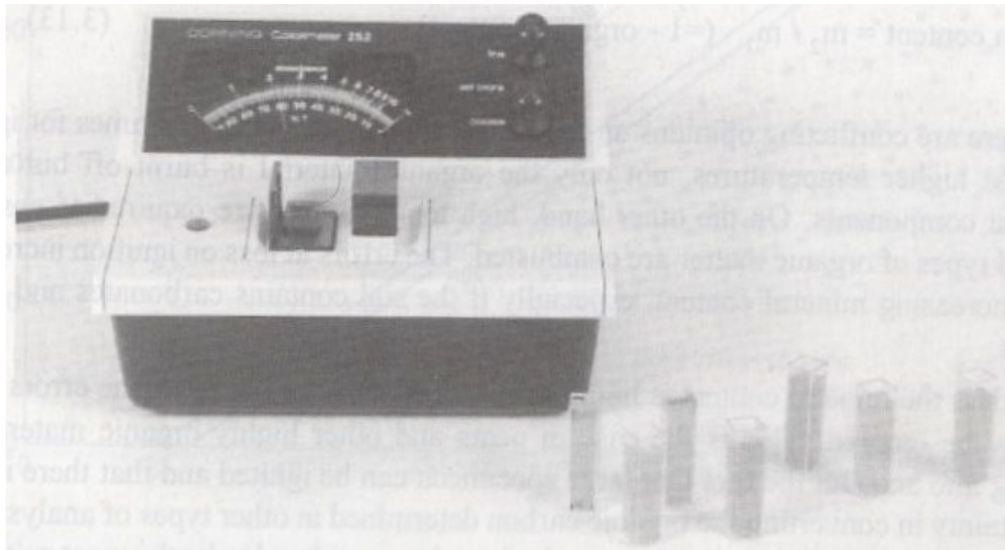


Figure 2.9 Measurement in a calorimeter (Larsson et al., 1987)

### 2.5 Index and Engineering Properties of organic soils

Even though the organic content of the most soils ranges from 0.5 to 5 % by mass, colloidal behavior of organic matter has a negative influence on the chemical and engineering properties of soil (Bohn et al, 1985).

The details of engineering properties of organic soils such as void ratio, water content, specific gravity, density, porosity, liquid limit and plastic limit are discussed here. Generally the void ratio of peats ranges from 9 (dense amorphous granular peats) to 25 (fibrous types with high contents of sphagnum) and usually it decreases with increase in the depth of the deposit (Bell,



2000). Peats have very high water content as the walls of cell tissue are microscopically thin, subsequently very little solid material can be disseminated through out an essentially liquid mass (Bell, 2000). Most of the water content in the fibrous peats occurs as free water in the large pores, capillary water in the small pores and as adsorbed, chemically bound, colloidal or osmotic water, however, the inter cellular and intra cellular water can be expelled by consolidation (Bell, 2000). The water content held in these soils primarily depends upon the morphology, structure of the material present and on the degree of humification (Bell, 2000). The water content of peats varies from 75 – 98% by volume of peat and in terms of dry weight it varies from few hundred percent in amorphous granular peats to 3000% in coarse fibrous varieties (Bell, 2000).

Many researchers have observed that organic matter increases the liquid limit and plastic limits (Rashid and Brown, 1975; Bush and Keller, 1981; Landva et al., 1983 and Bennett et al., 1985). The liquid limit of highly organic rich soils is found to be very high and depend on their drying history. Casagrande (1948) and Lambe and Martin (1956) have observed great changes in plasticity characteristics of organic soils after oven drying and even after air drying. Liquid limit of the peats is reduced by increasing the degree of humification and it depends upon plant detritus contained, degree of humification, and on the proportion of clay soil present (Bell, 2000). According to Hobbs (1986) liquid limit of fen peats, transition peats, and bog peats varies from 200 to 600%, 600 to 800%, and 800 to 1500% respectively. Odell et al. (1960) reported that the increase in organic carbon content by 1 or 2 percent may increase the Atterburg limits by 10 to 20 percent in clayey soils or montmorillonite.

Fen peats have water content value lower than liquid limit where as bog peats have water content values higher than liquid limit due to the presence of less mineral water (Bell, 2000). As the peat has high void ratio and water content, it undergoes significant volume change and leads to shrinkage on drying and the amount of shrinkage can occur ranges from 10 – 75% of the original volume, which indirectly reduces the void ratio from 12- 2 (Bell, 2000). Nevertheless, highly humified peats shrink more than less humified peats and reported to exhibit linear shrinkage strains of 35- 45% (Hobbs, 1986). Decomposed organic matter may behave as a reversible swelling system at high water contents; while, at some critical drying stage, this

reversibility ceases and usually this kind of phenomena is witnessed by an acute decrease in the Atterberg limits (Mitchell and Soga, 2005).

The catotelm and acrotelm are the two distinct soil layers in undisturbed peat bogs and the catotelm is the bottom layer of peat that is permanently below the water table. The permeability of acrotelm reduces by increasing the depth and permeability of catotelm depends on type of plant detritus, degree of humification and fibre content and ranges its values from  $1 \times 10^{-5}$  to  $5 \times 10^{-8}$  m/sec (Bell, 2000). Hanrahan (1954) reported that the permeability of peat varies depending on the load applied and length of time involved. Peat is a hydraulically anisotropic and exhibit different permeability properties in two different directions. Horizontal permeability is more than the vertical permeability and the ratio of horizontal to vertical permeability varies around 7.5 and it increases upon loading (Bell, 2000). In addition, peat has appreciable reduction in permeability with a decrease in their porosity. For example, if the porosity is halved, then permeability is reduced by three orders in magnitude (Bell, 2000).

Pore water pressure in the voids of the peat is increased due to the following; water is forced out of the pores due to the stress applied on the peat. With continuation of applying stress, the cell structure become distorted, eventually, the water in the plant cells is pressurized and moves through the openings in the cell walls and this water expulsion increases the pore water pressure (Bell, 2000). Specific gravity of the peats varies depending upon the mineral content of the soil and it ranges from 1.1 to 1.8. However, fen peats and bog peats in Britain are distinguished by their specific gravity and water content values (Bell, 2000). Bulk density of the peat is both low and variable and this value depends on the organic content, mineral content, water content and degree of saturation in the Peat. When the water content is above 600%, then the influence of both specific gravity and water content are negligible on bulk density. Low influence here is attributed to high degree of saturation or gas content (Bell, 2000). Amorphous granular peat has high bulk density compared to that of fibrous types (Bell, 2000).

Holtz and Krizek (1970) and Schmidt (1965) reported that the optimum moisture content for compaction increased with increasing organic content. In addition, the dry density value decreased for a soil with relatively low organic content (organic content < 20%).

Organic fraction of the organic soils consists of close to 5% of living microbes, plant roots and soil fauna and the rest of 95% of dead plant and animal residues. Subsequently, the organic content has become a source for carbon, nitrogen, sulphur, phosphorous; these elements have become a source for Cation Exchange Capacity (CEC) and pH of organic soils (Bohn et al., 1985). The cation exchange capacity and pH of the soil are 50 and 7.6 - 7.8 (Brazilian clay, Guanabara Bay, Rio de Janeiro City) respectively and organic content of soil at this site is reported as 4.13- 5.54% (Almeida & Marques, 2001).

The organic matter significantly increases the cation exchange capacity of soil, though the clay content contributes to some extent. The cation exchange capacity of soil organic matter ranges generally from 150 to 300cmol/kg, and can be as high as 1400cmol/kg. The variation of CEC due to organic matter also depends on soil pH. As the pH of soil increases, the contribution of soil organic matter increases (Stevenson, 1994). In general, organic soils with higher degree of decomposition have higher cation exchange capacity. The contribution of humic and fulvic acids mainly comes from the ionization of carboxyl group (COOH), and in less degree from phenolic OH and NH groups (Stevenson, 1994). Brady and Weil (1999) state that soil humus has a much higher CEC than clay minerals common in soils of the southern United States (Table 1.5). The CEC contributed by the organic fraction may range from 30 to 90 percent of the soil's CEC (Tindall and Kunkel, 1999). This high CEC will affect the absorption of Ca, Mg, and K.

Table 2.5 Cation Exchange Capacity of soil colloids at pH 7 (Brady and Weil, 1999)

Colloid	CEC (cmol <sup>(+)</sup> /kg) or meq/100g
Humus	200
Vermiculite	100
Smectite	150
Fine-grained micas	30
Kaolinite	8
Hydrous oxides	4

### 2.6 Characteristics of soil organic matter

Oxygen, nitrogen, phosphorous and sulphur play important roles in soil and organic mineral interaction and are also considered as basic sources of plant and animal nutrients (Deng & Dixon, 2002). All types of chemical bonds such as ionic, covalent, H bonds, ligand bonds and

Vander Waals bonds can also occur between clay minerals and organic material (Deng & Dixon, 2002). Soil organic matter is arbitrarily divided into humic and non-humic substances, non-humic substances constitute 20-30% where as humic substances constitute around 70-80% of soil organic matter respectively (Deng & Dixon, 2002). According to Plank (2001), the soil organic matter is composed of many parts, such as (1) intact plant and animal tissues and micro-organisms, (2) dead roots and other recognizable plant residues, and (3) a mixture of complex amorphous and colloidal organic substances no longer identifiable as plant tissues. Soil humus or humic material makes up 60 to 80 percent of the organic matter in soil; humus is a complex system of substances remaining in the soil after extensive chemical and biological breakdown of fresh plant and animal residues (Plank, 2001). The other 20 to 40 percent organic matter (OM) is less stable and partially decomposed.

According to Deng and Dixon (2002), chemically recognizable non-humic substances constitute carbohydrates, amino acids, proteins, peptides, fats, waxes, resins, organic acids, alkanes, organic bases and lignin; humic substances constitute humic acid (HA), fulvic acid (FA), humin, humatmalenic acid as described in the Table 2.6. Humic substances are formed by secondary synthesis reactions called as humification and they are divided into four different types based on the solubility in acid and alkaline solutions, where as non-humic substances are the chemically recognizable organic compounds as shown in the Table 2.6. Also, humus is defined as a dark substance with a colloidal structure, formed from dead organic substances, and the process is called humification (Larsson, 1996).

Table 2.6 Types of soil organic matter

HUMIC SUBSTANCES	NON HUMIC SUBSTANCES
<p>Humin</p> <p>Humic acid(HA)</p> <p>Fulvic acid(FA)</p> <p>Hymatomelanic acid</p>	<p>Carbohydrates</p> <p>(Monosacharides and polysaccharides)</p> <p>Nitrogenous compounds</p> <p>(Amino acids, Proteins, Peptides, Amino sugars, Pyrimidine, Purine bases)</p> <p>Fats, Waxes, Resins, Alkanes,</p> <p>Organic acids, Organic bases, Lignin.</p>
<p>These substances constitute 70-80% of the soil organic matter</p>	<p>These substances constitute 20-30% of the soil organic matter</p>

Humin is insoluble in either alkaline or acidic solutions; humic acid is soluble in alkaline solution, but precipitated when pH of the solution becomes less than 2 (Stevenson, 1982). Fulvic acids are soluble in both alkaline and acids, where as hymatomelanic acid is the alcoholic soluble portion of the humic acid (Stevenson, 1994). The fractionations of these substances from humas are presented in the Figure 2.10.

Humus is stable and relatively resistant to microbial attack; it is responsible for cation exchange capacity (CEC) of OM and can be divided into the following three groups (Brady and Weil, 1999):

- **Fulvic acid-** low molecular weight, light color, soluble in both acid and alkali, and most susceptible to microbial attack. Depending on conditions, the half-life (time it takes to destroy half of the material) is approximately 10 to 15 years.
- **Humic acid-** moderate molecular weight and color, soluble in alkali but insoluble in acid, and intermediate in degradation potential with a half-life >100 years.
- **Humin-** high molecular weight, dark color, insoluble in acid and alkali, and most resistant to microbial attack.

Soil contents of humic and fulvic acids vary by depth, climate, and geography (Thurman, 1985). Forest soils such as alfisols, spodosols, and ultisols generally are high in fulvic acids, whereas grassland soils such as mollisols are high in humic acids (Tindall and Kunkel, 1999).

Tindall and Kunkel (1999) reported that forest soils like spodosols, significant amounts of aluminum, iron, and organic matter have been mobilized and transported deeper into the profile in the B horizon. Podzols evaluated by Clare and Sherwood (1954) also showed variations in organic matter content. They concluded that “active” organic matter is formed in the vegetable top-soil and subsequently leached by rainwater into the B horizon where it is deposited at depths as great as 5 ft.

According to Soil taxonomy (1999) the soil organic matter is basically divided into twelve types and this information is presented in Table 2.7. According to Stevenson, (1994), the humic substances vary depending upon the depth and the profile of the different soils. However, the differentiation of the humic substances is difficult, due to the deficit of standard purification, extraction and fractionation methods. According to Stevenson, (1982) forest soils consist maximum of fulvic acid, whereas grassland soils consist of humic acid in which the major portion is gray humic acid as shown in the Pie chart in Figure 2.11.

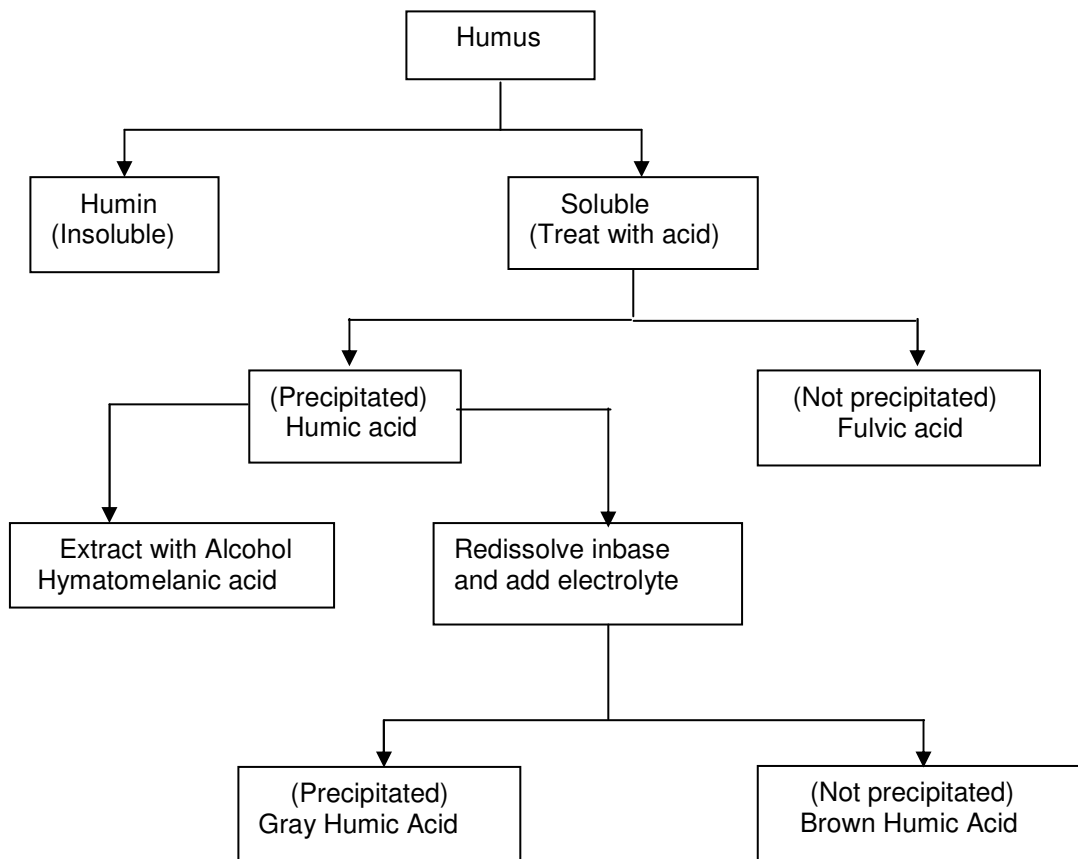
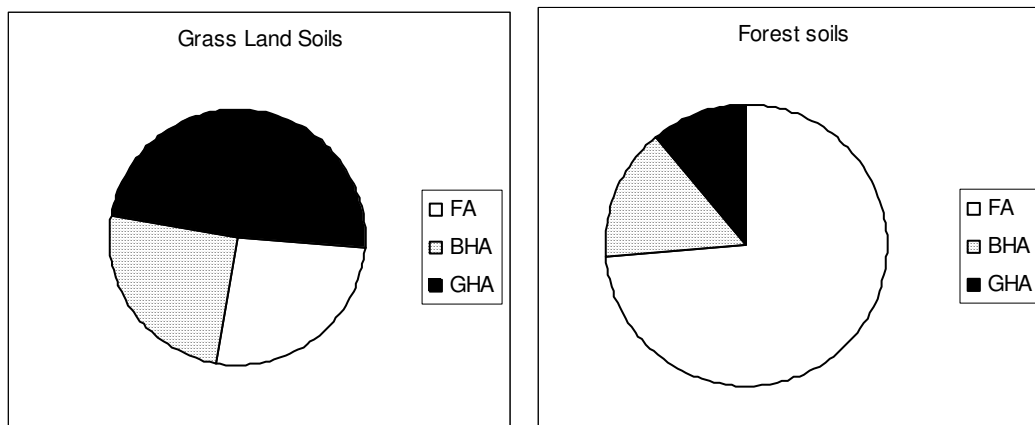


Figure 2.10 Fractionations Based on Solubility Characteristics (Stevenson, 1982)



FA = Fulvic acid; BHA = Brown humic acid; GHA = Gray humic acid

Figure 2.11 Pie chart showing the relationship of Humic acid and Fulvic acid (Stevenson, 1982)

Table 2.7 Major characteristics of 12 soil orders in soil taxonomy (Brady and Weil, 1999)

Name	Formative Element	Derivation	Major characteristics
Alfisols	Alf	Nonsense symbol	Argillic, Natric, or kandic horizon; high to medium base saturation
Andisols	And	Jap, <i>ando</i> Black soil	From volcanic ejecta, dominated by allophone or Al-humic complexes
Aridisols	id	L. <i>aridus</i> , dry	Dry soil, ochric epipedon, sometimes argillic or nitric horizon
Entisols	ent	Nonsense symbol	Little profile development, ochric epipedon common
Gelisols	el	L. <i>gelid</i> , <i>verycold</i>	Perma frost, often with cryoturbation (frost churning)
Histosols	ist	Gr, <i>histos</i> , tissue	Peat or bog > 20% organic matter
Inceptisols	ept	L. <i>inceptum</i> , beginning	Embryonic soils with few diagnostic features, ochric or umbric epipedon, cambic horizon
Mollisols	oll	L. <i>mollis</i> , soft	Mollic epipedon, high base saturation, dark soils, some with argillic or nitric horizons
Oxisols	ox	F. <i>oxide</i> , Oxide	Oxic horizon, no argillic horizon, highly weathered
Spodosols	od	Gr. <i>spodos</i> , Wood ash	Spodic horizon commonly with Fe, Al oxides and humus accumulation
Ultisols	ult	L. <i>ultimus</i> , Last ash	Argillic or kandic horizon, low base saturation
Vertisols	ert	L. <i>verto</i> , turn	High in swelling clays; deep cracks when soil dry

Kononova (1966) reported that the ratio of humic acid (500 to 870 meq/100g) to fulvic acid (900 to 1400 meq/100g) is maximum to Mollisols, ranging from 1.2-2.5 as presented in the Table 2.8. Kononova (1966) reported that fulvic acids are smallest representative of humic acids,

however, humic acid and fulvic acid are dissimilar in many respects but they possess a common structural pattern.

Fulvic acid is a colored organic matter having low molecular weight, where as humic acid is dark colored organic matter, high molecular weight compared to that of fulvic acid and their chemical properties are shown in the Table 2.9. Moreover, fulvic acid has more oxygen atoms and low carbon atoms compared to that of humic acid. Furthermore, fulvic acid is more reactive than humic acid, due to the presence of highly reactive carboxyl acid functional group. Nevertheless, Schnitzer and Khan (1972) claim humic acid consists of 54-59% of carbon, 3-6% of hydrogen, 1-6% nitrogen, 0.1-1.5% sulphur, and 33-38% of oxygen, where as fulvic acid consists of 41-51% of carbon, 4-75 hydrogen, 1-3% nitrogen, 0.1-3.5% of sulphur, and 40-50% of oxygen.

Table 2.8 Humic acid/fulvic acid ratios of some surface soils (Kononova, 1966)

Soil <sup>a</sup>	Humic acid/Fulvic acid	Soil <sup>a</sup>	Humicacid/Fulvicacid
Chernozem Deep Ordinary Southern	1.7 2.0-2.5 1.5-1.7	Gray forest	1.0
		Sod podzolic	0.8
Chestnut Dark Light	1.5-1.7 1.2-1.5	Brown desert Steepe soil	0.5-0.7
Serozem Typical Light	0.8-1.0 0.7	Krasnozen	0.6-0.8
		Tundra	0.3

<sup>a</sup> approximate equivalents in the comprehensive soil classification system



Table 2.9 Chemical properties of humic and fulvic acid (Stevenson, 1982)

Humic substances (pigmented polymers)			
Fulvic acid (oden)		Humic acid (Berzelius)	
Berzelius		Springer	
Crenic acid	Apocrenic acid	Brown humic acids	Gray humic acids
Light yellow	Yellow brown	Dark brown	Gray black

-----	increase in degree of polymerization-----	→
2,000?	-----increase in molecular weight-----	300,000? →
45%	-----increase in carbon content-----	62% →
48%	-----decrease in oxygen content-----	30% →
1,400	-----decrease in exchange acidity-----	500 →

### 2.7 Interaction of soil organic matter

The soil organic matter mainly consists of humic and non-humic substances. However, the major part of the soil organic matter is humus substances, and these humus substances are insoluble. Moreover, humic substances are bound by three mechanisms as stated below:

- a) Insoluble macromolecular complexes;
- b) Macromolecular complexes bounded by trivalent or divalent cations such as  $\text{Ca}^{2+}$ ,  $\text{Fe}^{2+}$ , and  $\text{Al}^{3+}$ ; and
- c) Combination with clay minerals by hydrogen bonding, Van der Waals forces and others.

In peats and highly organic soils, the insoluble macromolecular mechanisms are important, where the clay and metal ions content are lower than the organic amount content (Stevenson, 1994).

To better understand the interaction between clay and soil organic matter, it is necessary to understand the structure of clay minerals and their surface chemistry. Clay minerals are very minute crystalline substances evolved from chemical weathering of certain rock forming minerals, and chemically they are hydrous aluminosilicates plus other metallic ions (Holtz and Kovacs,

1981). According to Stevenson (1994), the most important clay minerals are kaolinite, mica, vermiculite, and smectite.

Kaolinite consist basically repetitive layers of tetrahedral sheet (silica) and octahedral sheet (alumina or gibbsite) as shown in Figure 2.12. It is called as 1:1 clay mineral, as sheets are held in such a way that, tips of the silica sheet and one of the layers of octahedral sheet form a single layer of 0.72nm thickness. The chemical formula of Kaolinite is  $\text{Si}_4\text{Al}_4\text{O}_{10}(\text{OH})_8$ . Moreover, kaolinite is a neutrally balanced and held by hydrogen bonding in between the successive layers of the basic layer (hydroxyls of octahedral sheet and the oxygens of tetrahedral sheet). So, there is no space in between Kaolinite minerals.

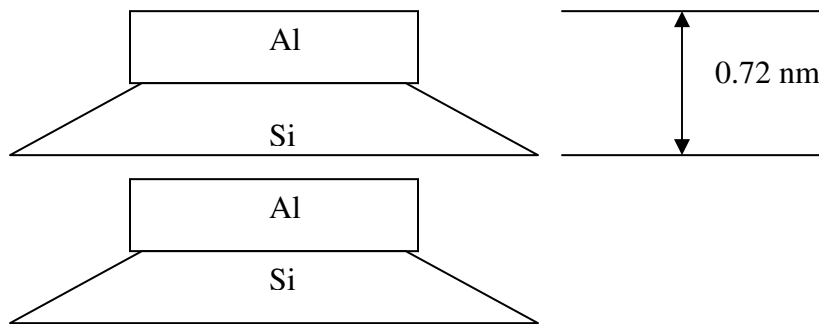


Figure 2.12 Schematic diagram of the structure of kaolinite (Lambe, 1953)

Halloysite is another 1:1 composite mineral. It differs from kaolinite when it is formed, by distortion or random stacking of the crystal lattice. Subsequently, it becomes tubular in shape. Water formed in between the layers can be easily driven out by heating or even air drying. Moreover, this process is irreversible, which plays an important role in the engineering properties. Because, classification and compaction tests made on air dried samples give different results compared to tests on samples at their natural water content.

Smectite is also called as Montmorillonite. It is an 2:1 composite mineral, as it contains two silica sheets and one alumina sheet (gibbsite) as shown in the Figure 2.13. Sheets are held in such a way that the two silica sheets with the tips of two tetrahedrons combining with the hydroxyls of the octahedral sheet forming a single layer of thickness 0.96nm. Smectite is a very small crystal, as the Vander waals forces between the tops of the silica sheets are very weak and there is net negative charge deficiency on octahedral sheet. Consequently, water and

exchangeable ions can enter and separate the layers. Nevertheless, they have very strong attraction of water molecules.

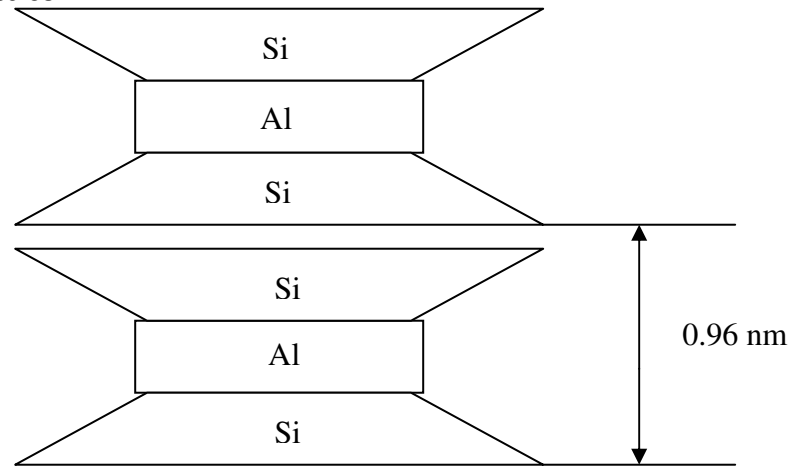


Figure 2.13 Schematic diagram of the structure of Montmorillonite (Lambe, 1953)

Illite is another important constituent of clay and has the similar structure that of smectite, but bonded with the potassium ion in between the interlayers. In addition, isomorphous substitution of aluminium for silicon ion in the silica sheets results in moderate reactivity to this mineral.

Chlorite, relatively common in clay soils is made up of repetitive layers of silica sheet, alumina sheet, and another silica and then either a gibbsite or brucite sheet (Holtz & Kovacs, 1981). This is a 2:1:1 composition mineral as mentioned with above composition. Chlorite may have isomorphous substitution or it may be missing the gibbsite layer, consequently water can enter between the sheets and swelling phenomenon occurs. However, it is less active than montmorillonite (Holtz & Kovacs, 1981).

There are many other clay minerals such as vermiculite, which is a 2:1 mineral similar to montmorillonite, but having two interlayers of water. Another clay mineral called as attapulgite, which is a chain silicate not having sheet structure, however, it has needle or rodlike appearance (Holtz & Kovacs, 1981).

According to Johnston and Tombacz (2002), reactive sites on soil particles are divided into two types called as polar and non polar sites. Where, polar sites are originated from isomorphous distribution and edge sites of minerals, and ionized functional groups of soil organic matter, while, non polar sites include neutral mineral surfaces and non polar or hydrophobic sites

of soil organic matter. Moreover, in Figure 2.14 polar sites are indicated by the dark gray shades, whereas non polar sites are indicated by light gray shades. However, non polar sites react with the non polar organic compounds.

According to Johnston and Tombacz (2002), 2:1 type minerals are permanently negative charged due to their isomorphous substitution in tetrahedral sheet, whereas 1:1 type minerals are neutrally charged. Moreover, the surface of 1:1 type mineral tetrahedral sheet is referred to be "neutral siloxane surface", and this surface is termed not to interact with H bond network of water molecule, consequently this surface is called as hydrophobic surface by Johnston and Tombacz (2002).

Furthermore, Johnston and Tombacz (2002) conclude edge sites of 2:1 and 1:1 minerals change with the pH and referred these to be conditionally charged sites, variable charge sites or pH dependent sites. Schulten and Schnitzer inform from the two dimensional model shown in Figure 2.14 describe that humic acid contains 21 carboxyl groups, which are directly responsible for high cation exchange capacity.

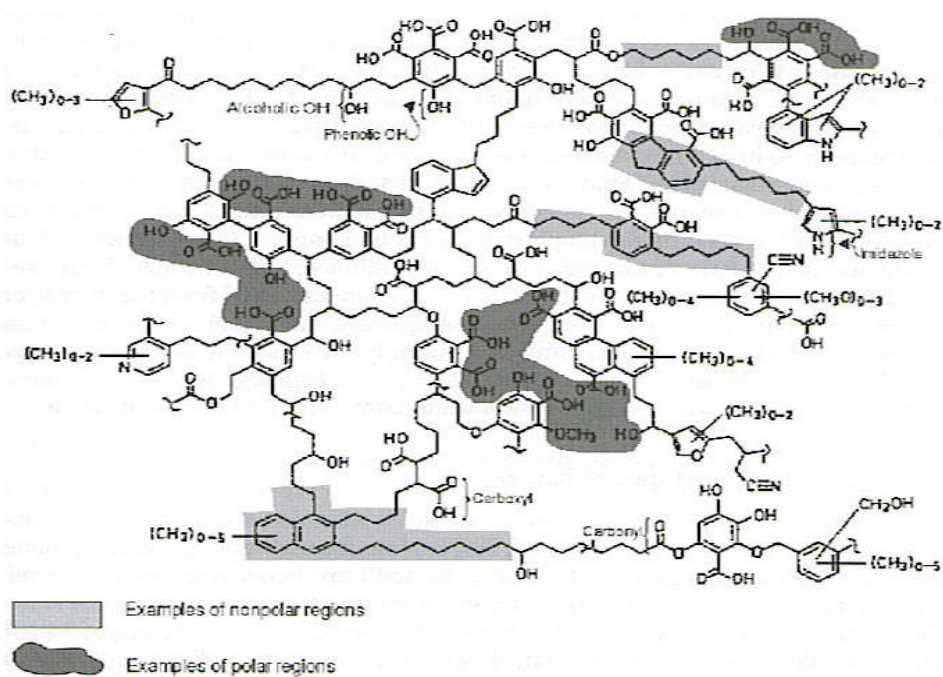


Figure 2.14 Polar and non polar sites of humic acid (Johnston and Tombacz, 2002)

Nevertheless, Stevenson (1994) concludes that reactions between soil organic matter and clay minerals occur by two mechanisms as mentioned below.

- a) by attachment to clay mineral surfaces, such as through cation and anion exchange, bridging by polyvalent cations (clay – metal ion – humic substances), hydrogen bonding, and Van der Waals forces.
- b) by penetration into the interlayer spaces of expanding-type clay minerals, such as smectite and vermiculite.

Figure 2.15 shows the types of bonds possible between the minerals and humic substances. Reactions can occur on surface layer of the clay minerals and also on the both edge sites of clay minerals (Stevenson, 1994). Electrostatic bonding occurs through cation exchange or protonation at the edge sites of clay minerals. However, under basic conditions, edge sites of clay minerals are negatively charged and attract the inorganic cations. Moreover, electrostatic bonding occurs when inorganic cations at the edge sites are replaced by the positively charged organic cations. Additionally, hydrogen bonding also occurs at the edge sites of clay minerals. Nevertheless, the order of bonding strength is as follows:

Covalent bonds > Hydrogen bonds > van der Waals forces.

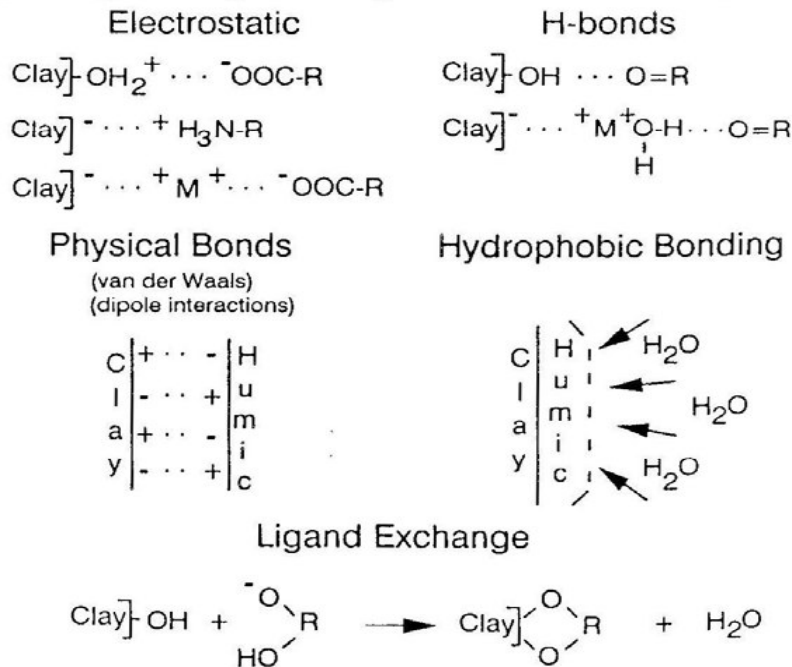


Figure 2.15 Types of bonds between minerals and humic substances (Stevenson, 1994)

Lagaly (1984) states that the organic matter interacts with clays by a) adsorption on particle surfaces by hydrogen bonds, b) ion exchange, c) attraction of large organic molecules to the clay surfaces by van der Waals forces, and d) intercalation, which is defined as the entry of organic molecules between silicate layers. The mobility of large organic molecules to clay surfaces by van der Waals forces may be contributed to the total amount of organic content held (Russell-Colom and Serratosa, 1987). The other important properties of organic molecules relative to their interaction with clays are their polarity, polarization, solubility. Size, and shape (Mitchell and Soga, 2005).

A schematic diagram of interaction between organic matter and metal ions are shown in the Figure 2.16. If polyvalent cations as indicated by M in the Figure 2.16 are present in the solution, then these ions neutralize both the negatively charged clay surface and organic anions. Subsequently, the adsorption of humic substances occurs. However, negatively charged clay surface and organic anions repel each other. Nevertheless, divalent cation  $\text{Ca}^{2+}$  ions doesn't form the strong complexes as compared to the complexes formed by  $\text{Fe}^{3+}$  and  $\text{Al}^{3+}$  with organic molecules or complexes.

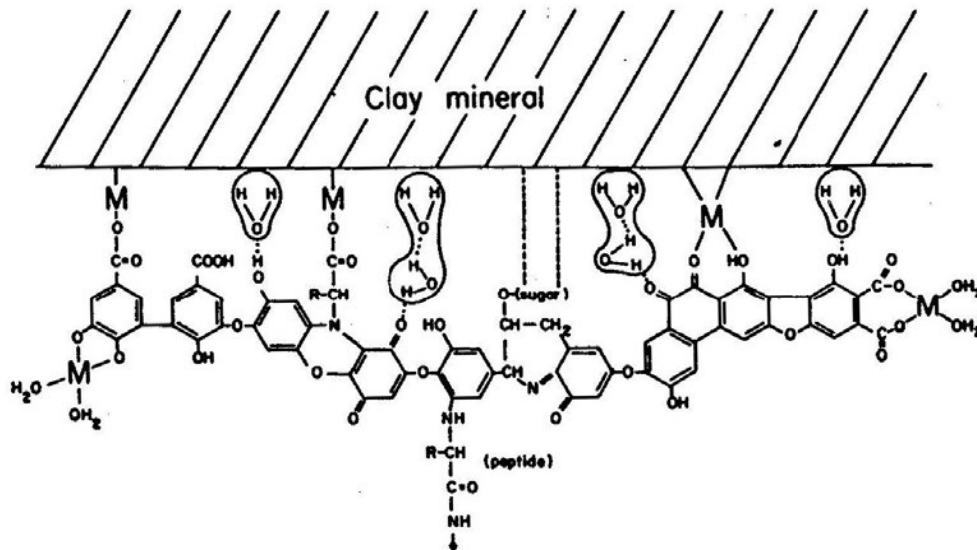


Figure 2.16 Schematic diagram of clay-metal ion-humic substance complex in soil (Stevenson, 1994)

Additionally, Stevenson (1994) claims that, complexes formed by the organic substance depend upon the organic content, type and on the amount of clay. However, soils like Mollisols, Histosols, almost all of the clay minerals are covered with the thin layer of organic matter. Because of these interactions, both physical and engineering properties of subsoils are altered. The next section describes these results.

### 2.8 Effects of organic matter on engineering properties of soils

It is well reported that the presence of organic content in a soil acts to the detriment of its engineering properties ((Edil and Wang, 2000)). Besides, soils with high organic content have exhibited inferior mechanical properties, for engineering purposes, to inorganic soils. These properties include high compressibility, low shear strength, low permeability, and poor compactibility; which are attributed to a very high capacity of moisture retention by the organic matter. Moreover, fibers present in it induce some anisotropy and internal reinforcement (Edil and Wang, 2000). Humification of the organic soils also alters the many mechanical properties of soil such as compressibility, strength and hydraulic conductivity.

These affects necessitates understanding the effect of organic matter on engineering properties of soils. The general properties of organic matter and its effect on natural soil are summarized in the Table 2.10.

Table 2.10 General properties of soil organic matter and associated effects in the soil (Stevenson, 1994)

Property	Remarks	Effect on soil
Color	The typical dark color of many soils is caused by organic soils	May facilitate warming
Water retention	Organic matter can hold up to 20 times its weight in water	Helps preventing drying and shrinking. Improves water-retaining properties of sandy soils
Combination with clay mineral	Cements soil particle into structural units called aggregates	Permits exchange of gases, stabilizes structure and increases permeability
Chelation	Forms stable complexes with $\text{Cu}^{2+}$ , $\text{Mn}^{2+}$ , $\text{Zn}^{2+}$ , and other polyvalent cations	Enhances availability of micronutrients to higher plants
Solubility in water	Insolubility of organic matter is due to its association with clay. Also, salts of divalent and trivalent cations with organic matter are insoluble	Little organic matter is lost by leaching
Buffer action	Exhibits buffering in slightly acid, neutral and alkaline ranges	Helps to maintain a uniform reaction in soil
Cation exchange	Total acidities of isolated fractions of humus range from 300 – 1400 cmoles/kg	Increases Cation exchange Capacity (CEC) of the soil. From 20-70% of the CEC of many soils is caused by organic matter
Mineralisation	Decomposition of organic matter yields $\text{CO}_2$ , $\text{NH}_4^+$ , $\text{NO}_3^-$ , $\text{PO}_4^{3-}$ and $\text{SO}_4^{2-}$	Source of nutrient of plant growth
Combines with xenobiotics	Affects bioactivity, persistence, and biodegradability of pesticides	Modifies the application rate of pesticides for effective control

### 2.8.1 Shear Strength

Shear strength of a soil is defined as the ultimate or maximum shear stress that can be with stand by soil. Two types of analysis are considered to analyze the shear strength on a potential failure surface and to compute the factor of safety; they are a) Total stress analysis b) Effective stress analysis. Total stress analysis and effective stress analysis assume undrained conditions and both drained and undrained conditions respectively. Shear strength is a basic parameter to be analyzed for the construction of structures on organic soils, due to its low limiting value for such soils. Shear strength of subgrade is important during early construction for supporting construction equipment and the structure by the end of the construction (Lechowicz, 1996). Changes in shear strength due to future changes in subgrade stress conditions are



required for the construction of pavements on the organic soils since the shear strength behavior of these soils is strongly affected by the effective stress state, pore pressure and by the stress history (Lechowicz, 1996). Furthermore, design of structures on organic soils requires understanding the shear strength and state of stress in the field (Edil and Wang, 2000). Shear strength parameters vary with plasticity in a normally consolidated soil (Larson, 1980; Ladd, 1985a) and the same is reported by Edil and Wang, 2000). Besides, shear strength varies in both over consolidated and normally consolidated states of organic soil (Bergdahl et al., 1987) as informed in (Edil and Wang, 2000).

Cohesion 'c' and internal friction angle ' $\phi$ ' are the two inherent shear strength parameters of the soil. Adams (1965) explained that the peats have extremely high frictional properties and the frictional angle ' $\phi$ ' for peats was found to be as high as 48°. The anisotropic consolidation of peats has little or no effect on the shear strength parameters (Adams, 1965). Peat fibers have a reinforcing effect and humus acts as the bonding agent (Landava et al, 1983). Edil and Wang (2000) reported that the shearing resistance of Peats would depend upon the orientation of the plane with respect to general alignment of fibers and demonstrated that fiber content would add upto 16° of the friction angle by giving zero contribution to the amorphous peats. The shear strength of organic soils increased with an increase in fiber content and these fibers present in the organic soil would act as reinforcement working under tension across the rupture surface (Arman, 1969). The strength and stiffness of organic rich soils generally depends on whether the organic matter is decomposed or containing fibers in it. If the organic matter is decomposed, the undrained shear strength and the stiffness, or modulus are reduced as a result of high water content and plasticity contributed by the organic matter. If the organic soil contains fibers, which can act as reinforcement, increases the strength (Mitchell and Soga, 2005).

The effect of organic content on the unconfined compressive strength behavior was to reduce the maximum strength attainable. Besides, it was inferred that the effect of organic content was less important than minor mineralogical or structural differences of soil types (Franklin et al., 1973). Figure 2.17 shows the variation of unconfined compressive strength of slightly organic soils (organic content < 20%) from Chicago with the organic content (Franklin et

al., 1973). Edil and Wang, (2000) reported that the shear strength parameters with high friction angles and relatively low cohesion 'c' intercepts from 0 to 6 kPa for Peaty soils.

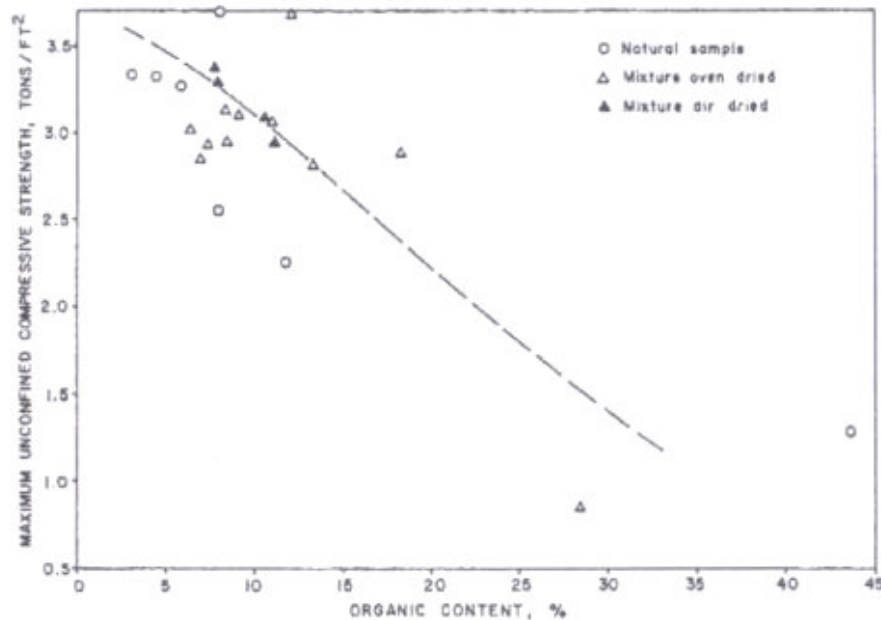


Figure 2.17 Variation of maximum UCS with organic content (Franklin et al., 1973)

### 2.8.2 Settlements and Compressibility

Peats and organic soils are known for their high compressibility and long term settlements. Settlements are defined as the total vertical deformation caused due to the load acting above that vertical section of the soil. Generally, the settlements are of two types, short term settlements and long term settlements. Long term settlements are due to the primary consolidation and secondary compression of the organic soils respectively. Due to the recent developments in soil reinforcement, construction of embankments on the soft soils, like peats and organic soils, forsaken the problem of excessive settlements beneath the structure (Edil and den Hann, 1994).

Cola and Cortellazo (1999) reported that peats and organic soils are one of the toughest foundation soils that exhibit unusual compression behavior, by having a high compressibility with significant secondary compression stage. Moreover, other parameters such as high in-situ void ratio, high water content and high values of compression index and secondary compression index values and these parameters are about ten times higher than normal clayey soils. Moreover,

behavior of the mixture (organic soils and binders) depends on the characteristics of natural peat and its stress history.

The compressibility of peats and organic soils are the highest among geotechnical materials (Mesri et al, 1997). The high compressibility of peats and organic soils is caused by the high natural water contents and void ratios. Figure 2.18 depicts the compression index ( $C_c$ ) and the natural water content ( $w_0$ ) of peats are approximately one order of magnitude higher than those of clay and silt deposits. The higher compressibility of organic soil is due to the tendency of organic matter to form complexes with clay particles. The complexation of organic matter increases the pore size and eventually increases the compressibility of soils (Stevenson, 1994). Landva and La Rochelle (1982) observed a linear relationship between compression index ( $C_c$ ) and water content ( $w$ ) as  $C_c = 0.115 w$  (%).

Consolidation of organic soil and peat deposits is more significant due to large secondary compression. For any natural soil, there exists a unique relationship between secondary compression index ( $C_\alpha$ ) and compression index ( $C_c$ ). According to the  $C_\alpha/C_c$  concept, the magnitude and behavior of the secondary compression index ( $C_\alpha$ ) with time is directly related to the magnitude and behavior of the compression index with vertical effective stress (Mesri et al. 1997). The  $C_\alpha/C_c$  concept can be applied in both over-consolidated and normal-consolidated regions, so that the  $C_c$  represents the slope of the compression curve in both of the regions. Table 2.11 presents the values of  $C_\alpha/C_c$  for various peat deposits which vary from 0.035 – 0.10. Table 2.12 summarizes values of  $C_\alpha/C_c$  for different soils. The high value of  $C_\alpha/C_c$  for peats is due to highly deformable organic particles. The high values of  $C_\alpha/C_c$  and  $C_c$  for peats indicate that the secondary compression index ( $C_\alpha$ ) of peats is more than one order of magnitude higher than that of clay and silt deposits.

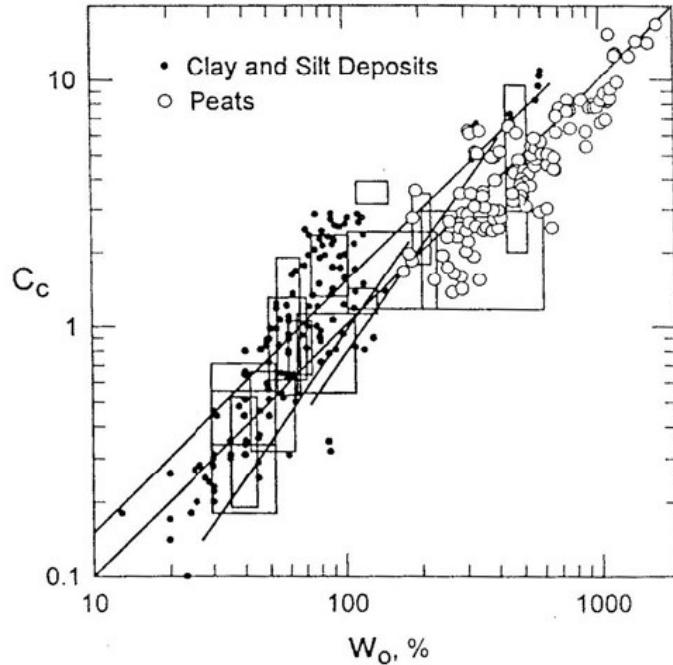


Figure 2.18 Natural water content ( $w_o$ ) and compression index for peats as compared to those of soft clay and silt deposits (Mesri et al, 1997)

Table 2.11 Values of natural water content ( $w_o$ ), initial vertical hydraulic conductivity ( $k_{vo}$ ), and  $C_a/C_c$  for peat deposits (Mesri et al, 1997)

Peat	$W_o$ (%)	$K_{vo}$ (m/s)	$C_a/C_c$	References
Fibrous peat	850	$4 \cdot 10^{-6}$	0.06-0.10	Hanrahan (1954)
Peat	520	---	0.061-0.078	Lewis (1956)
Amorphous and fibrous peat	500-1500	$10^{-7}$ - $10^{-6}$	0.035-0.083	Lea and Brawner (1963)
Canadian muskeg	200-600	$10^{-5}$	0.09-0.10	Adams (1965)
Amorphous to fibrous peat	705	---	0.073-0.091	Keene and Zawodniak (1968)
Peat	400-750	$10^{-5}$	0.075-0.085	Weber (1969)
Fibrous peat	605-1290	$10^{-6}$	0.052-0.072	Samson and Larochell (1972)
Fibrous peat	613-886	$10^{-6}$ - $10^{-5}$	0.06-0.085	Berry and Vickers (1975)
Amorphous to fibrous peat	600	$10^{-6}$	0.042-0.083	Dhowian and Edil (1981)
Fibrous peat	660-1590	$5 \cdot 10^{-7}$ - $5 \cdot 10^{-5}$	0.06	Lefbevre et al. (1984)
Dutch peat	370	---	0.06	Den Haan (1994)
Fibrous peat	610-850	$6 \cdot 10^{-8}$ - $10^{-7}$	0.052	Present study (1997)

Table 2.12 Values of  $C\alpha/Cc$  for various types of soils (Terzaghi et al, 1996)

Soil type	$C\alpha/Cc$
Granular soils including rockfill	$0.02 \pm 0.01$
Shale and mudstone	$0.03 \pm 0.01$
Inorganic clays and silts	$0.04 \pm 0.01$
Organic clays and silts	$0.05 \pm 0.01$
Peat and muskeg	$0.06 \pm 0.01$

Edil and den Hann (1994) claimed that the creep at constant vertical effective stress reported the maximum vertical settlements. This time dependent component of settlement is called as secondary compression. Moreover, secondary compression is very much high in peats and cannot be easily ignored as that of firmly inorganic soils. Secondary compression occurring after the hydrodynamic primary period is conventionally described by a linear void ratio- log time relationship with slope  $C\alpha$  where the time scale begins at the time of load increment application. Furthermore, tertiary compression is also present in the fibrous peats at certain stresses. Due to the high compressibility phenomenon lowering of ground water takes place, by which shrinking and oxidation of soils take place, and leads to the humification of peat with consequent increase in permeability (Vonk, 1994). Subsequently, oxidation of soil leads to formation of gas and it increases the excess pore water pressure in the soil (Vonk, 1994). However, these effects are not taken into account in the long term performance of the soil beneath the structure (Edil and den Haan, 1994).

Settlements are usually caused in the peats and organic soils due to their high compression behavior (Edil and den Haan, 1994). Edil and den Haan (1994) also stated that one dimensional compression behavior exhibited by the peats and organic soils is similar to those of clay and hence the consolidation curves of clays are used to determine the magnitude and rate of settlement of the organic soils. However, they also claimed that organic soils containing high organic matter and fibrous content, with low degree of humification does not exhibit similar clay compression behavior, due to their solid phase properties and soil structure.

According to Edil and den Hann (1994), choice of construction of structures on the peats and organic soils varies with respect to the consideration of economic and technical factors including avoidance of construction of fills over peats and organic soils, replacement of peat layers with granular fill materials, staged construction, Use of light weight fill, in situ improvements, deep foundations, Geotextiles, stripdrains, and in situ improvement by thermal compression.

### *2.8.3 Lateral earth pressure coefficient*

Coefficient of earth pressure ' $K$ ' of soil is defined as the lateral pressure of the earth at rest. According to Adam (1965), the coefficient of earth pressure at rest in peats and organic soils is as low as 0.18. However, Edil and Dhowian (1981) concluded the values of ' $K$ ' would be in between 0.3 and 0.53, depending upon the fiber content and the quality of the soil. Edil and Wang (2000) suggests that ' $K$ ' values vary depending upon the fibrous content of the soil, but not on the organic content of the soil and normally consolidated peats have typically lower  $K$  values than inorganic soils. They also suggested the  $K$  value of amorphous peats to be 0.49 and 0.33 for fibrous peats.

### *2.8.4 Compaction characteristics*

The compaction characteristics of slightly organic soils observed by Franklin et al. (1973) showed that the severe drying reduced the influence of organic content on the compaction behavior. It was also observed that with an increase in organic content, a reduction in optimum dry density and an increase in the optimum water content were recorded, which were depicted in Figures 2.19 and 2.20.

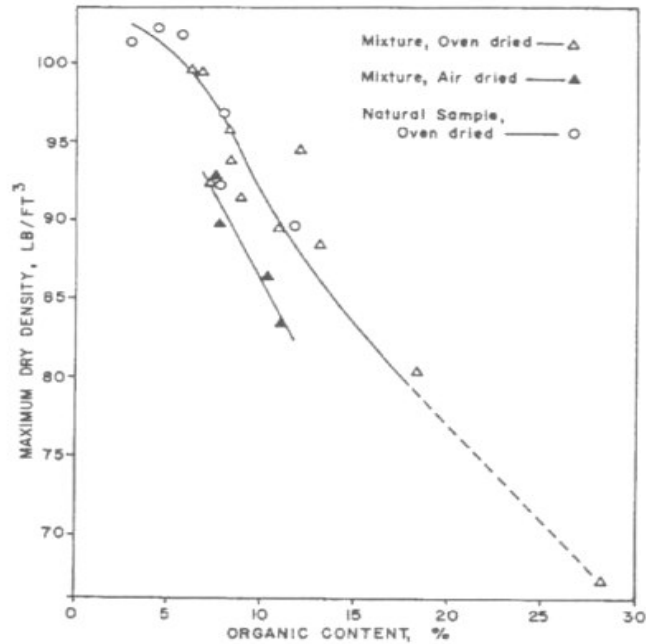


Figure 2.19 Variation of maximum dry density with organic content (Franklin et al., 1973)

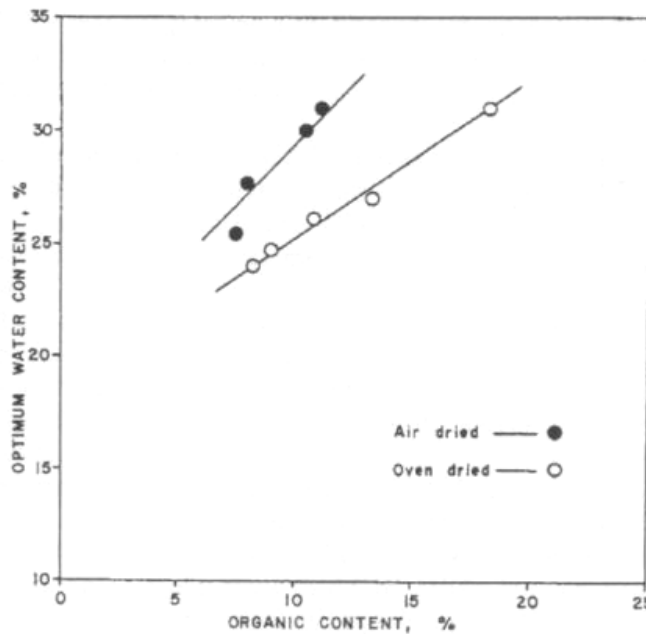


Figure 2.20 Effect of dry history on optimum water content (Franklin et al., 1973)

### 2.9 Chemical Treatment of Organic Soils

The difficulties associated with organic soils arise when those are treated with cement or lime stabilizers while organic matter inhibits cementitious reactions responsible for strength gain. There is a need to understand the fundamentals behind the chemical reactions contributing to

changes in geotechnical properties of stabilized organic soil beds (Hampton and Edil, 1998). Many researchers have adopted the deep mixing technique to stabilize organic soils while selecting a matrix of different stabilizers and soils having different organic contents, clay fractions, degree of decomposition, water content and pH. These mixture proportions were brought out after testing the mixtures with different combinations of materials and unconfined compression strength tests on stabilized specimens (den Haan, 1997, 1998; Huttunen et al., 1996; Huttunen and Kujala, 1996; Kujala et al., 1996; Odajima et al., 1995, Chen and wang, 2005). The outcome of these researches were development of correlations of different parameters with compressive strength of treated material. The major problem with this approach is that these correlations are mostly site specific and any extrapolation of these correlations from one site to another may not provide realistic results. Furthermore, if the soil contains organic matter, the adoptability of these correlations would become almost impossible. The organic matter content has a highly variable correlation with compressive strength of the stabilized product (Catton and Felt, 1943, Clare and Sherwood, 1956).

It is well understood, so far, that the strength gain in stabilized soft soil are due to hydration products formed by reactions between binding materials and water, and also reaction between the binding material, water and soil particles. However, it also depends on the type of binding material chosen, type of soil and water-binder ratio and curing conditions.

The major reactions that result in increase in shear strength of soft soil when quick lime is used as a binding material are:

1. Isomorphous substitution of calcium in the clay particles decreases the interlayer spacing and causes coagulation of the clay particles, thus reducing the plasticity of the soil.
2. Calcium hydroxide will be formed when the quicklime reacts with water.
3. The increase in pH in the system promotes the dissolution of silica in the clay particles which then reacts with the calcium oxides to form calcium silica hydrate (C-S-H) cementing compounds. These compounds form bonds either between the binder particles and soil particles or between the binder particles to form a stiff matrix.



The composition and structure of the C-S-H gel and the type and amount of other hydration products can alter due to the presence of organic matter in the soil (Hampton and Edil, 1998). The organic soil has the high water retention capacity that may limit the amount of water available for hydration reactions to occur. Hampton and Edil (1998) also demonstrated that the characteristics of the solid soil particles dominate the stabilization potential of the organic soil. Since there is a small fraction of clay minerals in the peats and organic soils, adding lime will not induce a pozzolanic reaction. Calcium hydroxide is the only hydration product formed in this reaction.

Bonomaluwa and Palutnicowa (1987) stated that 'the black humic acid in organic matter has a strong chemical affinity to calcium and hence where calcium is present in solution, the humic acid may react with the calcium and form insoluble calcium humic acid' (as reported by Chen and Wang, 2005). The beneficial affects of adding bentonite along with lime to the organic soil resulted in two fold. First, some excess water bound by the bentonite; second, the bentonite serves as a filler material and source of silica to facilitate the development of C-S-H gel. It is also observed that the blast furnace slag cement and anhydride mixture increases the strength of organic clay significantly more than lime-cement mixtures. The addition of a small amount of high aluminum cement appears to increase the compressive strength further (Hampton and Edil, 1998).

Besides, as humification or decomposition progresses in a peatland, the soil's pH, mineral content, bulk density, and cation exchange capacity increases. Increase in decomposition of soil organic matter is also reflected by higher microbial biomass found in the lime treated soils. Chan and Heenan (1999) observed the higher microbial biomass and hence higher decomposition rates in organic soils treated with lime. This is attributed to the increase in pH values in the limed soils

Organic matter forms complexes with alumino silicates and metal ions which can interfere with hydration reactions of cement. The lag in gaining in strength of the organic soil-cement mixture is due to the retention by the organic matter of the calcium ions liberated during the hydrolysis of the cement grains (Clare and Sherwood, 1954; Maclean and Sherwood, 1962).

Besides, the organic matter binds the calcium ions, and alters the system chemistry so the calcium silica hydrate gel can not form.

Figure 2.21 showing the variation of compressive strength with the ratio of free water to the stabilizer for sphagnum peat stabilized with several different binders (Hampton and Edil, 1998). Here the 'free water' is defined as the amount of water that can be extracted from the soil by 200cm head of suction. Figure 1.21 depicts that the increase in compressive strength with decreasing water/stabilizer ratio.

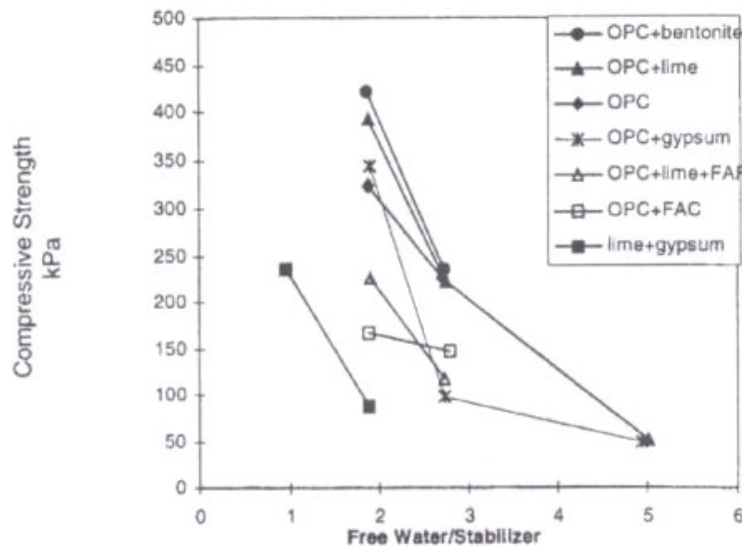


Figure 2.21 Variation of compressive strength of sphagnum peat with various binding agents after 14 days curing time (Hampton and Edil, 1998)

The supply of extra admixtures in cement stabilized organic soil may react with minerals on the surface of cement particles and water-immiscible hydration products may result. On the other hand, the addition of extra admixtures could accelerate cement hydroxylation and hydration in which calcium hydroxide, calcium silicate hydrate, sodium silicate hydrate and calcium aluminate hydrate may form (Chen and Wang, 2005).

Chen and Wang (2005) reported that, in such cases, ion exchange, granulation and hardening reactions take place between the hydration products and clay particles, resulting in an improvement of the strength of cement stabilized soils. It was also observed that the addition of crystal calcium sulphate offsets the precipitation of calcium due to humic acid and helps in crystallization of cement and thus accelerating the increase in strength of the cement soil (Chen

and Wang, 2005). Further, the addition of accelerator admixtures and aluminium sulphate also play their role in promoting early hydration of cement and compensating for the loss of aluminium minerals.

To visualize the changes in chemical bonds as a cement paste hydrated, and to track the changes in an organic soil treated with a binder, Fourier Transform Infrared Spectroscopy (FTIR) studies were performed at Delft Geotechnics by Hampton and Edil, (1998). FTIR scans depicts that polymerization of silicates was greatly hampered in soils with highly decomposed organic matter. Increase ettringite formation was also found in stabilized organic soils. Ettringite is not as strong as C-S-H gel, and in certain environments it may not be stable. Therefore, the binding agents most suitable for organic soils would contain higher percentages of silica for such as blast furnace slag (Hampton and Edil, 1998).

It is well understood from the above discussion that when organic rich soils are treated with chemical stabilizers such as lime/cement, the organic content inhibits the cementitious reactions between the stabilizers and the soil. The severity of these reaction would depend on the degree of humification of the the organic matter, ion exchange capacity of the organic matter, polarity etc. The supply of extra admixtures in chemical stabilized organic soil may react with minerals on the surface of cement particles and water-immiscible hydration products may result. On the other hand, the addition of extra admixtures could accelerate cement hydroxylation and hydration in which calcium hydroxide, calcium silicate hydrate, sodium silicate hydrate and calcium aluminate hydrate may form. It is also important to obtain the qualitative and quantitative measures of the organic content present in the soil to decide upon the type and amount of admixtures to accelerate the process of chemical stabilization.

#### 2.10 Treatment/ Stabilization methods utilized for organic soils

Odadjima et al. (1995) proposed a flow chart for selecting stabilizers based on the humic and fulvic acid content of the peaty soil. This flow chart was based on a study of cement stabilization investigations conducted on twenty one types of peats from Hokkaido (Japan). The strength increase of cement-stabilized soil is attributed to the physico-chemical reactions

including hydration and hardening of the cement and the interaction between the substances in the soil and the products of cement hydration (Pan, 2001 as stated in Chen and Wang, 2005).

Peat or organic soils are often excavated and refilled with a good construction material which is an economical solution if the thickness of these layers is marginal. Long term settlements of these deposits can be minimized by preloading method but this option is time consuming. Geosynthetics can also be used to increase the stability of structures constructed over these deposits, however, this method does not address the problems associated with the construction due to high water content and long term settlement potential of these deposits. If the thickness of such soft layers is high, alternate solutions are constantly looked for. Several different methods to stabilize the organic soils/peats are currently used in practice and they are explained below.

#### *2.10.1 Deep mixing*

Deep mixing method is a technique in which various cementitious materials such as lime or cement are blended into weak soils through hollow, rotated shafts with cutting tools and mixing paddles or augers at the tips to improve their mechanical properties. The materials may be injected in slurry or dry form (Bruce et al. 1998). Deep in-situ mixing chemical stabilization using lime and cement are adopted to treat organic soils and peats for the past three decades. The successful implementation of these techniques to improve the engineering properties of soft clays in Japan and Scandinavia were reported by many researchers (Okumura, 1996; Rathmayer, 1996). The extension of this method to organic soils has been very slow as organic soils hinder cementitious reactions (Hampton and Edil, 1998). However, extensive research conducted in Scandinavian countries showed the potential of this method to stabilize even soft and organic soils (Ahnberg and Holm, 1999).

Hampton and Edil (1998) demonstrated the beneficial effects of introducing bentonite along with lime to the organic soil through laboratory experiments on several peats and organic clay samples collected from Wisconsin and the Netherlands. Bentonite serves as a filler material and source of silica to facilitate the development of C-S-H gel. Bentonite can also hold some excess water that helps in hydration.

It is also observed that the blast furnace slag cement and anhydride mixture increases the strength of organic clay significantly more than lime-cement mixtures. Calcium chloride is used as an admixture to attempt to satisfy the calcium affinity of the organic matter. The addition of a small amount of high aluminum cement appears to increase the compressive strength further.

#### *2.10.2 Mass stabilization*

Mass stabilization is a new soil improvement technique where the stabilizer is mixed into peat, mud or soft clay in both horizontal and vertical directions through a mixing tool attached to an excavator machine and whole mass is strengthened to a homogeneous block structure. This method can be adapted to even organic soils/peats (Jelusic and Leppanen, 2003). The geotechnical properties of stabilized peat depend on physical as well as chemical properties of both untreated peat and the stabilizing agent. The stabilizer agents produced from industrial by-products such as fly ash, end products of sulphur removal process blast-furnace slag etc. can be used more economically in mass stabilization process for better results. Successful application of the mass stabilization technique to construct trial embankments over peat soils and a road for 5 km on mass stabilized peat soils near Lulea in northern Sweden was reported by Jelusic and Leppanen, (2003).

Hebib and Farrell (2003) studied the engineering properties of two types of peat soils obtained from the Irish Midland stabilized with five types of binders. The binders include cement, lime, pulverized fuel ash (PFA), palletized blast furnace slag cement and gypsum to form eight types of mixture combinations of these binders. They presented the results also through large scale laboratory model tests (the volume of the sample inside the test tank was  $5\text{m}^3$ ). The various tests conducted on these samples were cured at 7, 28, 90 and 360 days.

The unconfined compressive strength of both the stabilized peats with cement was significantly higher than the respective untreated material. However, the unconfined compressive strength obtained for a particular mixture of binders was varied markedly for the two peats tested, though both the peats having similar organic and water content. This observation is inline with the finding of Huttunen and Kujala (1996), who described that the strength achieved by stabilization

decreased with advanced decomposition in all types of peat tested. Besides, Tsutsuki and Kuwatsuka, as reported in Stevenson (1994), showed that the carboxyl (COOH) functional groups found in the humic acids increase during humification of the organic matter.

Stevenson (1994) explained that the maximum binding capacity of the humic acids is approximately equal to the content of acidic functional groups, primarily COOH. It was also concluded that the increase in compressive strength of peat, PFA, and lime mixture was low due to the low clay content in the peat. Higher strengths were achieved with blast furnace slag stabilizer. However, with the addition of 15% gypsum to the blast furnace slag resulted in threefold improvement in strength compared to the strength obtained with only blast furnace slag. Higher strength was achieved when the stabilized peat was preloaded.

The consolidation behavior (pre-yield) of cement-peat stabilized soil was found similar to that of stiff soil. The post-yield behavior of the specimens tested was approximately similar regardless of curing time and strength achieved. The secondary compression for cement stabilized peat was found to be less than that of natural peat. The permeability of the cement stabilized peat was similar or less than that of the natural peat depending on the state of stress during curing. The preloaded specimens yield lower permeability.

### *2.10.3 Vertical drains*

Koda et al (1989) reported the results of field and laboratory studies carried out on test embankments found on organic subsoil. The usefulness of prefabricated vertical drains in staged construction of embankment of organic soils located in the north-western part of Poland was demonstrated. It was deduced that there is a significant decrease in discharge capacity during embankment construction by stages, dependent on the type of drain filters (paper or polyester). However, they showed that the decreased discharge capacity has virtually no effect on consolidation rate as long as the discharge capacity is not less than 100 m<sup>3</sup>/year.

The influence of vertical geodrains on acceleration of consolidation of peat and gyttja was reported by Fursenberg et al (1983). A new rheological model of consolidation analysis considering the exponential variability of consolidation parameters for peat soils was proposed.

The following equations describe deformation process of the organic soil with vertical drains installed in it. Figure 2.22 shows the schematic picture of soil cylinder dewatered by vertical drain.

$$\frac{\partial u}{\partial z_0} = \frac{\partial \sigma}{\partial z_0} \dots\dots\dots$$

(Eq.3)

$$M \left[ \frac{\partial}{\partial x_0} \left( \frac{K_v^U}{1-U\epsilon_f} \frac{\partial \sigma}{\partial x_0} \right) \right] + N \left[ \frac{\partial}{\partial y_0} \left( \frac{K_h^U \sigma}{(1-U\epsilon_f)y_0} + \frac{K_h^U}{1-U\epsilon_f} \frac{\partial \sigma}{\partial y_0} \right) \right] = \frac{\partial U}{\partial t} \left[ 1 + \frac{1}{k_1} \frac{\partial \sigma}{\partial t} \right] \dots$$

(Eq.4)

Where,

$$M = \frac{k_{v0}}{\gamma_w H_0^2 \epsilon_f}$$

$$N = \frac{k_{h0}}{\gamma_w R^2 \epsilon_f}$$

U = excess pore water pressure

$\gamma_w$  = unit weight of water

$k_v, k_h$  = permeability coefficients in vertical and horizontal directions, respectively

$K_h = k_{hf}/k_{h0}$  and  $K_v = k_{vt}/k_{v0}$

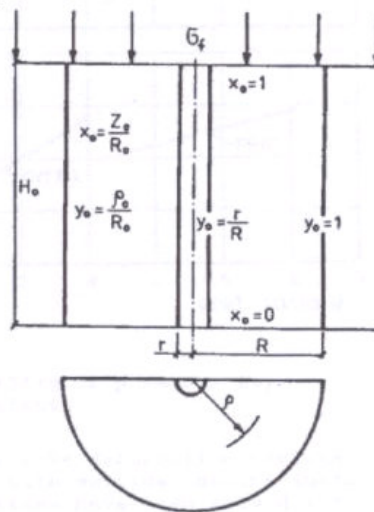


Figure 2.22 Schematic picture of soil cylinder dewatered by vertical drain (Fursenberg et al., 1983)

#### *2.10.4 Dry Jet Mixing*

(DJM) is a soil treatment and improvement technology which pneumatically delivers powdered reagents into the ground and mixes it with in-situ soils to form a soil-reagent column. The strength of the poor soft soil will result from the chemical reaction of soil and stabilized reagent. DJM provides the flexibility of selecting the type of reagent according to the condition of the in-situ soil which has been the major disadvantage of slurry type deep mixing technology. DJM was first developed by the Civil Engineering Research Institute of the Japanese Ministry of Construction in conjunction with the Japanese Construction Machine Research Institute in 1977 (Yang et al, 1998).

Yang et al (1998) demonstrated the construction procedures of dry jet mixing technique. They also showed the improvement of engineering properties of the treated soil such as shear strength, modulus of elasticity, compressibility and uniformity.

Through laboratory tests on Swedish peats and organic soils, Ahnberg and Holm (1999) reported that the cement slag binder used as stabilizer improved the mechanical properties of these soils. However, still better results were obtained by adding other types of binders. Nevertheless, by adding gypsum to cement slag is proved to be effective in stabilization of domle gyttja, but unsuitable for holma gyttja. Moreover, the chemical properties also influence the properties of binder. The strength of stabilized soil increases with increase in time duration. Furthermore, curing temperature also influence the strength of the stabilized soil and high temperatures should be preferably avoided for the stabilization of peat.

Lahtinen et al. (1999) reported that gyttja and peat soils stabilized by new binders such as blast furnace slag and gypsum combined with lime and cement are very potential compared to lime cement binders alone. They also concluded that the laboratory tests are very important for finding the binders suitable for stabilization of different types of organic soils.

#### 2.11 Summary

The literature review briefly discusses about the origin of organic soils and their physical and chemical properties in initial sections of this report. It is observed that the properties of organic soils are much deviated from the inorganic soils. Several researchers have reported the



high water retention capacity of organic soils (water content ranges as high as 1000% and more in certain cases of peats), which is responsible for various problems like low shear strength, high compressibility etc. Several test methods available to determine the amount of organic content are discussed thereafter. It can be seen that the loss of ignition method gives the amount of organic content on conservative side. Therefore, it is necessary to find out a way to accurately determine the amount of organic content in a soil.

The engineering properties of the organic soils are discussed and also brought out the influence of organic matter on different engineering properties of the soils. The presence of organic content greatly influences the engineering properties such as shear strength parameters, compressibility, compaction characteristics, etc. of the soils. The interaction of organic matter with the soil is discussed in later sections followed by a discussion on effect of organic content on the behavior of chemical stabilized organic soils or peats. It is learnt that the organic matter interacts with the stabilizer and inhibits the cementitious reactions to takes place, which are more responsible for the gain of strength. It is also inferred that the introduction of certain admixtures along with the common chemical stabilizers, such as lime and cement to the organic soil, can accelerate the cementitious reactions within the stabilized soil to help in gaining strength rapidly. Lastly, different methods adopted to treat the organic soils using chemical stabilizers are also reported.

CHAPTER 3  
SURVEY ON ORGANIC SOILS IN TEXAS

3.1 Introduction

In order to obtain a brief summary of the occurrence of organic soils over Texas and their impact on the performance of untreated/treated pavements, a survey questionnaire has been circulated to all 25 districts of Texas State. The information obtained from this survey has been analyzed and presented in graphical form. However, the response was received from 16 districts only. The response constitutes to sixty four percent of the total number of districts in texas as given in the graph shown in Figure 3.1.

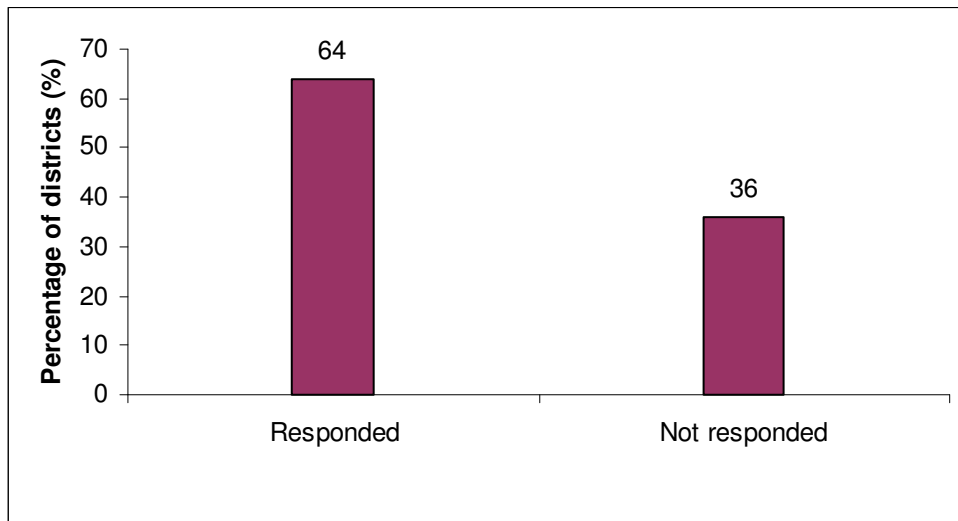


Figure 3.1 Response to the Questionnaire

3.2 Survey Analysis

1. Have you encountered any organics in subgrade soils from your district?

Organic soils are encountered occasionally forty four percent of the total number of districts responded to the survey, and none in regular basis. Fifty six percent of the total number

of districts responded, had not encountered any organics in its subgrade soils. A graph has been shown in the Figure 3.2.

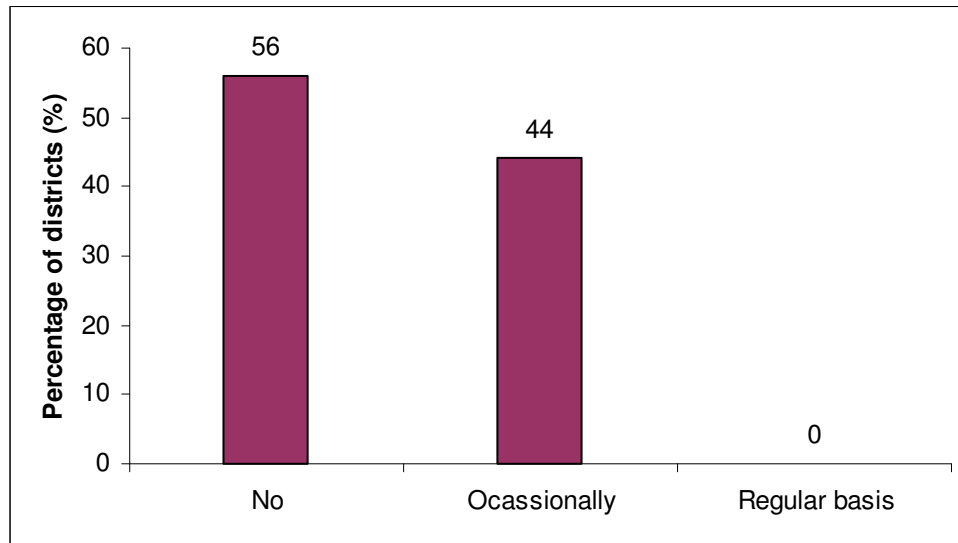


Figure 3.2 Have you encountered organic soils

2. In your opinion, how do you assess problems due to organic rich subgrades in your district?

From the above question, It has been understood that organic soils are encountered in forty four percent (44) of the total number of districts responded to this survey. On the other hand, thirty one percent (31) of the total number of districts responded to this survey had encountered problems due to the organic rich soil subgrades. Amarillo district doesn't experience any problems due to organics, though it is having organic rich subgrade soil. However, Austin experiences the considerable problem, but not the major one due to the organic rich subgrade soil. Graph is also demonstrated in the Figure 3.3.

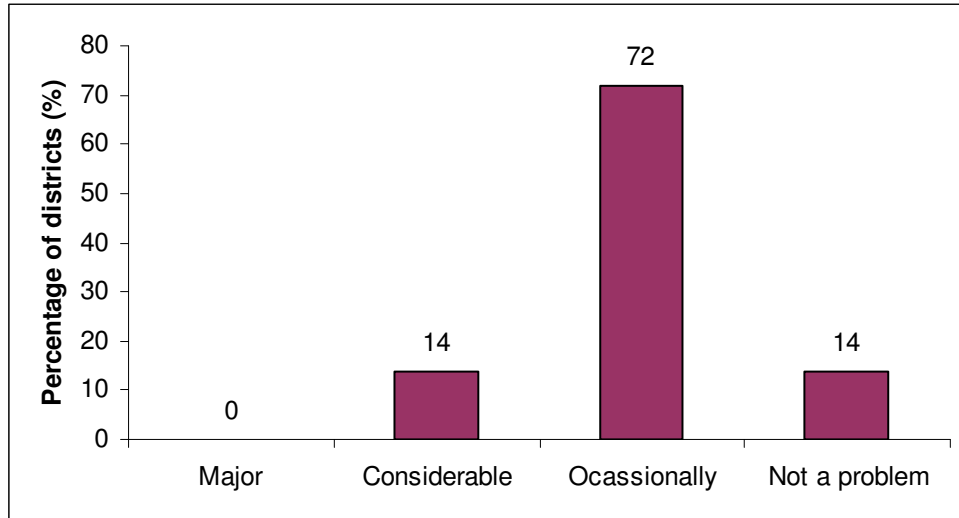


Figure 3.3 Problems due to organic soils

3. What laboratory method have you followed for the measurement of organics?

Different districts have been using different procedures to determine organic content in the soil. However, this question is answered only by the districts, those have encountered organics in the subgrade soil. On the other hand, seventy one percent of the districts (5) that had encountered organic soils use loss of ignition test (TxDOT procedure) to determine organic content. Amarillo is the only district that uses ASTM procedure, where as, Austin district mentions that it had not tested any soil to determine organic content, but it would perform the tests in future. A graph is also shown in the Figure 3.4.

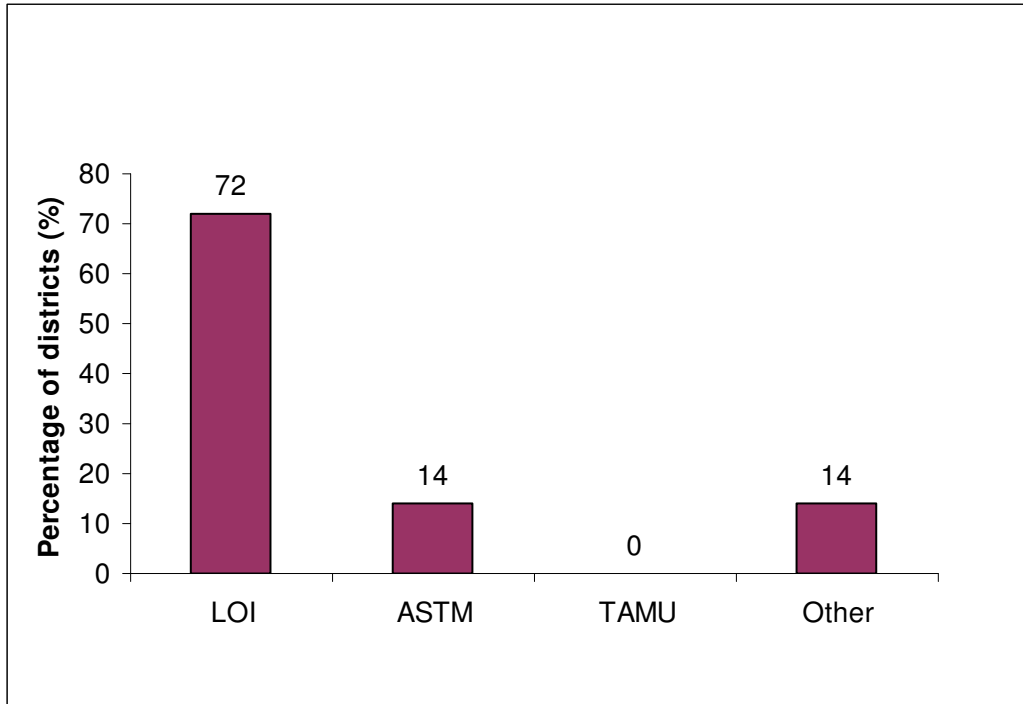


Figure 3.4 Methods used to find out organics by different districts

4. At what depths you have encountered the organics?

Organics are at an intermediate depth of one to three feet, for fifty eight percent of the districts that have encountered organic soils. Austin and Amarillo experiences organics at a intermediate depth of three to five feet and less than one feet respectively. On the other hand, Waco district experiences organics any where at a depth of less than five feet. A graph is also shown in Figure 3.5.

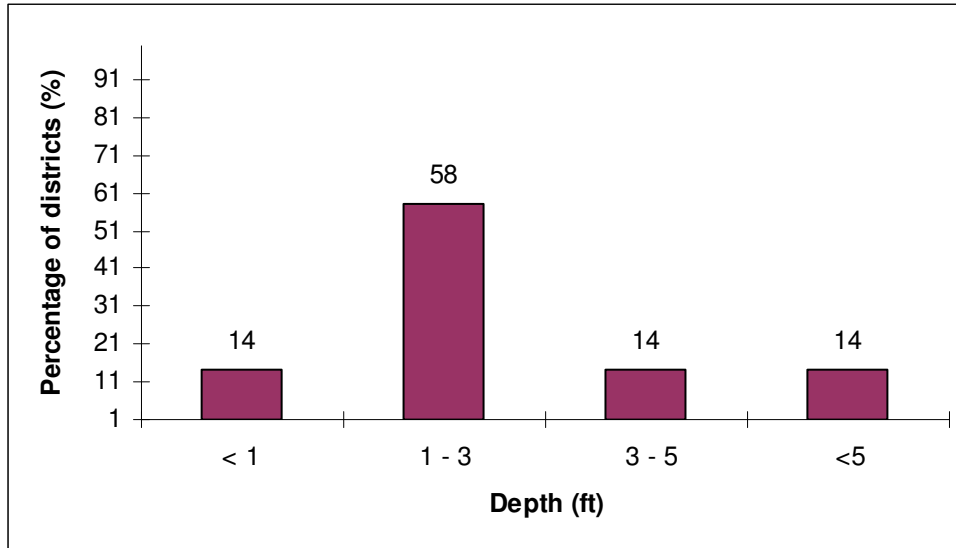


Figure 3.5 At what depth organic soils were encountered

5. Have you implemented any stabilization on the organic rich subgrades?

Stabilization is implemented by seventy one percent of the districts, which have encountered organics in the subgrade soils. However, Twenty nine percent of the districts didn't implement any stabilization technique, which have encountered organics in the subgrade. Graph is also shown in the Figure 3.6.

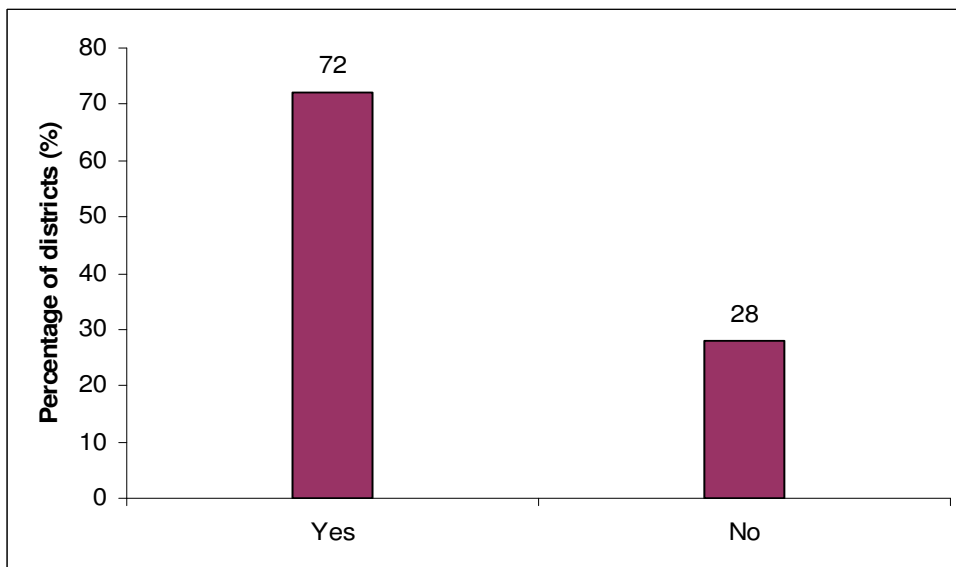


Figure 3.6 Implementation of stabilization on organic rich subgrades

6. If chemical modification is the choice, please check the stabilizer that has been used:

Chemical modifications are the major stabilization techniques used for the organic soils in Texas. Moreover, eighty percent of the districts, which implement stabilization to the subgrade of organic soils use lime as a stabilizer. However, fly ash is used by twenty percent of the districts, which implement stabilization to the subgrade of organic soils, to reduce the effects of organic soil rich subgrade. Graph is also demonstrated in Figure 3.7.

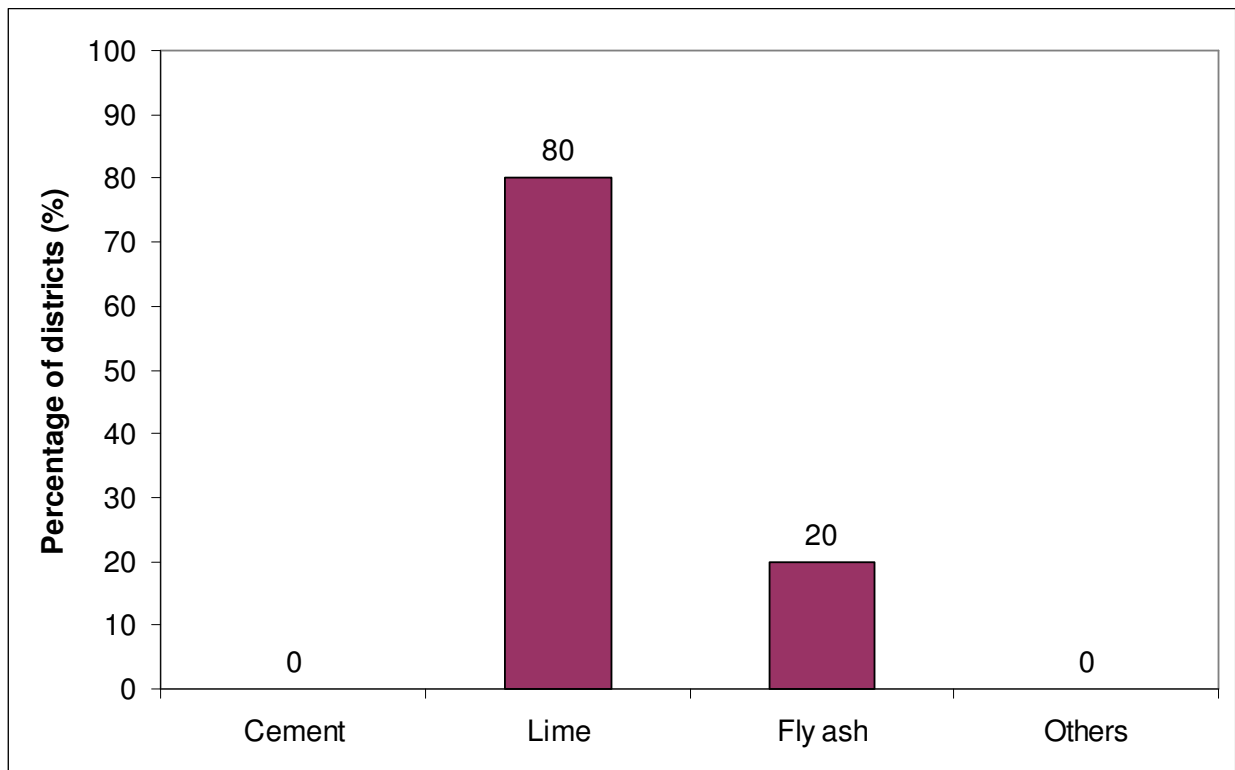


Figure 3.7 Types of stabilizers used

7. Which soil property was the major focus of your subgrade design?

Soil property is the major focus that occurs on the subgrade design; however different districts had taken care of different soil properties during the design of subgrade. In fact, swell shrink changes is the design property taken care by seventy two percent of the districts, that have encountered organic soils in the subgrade. However, strength and stiffness/resilient modulus properties are focused each by fourteen percent of districts, which have encountered organic soils in the subgrade. Graph is also shown in the Figure 3.8.

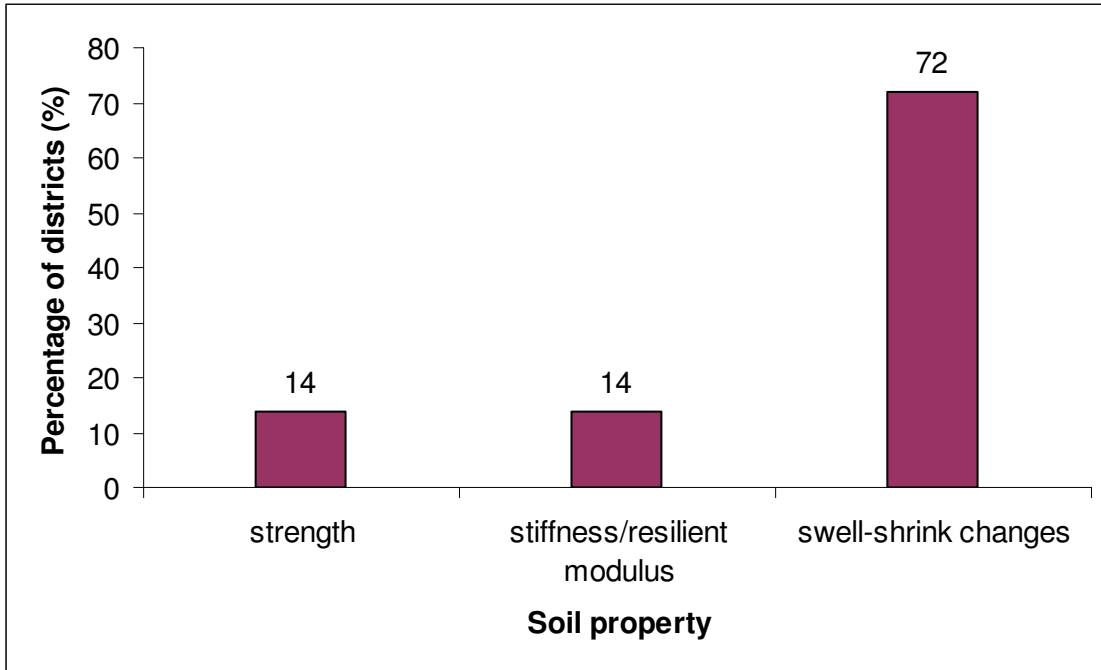


Figure 3.8 Which soil property is the major focus of subgrade design.

8. If any other modification or replacement of organics is implemented, please list the method followed

Amarillo and Fort Worth didn't answer the question, where as Austin doesn't use any modification or replacement techniques. However, Beaumont, Waco, and Wichita falls uses a method to remove and replace the problematic material with a better local fill material. On the other hand, San Angelo uses a method to mix the limestone material, which is available in the local area.

9. Have you experienced any major distress on stabilized organic rich subgrades?

San Angelo and Wichita falls didn't answer the question, where as Amarillo and Waco doesn't have any problems after stabilization of the subgrades. However, Beaumont, and Fort Worth experienced rutting and poor strength gain on the subgrade after stabilization of the subgrades. Where as, Austin experiences the problems such as Inhibiting calcium based additives; shrink-swell due to the ineffectiveness of the calcium-based additive. These results indicate, sixty percent of the districts that have implemented stabilization to organic rich subgrades have problems after stabilization.



### 3.3 Summary

The researchers have prepared a short survey to measure the extent of problems experienced by TxDOT when organic rich soils are encountered. This survey is responded by 16 districts, which counts to sixty four percent of the total number of districts present in Texas. From the survey response, it has been understood that organics in the subgrade are encountered by seven districts, which counts to forty three percent of the total number of districts responded to it. On the other hand, Seventy two percent of the districts which have encountered organic soils had implemented stabilization. In fact, Lime is used as a stabilizer by eighty percent of the districts, that have implemented stabilization in the organic rich subgrade soils. However, the results indicate, sixty percent of the districts that have implemented stabilization to organic rich subgrades have problems after stabilization. So, effects of the organics on stabilized soils are the major part of this thesis.

### 3.4 Survey Questionnaire

As part of Project 0-5540 "Mitigating the Effects of Organics in Stabilized Soils" the researchers have prepared a short survey to measure the extent of problems experienced by TxDOT when organic rich soils are encountered. We would very much appreciate you taking a few minutes to complete this survey.

Organic rich soils typically have a strong odor similar to the smell of sewage and are often dark in color. These soils typically do not respond well to calcium-based stabilizers (lime and cement) and may have a very low pH. Problems that typically occur are loss of strength over time, loss of stabilizer over time, or large amounts of stabilizer may be required to achieve acceptable strength/swell reduction. The image below shows a soil with a dark, organic-rich horizon in the center of the image.



Figure 3.9 Organic rich zone in subgrade soil.

“Districts Survey on Organics for TxDOT Project 0-5540”

NAME:

District:

Please click or check (with X) to the following questions. We thank you in advance for your input

1. Have you encountered any organics in subgrade soils from your district?

- Yes, on a regular basis       Yes, but occasionally       No

If the answer to the above question is NO, please move forward to Question No. 10.

2. In your opinion, how do you assess problems due to organic rich subgrades in your district?

- Major    Considerable, but not a major one    Occasional    Not a problem

3. What laboratory method have you followed for the measurement of organics?

Loss of Ignition (TxDOT Procedure)       ASTM Method  
 TAMU Soil & Crop Sciences Elemental Analyzer Method    Other,  
specify\_CSTM&P\_\_\_\_\_

4. At what depths you have encountered the organics? (If necessary, Please check more than 1)

Less than 1 ft       Between 1 and 3 ft       Between 3 and 5 ft  
 Between 3 and 5 ft

5. Have you implemented any stabilization on the organic rich subgrades?

YES       NO

6. If chemical modification is the choice, please check the stabilizer that has been used:

Cement       Lime       Fly Ash       Others

7. Which soil property was the major focus of your subgrade design?

Strength       Stiffness or Resilient Modulus       Swell and Shrink Changes

8. If any other modification or replacement of organics is implemented, please list the method followed:

Replaced subgrade soil prior to treatment.\_\_\_\_\_

9. Have you experienced any major distress on stabilized organic rich subgrades?

Poor Strength Gain       High Leaching of Chemical Stabilizer  
 Rutting       Others

10. We would like to contact you if we have any follow-up questions. Please list your email or phone number where we can reach you.

Email:

Tel:

We thank you very much for your input. We kindly request to send your survey response to email address of [anand@uta.edu](mailto:anand@uta.edu) or fax to 817-272-2630 or mail it to: Anand J. Puppala, PhD, PE, Professor, Box 19308, Department of Civil and Environmental Engineering, The University of Texas at Arlington, Arlington, TX 76019, USA.

## CHAPTER 4

### MATERIALS AND METHODS

#### 4.1 Introduction

As a part of the research investigations, a laboratory based experimental program was designed and conducted to test the soils sampled from Abilene, Austin, Beaumont, Bryan, Corpus Christi in Texas. This chapter describes the laboratory tests performed, test equipment and procedures employed in the research.

#### 4.2 Materials

Soil samples are obtained from 12 sites in six locations. The sites include Abilene, Austin (Parmer lane), Beaumont, Bryan (Huntsvillie and College station), and Corpus christie. Soil samples obtained from huntsvillie are at Interstate Highway 45 (IH 45). This include four locations termed as Trench 1 Top, Trench 3 Top, Trench 3 Bottom, and Trench 4 Top. Soil samples obtained from college station are at State Highway 6 (SH 6). This site include three locations termed as Eastside, Northbound, and Southbound. Soil samples obtained from corpus christi include two locations as Interstate Highway 37 (IH 37) and Farm to Market road 665 (FM 665). These soil samples are given sample notations as mentioned in Table 4.1. Here after, soil samples are denoted by these sample notations.

#### 4.3 Description of Basic Properties Tests

Tests conducted to measure basic soil properties in this research were specific gravity, sieve analysis, hydrometer analysis, Atterberg limits, organic content, and standard Proctor tests. These tests were conducted at the beginning of the experimental program. However, Atterberg limits, organic content, and standard proctor tests are conducted for all the materials including control soil, cement and lime treated soils.

Table 4.1 Site Discription and Sample Notation

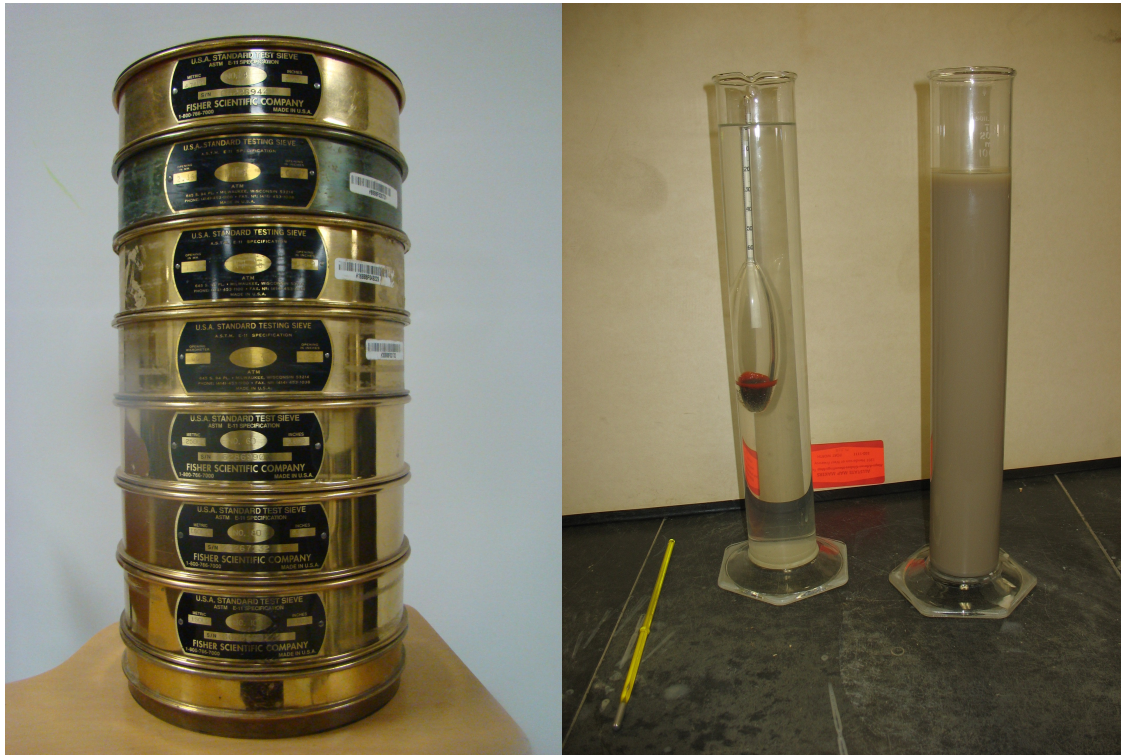
Name of the Site	Sample Notation
Abilene	ABL
Austin	AUSPL
Beaumont	BMT
Corpus Christie, (IH 37)	CCI37
Corpus Christie, (FM 665)	CCF665
Bryan, Huntsville, Trench 1 Top (I 45)	BI45T1T
Bryan, Huntsville, Trench 3 Top (I 45)	BI45T3T
Bryan, Huntsville, Trench 3 Bottom (I 45)	BI45T3B
Bryan, Huntsville, Trench 4 Top (I 45)	BI45T4T
Bryan, College Station, Eastside (I 45)	BS6E
Bryan, College Station, Northbound (SH 6)	BS6N
Bryan, College Station, Southbound (SH 6)	BS6S

This section explains the wet analysis for the determination of particle size distribution of the representative sample followed by the determination of Atterberg limits for each soil at undisturbed state. Moreover, it should be noted that the test procedures followed in this research are in accordance with TxDOT testing manual wherever applicable.

#### 4.4 Particle Size Distribution – Wet Analysis

The particle size analysis was performed according to the Tex-101-E (Method B) of TxDOT procedures. A representative sample was kept soaked in tap water for a period of 24 hours. A known weight (wet weight and water content determined) of sample was sieved through No. 10 sieve and washed thoroughly. The portion retained above No. 10 sieve was dried in the oven at 140° C to obtain the dry weight. The portion of the sample passing No 10 sieve was then washed through a stack of sieves ranging from sieve openings of 4.75 mm (No. 40) to 0.075 mm (No. 200) sieve until atleast 95% of the material passes the No. 40 sieve. Typical arrangement of sieves are shown in Figure 3.1 (a). The water content of the material left in the each of the sieves was reduced by placing the samples in 140° F oven and the dry weight of the samples was plotted

against the sieve openings to obtain the grain size distribution curves. The distribution of the grain sizes in test materials finer than 0.0075 mm was determined using TxDOT procedure Tex-110-E. Finer particle size analysis was performed using hydrometer analyses. Typical setup of hydrometer analysis is shown in the Figure 4.1 (b).



(a) (b)  
Figure 4.1 (a) Arrangement of Sieves (b) Hydrometer Analysis Setup

#### 4.5 Determination of Atterberg Limits

Atterberg limits were determined based on Tex-104-E to determine the liquid limit and Tex-105-E to determine the plastic limit. The procedure for preparation of wet samples for the test is identical to those explained in the previous section. The sample passing No. 40 sieve was allowed to slowly dry approximately below the liquid limit by placing the sample in a plaster of paris bowl with filter paper. An electric fan was provided above the bowl to facilitate early drying of the soil. The thick paste obtained was used for the determination of liquid limit and plastic limit. Water content measurement was made by microwave drying method based on the repeatable data reported by Hagerty et al. (1990). The difference between these limits is termed as the



#### 4.7 Standard Proctor Test

In order to determine the optimum moisture content and maximum dry unit weight of the soils in the current research program standard proctor compaction tests were conducted. The optimum moisture content of the soil is the water content at which the soils are compacted to a maximum dry unit weight. Samples exhibiting a high compaction unit weight are preferred for supporting civil infrastructure since the void spaces are minimum and settlements will be less.

Compaction tests were conducted on both control soil and treated samples to determine moisture content and dry unit weight relationships. Standard Proctor test method using Tex-114-E procedure was followed to determine moisture content vs. dry density relationships.

#### 4.8 Description of Engineering Tests

Engineering tests performed in this research were unconfined compressive strength (UCS) test, bar shrinkage test, 1 D free swell test. These tests have been performed in accordance with the TxDOT procedures. For each test, a total of two identical samples of control, lime and cement treated samples were tested and analyzed to understand the repeatability of the test results. Descriptions of engineering tests are given in the following sections.

##### *4.8.1 Unconfined Compressive Strength Test (UCS)*

The UCS tests are performed as per ASTM D 2166. The specimen is first 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 top plate (Figure 3.3(a)). Once the specimen is intact, it 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 specimen. Both deformation and corresponding axial loads on the specimen are recorded using a data acquisition system features of Wykeham Farrance software. Figure 4.3(b) depicts the shear failure of the specimen. The data retrieved from the computer program contains load (Q)-deformation (d) data and the same was analyzed for maximum unconfined compressive strength ( $q_u$ ) in psi or kPa. The following expressions show the computation of stress ( $\sigma$ ) and strain ( $\epsilon$ ) corresponding to the load-deformation data.

$$\epsilon = \delta / L \quad (3.3)$$



$$\sigma = Q/A_c \quad (3.4)$$

$$\text{and } q_u = \sigma_{\max} \quad (3.5)$$

where  $\delta$  = change in length,  $L$  = length of the specimen and  $A_c$  = corrected area of cross-section of the specimen and equal to  $A/(1-e)$ ;  $A$  is the initial cross-section area.

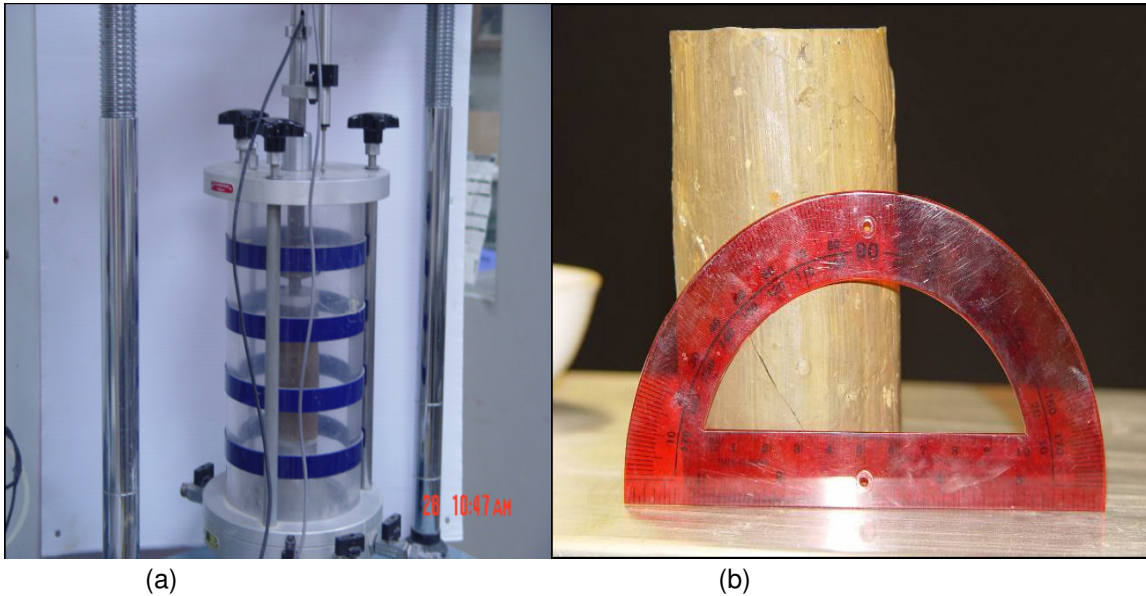


Figure 4.3 (a) UCS Test Setup (b) Shear failure of Specimen

#### 4.8.2 One-Dimensional Free Swell Test

The one-dimensional free swell test measures the amount of heave in the vertical direction of a laterally confined specimen in a rigid chamber. This test is conducted as per the ASTM standard method, D-4546. The schematic diagram of the one-dimensional free swell test is shown in Figure 4.4.

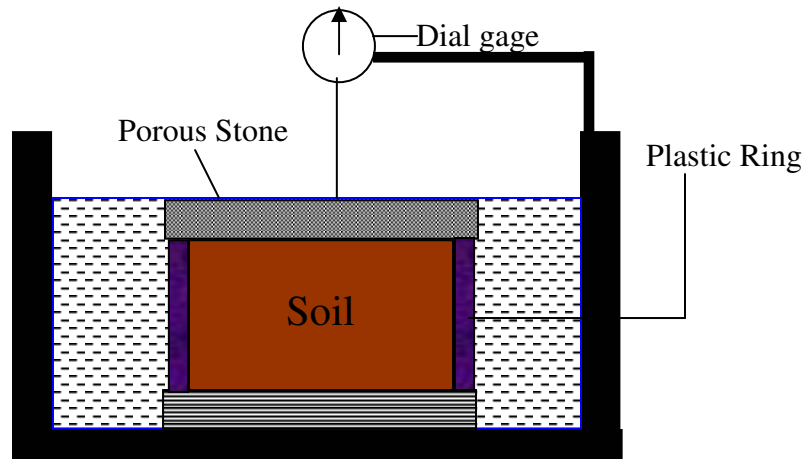


Figure 4.4 Schematic Diagram of One-Dimensional Free Swell Test



Figure 4.5 Laboratory Setup of One Dimensional Free Swell Test

Control soil samples of 2.5 inch diameter and 1 inch thickness were carefully prepared and placed in the plastic ring. Porous stones were placed on the top and bottom of the soil samples, which facilitates the movement of water to the soil sample. The samples were then transferred to the container, which was later filled with water in order to soak the entire sample. The amount of heave of the sample was recorded at various time intervals by a dial gauge. The displacement readings of the specimen were continued until there was no significant change in displacements for more than 24 hours. The percent swell was recorded for each sample by calculating the ratios of maximum free vertical swell to the initial height of the soil sample and is expressed in percentage. Figure 4.5 shows a laboratory setup of a one-dimensional free swell test used in this research.

#### 4.8.3 Linear Shrinkage Bar Test

TxDOT formulated a test procedure, the Linear Shrinkage Bar Test (Tex-107-E), to measure the linear shrinkage strains of the soils. This test provides a measure of linear shrinkage of a bar of soil paste in the bar type mold.

In this method, the soil was mixed at a moisture content level equal to the liquid limit state. Soil samples used for determining the linear shrinkage were first obtained by preparing the soil slurry at the liquid limit state. The slurry was then placed in a bar mold. Care was taken while placing the soil into the mold so that the entrapped air was removed. The sample was then air-dried at room temperature until its color slightly changed and was then placed in the oven at 105<sup>0</sup> C to reach oven dry conditions. Dried samples were removed and their length was measured. Percent linear shrinkage of the soil specimen was then calculated as a percent of the original bar length. Typical setup is shown in the Figure 4.6.

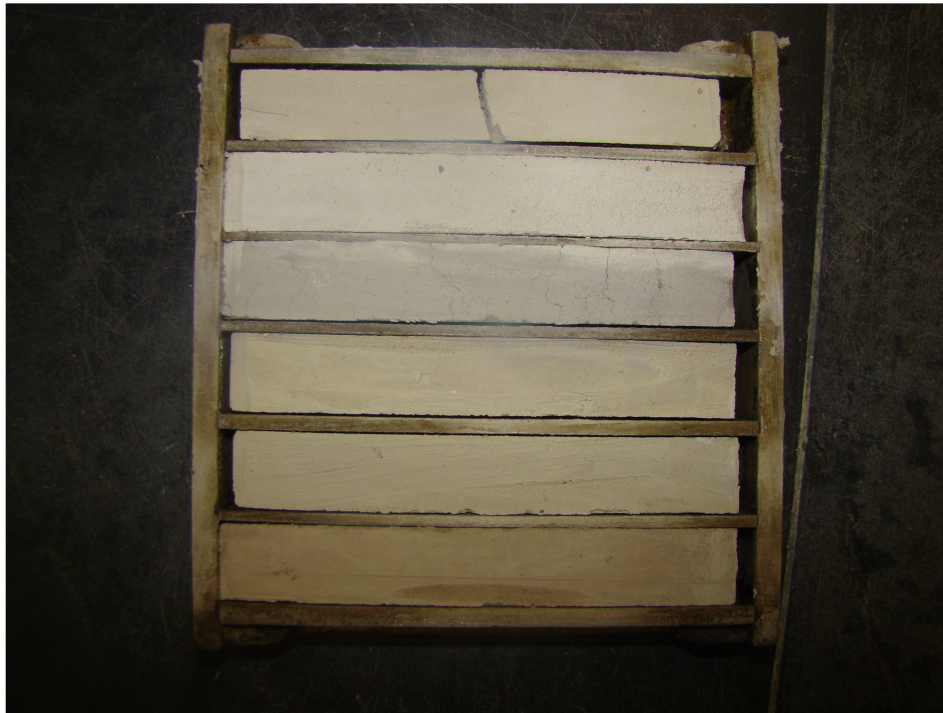


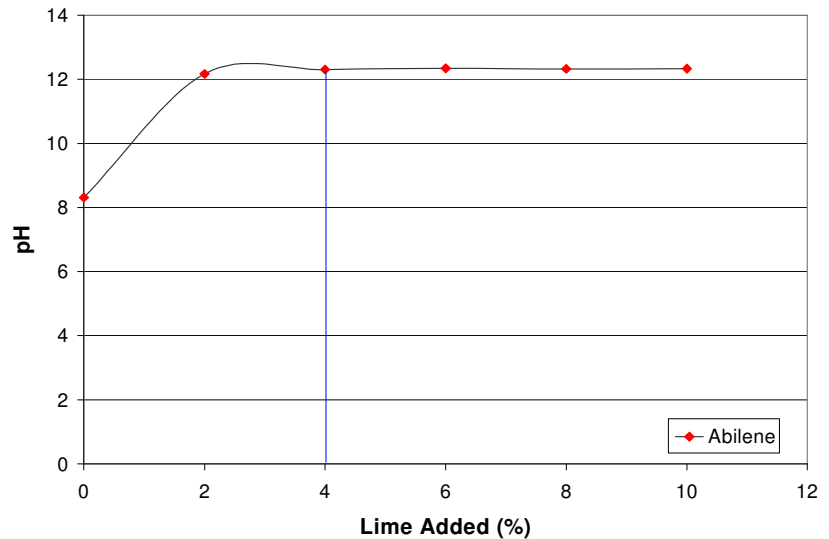
Figure 4.6 Linear Shrinkage Bar Mold

#### 4.8.4 Optimum Lime Content (Eades & Grim Procedure)

The current researches determined the optimum lime content values for soils following the procedure given by Eades and Grim (1966) and Tex-121-E method. Lime dosages in percentage by dry weight in the order of 0, 2, 4, 6, 8 and 10% are added to approximately 20 grams of air dried soil passing No. 40 sieve. These lime soil samples are transferred into a 250 ml plastic bottle with appropriate lid. Then 100 ml distilled water free of CO<sub>2</sub> in the ratio of 1:5 is added to these mixtures and the samples are 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. The pH values versus the binder dosage in percentage are plotted and the threshold value was determined beyond which any further addition of the binder doesn't change the pH of the soil-binder mixture. However, the procedure is explained in the form of flow chart shown in the Figure 4.8. Moreover, Ph calculation setup and a typical graph used for the calculation of optimum lime content are shown in the Figure 4.7(a) and 4.7 (b) respectively.



(a)



(b)

Figure 4.7 (a) Ph Test Setup (b) pH versus Percent Lime

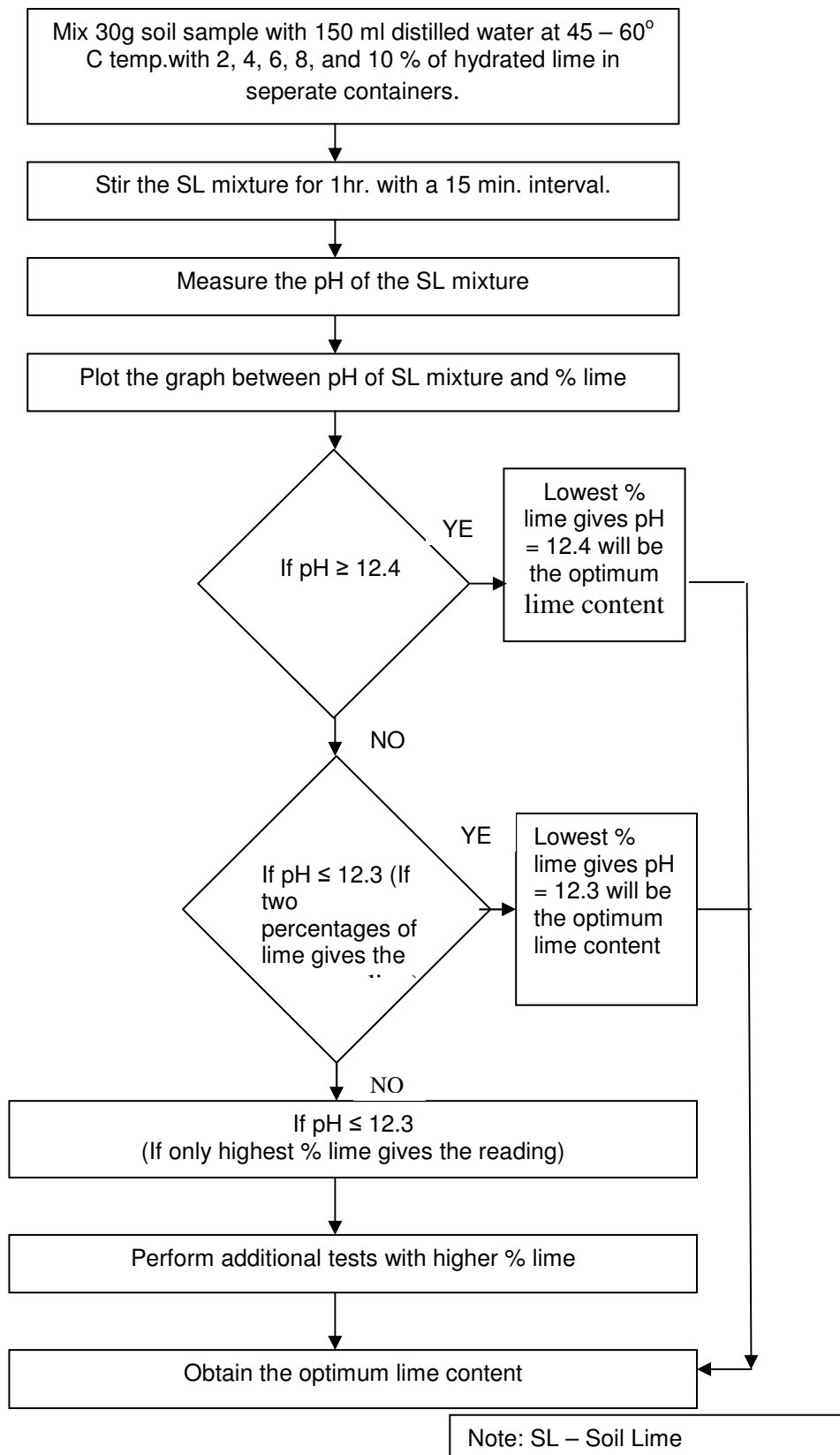


Figure 4.8 Optimum content of Lime for Stabilization of Soil (Eades & Grim Procedure)

#### 4.8.5 Optimum Cement Content

The current researchers determined the optimum cement content values for soils following the procedure given in TxDOT manual as Tex-120-E method. Initially, obtain the optimum moisture content and maximum density for a soil-cement mixture containing 6% cement in accordance with Tex-113-E. The amount of cement added is a percentage based on the dry mass of the soil. Now, recombine the sizes prepared in accordance with Tex-101-E, Part II to make three individual samples and add the optimum moisture content, from Tex-113-E to each sample (Mix the sample thoroughly). Cover the mixture to prevent loss of moisture by evaporation. These wetted samples are allowed to stand for at least 12 hours before compaction. However, if the PI is less than 12, the standing time may be reduced to not less than three hours. Prior to compaction, replace any evaporated water and thoroughly mix each specimen. Compact the specimen in four layers using Tex-113-E compactive effort. Now, Alter the percent molding water slightly as the percent cement is increased or decreased. This is performed in order to mold nearer optimum moisture content without running a new M/D curve for each percentage of cement. (However, a new M/D curve for each percentage of cement may be performed, if desired).

The following rule is used to vary the molding water content

$\% \text{ Molding water content} = \% \text{ Optimum moisture content from M/D curve} + 0.25 (\% \text{ cement increase}),$

where % cement increase is given as difference in cement content between curve and other cement contents. Use 4, 8, and 10% cement to complete the full set.

By, using the moisture contents outlined above, mold three specimens for each percentage of cement content. After the top surface of each specimen has been leveled and the specimen measured, carefully center over porous stone and remove specimen from mold by means of small press. Place a card on each specimen showing the laboratory identification number and the percent of cement. Now, store the test specimens on the same day they are molded, with top and bottom porous stones, in the damp room for seven days. (These specimens are not subject specimen to capillary wetting or a surcharge). After the curing period of seven

days, remove the test specimens from damp room and use a cloth to remove any free water on surface of the specimen. The specimens are now ready for compressive strength test.

Subsequently, unconfined compressive strength tests are conducted, and results are plotted between the unconfined compressive strength and percentage of cement added. Optimum cement content (%) is chosen as the percentage which gives an unconfined compressive strength of 150psi or 1035kPa. A typical graph used for the calculation optimum cement content is shown in the Figure 4.9.

*4.8.6 Testing program of Control soil, Cement and Lime treated samples*

After the determination of optimum lime and cement contents used for stabilization of the soils, optimum moisture/density relationship is determined for each mixture of (soil + stabilizer) sample with standard proctor compaction. Subsequently, the unconfined compressive strength soil samples for control soil, lime and cement treated are prepared. Then, the above prepared soil samples are left in the damp room for an interval of 7, 28 and 56 days. Now, the unconfined compressive strength (UCS) will be determined (at 7, 28 and 56 days) for each soil/stabilizer combination to see if there is any strength benefit achieved with the lime and cement additives.

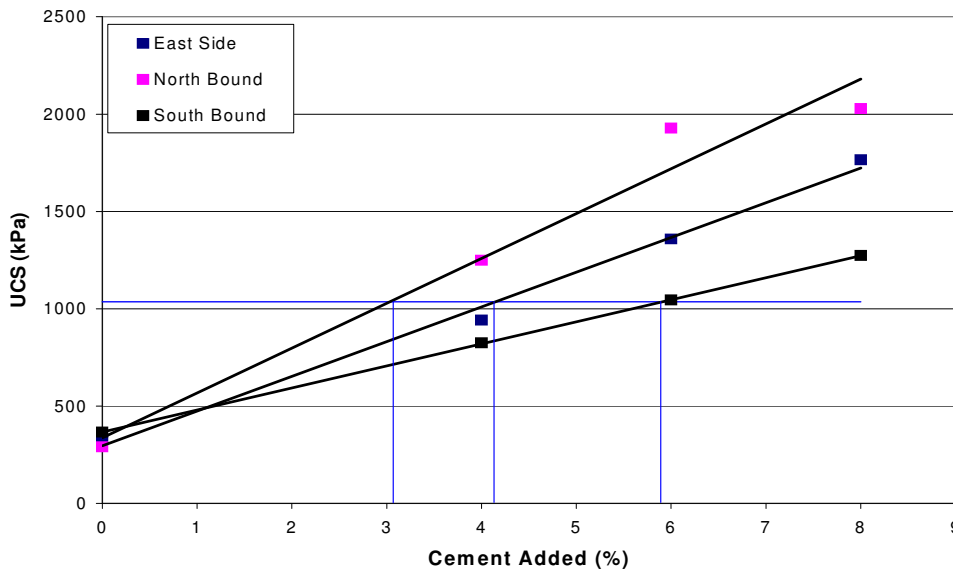


Figure 4.9 UCS versus Percent Cement added

#### 4.9 Summary

This chapter provides a comprehensive summary of the experimental program performed in this research. Test procedures and equipment used are described along with basic engineering properties and grain size distributions of the control materials used in the experiments. All the soils contain organic content. Soils are classified as per unified soil classification. On the other hand, Atterberg limits are determined for control, lime and cement treated samples. Compaction tests are performed for control soil samples, Samples treated with cement at six percent, and samples treated at optimum lime and cement content. Optimum lime and cement contents are determined by eades & grim method, and 7days curing method respectively. Then, UCS samples are prepared for control soil, at optimum lime and cement content and left in the curing room. Unconfined compressive strength tests are conducted for control soil, lime and cement treated samples at intervals of 7, 28 and 56 days intervals. Linear shrinkage bar tests are performed for control, lime and cement treated samples. Free swell tests are conducted only for control soil samples. The experimental test results and analysis are summarized in the next chapter.



## CHAPTER 5

### ANALYSIS OF TEST RESULTS

#### 5.1 Introduction

This chapter presents a comprehensive analysis of both basic and engineering test results conducted in this research. The analysis evaluates the potentials of lime and cement stabilizers to provide enhancements to organic soil properties. The effectiveness of each stabilizer and their influence on strength at different curing periods such as 7, 28 and 55 days, plasticity index, and shrinkage strain properties on organic rich soils as well as on the control soil are explained. This chapter is divided into two sections; each section describes the basic and engineering properties of control and treated soils. They are explained in the flow chart shown in Figure 5.1. In this chapter, soils are referred to with their notations as described in section 4.2.

#### 5.2 Properties of Control Soils

This section includes the basic properties of control soils such as organic content, specific gravity, Atterberg limits, compaction characteristics, and optimum lime and cement content determination.

##### *5.2.1 Organic Content*

The organic content test was conducted to measure the amount of organic content present in soil specimens. Table 5.1 and Figure 5.2 present the amount of organic content present in the control soil samples. The amount of organic content present in the soil specimens are in the range of 1.5 to 6.1 percent. From Table 5.2 and Figure 5.2, it can be observed that both the samples BI45TIT and CCI37 have the highest and lowest organic content of 6.1% and 1.5% respectively.

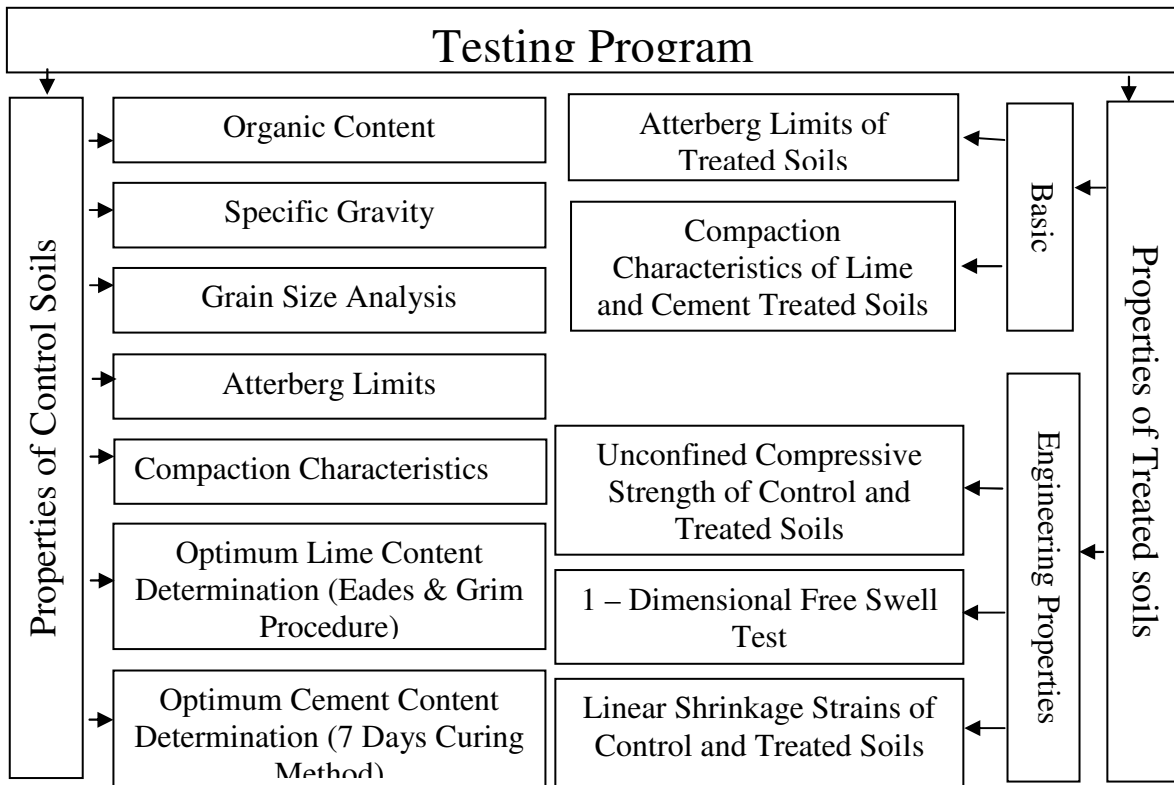


Figure 5.1 Flow Chart of the Sections Explained in this Chapter

Table 5.1 Organic Matter Present in Control Soils

Sample Notation	Organic Content (%)
ABL	4.4
AUSPL	4.8
BMT	4.6
CCI37	1.5
CCF665	3.7
BI45T1T	6.1
BI45T3T	3.7
BI45T3B	4.4
BI45T4T	4.4
BS6E	2.1
BS6N	2.2
BS6S	2.3

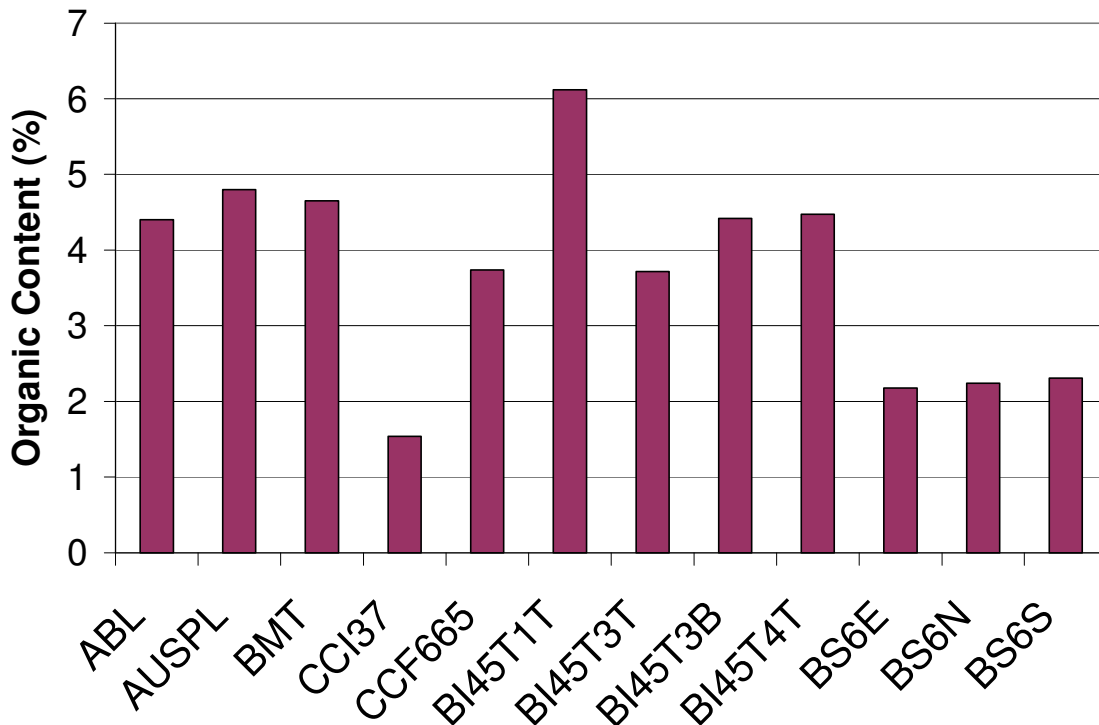


Figure 5.2 Organic Content of Control Soils

### 5.2.2 Specific Gravity

Specific gravity tests were conducted on the control soils. The specific gravity test provides an indirect explanation on possible constituents of soil and this property compares the unit weight of the material with respect to the unit weight of water. Table 5.2 and Figure 5.3 presents the specific gravity test results of all control soils.

Table 5.2 Specific Gravity of Control Soils

Sample Notation	Specific Gravity
ABL	2.53
AUSPL	2.57
BMT	2.58
CCI37	2.52
CCF665	2.51
BI45T1T	2.37
BI45T3T	2.45
BI45T3B	2.62
BI45T4T	2.48
BS6E	2.59
BS6N	2.58
BS6S	2.57

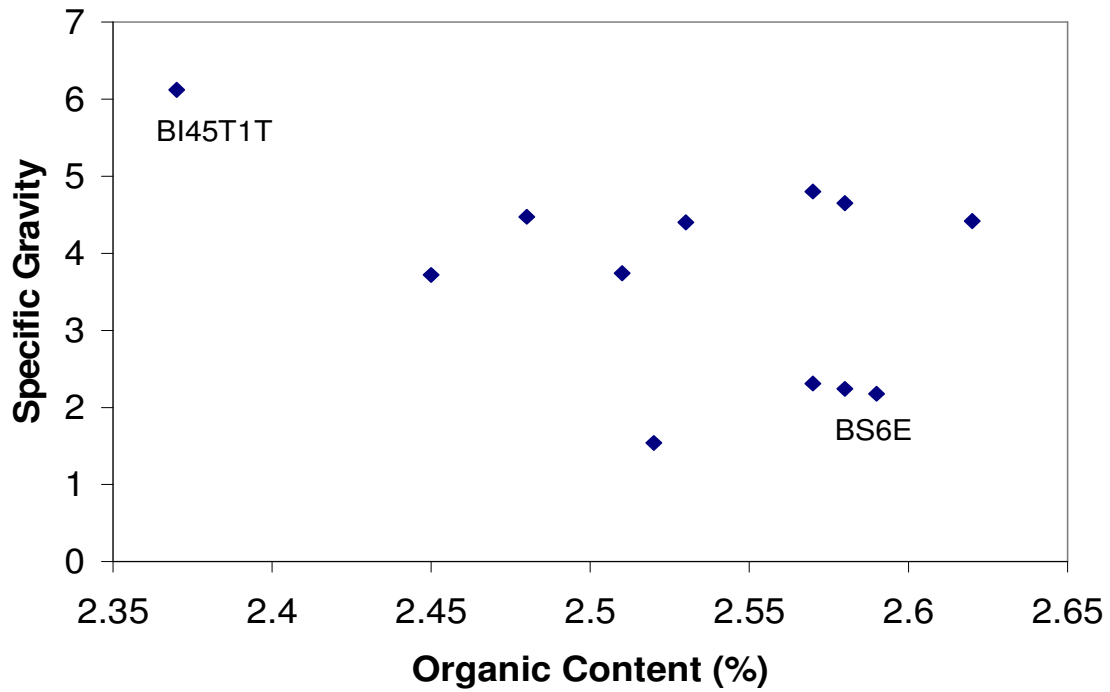
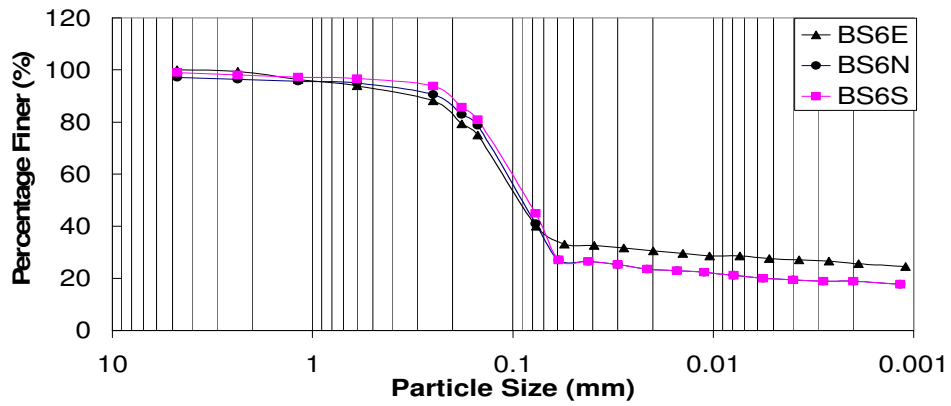


Figure 5.3 Comparison of Optimum Specific Gravity with Organic Content

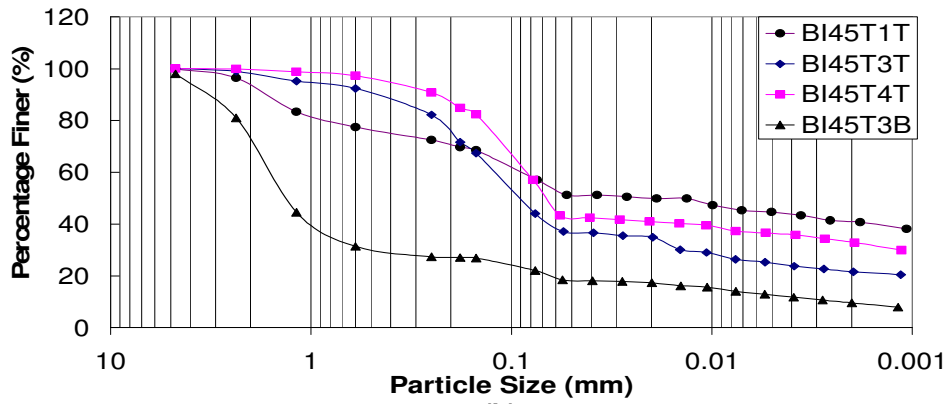
Based on the specific gravity results, it can be summarized that the control soils exhibit specific gravity values in the range of 2.37 to 2.62. These specific gravity values are low when compared to the inorganic soils which are usually in the range between 2.5 to 2.7. These low values are attributed to the amount of light weight organic content present in these control soils. Several researchers have reported the similar results in the literature (Terzaghi, 1996, Mitchell & Soga, 2005). Figure 5.3 compares the organic content and specific gravity results and can be seen that soil with higher organic content (BI45T1T) has lower specific gravity and vice versa. This observation confirms that the organic content dominates the behavior of organic rich soils.

### *5.2.3 Grain Size Distribution*

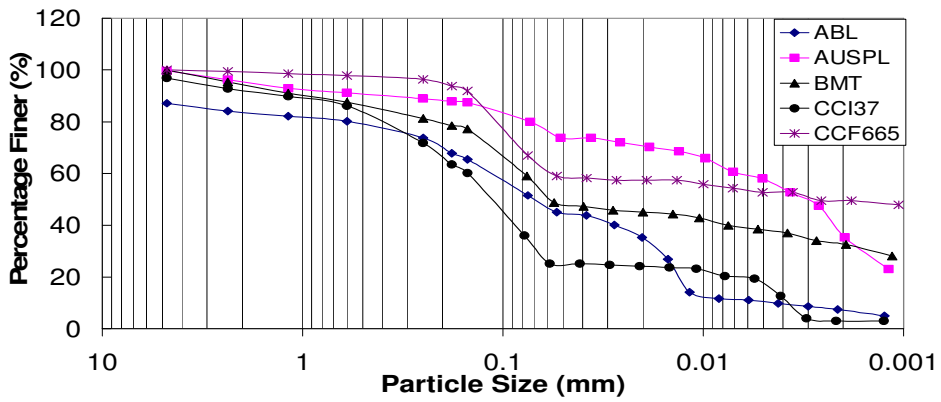
Sieve and hydrometer analyses were conducted on the control soils to determine the grain size distribution of all the test materials and these results are presented in Table 5.3. Figure 5.4 (a), (b) and (c) present the grain size distribution plots of the control soils.



(a)



(b)



(c)

Figure 5.4 Grain-size Distribution Curves of Control Soils

Table 5.3 Particle Size Details of Control Soils

Soil Notation	D <sub>10</sub> (mm)	D <sub>30</sub> (mm)	D <sub>50</sub> (mm)	D <sub>60</sub> (mm)
ABL	0.004000	0.01500	0.0740	0.0800
AUSPL	0.000950	0.00150	0.0020	0.0065
BMT	0.000930	0.00150	0.0720	0.0750
CCI37	0.003800	0.00380	0.0800	0.1500
CCF665	0.000090	0.00095	0.0025	0.0750
BI45T1T	0.000090	0.00095	0.0150	0.0750
BI45T3T	0.000088	0.00150	0.0700	0.0750
BI45T3B	0.003000	0.50000	1.5000	0.0750
BI45T4T	0.000085	0.00150	0.0800	0.0750
BS6E	0.000900	0.07800	0.0730	0.1000
BS6N	0.000930	0.08500	0.0690	0.0800
BS6S	0.000950	0.08500	0.0710	0.0750

Note: D<sub>10</sub> - Diameter of particle at which 10% is finer than that size

D<sub>30</sub> - Diameter of particle at which 30% is finer than that size

D<sub>50</sub> - Diameter of particle at which 50% is finer than that size

D<sub>60</sub> - Diameter of particle at which 60% is finer than that size

From the Figure 5.4 and Table 5.3, it can be observed that all the control soils except BI45T3B and CCI37 have fine fraction (% passing No. 200 sieve) greater than 50% and hence these soils are classified as silts and clays. On the other hand, CCI37 and BI45T3B are classified as Sands, as their fine fraction is less than 50%.

Additionally, Figure 5.2 and Table 5.1 illustrates that the soil samples contain the organic content greater than 1.5 percent and less than 6.2. According to Karlson and Hansbo (1981), soils having organics in the range of 2% to 6% are termed as low organic soils, and soils having organics in the range of 6% to 20% are termed as medium organic soils. Therefore, the present soil samples are classified as 'Organic silt, Organic clay and Organic sand' of medium organic content levels.

In addition, the soils can also be classified by using USCS classification. For example, If BI45T3T soil is classified by using USCS classification, BI45T3T soil passes greater than sixty percent from No 200 sieve, and therefore it is a fine grained soil. Further soil classification is done based on the casagrande's plasticity chart. Based on the casagrande's plasticity chart, soil sample falls below the A – line and have liquid limit less than 50. Therefore, soil is classified as ML or OL.

#### *5.2.4 Atterberg Limits*

Atterberg limits tests explain the plastic nature of soils. Atterberg tests were conducted to measure the consistency of the control and treated soils. The plasticity indices (PI) were calculated by first measuring the liquid limit (LL) and plastic limit (PL) values, and then calculating the difference between them.

Table 5.4 and Figure 5.5 show the plasticity indices of the control soils which varied from 5 to 38. The BI45T3T soil exhibited low PI value and BI45T1T soil exhibited high PI value. Based on the amount of organic content and plasticity indices of control soils, they are divided into four different groups as shown in Figure 5.5 and presented as follows.



Group I – Organic Content < 3% and PI < 15%

Group II – Organic Content > 3% and PI < 15%

Group III – Organic Content > 3% and 15% ≤ PI ≤ 25%

Group IV – Organic Content > 3% and PI > 25%

Table 5.4 Atterberg Limits of Control Soils

Sample Notation	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index(%)
ABL	36	17	19
AUSPL	46	23	23
BMT	42	19	23
CCI37	32	22	10
CCF665	51	21	30
BI45T1T	59	21	38
BI45T3T	27	22	5
BI45T3B	49	27	22
BI45T4T	35	23	12
BS6E	24	17	7
BS6N	28	16	12
BS6S	27	14	13

From the graph shown in Figure 5.5, it can be illustrated that plasticity index of the soil has increased with an increase in the organic content of the soil. According to Jenny (1941), soils with high plasticity index should have high organic content than soils with low plasticity index. This observation confirms that the present soils follow the same trend of results i.e. soil with high organic content has higher plasticity index. Table 5.5 summarizes the organic content and plasticity indices for all grouped control soils.

Table 5.5 Classification of Soils Based on Organic Content and Plasticity Index

Group I, OC < 3%, PI < 15	Sample Notation	PI	OC (%)
	BS6E	7	2.18
	BS6N	12	2.24
	BS6S	13	2.31
	CCI37	10	1.54
Group II, OC > 3%, PI < 15	Sample Notation	PI	OC (%)
	BI45T3T	5	3.72
	BI45T4T	12	4.47
Group III, OC > 3%, 15 ≤ PI ≤ 25	Sample Notation	PI	OC (%)
	ABL	19	4.40
	BI45T3B	22	4.42
	BMT	23	4.65
	AUSPL	23	4.80
Group 4, OC > 3%, PI > 25	Sample Notation	PI	OC (%)
	CCF665	30	3.74
	BI45T1T	38	6.12

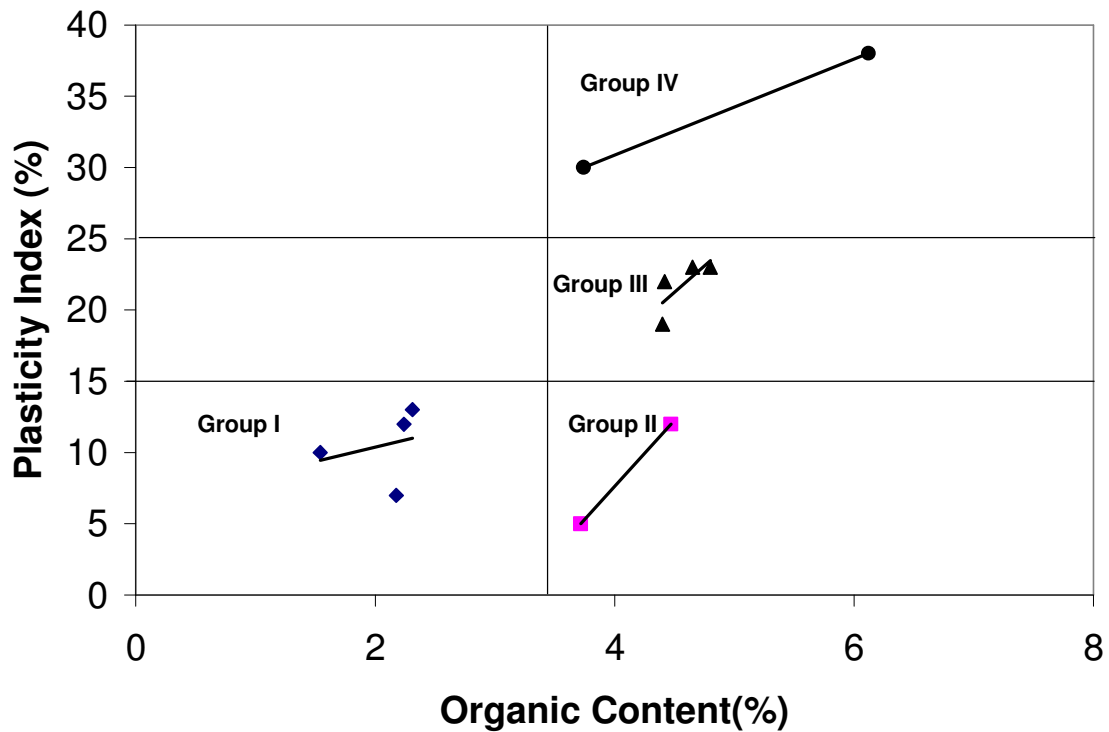


Figure 5.5 Classification of Soils Based on Organic Content (%) and Plasticity Index (%)

#### 5.2.5 Standard Proctor Compaction Test Results

Standard Proctor tests were conducted on the control soils to determine the optimum moisture content and dry unit weight relationships. Figure 5.6 presents the typical plot for moisture content - dry unit weight curves of the control soils for Interstate highway 45 at Huntsville in Bryan district. Table 5.6 presents optimum moisture content and dry unit weights of all the control soils and these values were used for soil specimen preparation for engineering tests.

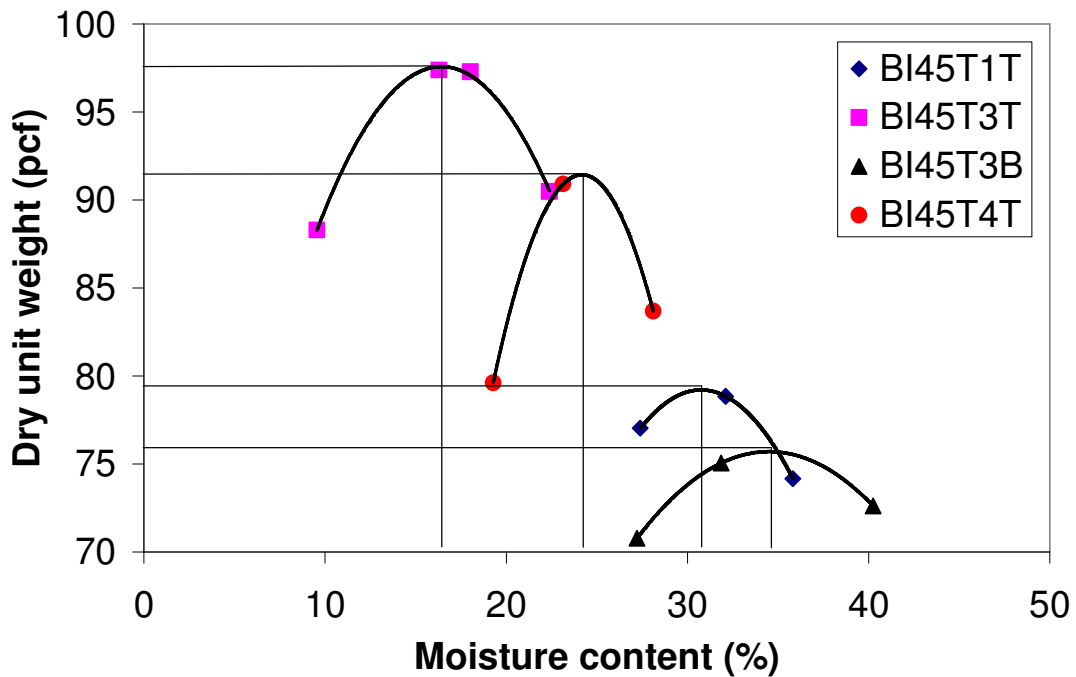


Figure 5.6 Moisture Content – Dry Unit Weight Curves of Control Soils Sampled from Interstate Highway 45 at Huntsville in Bryan District

Table 5.6 Optimum Moisture Content and Dry unit weight of Control Soils

Sample Notation	Optimum Moisture Content (%)	Dry Unit Weight (pcf)
ABL	17.7	99.8
AUSPL	20.0	93.2
BMT	17.7	99.1
CCI37	16.3	103.8
CCF665	24.5	90.5
BI45T1T	31.0	79.2
BI45T3T	16.5	97.8
BI45T3B	34.2	75.8
BI45T4T	24.0	91.5
BS6E	16.5	102.0
BS6N	13.5	106.8
BS6S	14.5	110.5

The influences of organic content (%) on optimum moisture content of compacted soils are presented in Figure 5.7. It can be observed from this Figure that an increase in the organic content resulted in an increase of optimum moisture content of the organic soils. This can be explained from the fact that the organic matter has high retention capacity to hold water (Terzaghi et al., 1996). Therefore, with an increase of organic content, there is an increase in optimum moisture content of the compacted soil.

The influence of organic content on the compaction dry density is show in Figure 5.8. From the data shown in Figure 5.8, it can be concluded that with increase in the organic content dry unit weight of the soil is decreased.

From Figures 5.7 and 5.8, it is to be noted that the behavior of soil samples arrow marked (CCI37 and BI45T3B) come under soil groups I and III respectively are different from their respective groups which may be due to their clay mineralogy. Further mineralogical and chemical studies are required to understand the constituents of these soils to interpret their behavior.

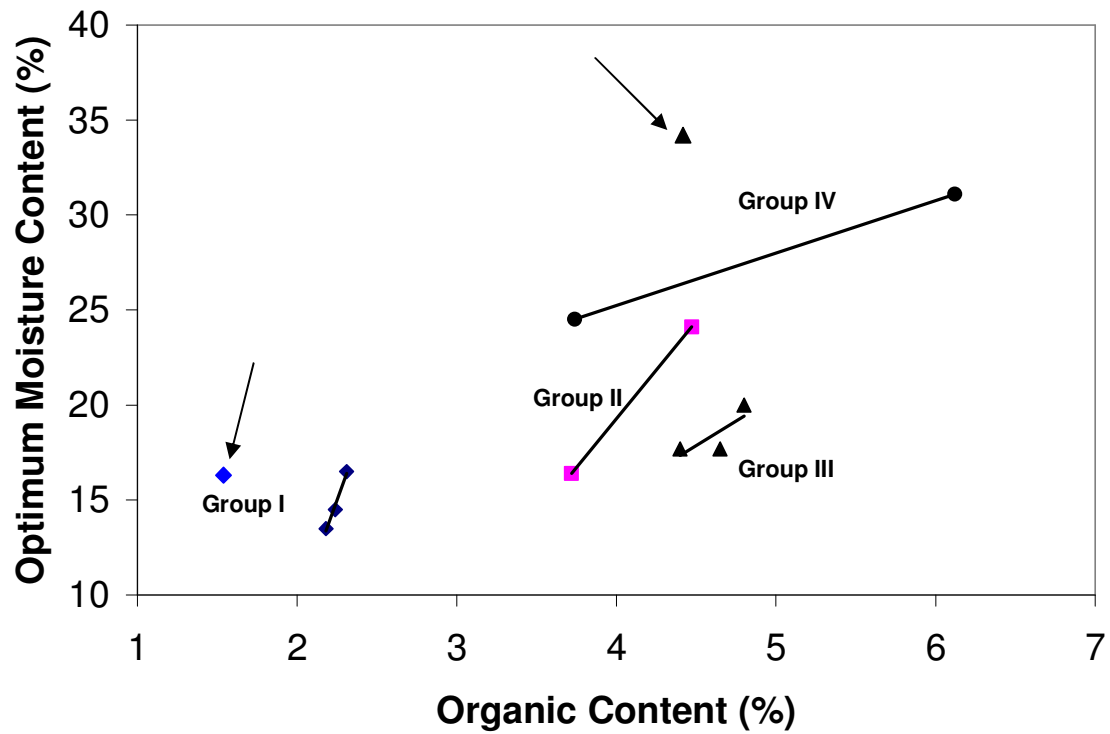


Figure 5.7 Influence of Organic Content (%) on Compaction Optimum Moisture Content

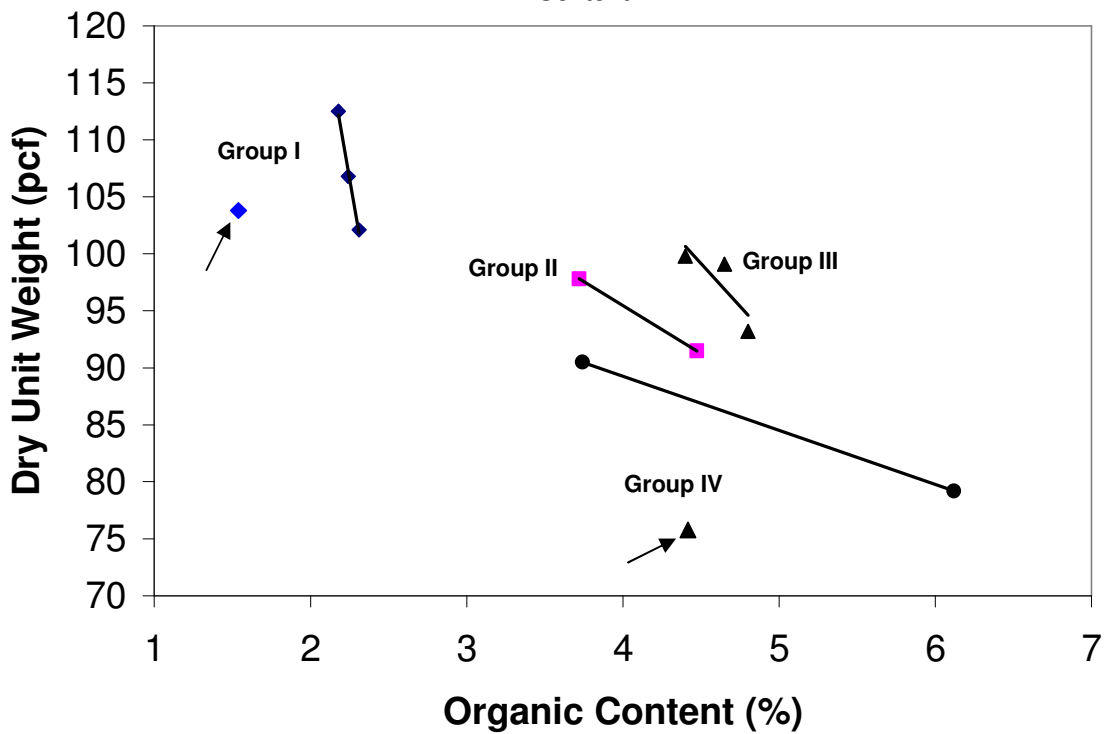


Figure 5.8 Influence of Organic Content (%) on Compaction Optimum Dry Unit Weight

### 5.2.5 Optimum Lime Content Determination

The optimum lime content is determined by the Eades and Grim procedure as explained in Chapter 4. This test is conducted to determine the optimum lime content (%) for a particular soil sample and to use this percentage to perform the lime stabilization. The lime content is determined by performing the pH test on the soil samples by adding 2%, 4%, 6%, 8%, and 10%. Graphs are plotted in between pH of the soil lime mixture and percentage of lime added to the soil. The lime content corresponding to pH concentration equal to the 12.3 is taken as optimum lime content (%). A typical graph of optimum lime content determination is shown in the Figure 5.9. Optimum lime contents determined from various present organic soils are tabulated in the Table 5.7.

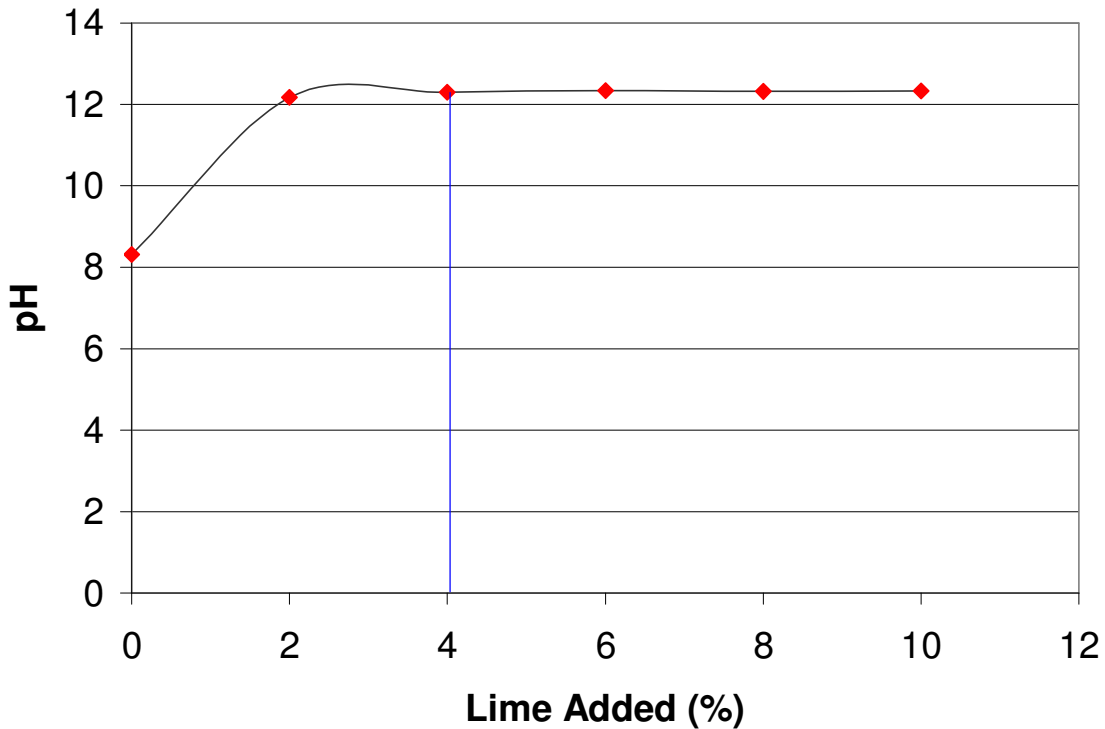


Figure 5.9 Lime Content Determination Graph of Abilene Soil

Table 5.7 Optimum Lime Content of the Soil Samples

Sample Notation	Optimum Lime Content (%)
ABL	4.0
AUSPL	8.0
BMT	6.0
CCI37	4.0
CCF665	8.0
BI45T1T	8.0
BI45T3T	6.0
BI45T3B	8.0
BI45T4T	6.0
BS6E	8.0
BS6N	6.0
BS6S	8.0

5.2.6 Optimum Cement Content Determination

Optimum cement content of the present organic soils is determined by Tex-120-E standard method. Various cement treated soils cured for seven days were used and UCS tests were conducted on the cured samples. Prior to conduct UCS tests, all soils are treated with a cement content of 6% and these treated soils were subjected to standard proctor compaction tests to determine the optimum moisture content of each soil for 6% cement content. The optimum moisture content and maximum dry unit weight results for the soils treated with a cement content of 6% are shown in Table 5.8. The molding water content necessary for other cement contents (other than 6%) was calculated using the following formula.

$\% \text{ molding water} = \% \text{ optimum moisture from M/D curve} + 0.25 (\% \text{ cement change from 6\%})$	$\longrightarrow$	Equation 5.1
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Table 5.8 Compaction Characteristics of 6% Cement Treated Soils

Name of the Site (Sample Notation)	Optimum Moisture Content (%)	Dry Unit Weight (pcf)
ABL	19.0	93.9
AUSPL	20.7	93.7
BMT	17.9	93.1
CCI37	16.1	98.5
CCF665	22.0	101.0
BI45T1T	29.1	69.5
BI45T3T	16.8	97.1
BI45T3B	31.0	76.0
BI45T4T	21.7	89.1
BS6E	14.2	102.7
BS6N	14.7	104.0
BS6S	16.2	95.7

After determining the optimum moisture content (%) and dry unit weight (pcf) of soil treated with 6% cement content, the molding moisture contents for other percentages of cement contents (2%, 4%, 8% and 10%) are determined. A typical calculation is shown below and the results are summarized in Table 5.9 for Abilene soil.

Let us consider a cement content of 4% for calculation purpose and the molding water content for this percent cement is calculated as per the equation 5.1:

$$\% \text{ molding water content} = 19.0 + 0.25*(4\% - 6\%) = 18.5\%$$

Table 5.9 Moisture-Density Characteristics

Soil Type	Cement Content, %	Optimum Moisture Content, %	Max. Dry Unit Weight (pcf)
Abilene	0	17.7	99.8
	2	18.0	N/A
	4	18.5	N/A
	6	19.0	93.9
	8	19.5	N/A
	10	20.0	N/A

It is noted here that the optimum moisture content for 2%, 4%, 8% and 10% shown in the above table are not true optimum moisture contents of treated soils. It is a molding water content used to mix the soil with cement to ease and reduce the experimental errors.

Tex-120-E does not recommend a target unconfined compressive strength. However, Tex-121-E (Soil Lime Testing) method mentions that target strength of 150 psi (1035kPa) should be achieved for a treated soil. Higher strengths are not recommended because they can lead to cracking. The optimum cement contents obtained from this procedure are summarized in the Table 5.10.

Table 5.10 Optimum Cement Content of the Soil Samples

Sample Notation	Optimum Cement Content (%)
ABL	2.5
AUSPL	3.5
BMT	5.0
CCI37	5.5
CCF665	6.5
BI45T1T	6.5
BI45T3T	5.0
BI45T3B	8.0
BI45T4T	5.5
BS6E	4.0
BS6N	3.0
BS6S	6.0

The Engineering properties of control soils such as UCS, linear shrinkage strain and 1-dimensional free well strain are determined according to the test procedures described in Chapter 4. These results are discussed and compared with the Engineering properties of soils treated with optimum lime and cement contents in the following appropriate sections.

### 5.3 Properties of Treated Soils

This section includes the basic properties of treated soils such as Atterberg limits, compaction characteristics and Engineering Properties. Engineering properties measured included unconfined compressive strength or UCS, linear shrinkage strains and 1-Dimensional free swell strains.

### 5.3.1 Basic Properties of Treated Soils

#### 5.3.1.1 Atterberg Limits

Atterberg limits of the soils were determined, after treating the soils with optimum cement and lime content. Optimum cement and lime content values are shown in Table 5.10 and Table 5.7. The Atterberg limits of soils treated with lime and cement are presented in the Table 5.11 and 5.12 respectively.

Table 5.11 Atterberg Limits of Lime Treated Soils

Sample Notation	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index(%)
ABL	35	23	12
AUSPL	43	31	21
BMT	42	31	11
CCI37	32	24	8
CCF665	46	30	16
BI45T1T	58	28	30
BI45T3T	31	28	3
BI45T3B	33	27	6
BI45T4T	42	34	8
BS6E	24	21	3
BS6N	30	23	7
BS6S	30	20	10

Figure 5.10 compares the plasticity indices of both lime and cement treated soil specimens with control soils. From the graph, it can be illustrated that, treated soils have low plasticity index when compared to the untreated soils. It is to be noted that lime treated soils have exhibited low PI values than cement treated soils.

Table 5.12 Atterberg Limits of Cement Treated Soils

Sample Notation	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index(%)
ABL	38	23	15
AUSPL	49	30	19
BMT	42	22	20
CCI37	35	28	7
CCF665	51	25	26
BI45T1T	68	34	34
BI45T3T	32	28	4
BI45T3B	49	30	19
BI45T4T	41	31	10
BS6E	27	22	5
BS6N	31	22	9
BS6S	28	17	11

To quantify the reduction in PI values a non-dimensional factor called Reduction Factor of plasticity index ( $R_f$ ) is introduced and defined as the ratio of the plasticity index of treated (Lime / Cement) soil to the plasticity index of the untreated soil. The reduction factors for both cement and lime treated soils were calculated and these results are summarized in Table 5.13 by separating them with their groups. From these results it can be seen that the reduction factors are more predominant in soil group I. Moderate increase in reduction factors are observed for soil groups II, III and IV. The influence of chemical treatment is impacted by the amount of organic matter in the control soil which was subjected to chemical treatment.

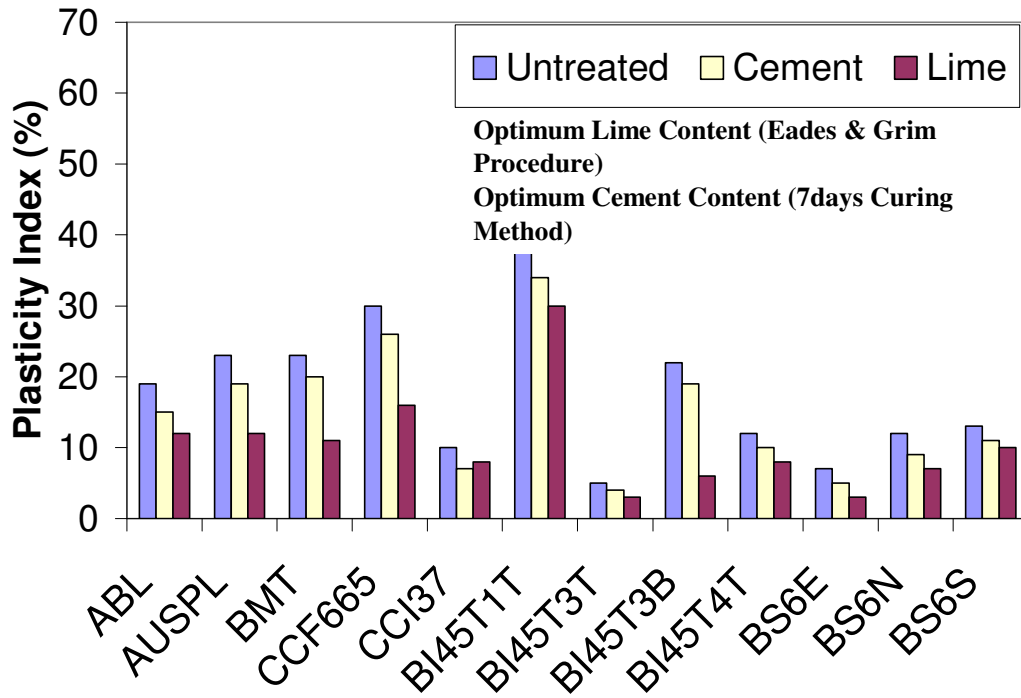


Figure 5.10 Comparisons of Plasticity Indices of Treated and Untreated Soils

Table 5.13 Reduction Factors of Soils Treated with Cement and Lime

Group I, OC < 3%, PI < 15	Sample Notation	$R_{f(Lime)}$	$R_{f(Cement)}$	OC (%)
	BS6E	0.42	0.71	2.18
	BS6N	0.58	0.75	2.24
	BS6S	0.76	0.84	2.31
	CCI37	0.80	0.70	1.54
Group II, OC > 3%, PI < 15	Sample Notation	$R_{f(Lime)}$	$R_{f(Cement)}$	OC (%)
	BI45T3T	0.60	0.80	3.72
	BI45T4T	0.66	0.83	4.47
Group III, OC > 3%, 15 < PI < 25	Sample Notation	$R_{f(Lime)}$	$R_{f(Cement)}$	OC (%)
	ABL	0.63	0.78	4.40
	BI45T3B	0.27	0.86	4.42
	BNT	0.47	0.86	4.65
	AUSPL	0.52	0.82	4.80
Group IV, OC > 3%, PI > 25	Name of the Site	$R_{f(Lime)}$	$R_{f(Cement)}$	OC (%)
	CCF665	0.53	0.86	3.74
	BI45T1T	0.78	0.89	6.12

From the graphs shown in the Figure 5.11, Reduction factor ( $R_f$ ) of the soil increases with an increase in the Organic Content (%). The graph also illustrates that, Reduction factor ( $R_f$ ) of the soil treated with lime is less compared to the soil treated with cement. Plasticity index of the organic soil treated with lime is more efficient than cement. Moreover, as the organic content increases, it becomes less effective in reducing the Plasticity Index of the soil for both lime and cement treated soils. This explains the importance of organics on the chemical treatment.

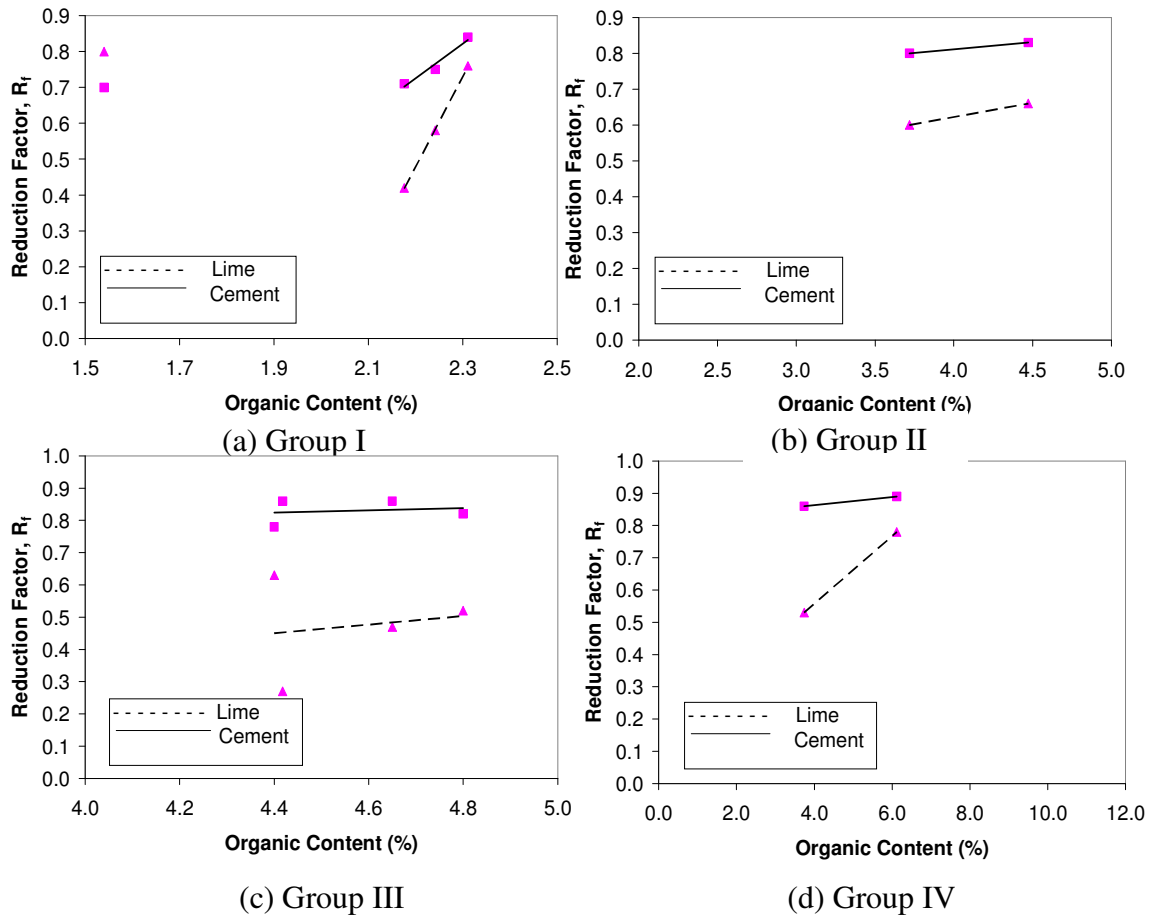


Figure 5.11 (a), (b), (c), (d) Comparison of Reduction factors  $R_f$  of Lime and Cement with Organic Content (%)

### 5.3.1.2 Compaction Characteristics

Compaction characteristics of treated soil are obtained to perform engineering properties. The optimum lime and cement contents determined earlier (Table 5.7 and Table 5.10) are used to prepare the compaction specimens. The compaction characteristics of the treated soil are determined as per the procedure explained in Chapter 4. The Optimum moisture content (%) and Dry unit weights (pcf) of optimum lime and cement treated soils are presented in the Tables 5.14 and 5.15 respectively.



Table 5.14 Optimum Moisture Content and Dry unit weight of Lime Treated Soils

Sample Notation	Optimum Moisture Content (%)	Dry Unit Weight (pcf)
ABL	18.4 (17.7)	93.6 (99.8)
AUSPL	24.7 (20.0)	87.7 (93.2)
BMT	20.6 (17.7)	93.1 (99.1)
CCI37	16.5 (16.3)	99.5 (103.8)
CCF665	25.9 (24.5)	84.4 (90.5)
BI45T1T	33.6 (31.0)	75.4 (79.2)
BI45T3T	19.9 (16.5)	92.1 (97.8)
BI45T3B	36.0 (34.2)	78.2 (75.8)
BI45T4T	25.9 (24.0)	85.0 (91.5)
BS6E	18.2 (16.5)	95.0 (102.0)
BS6N	15.1 (13.5)	101.0 (106.8)
BS6S	18.7 (14.5)	89.5 (110.5)

Table 5.15 Optimum Moisture Content and Dry unit weight of Cement Treated Soils

Sample Notation	Optimum Moisture Content (%)	Dry Unit Weight (pcf)
ABL	18.6 (17.7)	95.7 (99.8)
AUSPL	20.4 (20.0)	94.3 (93.2)
BMT	17.7 (17.7)	98.9 (99.1)
CCI37	15.9 (16.3)	101.8 (103.8)
CCF665	22.5 (24.5)	90.6 (90.5)
BI45T1T	29.0 (34.2)	69.7 (79.2)
BI45T3T	17.2 (24.0)	96.8 (97.8)
BI45T3B	29.4 (34.2)	76.6 (75.8)
BI45T4T	21.1 (24.0)	90.0 (91.5)
BS6E	14.5 (16.5)	103.3 (102.0)
BS6N	14.6 (13.5)	104.2 (106.8)
BS6S	16.2 (14.5)	95.7 (110.5)

### *5.3.2 Engineering Properties*

This section discusses all the engineering tests conducted in this research. These tests include unconfined compressive strength test, 1- Dimensional free swell test, and linear shrinkage test. Unconfined compressive strength test and linear shrinkage test were performed on both control and treated soils, where as 1 – Dimensional free swell test was performed only on control soils. Unconfined compressive strength and vertical free swell tests were performed at optimum moisture content and maximum dry unit weight state whereas the linear shrinkage bar test was performed at liquid limit state.

#### 5.3.2.1 Unconfined Compressive Strength (UCS) Test

Unconfined compressive strength tests were conducted on samples treated with optimum lime and cement content at different curing intervals of 7, 28 and 56 days and same tests on control soils were conducted on samples cured after zero days.

##### 5.3.2.1.1 Unconfined Compressive Strength (UCS) Test for Control Soils

UCS tests performed on all control soils at zero days curing period are reported in the Figure 5.12. From this graph, it can be seen that there is no specific trend observed to understand the results. Hence, these soils are divided and mentioned as per the section 5.2.4. These values are again shown in the Table 5.16 to reduce the confusion. A graph is also plotted in between the Organic content and compared with the values resembled in the literature. This graph is shown in the Figure 5.13.

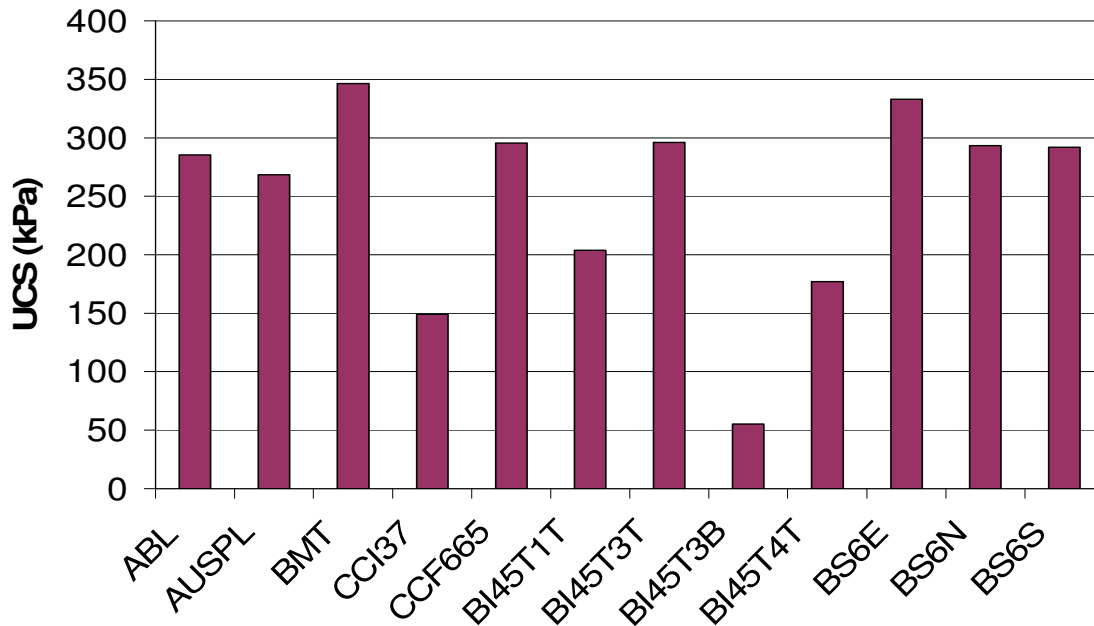


Figure 5.12 Unconfined Compressive Strength of Control Soils at Zero days

Table 5.16 Classification of Organic Soils Based on Constant Plasticity Index and Different Organic Content

Group I	Sample Notation	UCS (kPa)	Organic Content (%)
	CCI37	149	1.54
Group II	Sample Notation	UCS (kPa)	Organic Content (%)
	BS6E	333	2.18
	BS6N	294	2.24
	BS6S	292	2.31
Group III	Sample Notation	UCS (kPa)	Organic Content (%)
	BI45T3T	296	3.72
	BI45T4T	177	4.47
Group IV	Sample Notation	UCS (kPa)	Organic Content (%)
	ABL	286	4.40
	BI45T3B	56	4.80
	BMT	347	4.65
	AUSPL	269	4.80
Group V	Sample Notation	UCS (kPa)	Organic Content (%)
	CCF665	296	3.74
	BI45T1T	204	6.10

The UCS results are now re-plotted based on their grouping and presented in Figure 5.13. From this Figure, it can be mentioned that the organic content has moderate influence on the UCS of the present soils. This is expected as strength of the soil is dependent of soil type and clay mineralogy.

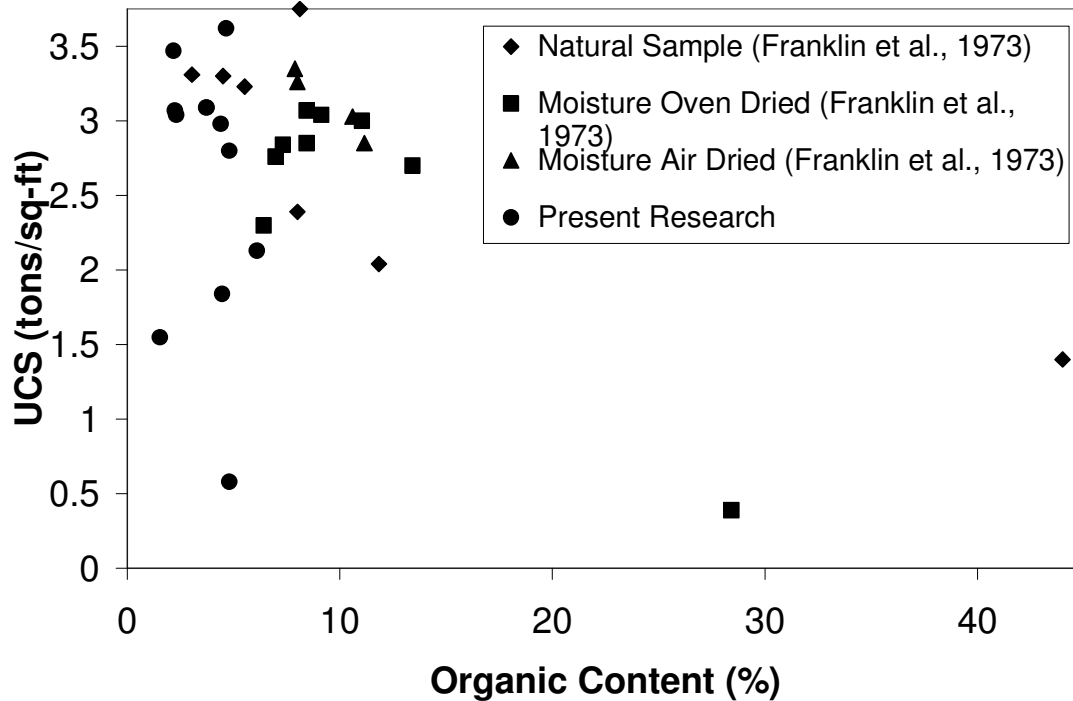


Figure 5.13 Variation of Unconfined Compressive Strength with Organic Content Based on Grouping

From the Figure 5.13, it is observed that samples used by Franklin et al., (1973) having low organic content had a strength ranging from 2 to 3.75 tons/sq-ft, where as present research samples having low organic content has a strength ranging from 0.5 to 3.65 tons/sq-ft.

#### 5.3.2.1.2 Unconfined Compressive Strength (UCS) Test for Treated Soils

As mentioned earlier, UCS tests on all soil samples treated with optimum lime and cement content were carried out at different curing periods. In addition, the pH concentration and the organic content of all the above UCS tested soil samples were also determined after

each curing period. The strength of soil samples treated with lime and cement at different curing periods is presented in Figures 5.14 and 5.15 respectively.

From the Figure 5.14, strength of the lime treated soil is reduced with increase in the organic content in each individual group. A typical soil is taken from each group and plotted for strength and there is a moderate reduction in strength, with increase in organic content.

From the Figure 5.14, it can be noticed that a slight reduction in strength of soil after 56 days for BI45T3T and BI45T4T. This reduction in strength may be due to the formation of Insoluble calcium humic acid and the moderate reduction of pH

From the Figure 5.15, strength of the cement treated soil is reduced with increase in the organic content in each individual group. A typical soil is taken from each group and plotted for strength and there is a reduction in strength, with increase in organic content. It can also be noticed that a slight reduction in strength of soil after 56 days for all the soil samples. This reduction in strength may be due to the formation of Insoluble calcium humic acid and the moderate reduction of pH.

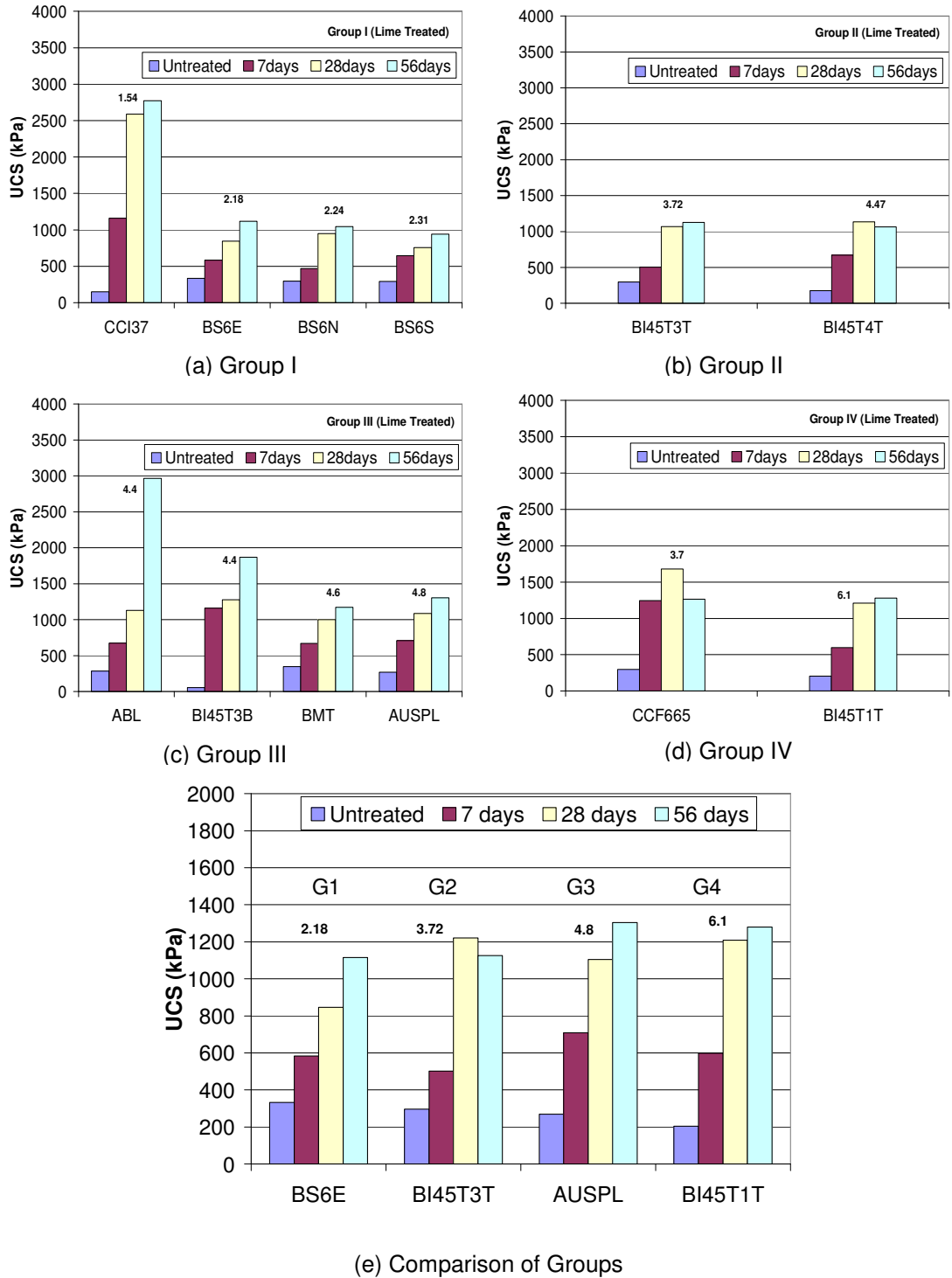


Figure 5.14 (a), (b), (c), (d), (e), UCS of Lime Treated Samples at Intervals of 7, 28 and 56days

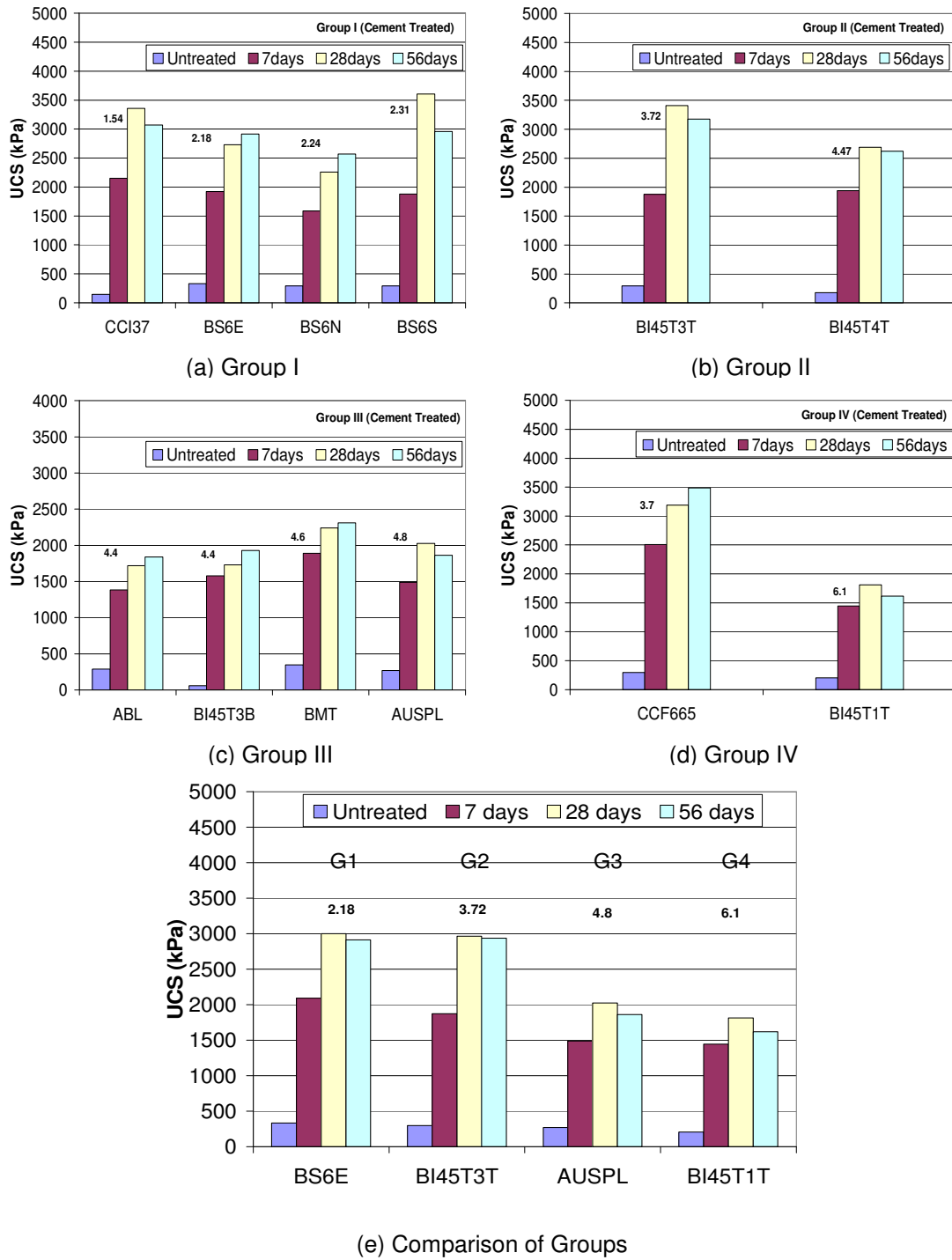


Figure 5.15 (a), (b), (c), (d), (e) UCS of Cement Treated Samples at Intervals of 7, 28 and 56 days

Variation of pH of the lime treated soils with time (days) is shown in Figure 5.16. Formations of Insoluble humic acid at these locations are explained in the following paragraphs, which may be lowering the pH values to a small degree.

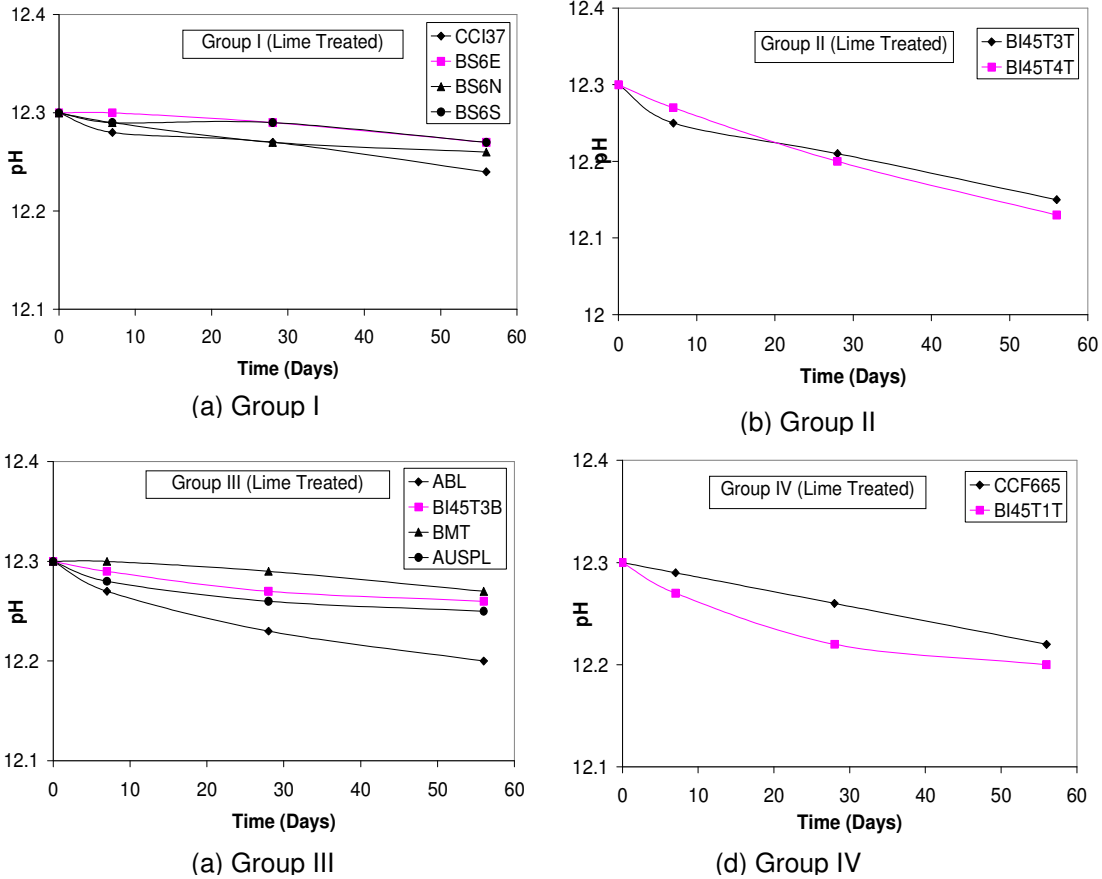


Figure 5.16 (a), (b), (c), (d) Variation of pH of Lime Treated Samples at Intervals of 7, 28 and 56 days

To explain the humic acid formation, a brief history of organic soils formation in Texas is needed. Soil samples obtained from Abilene, Austin, Bryan, Beaumont and Corpus Christi are shown on the MAP, which is presented in the Figure 5.17. From the Figure 5.17, it can also be noted that the soil samples are obtained from the locations having dominant soil orders as Alfisols, Ultisols, Vertisols, and Mollisols.



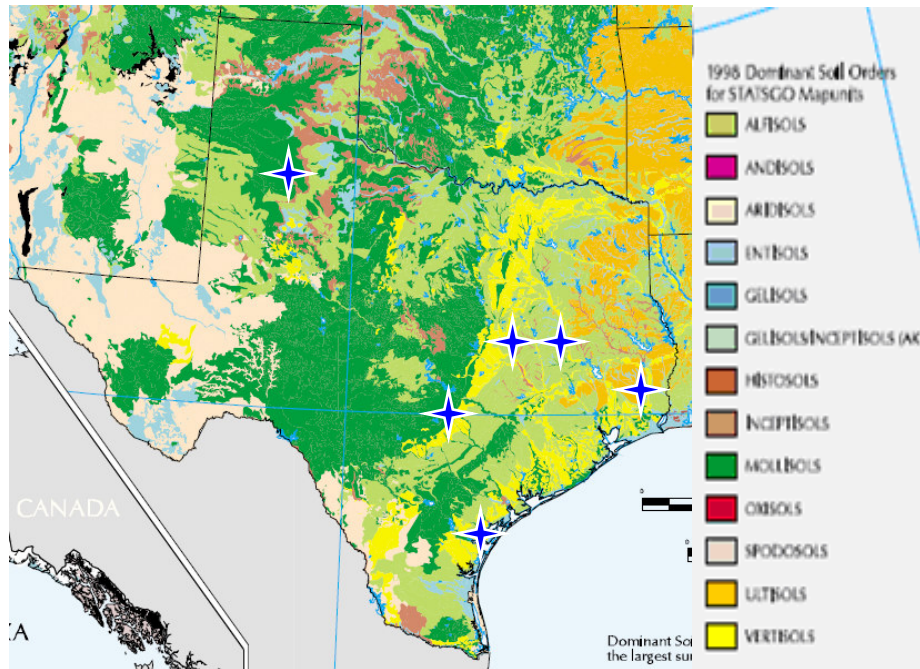
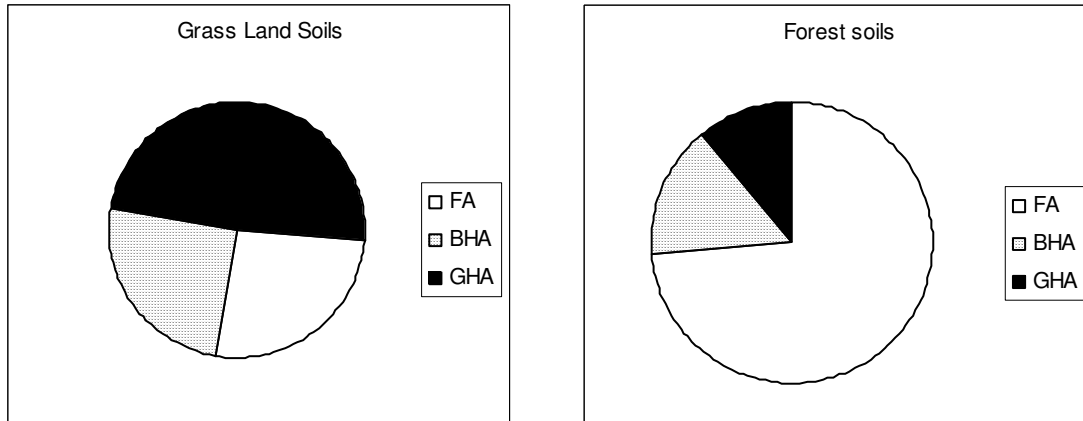


Figure 5.17 Texas Map Showing the Dominant Soil Orders for STATSGO Mapunits (Soil Taxonomy, 2006)

According to Tindall and Kunkel (1999), alfisols, spodosols, and ultisols are generally high in fulvic acids classified as forest soils, whereas mollisols are high in humic acids are classified as grassland soils. However vertisol is neither a grassland soil nor forest soil. Moreover, Stevenson, (1982) say forest soils consist maximum of fulvic acid, whereas grassland soils consist of humic acid in which the major portion is gray humic acid as shown in the Pie chart in Figure 5.18.

Bonomaluwa and Palutnicowa (1987) stated that 'the black humic acid in organic matter has a strong chemical affinity to calcium and hence where calcium is present in solution, the humic acid may react with the calcium and form insoluble calcium humic acid' (Chen and Wang, 2005).



FA = Fulvic acid; BHA = Brown humic acid; GHA = Gray humic acid

Figure 5.18 Pie chart showing the relationship of Humic acid and Fulvic acid (Stevenson, 1982)

Therefore, the soils obtained from the above mentioned locations are forest and grassland soils, as per the map obtained from Soil taxonomy (2006). Hence, there is a chance of formation of humic acid from the soil sample selected areas. From Figure 5.16 and Figure 5.17, it can be noted that pH of the soil is decreased. Figure 5.20 and Figure 5.21 show that the organic content of the soil was decreased when it was treated with lime or cement. From these observations, it can be concluded that, reactions are taking place between organic content and lime/cement. If pH of the soil is decreased, then there is a chance of formation of acids. The acidic reactions may be in between humic acid and calcium and form insoluble calcium to humic acid. This might have contributed to low strength at high curing periods.

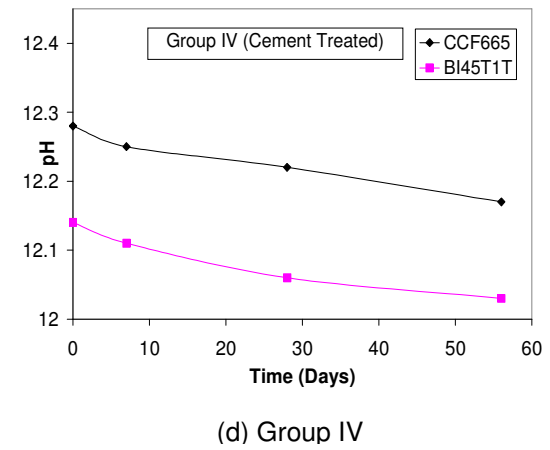
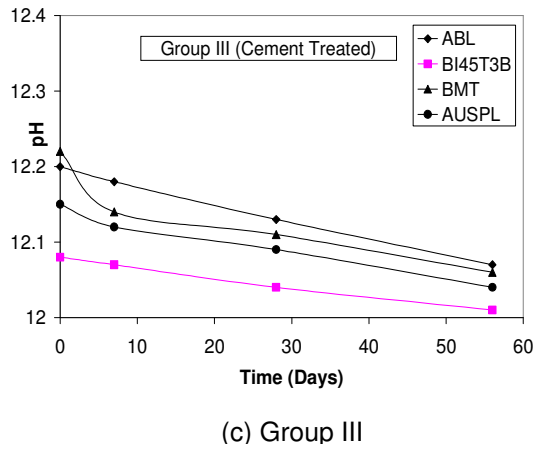
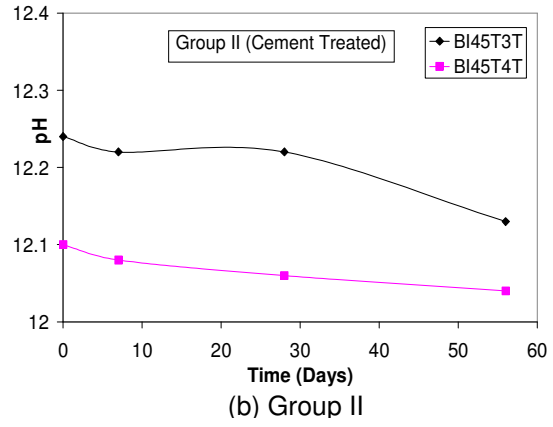
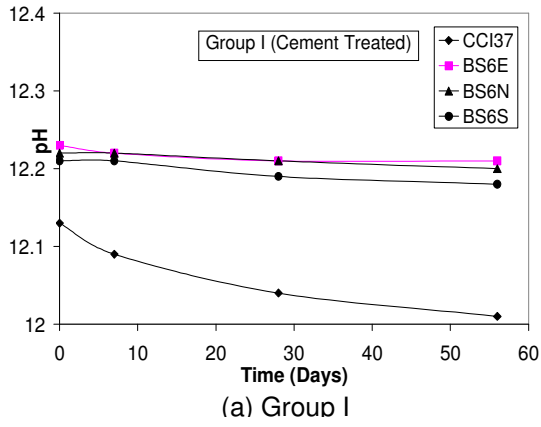


Figure 5.19 (a), (b), (c), (d), Variation of pH of Cement Treated Samples at Intervals of 7, 28 and 56days

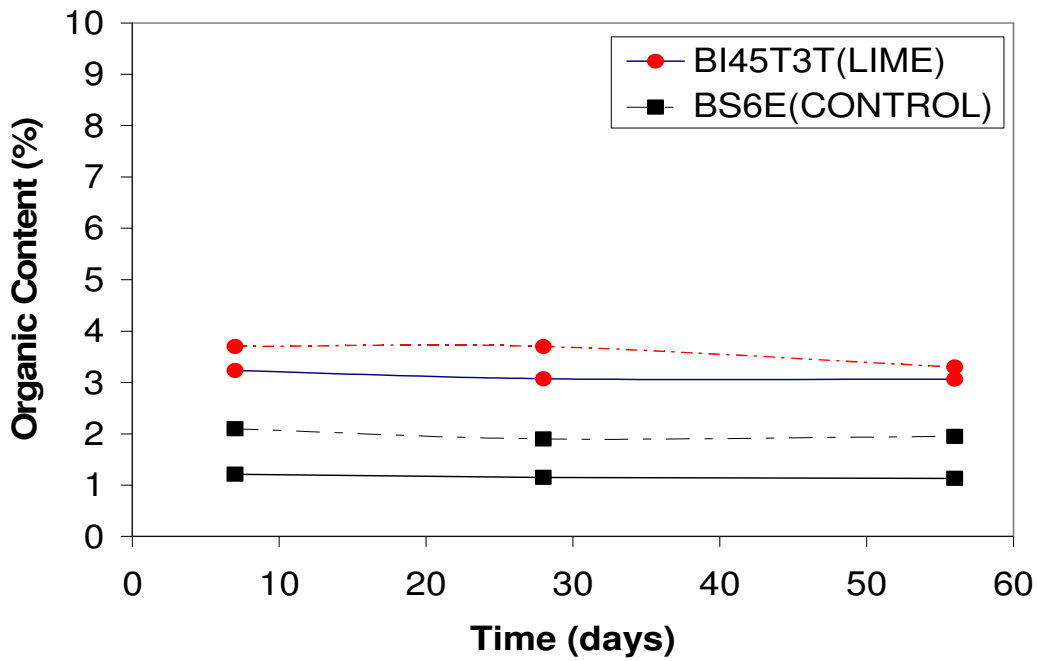


Figure 5.20 Comparison of Lime Treated Samples Organic Content with Control Soils Organic Content at Intervals of 7, 28 and 56days

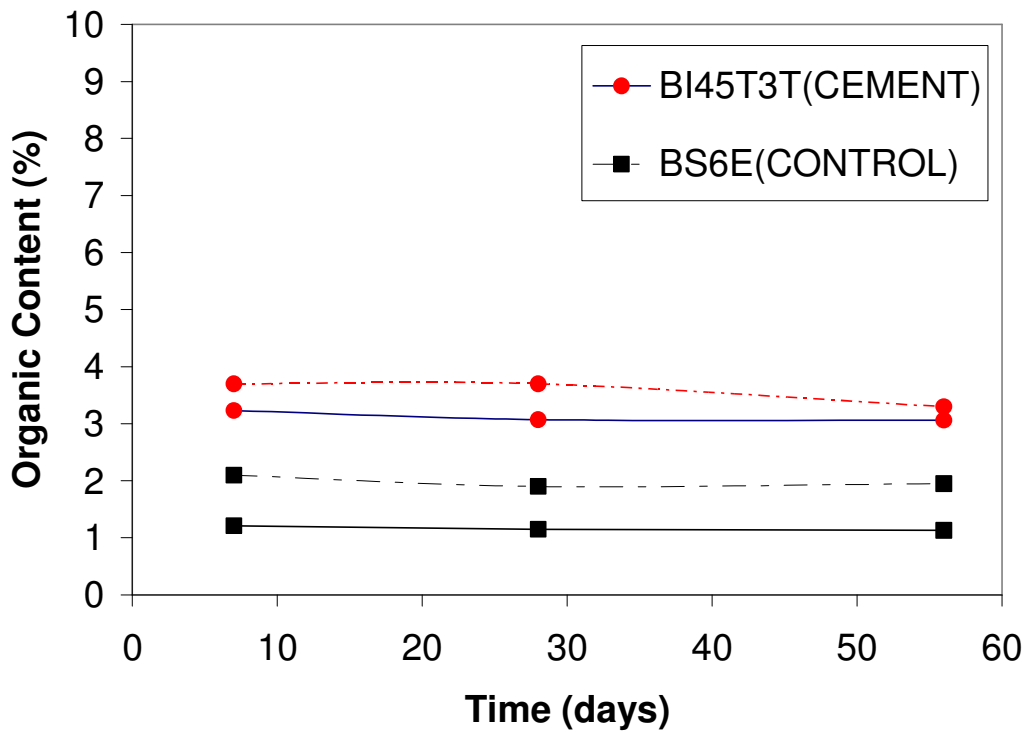


Figure 5.21 Comparison of Cement Treated Samples Organic Content with Control Soils Organic Content at Intervals of 7, 28 and 56days

Additionally, as per the discussion made in the literature review and section on chemical treatment of organic soils, the increase in pH in the treated soil system promotes the dissolution of silica in the clay particles which then reacts with the calcium oxides to form calcium silica hydrate (C-S-H) cementing compounds. However, in these organic soils pH is decreasing slightly and hence it is assumed that calcium is forming compounds with humic acid. This may have caused a reduction of strength in the majority of soils studied in this research. However, the strengths of BI45T3B and BS6N after 56 days are not reduced; and this phenomenon could be attributed to the absence of humic acid.

Chemical studies are not planned as a part of this research and hence exact causes for variations in strengths are difficult to point out.

#### 5.3.2.1.3 Strength Factors

In order to explain the strength increment for treated soils, two strength factors are introduced and explained below:

- i) LISF – Lime Induced Strength Factor

$$\text{LISF}_n = \frac{\text{Strength of lime treated specimen at n days}}{\text{Strength of untreated specimen at n days}}$$

- ii) CISF – Cement Induced Strength Factor

$$\text{CISF}_n = \frac{\text{Strength of cement treated specimen at n days}}{\text{Strength of untreated specimen at n days}}$$

Where n is the number of days.

The LISF and CISF values are determined for 7, 28 and 56 days, and graphs are plotted between the strength factors and organic content. The graphs are shown in the Figure 5.22 with three different groups as classified in the section 5.3.2.1.1.

From the graphs shown in the Figure 5.22, the following conclusions are drawn:

- i) Both lime induced strength factor and cement induced strength factor decreased with an increase in the organic content

ii) Lime induced strength factors are low when compared to the cement induced strength factors.

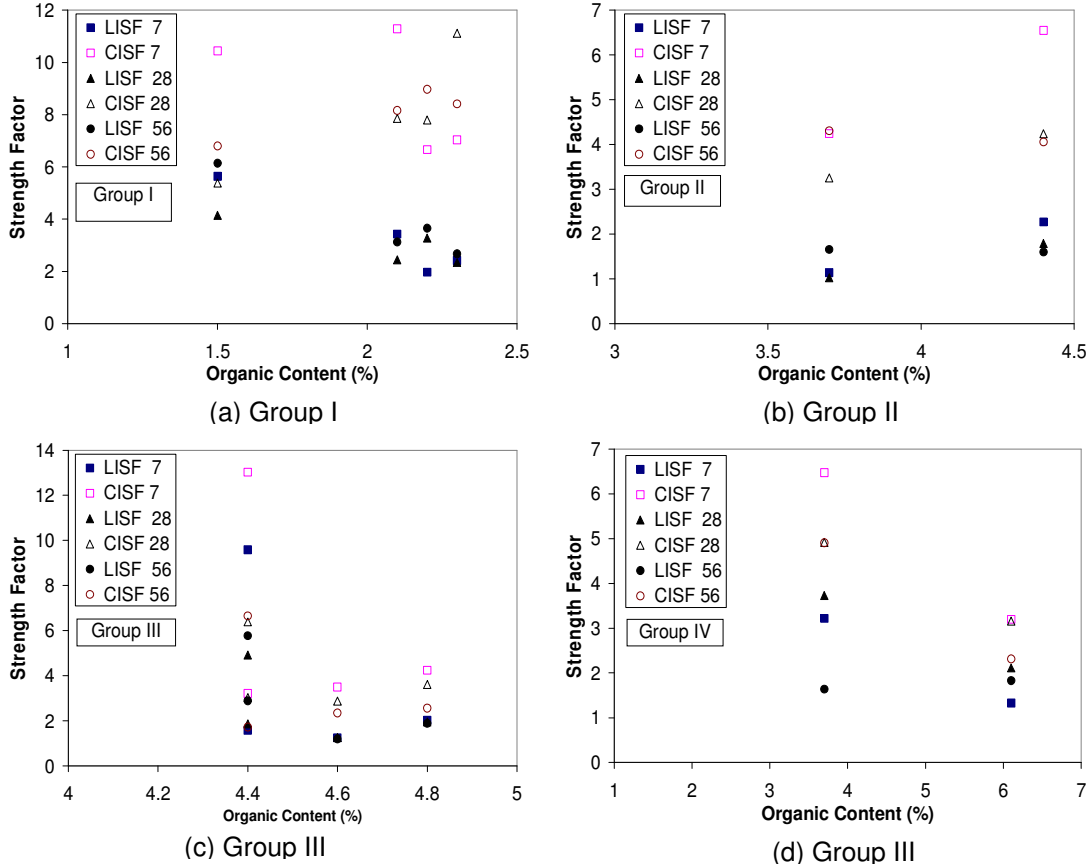


Figure 5.22 (a), (b), (c), (d), Variation of Strength Factors of Treated Samples at Intervals of 7, 28 and 56days with Organic Content

### 5.3.2.2 1 – Dimensional Free Swell Test

The one-dimensional free swell test was used to measure the amount of free swell strain in the vertical direction. The test was continued until there was no significant change in displacements for more than 24 hours.

Figure 5.23 presents swell strains of the control soil at different periods. Table 5.17 shows the free vertical swell strains in percent of the control soils.

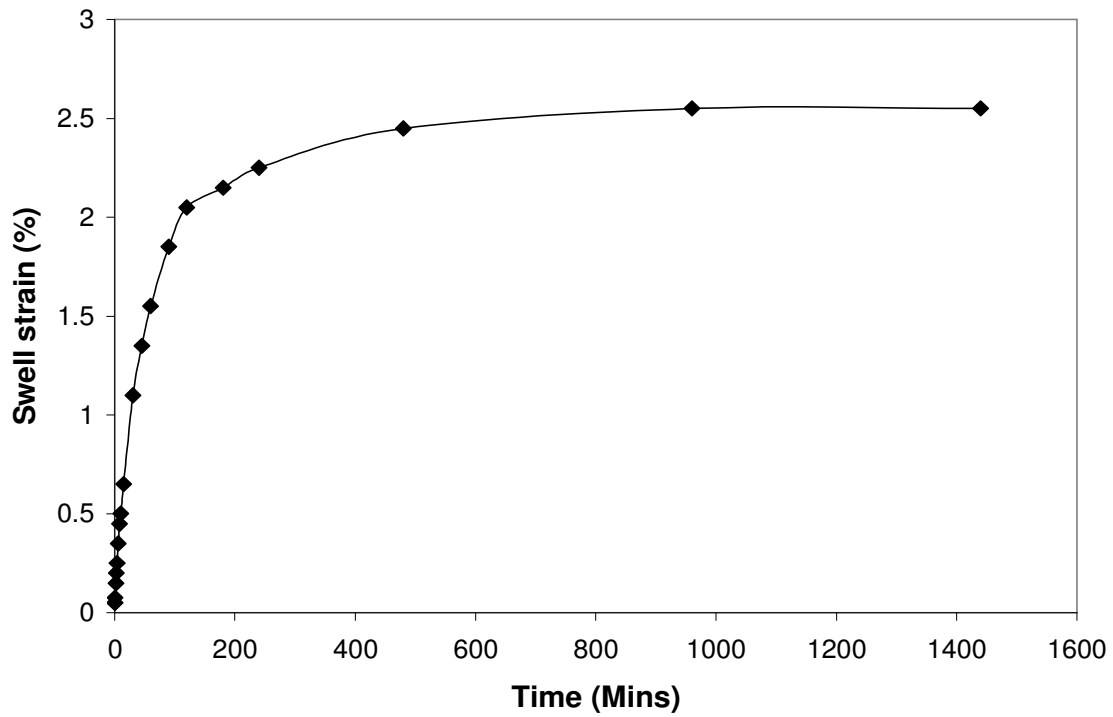


Figure 5.23 Free Vertical Swell Strain of Trench 3 Bottom Control Soil

Table 5.17 Free Vertical Swell Strain of Control Soil Samples

Sample Notation	Free Vertical Swell Strain (%)
ABL	8.4
AUSPL	12.1
BMT	11.9
CCI37	7.9
CCF665	15.8
BI45T1T	9.5
BI45T3T	6.0
BI45T3B	2.5
BI45T4T	14.4
BS6E	4.0
BS6N	5.7
BS6S	7.9

After determining the free vertical swell strains, graphs are plotted between free vertical swell strain and organic content at constant plasticity index as per the classification groups mentioned in the section 5.3.2.1.1. Graphs are shown in the Figure 5.24.

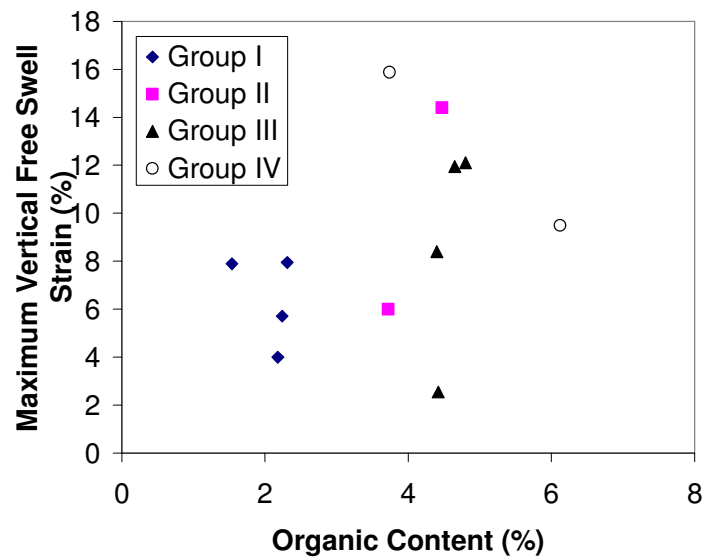


Figure 5.24 Variation of Vertical Free Swell Strain with Organic Content

From Table 5.17 and Figure 5.24, the following observations are made:

- The maximum amount of swelling was recorded for CCF665 and this value was 15.8% after 1 day of soaking.
- The vertical free swell strain values of all soils varied from 2.5% to 15.8%.
- The vertical free swell strain increased with an increase in the organic content, due to more water retention capacity of organics.



### 5.3.2.3 Linear Shrinkage Test

Linear shrinkage test was conducted on the control soil and on treated soils at liquid limit of the soil. Table 5.18 presents the linear shrinkage strain values for the control and treated soils at liquid limit. Figure 5.25 presents the linear shrinkage strain values for the control and treated soils at liquid limit. Figure 5.26 presents the variation of linear shrinkage strain with organic content.

Table 5.18 Linear Shrinkage Strains of Control and Treated Soils

Name of the Site (Sample Notation)	Linear Shrinkage Strain (%)		
	Control	Lime	Cement
ABL	7.8	3.9	2.2
AUSPL	14.9	6.3	2.9
BMT	12.0	6.2	3.6
CCI37	9.5	5.6	3.4
CCF665	16.5	2.4	1.1
BI45T1T	11.7	9.4	2.7
BI45T3T	6.3	3.7	1.3
BI45T3B	4.8	4.1	2.5
BI45T4T	9.9	4.2	2.8
BS6E	5.2	1.7	0.3
BS6N	5.1	3.1	2.4
BS6S	5.0	3.1	2.4

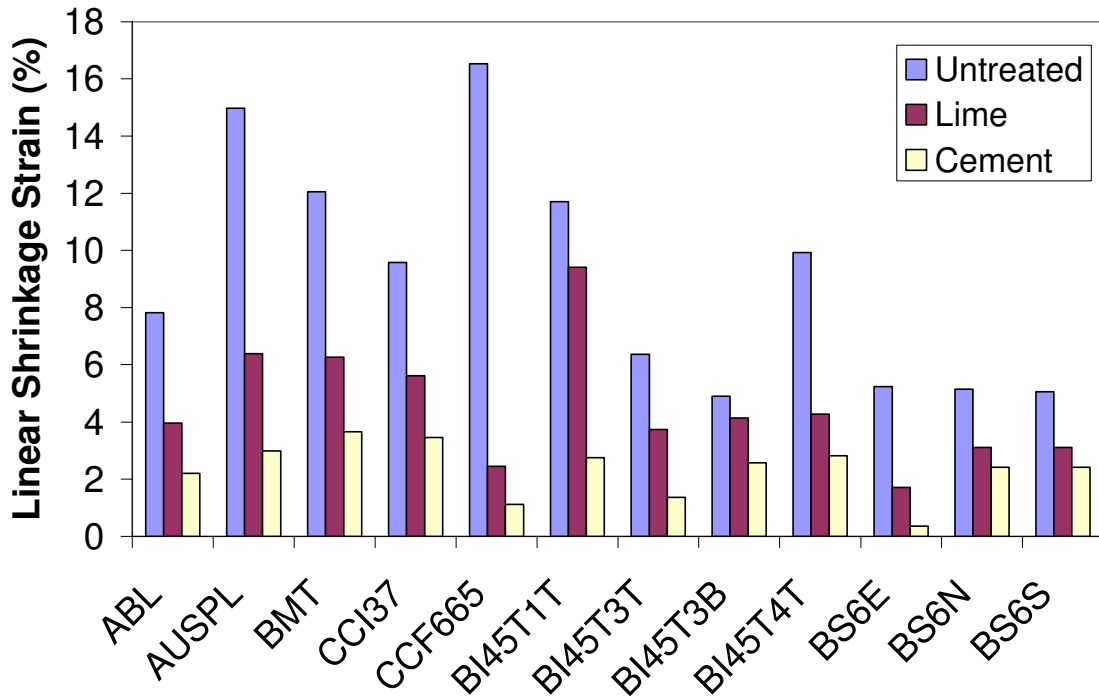


Figure 5.25 Comparison of Linear Shrinkage Strain for Control and Treated Soils

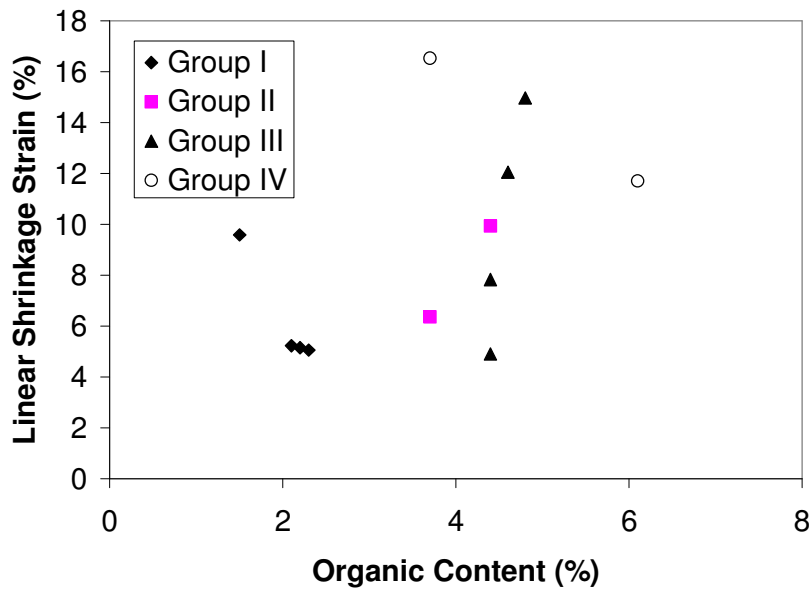


Figure 5.26 Variation of Linear Shrinkage Strain with Organic Content

From Table 5.18, Figure 5.25 and Figure 5.26, the following observations are made:

- Linear shrinkage strain values of all control and treated soils varied between 0.3% and 16.5%.
- Linear shrinkage values are increased with an increase in the organic content.
- In treated soils, cement treated soils exhibited low linear shrinkage strains, when compared to lime treated soils.

#### 5.4 Summary

Basic properties of the soils such as specific gravity, Atterberg limits and compaction characteristics are changed with respect to the proportion of organic content. Engineering properties of soils such as unconfined compressive strength, vertical free swell strain and linear shrinkage strain are also affected due to the presence of organic content. In order to improve the properties of these soils, they are treated with lime and cement. This improvement factor is also affected due to the presence of organic content. Particularly, unconfined compressive strength of the soil is decreased after 56 days of treatment. This may be due to the presence of organics and humic acid in the soil. However, a detailed analysis with increased curing time and preparation of artificial samples with known organic content and humic acid may give better insight into the behavior and strength gain properties of soils due to stabilization.

CHAPTER 6  
SUMMARY AND CONCLUSIONS

6.1 Summary and Conclusions

The main objective of present research work was to investigate the effects of organic content present in the soil on various basic and engineering properties, when stabilized with lime and cement. A survey has been first performed with various TxDOT districts to learn their experiences with the organics in soils and problems associated with the stabilized organic soils.

Soil samples were later collected from 12 locations from six sites and these soils are considered for the present research. An experimental program was designed to perform various basic and engineering tests for both control and treated soils. Control soil is treated with optimum lime and cement content. The optimum lime and cement contents were obtained by using Eades and Grim procedure and a 7-day curing method respectively. Experimental test results were analyzed to assess the effects of organic content on basic and engineering properties of control and treated soils.

The following major conclusions can be made from the analysis of laboratory test results:

1. The organic content of all the control soils varied from 1.5% to 6.1%. The maximum and minimum percentage of 6.1% and 1.5% was measured in BI45T1T and CCI37 soil samples respectively. Therefore, soils are classified as organic soils.
2. The specific gravity of soils varied from 2.37 to 2.62. These specific gravity values are low compared when compared to the inorganic soils. These low values are attributed to the amount of light weight organic content present in the soils.

3. Plasticity Index of the control soils varied from 5 to 38. The plasticity Index of the soil is increased with increase in the organic content. Reduction of plasticity index is low for high organic soils and high for low organic soils, when treated with lime or cement.
4. Optimum moisture content of soils increases with increase in the organic content. This can be explained from the fact that the organic matter has high water retention capacity. Dry unit weight of the soil decreases with increase in organic content. This decrease is due to the fact that the increase in organic material decreases the soil unit weight.
5. Organic content has moderate influence on the UCS of the present control soils. This is expected as strength of the soil is dependent of soil type and clay mineralogy. Unconfined compressive strength of the soil is reduced after 56 days of curing, when it is treated with lime and cement. This could be due to the following reasons:
  - Moderate reduction of pH in the treated soils as curing period progress.
  - Formation of inorganic calcium humic acid when calcium present in the stabilizer is reacted with humic acid present in the soil.
6. Strength improvement factor of the soil is decreasing with increase in the organic content, when treated with lime or cement.
7. 1- Dimensional free swell strains of all the soils varied from 2.5% to 31.2%. The vertical free swell strain increased with an increase in the organic content, due to more water retention of capacity of organics.
8. Linear shrinkage strain values of all control and treated soils varied between 0.3% and 16.5%. Linear shrinkage strain values increased with increase in the organic content. In treated soils, cement treated soils exhibited low linear shrinkage strains, when compared to lime treated soils.

## 6.2 Future Research Recommendations

Stabilized organic soils have shown some interesting results for laboratory tests performed at higher curing periods. Continuing research on stabilized organic soils will certainly give the necessary precautions to be taken, when soils having organic content are treated with lime or cement.

1. A detailed analysis with increase of curing time should be performed on the soil samples. When a soil is treated with lime or cement, the strength gain due to the addition of stabilizer would be increasing with increase in time, and it becomes constant after certain point of time. Where as, strength reduced due to humic acid addition is not known with increase of time. Therefore, it is recommended to perform the UCS tests at higher curing periods. This is very clearly explained with an hypothetical graph shown in Figure 6.1. This point is important, because life span of humic acid is very high (Half life time > 100 years)
2. The reduction of strength in the soil could be due to clay mineralogy or any other properties. In order to reduce the confusion, artificial soil samples are prepared with known organic content and humic acid. This may give better understanding of the strength loss.
3. Research is also needed to study chemical properties of humic acid, and develop a method to remove humic acid from the soil.
4. Researchers can also work on stabilizing organic soil with non calcium based stabilizers, so that humic acid doesn't have any material to form a compound.

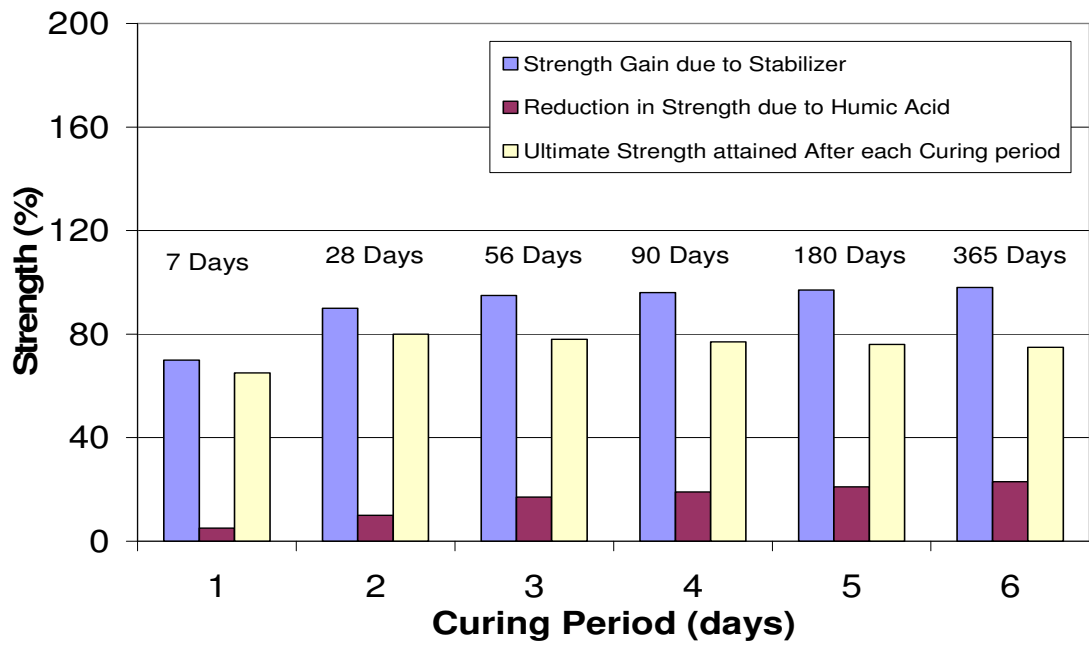


Figure 6.1 Ultimate Strength Attained with Increase in Curing Period

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