LABORATORY AND FIELD INVESTIGATIONS TO ADDRESS EROSION, VOLUME CHANGE AND DESICCATION CRACKING OF COMPOST AMENDED EXPANSIVE SUBSOILS

by

NAPAT INTHARASOMBAT

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ABSTRACT

LABORATORY AND FIELD INVESTIGATIONS TO ADDRESS EROSION,

VOLUME CHANGE AND DESICCATION CRACKING OF

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Napat Intharasombat, PhD.

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Supervising Professor: Anand J. Puppala

Desiccations cracks are formed during drying process of fine grained cohesive soils in summer and these cracks often appear on unpaved subgrades due to direct exposure to sun. These cracks allow surface runoff infiltration into subsoils and eventually weaken adjacent base and subgrade layers. The loss of support from these underlying layers results in both longitudinal and transverse cracks in paved shoulders and pavements.

Composting is a successful method of recycling organic waste material into stabilized materials that could be used for erosion control and landscaping applications. Since compost is rich in fibrous material and exhibits moisture affinity characteristics, it is theorized that compost material can be used to stabilize expansive soils in order to control desiccation or shrinkage cracks in them during dry seasons, which lead to considerable reductions in pavement distresses caused by longitudinal and transverse cracks.

In order to verify the compost stabilization process, a comprehensive research study was conducted at four distinct test sites near Stephenville, Lubbock, Bryan and Corpus Christi cities of the state of Texas, respectively. Composts comprising of biosolids, dairy manure, cotton burr, cow manure, feedlot manure and wood compost were considered for stabilizing local expansive soils of these four sites. Laboratory studies were first conducted on the compost materials and compost amended soils to address their volume change and strength behaviors. These studies were used to establish compaction moisture content and dry unit weight conditions for the construction of compost amended covers for further field verification studies.

In field investigations, a control plot with no composts as cover and several test plots with Compost Manufactured Topsoils (CMTs) as cover materials were designed and constructed. Both quantitative and qualitative data was collected from moisture and temperature sensors embedded in test plots, digital imaging related surface cracking studies, elevation surveys, visual observations of paved shoulder crack patterns and vegetation growth on the plots. The collected data was analyzed with statistical comparison t-tests, which indicated that majority of compost test plots showed that they had lesser moisture and temperature variations than those of the Control Plots. This indicates the ability of composts to insulate soils from surficial temperature changes and thus maintain uniform moisture levels in the subsoils.

Majority of CMT plots constructed at four sites were able to retain moisture contents close or above the initial compaction moisture contents. This resulted in lesser desiccation cracks in CMT test plots. The reduction in desiccation cracking was attributed to the presence of fibrous materials in composts, which serve as natural reinforcements in the CMTs. Thus, the CMTs were able to withstand tensile forces generated from drying of the subsoil.

Other recommendations related to CMT types and field compaction densities as well as erosion potentials of the test plots are explained. Causes for pavement distress resulting from both shoulder and subsoil cracking are identified and potential mitigation methods using compost stabilization techniques are described.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Desiccation cracking in expansive cohesive soils has long been a significant problem for the Texas Department of Transportation (TxDOT) since these cracks allow surface runoff water infiltration into subsoil layers and eventually weaken both the base and subgrade of pavements. These cracks are generally formed during the drying process of fine grained cohesive soils and often appear on unpaved shoulder subgrades where they are vulnerable to further drying due to direct exposure to high temperature and wind conditions. Both softening and volume changes of the underlying soils here could result in severe distress to pavements which will deteriorate the structural performance of pavements. If left untreated, these deteriorations will eventually propagate under and upward through the paved shoulder and travel lanes as seen in Figure 1.1. Surficial cracks in both the longitudinal and transverse directions can be seen in Figure 1.2. Annual maintenance to seal and/or repair these shoulder and highway distress problems cost several millions of dollars statewide. Hence, protection and maintenance of unpaved shoulder subsoils are key elements to the protection of the integrity of the roadways and related paved structures (Booze-Daniels et al., 2000).

Effective remediation methods must be immediately applied to prevent desiccation cracking of subsoils. Several chemical and mechanical treatment methods have been used to stabilize expansive shoulder subgrades. However, these methods have their own limitations and restrictions. Some are expensive, some less effective and some are not suitable in sulfate rich soils. Compost materials, given their moisture affinity (hydrophilic), low permeability and fibrous characteristics, are expected to reduce swell and more importantly shrinkage behaviors of underlying natural subsoils by encapsulating and reinforcing them. As a result, pavement shoulder cracking could be mitigated.

Figure 1.1 Shoulder cracking of SH 108 (Transverse Cracks)

Figure 1.2 Longitudinal and transverse cracks

However, to truly understand the effectiveness of compost covers on adjacent shoulder soils to mitigate expansive soil movements, a thorough research study was undertaken. The research, funded by the Texas Department of Transportation (TxDOT), attempted to investigate the compost amendments with the shoulder soils to mitigate cracking in them and in the travel lanes.

1.2 Research Objectives

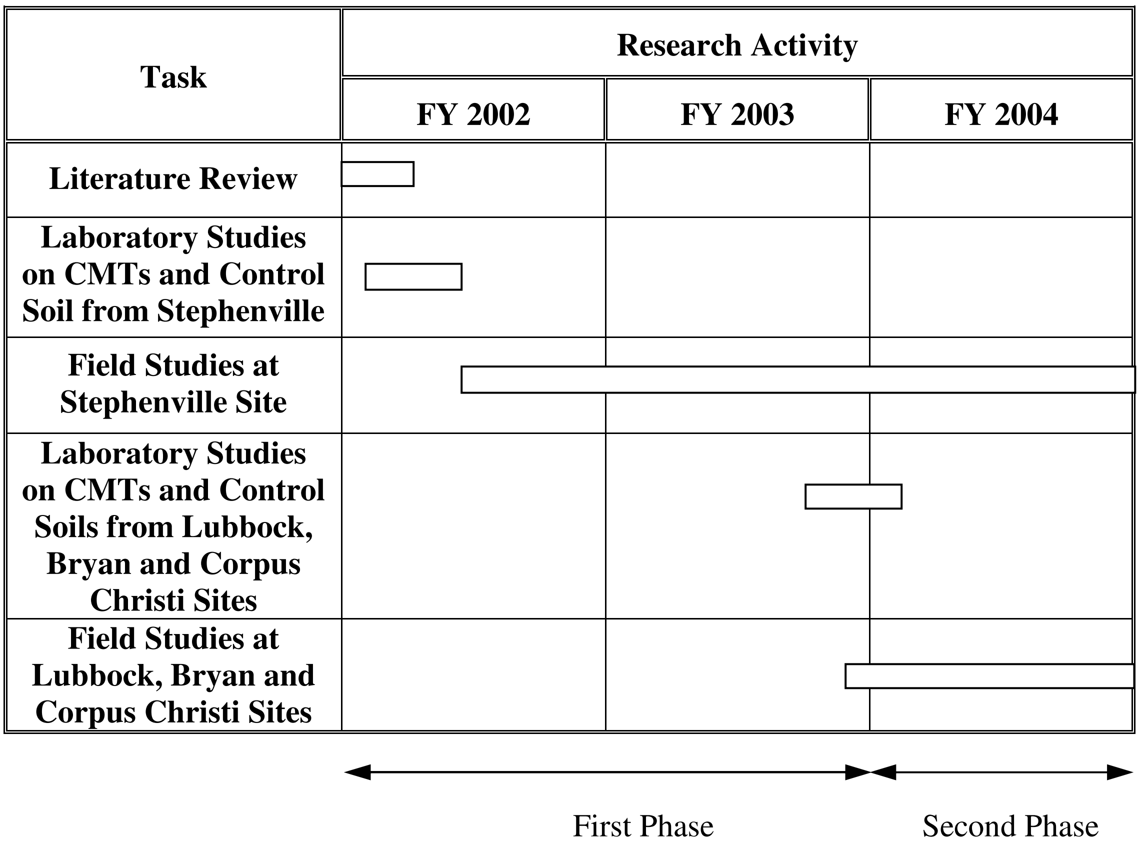
The increasing awareness and use of recycled materials and byproducts in highway construction and maintenance projects has resulted in better performance of highways and enhanced recycling applications of recycled materials. State highway agencies have been evaluating and studying suitable recycled materials and by-products in highway construction and maintenance operations for many years. One of the recycled materials that can provide similar benefits is compost material.

Several research groups in the United States as well as in other parts of the world have effectively demonstrated the use of compost for various landscape and erosion control applications in highway construction. It can also be discerned from the review of literature that the use of compost is recommended in order to reduce the landfilling of these source materials. This will save cost and space. One of the methods of using recycled solid wastes in an environmentally friendly way is to use them in appropriate highway maintenance projects in order to reduce the cost of highway construction and maintenance (Shelburne et al., 1998).

Considering all the above, this research study was developed to address the use of these compost materials for better encapsulation of adjoining shoulder soils in order to mitigate both shoulder subsoil and pavement cracking, in dry to semi-dry environments. This study has focused on several types of inexpensive recycled composts both in pure and blended forms, to be used to amend adjoining shoulder cover soils to mitigate shoulder cracking**.** The compost amended soil is also termed as Compost Manufactured Topsoil (CMT).

The study was divided into two phases: data collection in the first 2 years and data collection in the last and third year. The first phase was conducted at Stephenville, Texas to evaluate the effectiveness of CMT in mitigating shoulder cracking as well as mixing proportions, treatment width and length. The second phase, which was attempted two years later, was conducted to verify and extend the compost application following the recommendations from phase 1 to other regions (Lubbock, Bryan and Corpus Christi sites) and also study the long term effectiveness of compost amended soils to control pavement cracking at Stephenville site. Table 1.1 presents the schedule of research activities.

Table 1.1 Schedule of Research Activities



FY (September-August)

Both laboratory and field studies were conducted in both phases. Laboratory tests conducted to measure basic and engineering soil properties in this research were specific gravity, sieve analysis and hydrometer tests, Atterberg limits, organic content, standard Proctor tests, free swell test and linear shrinkage test. Laboratory tests primarily provided the compaction dry unit weight and moisture contents for the construction of field test plots.

Several parameters were monitored as a part of a field studies. Performance parameters such as shrinkage and swelling of shoulder subgrades, moisture and temperature fluctuations, as well as erosion were monitored in field conditions. Parameters such as moisture and temperature readings were used to verify the encapsulation effects of composts on the underlying soil layers. Shrinkage, elevation surveys and erosion analyses were used to address the survivability of the cover materials during exposure to elements, swell and shrinkage movements. Results of these investigations are covered in this dissertation.

A successful completion of the research would not only verify the potentials of compost amended soils in mitigating soil related cracking problems on pavement shoulders, but also provide an opportunity to enhance organic soil amendments for vegetation growth and erosion control. This would also provide a cost effective and environmentally friendly solution, since original sources of composts would be subjected to landfilling, incineration and other disposal methods in Texas. The study also allowed us to understand the long-term performance of the compost amended soils and estimate the service life of these amended covers from the monitored data from the Stephenville site.

1.3 Organization of the Dissertation

This dissertation consists of six chapters.

Chapter 1 provides an introduction, background history explaining the significance of the project, research objectives, and organization to provide a framework of the completed research.

Chapter 2 presents a literature review on compost types and their applications in geotechnical and geo-environmental engineering areas. Mechanisms causing cracking of the pavement lanes and different maintenance remedies currently used are also discussed in this chapter.

Chapter 3 covers a brief overview of the laboratory studies conducted on Compost Manufactured Topsoils (CMTs). This chapter discusses the selection of the compost materials, laboratory studies and ranking analysis for the CMTs.

Chapter 4 presents information pertaining to the field studies. Such information includes temperature and moisture fluctuations, erosion, shrinkage analysis, paved shoulder cracking and vegetation reestablishment. Site evaluation procedures and instrumentation are also discussed in this chapter.

Chapter 5 covers a comprehensive analysis of the findings from the first phase of studies. This chapter also discusses statistical methods of analysis to evaluate the overall performance of CMTs to stabilize expansive soils.

Chapter 6 presents a comprehensive analysis of the extension and verification studies attempted as a part of second phase. A ranking analysis was performed to evaluate the overall performance of each CMT at each site.

Chapter 7 presents the conclusions of the experimental research studies and future recommendations.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter provides a background to the present research study by reviewing the existing literature on compost materials and applications. The information is gathered from several electronic databases including the Transportation Research Information Service (TRIS) and American Society of Civil Engineers (ASCE). Several publications of the National Co-operative Highway Research Program (NCHRP) and Transportation Research Board (TRB) were also reviewed. Since the intent of this study is to investigate compost material covers as a preventive measure of shoulder cracking, the first part of the chapter is devoted to an understanding of the recycled compost materials and compost applications in geotechnical and geo-environmental engineering areas. Following this, mechanisms causing cracking of the pavement lanes and adjacent shoulder soils are discussed. This section also describes different maintenance remedies currently used to reduce paved and unpaved shoulder cracking. The last section delineates the scope of the present research study along with the objectives.

2.2 Compost Conditions and Prerequisite Materials

A large amount of waste materials are produced in the state of Texas. There have been numerous attempts to explore different applications to recycle these materials in highway construction (Collins et al., 1994). The increased attention to the possibilities and prospects of utilizing recycled materials can be attributed to two important advantages that it can provide. One, the proper use of recycled materials in highway applications can lead to better quality roads at lower costs and two, it can also resolve some of the environmental problems related to waste management and shrinking landfill space.

Composting is recognized as one of the innovative ways of recycling organic waste materials, by converting materials rich with pathogens to materials that could be effectively used in various day to day applications, such as landscaping and erosion control. Composting has the ability to improve the chemical, physical and biological characteristics of soils, as shown in Table 2.1.

Table 2.1 Benefits of Compost Addition Identified by Various Investigators

	USCC	**US EPA**	**Mitchell, D.**	**Univ. of Georgia**	**Univ. of Florida**
Improves soil structure, porosity, bulk density	✓		✓		
Increases water holding capacity of soil	✓	✓		✓	✓
Increases infiltration and permeability of soils	✓		✓	✓	
Erosion control	✓		✓	✓	
Helps moderate soil temperatures					✓
Adds organic bulk and humus to regenerate poor soils		✓	✓	✓	✓
Helps suppress plant diseases and pests		✓			

(Modified from Jennings et al., 2003)

The physical and chemical characteristics of compost vary according to the nature of the starting material, the conditions under which the composting operation was carried out, and the extent of the decomposition. In order to ensure successful compost use, these conditions and prerequisites must be controlled.

2.2.1 Compost - Conditions and Prerequisites

Compost used for a specific purpose, or with a particular soil type, works best when it is tailor-made or specially designed (USEPA, 1997). For instance, compost that is intended to prevent erosion might not provide the best results when used to assuage soil compaction and vice versa. Technical parameters to consider when customizing a compost mixture include C/N ratio, particle size, oxygen, moisture, temperature, pH level, maturity, stability and organic content, all of which can be adjusted to fit a specific application and soil type. The prerequisites for obtaining proper compost are discussed below.

2.2.1.1 Optimum carbon/nitrogen ratio

Microorganisms require specific nutrients in available form, adequate concentration and proper ratio for an efficient composting process. Some microorganisms cannot use certain forms of nutrients because they are unable to process them (USEPA, 1997). Most microorganisms cannot easily break down large molecules, especially those with different types of bonds, and this slows down the decomposition process significantly (USEPA, 1997). As a result, some types of feedstock break down more slowly than others, regardless of composting conditions (Gray et al., 1971a).

With respect to the nutritional needs of the microbes active in composting, the C:N ratio is the most important factor that requires attention (Diaz et al., 1993). High C:N ratios (i.e., high C and low N levels) inhibit the growth of microorganisms that degrade compost feedstock. Low C:N ratios initially accelerate microbial growth and decomposition. With this acceleration, however, available oxygen is rapidly depleted and anaerobic, foul-smelling conditions result if the pile is not aerated properly. The excess N is released as ammonia gas (USEPA, 1997). Extreme amounts of N in a composting mass can form enough ammonia to be toxic to the microbial population, further inhibiting the composting process (Gray et al., 1971b; Haug, 1980).

2.2.1.2 Particle size

The significance of particle size is in the amount of surface area of the waste particles exposed to microbial attack (Diaz et al., 1993). The size of feedstock materials entering the composting process can vary significantly. In general, the smaller the shreds of composting feedstock, the higher the composting rate (USEPA, 1997). Smaller feedstock materials have greater surface areas in comparison to their volumes. This means that more of the particle surface is exposed to direct microbial action and decomposition in the initial stages of composting (USEPA, 1997). Smaller particles within the composting pile also result in a more homogeneous mixture and improved insulation (Gray et al., 1971b). Increased insulation capacity helps maintain optimum temperatures in the composting pile. At the same time, the particles should not be too small to create too much compacting.

2.2.1.3 Oxygen

Composting can occur under aerobic (requires free oxygen) or anaerobic (without free oxygen) conditions. Nevertheless, aerobic composting is considered to be much faster than anaerobic composting. Anaerobic composting tends to generate more odors, and gases such as hydrogen sulphide and amines are produced in the absence of oxygen. Methane is also produced in the absence of oxygen (USEPA, 1997).

2.2.1.4 Moisture content

The moisture content of a composting pile is determined by many other composting parameters such as moisture content of the feedstock, microbial activity within the pile, oxygen levels and temperature (USEPA, 1997). Microorganisms require moisture to assimilate nutrients, metabolize new cells and reproduce. If the moisture content is below 35 to 40 percent, decomposition rates are greatly reduced, and decomposition virtually stops below 30 percent. If the moisture content is too high, it leads to anaerobic conditions resulting in odor complaints (Gray et al., 1971b). For most compost mixtures, 55 to 60 percent is the recommended upper limit for moisture content (Richard, 1992).

2.2.1.5 Temperature

Temperature is a critical factor in determining the rate of decomposition that takes place in a composting pile. Composting temperatures largely depend on how the heat generated by the microorganisms is offset by the heat lost through controlled aeration, surface cooling, and moisture losses (Richard, 1992). The most effective composting temperature is between 35^0C and 65^0C (Girovich, 1996). If temperatures are less than 20^0C, the microbes do not propagate and the decomposition process slows down. If temperatures are greater than 59^0C, some microorganisms are inhibited or killed, and the reduced diversity of organisms results in lower rates of decomposition (Finstein et al., 1986; Strom, 1985). Microorganisms tend to decompose materials most efficiently at the higher ends of their tolerated temperature ranges. The rate of microbial decomposition therefore increases as temperatures rise until an absolute upper limit is reached. As a result, the most effective compost-managing plan is to maintain temperatures at the highest level possible without inhibiting the rate of microbial decomposition (Richard, 1992; Rynk, 1992).

2.2.1.6 Hydrogen Ion level (pH)

The pH of a substance is a measure of its acidity or alkalinity, described by a number ranging from 1 to 14. A pH of 7 indicates a neutral substance, whereas a substance with a pH level below 7 is considered to be acidic and a substance with a pH higher than 7 is alkaline. In general, bacteria prefer a pH between 6 and 7.5. Fungi thrive in a wider range of pH levels than bacteria, in general, preferring a pH between 5.5 and 8 (Boyd, 1984). If the pH drops below 6, microorganisms, especially bacteria , die off and decomposition slows (Wiley, 1956). If the pH reaches 9, nitrogen is converted to ammonia and becomes unavailable to organisms (Rynk et al., 1992). This can also decelerate the decomposition process.

2.2.1.7 Source materials

Compost materials are prepared from a number of source materials (Benedict et al., 1998; Tchobanologus et al., 1993; He et al., 1995; Oweis et al., 1998; Shelburne et al., 1998). These include municipal solid waste (MSW), animal manure, backyard organic waste, farm waste, biosolids from wastewater treatment plant, and from vegetable and meat processing wastes. The generalized chemical equation expressing reactants and products is expressed below:

$$\text{Organic Fraction} + O_2 + \text{Nutrients} + \text{Microorganisms} \xrightarrow{\text{(Seeding)}} \text{Finished compost}$$

$$\text{New cells} + \text{Dead cells} + CO_2 + HO_2 + NO_3^{-} + SO_4^{2-} + \text{Heat}$$

2.2.2 Various types of compost materials

Compost is disinfected and is a stable decomposed organic material obtained from composting of different types of wastes. Composting is a natural process of aerobic, thermophilic, microbiological degradation of organic wastes into a stabilized, useful product that is free of odors and pathogens and can be used for a variety of purposes (Girovich, 1996). The following sections describe different types of compost materials primarily used in the research. It should be mentioned that compost originating from the same source material may have different properties due to the different process steps used during composting.

2.2.2.1 Animal Manure

All animal by-products can include manure and bedding from various animals. Compost produced from manure is known for possessing higher nutrient concentrations and typically low contaminant concentrations. When used appropriately, it improves biological activity, and soil-chemical properties (Schmitt et al., 1998). Bacteria and humus present in manure compost have the ability to increase microbial activity in the soil. This helps to improve soil structure. The animal manures used in this research were Dairy Manure Compost (DMC), Feedlot Manure Compost (FMC) and Cow Manure Compost

2.2.2.2 Biosolids Compost (BSC)

Biosolids are the nutrient-rich organic solid residue derived from residential, commercial, or pre-treated industrial wastewater processing. Biosolids are treated to reduce pathogens and contain only minimal levels of heavy metals and organic contaminants. Only biosolids that meet a "Class A grade" (exceptional quality) as outlined in the US EPA's 40 CFR Part 503 regulations can obtain permits for general distribution (USCC, 2001). This material, after composting, is known as Biosolids Compost (BSC) and can be used for landscaping applications. BSC is also rich in wood fibers and hence provides natural soil modification.

2.2.2.3 Cotton Burr Compost

According to the National Agricultural Statistics Service (NASS, 2005), in 2004, all cotton production in the state of Texas was estimated at 7.85 millions of 480-pound bales. Depending on the harvesting and ginning equipment, the process of making one bale of cotton will result from 0.2 to 0.35 ton of residue (gin trash) (Hilbers, 2003). Therefore in Texas, there would be 1.57 to 2.75 million tons of gin trash produced in 2004. The cotton burr is slightly chunkier, which helps lighten up the soil and retain water therefore, making it possible to use as soil amendment. Figure 2.1 shows cotton fields near Lubbock, TX.

Figure 2.1 Cotton fields near Lubbock, TX

2.2.2.4 Wood Compost

Wood wastes consist of tree trimmings, scrap wood, pallets, lumber, shipping containers and construction wastes. Wood waste that cannot be used in its original form can be processed into a variety of products. These include compost for soil improvement, mulch for weed control and wood chips for landscaping or trail stabilization. Wood that is composted makes excellent compost and soil amendments, which conserves water, reduces erosion, and lessens or eliminates the need for fertilizer (CIWMB, 2002).

2.3 Composts in Landscaping and Geotechnical Applications

Compost used in highway construction is mostly derived from yard waste, but can also be produced from other fractions of the MSW stream, either pre-source separated or commingled (Shelburne et al., 1998). In addition, it can be derived from agricultural wastes (manure and crop residues) and domestic residuals such as sewage and biosolids. The major application of compost is along highways as mulch, blended topsoil replacement, commercial fertilizer supplement, and soil amendments (DeGroot et al., 1995). Research work is being carried out to expand its use to control weeds and erosion (Alexander and Tyler, 1992) as well as in controlling the plant pathogens (Grebus et al., 1994).

Compost is mainly used for landscaping and topsoil applications. A review of the relevant literature reveals that currently six states use composts for these geotechnical and aesthetic applications (DeGroot et al., 1995). The Minnesota Department of Transportation (MnDOT) has specified compost as a standard specification item for the past nine years to use it in the place of topsoil and peat moss (Mitchell, 1997). The State of Virginia uses compost for siltation control (Shelburne et al., 1998). The Coalition of Northeastern Governors, whose member states are Connecticut, Maine, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, and Vermont, has drafted specifications to use compost as compost horticultural mulch, erosion control mulch, erosion control filter berm, compost-manufactured loam, and compost amendment loam (topsoil) manufactured in place (DeGroot et al.. 1995).

It is also reported that the composted sewage sludge from the City of Forth Worth has been given to the Texas Highway Department for more than 10 years for landscaping highway medians and rights of way (Collins et al., 1994). Currently, the USEPA summarizes in a report that the state of Texas is one of the leading proponents of use of compost in various highway applications (USEPA, 1997). Current data shows that TxDOT has become the largest user of compost among state DOTs in the nation. The majority of these applications are attributed to compost application programs initiated by a cooperative effort between TxDOT and TCEQ (formerly TNRCC) to address water quality issues, particularly in the Bosque/Leon river watersheds located in central Texas. Besides these current levels of application, it is also possible that compost can be used to enhance the biological, chemical, and physical properties of soil. Compost improves physical properties of the soil including the texture of soil (Tester, 1990). Compost reduces the bulk density of soil and increases water retention capacity, infiltration, and resistance to wind and water erosion of soils (Diaz et al., 1993). Further, it increases the aeration capacity and structural and temperature stability. Compost also serves as a physical barrier between rainfall and surface soil (Diaz et al., 1993), dissipating the effect of impact energy from rainfall and minimizing erosive forces.

Compost materials have other several potential applications and can be used by a variety of sectors. These include landscaping, land reclamation, erosion control, top dressing (e.g., for golf courses, park land), agriculture, residential gardening and nurseries (Diaz et al., 1993). Currently, many state Department of Transportation agencies (DOTs) have utilized compost in highway construction for different applications. Table 2.2 presents a summary of these projects, compost types and application areas used by the selected state DOTs. The table provides projects that illustrate a variety of potential applications for compost, as well as projects from a variety of geographical regions, representing different climatic conditions and soil types (USCC, 2001).

From the literature review listed in Table 2.2, compost has been used in various applications including erosion control, revegetation, biofiltration, bioremediation and landscaping. Since compost is rich in nutrients and fibrous materials and exhibits moisture affinity characteristics, it is theorized that compost can be used to stabilize expansive soils in order to control desiccation cracks on the adjoining soil surfaces under the pavements. However, no studies were either available or conducted to address this application of compost to reduce subsoil cracking. In this research, an attempt was made for the first time to study the potential benefits of compost amendments to mitigate cracking in shoulder subgrades which are expansive.

2.4 Pavement Cracking Along Shoulders

Expansive subgrades are encountered in subsoils of various districts in Texas. The primary problem associated with expansive soils is that their movements are significantly greater than the elastic and plastic compressible deformations; these heave movements result in an uneven pattern causing extensive damage to the structures and pavements resting on those soils (Nelson and Miller, 1992). Expansive soils located in regions of cool and wet periods followed by prolonged hot dry periods are more prone to such problems. After a dry period, the soils will have relatively low moisture content, resulting in high swell potentials. Differential movements in the subgrade soils underneath pavement often cause cracking of shoulders and pavements (Chen, 1988; Nelson and Miller, 1992). The initial shoulder cracks allow intrusion of surface water into adjacent soil mass and hence weaken the base and subgrade soil layers, as seen in Figure 2.2. The shrink and heave movements and softening of these layers will further result in the continued deterioration of traveling lanes by causing surface cracks in them.

Table 2.2 Literature Review of Recent Compost Applications in Highways

Reference	**Compost materials**	**Application areas**
Connecticut DOT	Compost consisting of mushroom substrate	Landscape Plantings
Connecticut DOT	Compost consisting of yard trimmings	Wetlands Creation
Florida DOT	Biosolids and yard trimmings, biosolids and Municipal Solid Waste (MSW)	Turf Establishment
Idaho DOT	Dairy Manure Compost	Vegetation Establishment
New Hampshire DOT	Compost consisting of Municipal Solid Waste (MSW)	Wildflower & Roadside Plantings
Oregon DOT	Yard trimmings compost	Erosion Control
Texas DOT	Dairy Manure Compost	Revegetation Difficult Slopes
Virginia DOT	Yard trimmings compost	Wildflower Plantings
Washington State DOT	Biosolids Compost	Soil Bioengineering

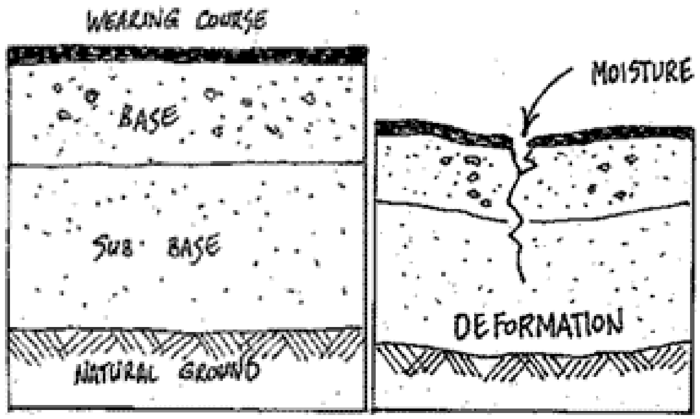


Figure 2.2 Example of a road pavement in a good condition and poor conditions
(Source: www.roads.act.gov.au)

2.5 Potential Remedies

Prior to cracks development in the pavement shoulders, maintenance remedies must be applied on adjacent expansive subsoils immediately to reduce continuing damage. Several chemical and mechanical treatment methods have been used to stabilize expansive soils (Hausmann, 1990; Kota et al., 1996; Viyanant, 2000). Treatment methods that are generally used to stabilize expansive soils are:

- Chemical additives
- Prewetting
- Soil replacement with compaction control
- Moisture control
- Surcharge loading
- Thermal methods

Of all these methods, chemical and mechanical stabilization methods are frequently used as they provide faster and more efficient stabilization results (Hausmann, 1990). However, these methods can be expensive and time consuming due to the cost of fill materials and the time needed for reducing swell behaviors. Due to these limitations, alternate methods are being explored for treating expansive subgrades. For example, the method of using encapsulation of expansive subgrades by geomembranes and chemical grouts yielded promising results (Nelson and Miller, 1992). However, this method is expensive due to the large volume of soil needed for encapsulation.

2.6 Summary

An attempt is made in this chapter to review various recycled materials used in highway construction. From this review, compost can be identified as a potential low cost recycled material that can be used to mitigate shoulder cracking. This, in turn, can reduce the costs required for highway maintenance. Shoulder crack mitigation is of high importance to highway maintenance. Hence, a brief discussion of various methods to mitigate shoulder cracks from expansive soil movement is described in this chapter. From the literature review, it is clear that no studies addressed the applications of compost materials to mitigate shoulder cracking. This study is a first time attempt in this direction and has comprehensively addressed the potential of compost materials for amending topsoils in order to mitigate shoulder cracking in the field.

CHAPTER 3

OVERVIEW OF LABORATORY STUDIES

3.1 Introduction

As a part of the research investigations, a laboratory based experimental program was designed and conducted to test recycled compost materials and the soil sampled from Stephenville, Lubbock, Bryan and Corpus Christi Texas. These soils were sampled from the areas that experienced pavement distresses and were chosen as the control soils. The control soils and the compost materials were mixed at different proportions. The final products were termed Compost Manufactured Topsoils or CMTs in this dissertation. A summary of the laboratory results and ranking analysis is presented in this chapter.

3.2 Selection of composts

There were several types of compost initially considered in this study. However, not all composts can be used for a specific purpose or with a particular soil type. Some work best when it is tailor-made or specially designed to fit the user's needs (USEPA, 1997). Compost can be produced from many feedstocks and they are typically rich in organic matter. Factors which affect the selection and use of composted material include feedstock properties, regulations, product uniformity, contaminant levels and economic considerations relating to distribution and utilization benefits

(Shiralipour et.al., 1992). The user must also consider specifications agencies use in the specific area. The specifications for compost should apply to a range of characterictics and require manufacturer testing for stability, maturity, organic and nutrient content, pH, salts, density, infiltration and particle size (Black et al., 1999).

A study conducted at the University of Texas at Austin by Kirchoff (2002) was used as the basis for the selection of compost materials to be used at Stephenville site. The study conducted by UT Austin indicates that only two composts, Dairy Manure Compost and Biosolids Compost, met or came close to the specifications of TxDOT and the United States Environmental Protection Agency (USEPA) for using them as potential soil amendments (Kirchhoff, 2002). Therefore, Dairy Manure and Biosolids Composts were chosen for Stephenville site. Two locally available composts were considered for the Lubbock, Bryan and Corpus Christi sites. An attempt was made to select the composts similar to those used in Stephenville and those that meet the TxDOT compost specifications. Table 3.1 presents picture of composts used at each site.

Table 3.1 Types of Compost

Stephenville		**Dairy Manure Compost** **Organic Content 10%**		**Biosolids Compost** **Organic Content 41%**
Lubbock		**Cotton Burr Compost** **Organic Content 65%**		**Feedlot Manure Compost** **Organic Content 30%**
Bryan		**Biosolids Compost** **Organic Content 58%**		**Wood Compost** **Organic Content 68%**
Corpus Christi		**Cow Manure Compost** **Organic Content 18%**		**Biosolids Compost** **Organic Content 45%**

3.3 Experimental Design

3.3.1 Sample Preparation Procedure

Since the amounts of compost and water were calculated as percentages of dry weight of the total sample, the control soil was oven dried prior to mixing with the compost materials. A representative dry soil was collected and weighed. The compost materials were not oven dried during CMT preparation in order to preserve the same original properties. The water content needed in the compost was also calculated based on the total dry unit weight of the soil and compost mixture.

The three required components of the mixture, dry soil, compost material, and water, were then added and mixed manually until a uniform mixture was obtained. All tests were performed on samples compacted from this mixture. Two moisture levels were used in the preparation of the CMT mixture. These were optimum moisture content and wet of optimum moisture content levels (at 95% maximum dry density). After the preparation of soil specimens of different dimensions for different tests, the laboratory tests were performed immediately on the CMT samples.

3.3.2 Description of Basic Properties Tests

Tests conducted to measure basic soil properties in this research were specific gravity, sieve analysis and hydrometer tests, Atterberg limits, organic content, and standard Proctor tests. These tests were conducted at the beginning of the experimental program and the physical soil properties of all materials including Control Soils and CMTs are presented here. Specific gravity, which is defined as the ratio of unit weight of soil to unit weight of water, of present test materials was determined as per TxDOT procedure Tex-108-E. The distribution of the grain sizes in test materials was determined using TxDOT procedure Tex-110-E. This method was also followed to determine the amount of soils finer than the No. 200 sieve. Finer particle size analysis was performed using hydrometer analyses.

Atterberg limits of present soils were determined by performing TxDOT procedures, Tex-104-E to determine the liquid limit and Tex-105-E to determine the plastic limit. The difference between these limits is termed as the plasticity index (PI). The plasticity index is generally used to classify the plastic nature and expansive potential of the soils.

Organic contents of composts and CMTs were determined by following the ASTM D-2974-87 procedure. Ash content was determined to calculate the organic content. First, the soil was oven dried for 24 hours and the weight of the soil sample was measured and reported as 'A' grams. The soil was then taken in a porcelain dish and placed in a muffle furnace maintained at a constant temperature of 440^{o}C and held there until the specimen was ashed completely. The dish was covered with an aluminum foil and placed in a desiccator until the sample cooled down completely. The weight of this ashed sample was measured and reported as 'B' grams. The ash content was calculated as a ratio of (B/A) expressed in percentage and the organic content was calculated in percent as "100 - Ash content in percentage."

In order to determine the compaction moisture content and dry unit weight relationships of the soils in the present research program, it was necessary to conduct standard Proctor compaction tests on soils to establish compaction relationships. The optimum moisture content of the soil is the water content at which the soils are compacted to a maximum dry unit weight condition. Samples exhibiting a high compaction unit weight are best in supporting civil infrastructure since the void spaces are minimal and settlement will be less. Compaction tests were conducted on both control soil samples and CMT 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.

3.3.3 Description of Engineering Tests

Engineering tests performed in this research were bar linear shrinkage test, direct shear test, free swell test, and permeability test for Stephenville materials. Since the volume change behavior of the materials governs the performance of the CMT, only linear shrinkage test and free swell test were conducted for materials from Lubbock, Bryan and Corpus Christi. These tests have been performed as per available TxDOT procedure and at two moisture contents. For each test, a total of three identical samples of control and amended soils were tested and analyzed to understand the repeatability of the test results.

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.

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.

The shear strength parameters of a soil can be determined in the laboratory by conducting a Direct Shear Test (ASTM D3080) on compacted soil samples.

Permeability refers to the movement of water within the soil. The water movement will have profound effects on soil properties, drainage conditions and moisture holding capacities. In predicting the flow of water in soils, it is imperative to evaluate the coefficient of permeability for a given sample. The test was conducted as per ASTM D2434.

3.4 Laboratory Results

3.4.1 Stephenville Site

This section summarizes a comprehensive analysis of both basic and engineering laboratory test results conducted on both compost and amended soils. The first part of the analysis is devoted to the evaluation of the potential of each compost material in providing enhancements to the properties the Control Soil from the Stephenville site. The effectiveness of each compost material and their influence on PI, strength, permeability, swell and shrinkage strain properties of the Control Soil (CS) are also explained. Ranking analysis based on targeted soil properties was performed to determine compaction moisture content for the field test plots. More details on these test results can be found in the later part of this chapter and Puppala et al., 2004. Table 3.2 defines various notations used to identify the compost amended soils and the Control Soil in this dissertation. The compost proportions were considered based on the standard Proctor test results of compost amended soils. Higher Dairy Manure Compost proportions were used since the amended soils still provided high maximum dry density. On the other hand, Biosolids Compost, which was a soft material in nature due to the presence of wood chips, required lower proportions in order to maintain the reasonable maximum dry density.

Table 3.2 Compositions of CMT

Designation	Percents of Constituents
CS	Pure Control Soil
CMT 1	75 % Dairy Manure Compost and 25% Control Soil
CMT 2	100 % Dairy Manure Compost
CMT 3	20 % Biosolids Compost and 80% Control Soil
CMT 4	30 % Biosolids Compost and 70% Control Soil

3.4.1.1 Basic Tests

Basic tests include Atterberg limits, organic content and standard Proctor tests. Table 3.3 presents the physical soil properties of all materials, including Control Soils and CMTs. From the table, the addition of compost resulted in the reduction of the maximum dry density. This is attributed to the ability of compost to loosen up soil particles. This reduction in maximum dry density along with the added organic content should benefit the vegetation growth.

Table 3.3 Physical properties of the Control Soil and CMTs from Stephenville Site

Property	Stephenville				
	CS	CMT 1	CMT 2	CMT 3	CMT 4
PI	28	18	12	35	28
Organic (%)	2.4	5.9	6.3	11.3	14.2
Dry Density (pcf)	99.7	92.8	88.7	77.6	68.9
Moisture Content (%)	22.2	24.8	25.9	32.2	41.5

3.4.1.2 Engineering Tests

(i) Direct Shear Test

The shear strength parameters of a soil can be determined in the laboratory by conducting a Direct Shear Test as per ASTM D3080 on compacted soil specimens at three different confining pressure conditions of 14, 28, and 42 psi, respectively. Table 3.4 summarizes these direct shear test results of control and amended soils in the form of cohesion intercept and friction angle. These results are reported for both compaction moisture conditions close to optimum and wet of optimum levels.

Table 3.4 Shear Strength Parameters of the Control and CMTs from Stephenville Site

Soil Type	**@ Optimum**		**@ Wet of Optimum**		**Shear Strength (τ) ****	
	Cohesion (c) (psi)	**Friction Angle, ϕ in degrees**	**Cohesion (c) (psi)**	**Friction Angle, ϕ in degrees**	**Optimum (psi)**	**Wet of Opt. (psi)**
CS	17.1	3.0	12.2	2.5	17.8	12.9
CMT 1	15.5	21.0	12.4	13.0	21.1	15.7
CMT 2	8.5	26.0	6.0	23.0	15.6	12.2
CMT 3	20.8	22.5	17.4	19.0	26.9	22.4
CMT 4	16.8	23.5	16.1	19.5	23.2	21.2

**$\tau = c + \sigma \tan \phi$, where $\sigma = 14$ psi

The Control Soil was observed to have very low friction angles at optimum and wet of optimum moisture contents. These results are consistent with those expected for medium clay. The Dairy Manure Compost exhibited lower cohesion and higher friction angles due to the coarser compost particles. The Biosolids Compost amended soils showed higher cohesion values and higher friction angles also due to the coarser compost particles. This can be attributed to the presence of yard trimming and coarse sized particles in the BSC material. Based on the shear strength property at 14 psi confinements, both CMT 3 and CMT 4 (BSC materials) are slightly higher than CMT 1 and CMT 2 (DMC materials). Overall, moderate strength enhancements were recorded when the Control Soil was stabilized with composts.

(ii) One-Dimensional Free Swell Test

The One-Dimensional Free Swell Test (ASTM D4546) measures the amount of heave in the vertical direction of a laterally confined specimen in a rigid chamber. The test results are presented in Table 3.5.

Table 3.5 Free Vertical Swell Strains of the Control and CMTs from Stephenville

Soil Description	**@ Optimum Moisture Content (%)**	**@ Wet of Optimum Moisture Content (%)**
CS	11.4	5.6
CMT 1	24.6	22.8
CMT 2	23.8	22.5
CMT 3	27.9	23.2
CMT 4	31.2	28.4

The compost materials have more water holding capacity than the Control Soil. Because of this, when the soil sample was saturated, the compost amended soils exhibited more swelling. These numbers demonstrate that the Biosolids Compost has more water holding capacity than the Dairy Manure Compost and the swell percentage increased with the percentage increase of compost. High swell numbers in the Biosolids Compost amended soils are attributed to the presence of higher amounts of organic matter present.

(iii) Linear Shrinkage Bar Test

The Linear Shrinkage Bar Test as per TxDOT Test Method Tex-107-E was conducted 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. The results are summarized in Table 3.6.

Table 3.6 Linear Shrinkage Strain Values for the Control and Compost Amended Soils from Stephenville Site

Soil Description	**@ Optimum**	**@ Wet of Optimum**	**@ Liquid Limit**
CS	14.0	17.0	23.4
CMT 1	6.0	8.0	10.0
CMT 2	4.2	4.8	5.7
CMT 3	5.8	6.5	14.3
CMT 4	10.7	12.2	18.1

The shrinkage strain values in the DMC amended soils decreased with an increase in dairy manure content at all three moisture content values as shown in Table 3.6. This decrease is due to the reductions in plasticity characteristics.

The BSC amended soils exhibited higher shrinkage strain values than the DMC amended soils. This increase is due to the presence of higher natural moisture content in these soils as shown in Table 3.5. Higher moisture presence is attributed to organic matter present in these soils, which are known to attract and contain moisture. Though the BSC amended soils had higher initial natural moisture contents, the shrinkage strain values were still low because of the presence of wood chips and yard trimmings. These natural fibers provide shrinkage resistance to natural soils. Overall, compost amendments resulted in the decrease of linear shrinkage strain potentials of the Control Soil. This indicates that the compost amendment has the potential to reduce desiccation or shrinkage cracking in soils.

(iv) Permeability Test

Permeability refers to the movement of water within the soil and this test was conducted as per ASTM D2434. The water movement will have profound effects on the soil properties, drainage conditions and moisture holding capacities. In predicting the flow of water in soils, it is imperative to evaluate the coefficient of permeability for a given soil sample. Table 3.7 presents the permeability test results.

Table 3.7 Coefficient of Permeability of the Control Soil and CMTs from Stephenville Site

Soil Description	**@ Optimum (cm/sec)**	**@ Wet of Optimum (cm/sec)**
CS	1.2×10^{-8}	3.0×10^{-9}
CMT 1	4.2×10^{-8}	4.3×10^{-9}
CMT 2	8.9×10^{-8}	8.7×10^{-9}
CMT 3	7.8×10^{-8}	9.7×10^{-9}
CMT 4	1.2×10^{-7}	7.8×10^{-8}

All the soils were observed to have higher permeability values at optimum moisture content than at wet of optimum moisture content. An increase in the compaction moisture content results in a decrease in the soil permeability. This decrease is attributed to the soil structure, which becomes dispersed or parallel oriented soil structure at high moisture contents. Such parallel oriented soil structures impede the hydraulic flow through them.

Soils mixed with the Biosolids Compost exhibited low permeability values. This is because soils with high plasticity properties have a thicker double layer, possess greater dispersive structure, and hence exhibit lower permeability. The reduced water absorption capacity indicates a decrease in the double layer thickness and therefore an increase in soil permeability (Mitchell, 1993).

The Dairy Manure Compost amended soils exhibited slightly higher permeability values than the Control Soil. This is because the mean diameter (D_{50}) of Dairy Manure Compost is more than D_{50} of the Control Soil. Permeability property depends on soil size and hence high permeability properties were obtained for Dairy Manure Composts.

Although the addition of compost slightly resulted in the increase of coefficient of permeability, the permeability properties of the amended soils were still considered low and similar to those of natural clays. These flow properties allow rainfall to infiltrate into subsoils rather than leaving the site area as a water runoff. This implies that CMTs have abilities to encapsulate infiltrated moisture content, which would help in reducing desiccation cracking during dry seasons.

3.4.1.3 Ranking Analysis

The following scale system was used in which the transformation of each soil property from problematic levels to non-problematic levels is assigned a numeric ranking. Non-problematic soil property levels here are those that correspond to lower shrinkage cracking conditions. The magnitude of ranking is based on the severity of the soil problem. The worst soil condition is given a rank of 1 and the best soil condition is given a rank of 5. In between conditions, ranks of 2 to 4, are assigned for different ranges of soil properties. Table 3.8 summarizes the soil characterization based in different soil properties.

Table 3.8 Soil Characterization Based in Different Properties of the Soils

PI**	**Vertical Swelling Strain* (%)**	**Linear Shrinkage Strain * (%)**	**Shear Strength** psi (kPa)**	**Coefficient of Permeability (cm/sec)**	**Rank**	**Soil Condition**
$0 \leq PI \leq 5$	0 - 0.5	< 5.0	> 28 (200)	$<10^{-8}$	5	Best
$5 < PI \leq 15$	0.51 - 1.5	5.0 – 8.0	21–28 (150–200)	10^{-7} - 10^{-8}	4	Better
$15 < PI \leq 25$	1.51 – 4.0	8.1 – 12.0	14–21 (100–150)	10^{-6} - 10^{-7}	3	Good
PI > 25	> 4.0	12.1 – 15.0	7–14 (50–100)	10^{-5} - 10^{-6}	2	Poor
PI > 50	> 8.0	>15.0	0–7 (0–50)	10^{-4} - 10^{-5}	1	Worst

* Nelson and Miller, 1992; **Wattanasanticharoen, 2000

Table 3.9 presents the ranking of the Control Soil and CMTs based on both physical and engineering test results. From the table, it can be observed that all the soils have an equal or better ranking at the optimum moisture content level (designated O in the table) than at the wet of optimum moisture content level (designated W in the table). By looking at the Impact Value (IV) column, all CMTs have equal or higher impact values than the Control Soil. CMT 2 has the best ranking when compared to the other amended soils. DMC has enhanced the Control Soil ranking from a poor to a good ranking. Likewise, BSC (at 20% dosage level) has enhanced the Control Soil ranking.

Same priorities were given to the first impact value (IV^1). Higher priorities were given to the volume change characteristics of the materials (FS and LS)in the second impact value (IV^2). Since the materials will be placed on roadside shoulders, material strengths (τ) were also given higher priority.

Table 3.9 Ranking of the Control Soil and CMTs
Based on Test Results

Soil Type	**w%**	**PI**	**FS**	**LS**	**τ**	**k**	**IV^1**	**IV^2**	**IV^3**
CS	O	2	1	2	3	5	2.6	2.1	2.3
	W	2	2	1	2	5	2.4	2	2
CMT 1	O	3	1	4	3	5	3.2	2.9	2.9
	W	3	1	4	3	5	3.2	2.9	2.9
CMT 2	O	4	1	5	3	5	3.6	3.3	3.3
	W	4	1	5	2	5	3.4	3.2	3.1
CMT 3	O	2	1	4	4	5	3.2	2.9	3
	W	2	1	4	4	5	3.2	2.9	3
CMT 4	O	2	1	3	4	4	2.8	2.5	2.7
	W	2	1	2	3	5	2.6	2.1	2.3

Where, k - Coefficient of permeability (cm/sec); τ- Shear Strength (kPa);

- $I.V^1 = 0.2\ (PI) + 0.2\ (FS) + 0.2\ (LS) + 0.2\ (\tau) + 0.2\ (k)$
- $I.V^2 = 0.15\ (PI) + 0.3\ (FS) + 0.3\ (LS) + 0.15\ (\tau) + 0.1\ (k)$
- $I.V^3 = 0.15\ (PI) + 0.25\ (FS) + 0.25\ (LS) + 0.25\ (\tau) + 0.1\ (k)$

The laboratory test results yielded the following four important conclusions:

1. Compost amendments reduced in the linear shrinkage strains of the Control Soil.
2. Compost amendments moderately increased in the shear strength of the soil.
3. Compost amendments considerably increased in swell strain potentials of the Control Soil.
4. Compost amendments slightly decreased of permeability properties in soils.

Considering the decrease in shrinkage strain potentials and strength enhancements, it is expected that these amendments in field conditions would lead to less desiccation cracks in adjoining shoulder soils, which are the possible causes of paved shoulder and travel lane subgrade soil cracking. Hence, field test plots were recommended to test the same four materials at different depths and widths. Details of these studies are explained in the next few chapters.

3.4.2 Lubbock, Bryan and Corpus Christi Sites

Basic and engineering tests were conducted on both control and compost amended soils. These tests included standard proctor compaction, organic content determination, free swell and linear shrinkage tests. Tables 3.10 to 3.12 present these test results. From the results of the field study at Stephenville site, 20% compost by dry weight was recommended for the second phase.

The test results at Lubbock, Bryan and Corpus Christi showed similar trends as the laboratory results of Stephenville site. Compost amendments reduced the PI, dry density and linear shrinkage of the Control Soil. The swell strain potentials and moisture contents also increased due to the hydrophilic nature of the compost materials.

Table 3.10 Test Results of the Control Soil and CMTs from Lubbock Site

Property	Lubbock		
	Control Soil	Feedlot Manure Compost	Cotton Burr Compost
PI	14	10	8
Organic Content (%)	2.3	7.9	14.8
Dry Density (pcf)	123.5	103.3	93.3
Moisture Content (%)	9.9	16.3	18.9
Free Swell (%)	12.3	18.8	30.9
Linear Shrinkage (%)	7.0	4.0	5.0

Table 3.11 Test Results of the Control Soil and CMTs from Bryan Site

Property	Bryan		
	Control Soil	Biosolids Compost	Wood Compost
PI	18	6	5
Organic Content (%)	4.2	15	17
Dry Density (pcf)	112.2	88.7	90.9
Moisture Content (%)	15.2	23.7	17.9
Free Swell (%)	1.7	4.8	21.4
Linear Shrinkage (%)	5.0	3.6	3.4

Table 3.12 Test Results of the Control Soil and CMTs from Corpus Christi Site

Property	Corpus Christi		
	Control Soil	Cow Manure Compost	Biosolids Compost
PI	47	28	33
Organic Content (%)	3.2	6	11.5
Dry Density (pcf)	104.4	98.1	91.5
Moisture Content (%)	15.9	20.3	21.9
Free Swell (%)	28.7	27.4	16.1
Linear Shrinkage (%)	18.0	16.1	15.9

3.5 Summary

A summary of laboratory test methods and results of both the Control Soil and CMTs were presented and analyzed in this chapter. All CMTs showed significant improvement in the soil properties with Dairy Manure Compost amendments yielding slightly better improvements than Biosolids Compost amended soils in the laboratory environment. These materials were considered for further usage in field applications, which are described in the next chapter.

All these laboratory observations and interpretations required further experimental verification by studying them in field treatments. Hence, it can be stated that the main objective of this research was to assess the effectiveness of locally available compost materials for better treatment and encapsulation of underlying expansive clayey soils under field conditions.

CHAPTER 4

CONSTRUCTION OF FIELD PLOTS AND MONITORING: FIRST PHASE

4.1 Introduction

Due to the improvement to the Control Soil based on the laboratory results, the field study was designed and implemented to evaluate the performance of the CMTs in field conditions. The Control Soil and CMTs were mixed at the same proportions that were used in the laboratory investigations. These were mixed into and compacted over local soils to serve as a cover material for the existing soils. This chapter describes the site selection and construction, instrumentation and site evaluation procedures followed in the research. As noted in Chapter 1, data monitoring was attempted in two phases, data collection and analysis of the first two years (seventeen months), and the same in the third and final year. It should be noted that the last three sites were constructed and monitored during second phase studies. Phase 1 results from Stephenville, Texas were presented in this chapter.

4.2 Site Selection

The site was in Stephenville, Texas. The site was situated on US Highway 108 north of Stephenville, Texas. The site was chosen based on the availability of composts and past soil related cracking problem in this area. Two composts, Dairy Manure Compost and Biosolids Compost, were utilized in the field studies. They were mixed with the control soil following the recommended proportions from the laboratory studies. The local soil was classified as clay with low plasticity or lean clay (CL) as per the Unified Soil Classification System (USCS) and as A-7-6 as per the AASHTO classification.

4.3 Design Method

Prior to construction, soil from the test plots was collected and evaluated in the laboratory. Composts were acquired from local sources and mixed with the control soil to form different types of Compost Manufactured Topsoils or CMTs. These CMTs were intended to be used as shoulder cover materials by studying their soil characteristics and evaluating their performance in field conditions.

Both physical and engineering properties of CMTs and the control soil were first determined in the laboratory, as presented in the Chapter 3. Based on these engineering property evaluations, various proportions of CMTs and their compaction properties were established for field treatments.

A spreadsheet-based program (Figure 4.1) was developed to compute compost and water quantities. The program used input parameters, which included moisture content and dry unit weight properties of composts and subsoils, as well as targeted or design compaction characteristics of CMTs. Both moisture contents and dry unit weights of the control soil and compost materials transferred to the test site were determined prior to construction. The output parameters of the program were the amount of compost needed, amount of topsoil that needs to be tilled, and the amount of water in gallons to be added in order to mix the compost with the soils.

Description	Quantity	Unit
Length of the strip, L	1	ft
Width of the strip, B	1	ft
Thickness to be treated, t	1	in
Compost in-situ moist unit weight	1	pcf
Compost moisture content	1	%
Site soil moisture content	1	%
Site soil dry unit weight	1	pcf
Percent compost in CMT	1	%
CMT dry unit weight	1	pcf
CMT moisture content	1	%
Scrape off depth, t_1	0.0	in
Tilling depth, t_2	1.0	in
Volume of compost	0.00	CY
Water needed	0.00	Gallons

Figure 4.1 Spreadsheet-based program to compute volumes of compost and water quantities

4.4 Construction of Test Plots

The field construction was started by first by removing the top layer (thickness is t_1 in.) of the soil, which was composed of vegetation and other organic matter. The 'maintainer' was then used to blade the remaining shoulder subgrade section to the required grade and cross-section in accordance with the specifications obtained from the spreadsheet-based program. Figure 4.2 shows a photograph of this step in the field.

Figure 4.2 Maintainer to blade the subgrade shoulder

The shoulder was then scarified to full length (which is 50 ft. long test section and 25 ft. long of transition), width (variable) and tilling thickness (t_2 in.) using a rotary tiller. Any lumps in the subgrades were broken up such that no large sized particles (2 in. or above) were present in the tilled soil (Figure 4.3).

Figure 4.3 Rotary tiller for tilling operations

Compost materials were transferred to the test sections as shown in Figure 4.4, and the material was then distributed evenly over the test section with a maintainer. The compost materials were mixed with the tilled topsoil using the same tiller. At least eight passes of the rotary tiller were applied for the initial soil mixing. At this juncture, the required water in gallons was uniformly distributed over the compost and topsoil mixture (Figure 4.5). These three materials, compost, soil and water, were again mixed with the tiller for another 8 passes. This mixing was completed within an hour after placement and mixing of all three materials.

Figure 4.4 Distributing composts on the tilled test plot

Figure 4.5 Application of water over the CMT loose mixture

The mixed CMT was then compacted with a smooth drum roller (Figure 4.6) for at least 8 passes within an hour after mixing. Both moisture content and dry unit weights of the compacted material in the field were measured using a nuclear gauge at different locations.

The average values of these measurements were used in the following Equations 1 and 2 to calculate the relative compaction (R) and water content of the compacted CMT.

$$R\ (\%) = \{\gamma_{d\ (field)}/\gamma_{d\ (lab\_max)}\} \times 100 \geq 0.95 \quad (1)$$

$$\text{Field moisture content of CMT} = w_{field} = w_{opt} + 1 \text{ to } 2\% \quad (2)$$

where $\gamma_{d\ (field)}$ is the dry unit weight of compacted CMT cover; $\gamma_{d\ (lab\_max)}$ is the maximum dry unit weight of compacted CMT from the TEX-113/114-E compaction test method used in the laboratory; w_{field} is the field moisture content of the compacted CMT in %;

and w_{opt} is the optimum moisture content of the CMT from the laboratory TEX-113/114-E compaction test.

Figure 4.6 Smooth drum roller used for soil compaction

The shoulder subgrade soil was re-compacted with two more passes using the same roller when the compaction criterion was not met (i.e. when the R value is less than 0.95 or moisture content is not within the allowable values or both). Compaction moisture content and dry unit weights were measured again to recalculate and assess the targeted R and moisture content values in the field. When the criterion was met, then the construction of the test section was completed. If not, the same steps were repeated using additionally two passes of the same roller. In the case of high moisture contents in the field, compact the CMTs after drying the subgrade in natural conditions for 6 to 8 hours.

During construction, care was taken to prevent spillage of composts on roadways over which the hauling was done. Any spilled material was cleaned up immediately. All compost materials were removed and the general condition of the test site was left as good as or better than before construction. Final approval of the cleanup shall be given by the Department of Transportation Inspector.

4.5 Installation of Sensors

After construction of the test sections, moisture and temperature probes were installed. These sensors were selected for field instrumentation since the objective of the research is to assess the subgrade moisture and volume change conditions due to construction of a CMT cover system over the shoulder section. Both moisture and temperature probes were selected to provide real time moisture and temperature data. Site surveys and digital image studies were considered since they provide volume changes in underlying soils.

Sensors were placed after the construction of the test sections rather than during the construction due to the sensitivity of the equipment to the weight of the construction equipment. Several moisture and temperature probes were acquired and used in the field site installation. Square shaped holes were carefully excavated up to 6 in., 12 in., and 18 in. at Stephenville site. A moisture sensor was placed at the bottom of each hole, and one temperature sensor was placed at the 6 in. hole. Figure 4.7 depicts these sensors. Prior to placement of the sensor, a small 0.5 in. depression was made at the bottom of the hole, in which the sensor was carefully placed such that there were no air gaps between the sensor and soil. The excavated soil was then placed in the hole and compacted in short lifts (4 in.). Extreme care was taken to ensure the compaction was similar to the adjoining subsoils. The sensors placement is shown in Figure 4.8.

Figure 4.7 Placement of sensors in a test section

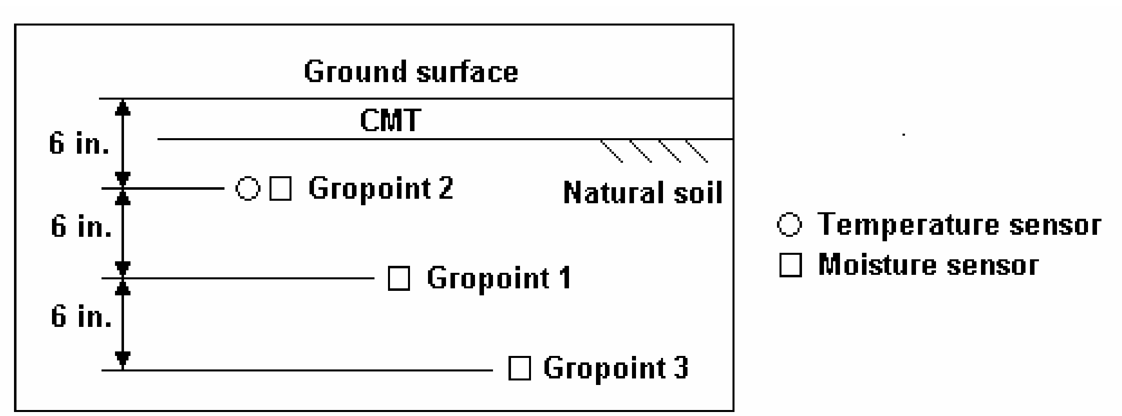


Figure 4.8 Placement of sensors

4.6 Detailed Construction of Stephenville Site

In the field, sixteen test plots with CMTs of different widths and thicknesses were constructed and studied. Two widths (5 ft. and 10 ft.) and two thicknesses (2 in. and 4 in.) were studied. One Control Plot (CP) with no CMT was included for comparison studies and this plot was established as the untreated or Control Plot. To simplify the names of all variables, the following notation is used throughout the dissertation to identify various CMTs with different widths and thicknesses. Every sample was assigned a notation set in the form of CMT4-10-4 where the first notation set, CMT4, indicates the type of CMT used as the top soil cover. The second part of the notation describes the treatment width (for example, 10 indicates 10 ft. wide) and the third number shows the treatment thickness in terms of in. (for example, 4 indicates 4 inch thickness). Table 4.1 presents details of these test plots.

Table 4.1 Details of Test Plots at Stephenville Site

Plot	Plot Name	Material	Shoulder width (ft)	Thickness (in)
1	CMT4-10-4	BSC	10	4
2	CMT3-10-4	BSC	10	4
3	CMT2-10-4	DMC	10	4
4	CMT1-10-4	DMC	10	4
5	CMT4-10-2	BSC	10	2
6	CMT3-10-2	BSC	10	2
7	CMT2-10-2	DMC	10	2
8	CMT1-10-2	DMC	10	2
9	CMT4-5-2	BSC	5	2
10	CMT3-5-2	BSC	5	2
11	CMT2-5-2	DMC	5	2
12	CMT1-5-2	DMC	5	2
13	CMT4-5-4	BSC	5	4
14	CMT3-5-4	BSC	5	4
15	CMT2-5-4	DMC	5	4
16	CMT1-5-4	DMC	5	4
17	CP-10-4	CS	10	4

The field test plot construction began on March 27, 2003 and was completed on March 28, 2003. The test site is approximately 1275 feet in length and is located between the right of way (ROW) boundary fence and paved shoulder edge on the west side of the highway. One CP and 16 CMT test plots built with the four different CMTs as shoulder covers were constructed at the test site. Each plot was 50 ft. long with a transition zone of 25 ft to separate each plot in order to ensure that the adjacent compost materials would not affect the field results on any other test plot (Figure 4.9).

In each plot, compost was mixed with the natural top soil at targeted proportions and then compacted into CMT plots of different dimensions with a smooth roller. Each test plot was instrumented with three moisture probes and one temperature probe to monitor fluctuations in the subsoils. In addition, erosion, shoulder cracking, paved shoulder cracking and vegetation growth were also periodically investigated. These are described later in this chapter.

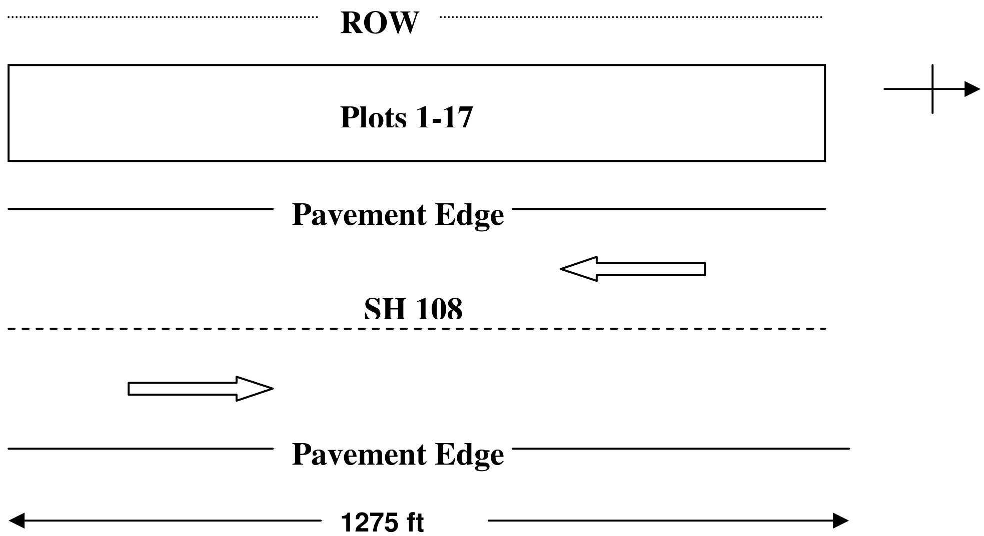


Figure 4.9 Illustration of field site

4.7 Field Tests on the Test Plots

Since the main objective of this research was to design various CMT test plots of different sizes and then monitor the performance of these plots, an attempt was made to collect extensive data from all of the test plots. The data collected in the field covers: (1) moisture and temperature fluctuations, (2) surface erosion, (3) shrinkage properties, (4) paved shoulder crack propagation, and (5) vegetation growth. The data collected was statistically analyzed to evaluate the effectiveness of the selected compost materials, widths, and thicknesses as cover materials. The following sections the describe detailed evaluation procedures used throughout this research.

4.7.1 Temperature and Moisture Data

Instrumentation of the test plots played an important role in understanding the effectiveness of compost materials for providing moisture and temperature encapsulation of the natural subgrade. Encapsulation means that the compaction moisture content of subgrade soils does not vary significantly when compared with the moisture variations of a Control Plot due to seasonal changes. To investigate the moisture and temperature encapsulation mechanisms, moisture (also known as Gropoint sensors) and temperature probes were installed immediately after construction of the test plots (Figure 4.10).

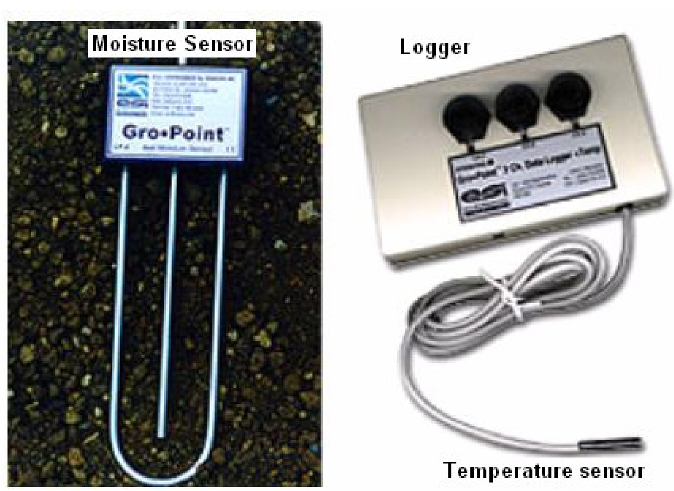


Figure 4.10 Temperature and moisture probes and a logger

The moisture sensor used here works on the principle of Time Domain Transmissometry (TDT) technology and provides volumetric moisture contents. It measures the one-way propagation time. The pulse reading is observed at the other end of the transmission line from the transmitter of the sensor. The propagation time of an electromagnetic wave along a given length of transmission line is proportional to the square root of the permittivity of the medium the transmission line is immersed in. For the medium of soil/water/air, in this project the permittivity of the water dominates the mixture of permittivity and the measurement can then be used to determine the volumetric water content of the soil mixture. Volumetric moisture contents are related to gravimetric moisture contents by the density of the soil medium. The relationship is shown in the following equation:

$$\theta_G = \theta_V * \frac{\rho_W}{\rho_S}$$

Where θ_G = Gravimetric soil moisture content;

θ_V = Volumetric soil moisture content;

ρ_w = Density of water and

ρ_s = Bulk density of soil.

Both moisture and temperature probes provide real time volumetric moisture content and temperature data. The data was stored in a data logger stationed at each test plot, and the data was downloaded to a computer during site visits. A typical example of the moisture and temperature data from a sensor collected till August 2004 is presented in Figure 4.11.

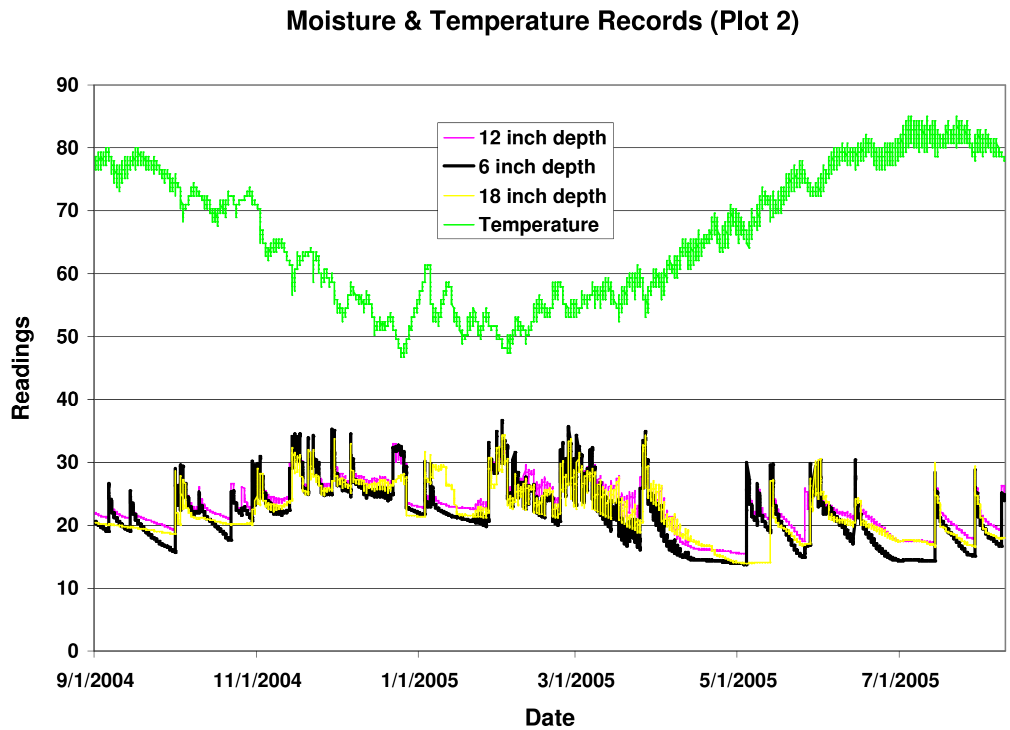


Figure 4.11 Volumetric moisture and temperature data (PLOT 2)

The temperature readings clearly show the day and night temperature variations as well as seasonal temperature variations. The moisture readings measured by Gropoint sensors also reflect the moisture variation trends expected at various depths. Note that the Gropoint 2 moisture sensor denotes readings at the shallow depth (6 in.) and Gropoint 3 moisture sensor identifies with moisture readings at the deep depth (18 in.). As expected, the moisture fluctuations from the shallow depth sensor (thick line) are higher than those at the other 2 depths, explaining that the near surface depth is susceptible to seasonal temperature variations. Both moisture and temperature fluctuations were continuously monitored and this data was analyzed to assess the encapsulation effects. Test data collected from the entire test and Control Plots are included in Appendix A.

4.7.2 Erosion Analysis

Topographic surveys were periodically conducted during moisture and temperature data collection, and these results were used to evaluate vertical movements (swell/shrinkage volume changes) of the encapsulated surface and any grading (elevational) changes in both longitudinal and transverse directions. A Total Station survey instrument was used to measure the elevation of each spot in each test plot which was marked by a spike. Each plot had 5 spikes set in both the longitudinal and transverse directions, as shown in Figure 4.11. The distance from the spikes in the longitudinal direction was 10 feet. Depending on the width of the test plot, the distance from spikes 4 to 2 and spikes 2 to 5 were set at 2 and 4 feet for the 5 foot and the 10 foot wide test plots, respectively. Typical surveying data collected from the survey is presented in Table 4.2.

The vertical displacements were calculated by subtracting the elevation of each spike from an initial elevation, which was established at the beginning of the monitoring process immediately after the test plot construction in April, 2003. For example, the elevation of spike 3 on June 1, 2003 would be equal to -9.79-(-9.75) or -0.04 ft. This implies that the surface of the test plot has been eroded by an amount of 0.04 feet.

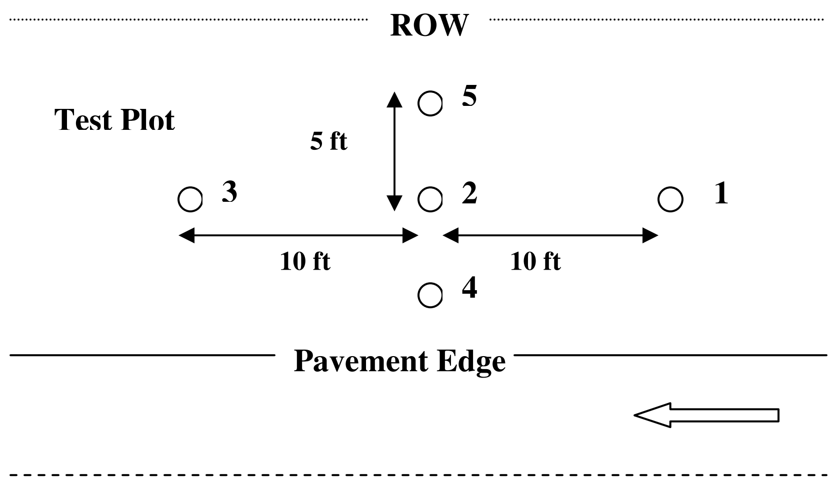


Figure 4.12 Typical section showing spike orientation

Table 4.2 Typical Surveying Data from Test Plot 1

Date	**Station 1 (BSC)**				
	1	**2**	**3**	**4**	**5**
Apr 3 03	-9.65	-9.74	-9.75	-9.18	-10.42
Apr 15 03	-9.54	-9.69	-9.68	-9.12	-10.35
Apr 24 03	-9.59	-9.7	-9.73	-9.2	-10.39
Jun 01 03	-9.65	-9.82	-9.79	-9.23	-10.44
Jun 16 03	-9.63	-9.76	-9.77	-9.22	-10.51

Potential elevation changes of each plot were calculated using the average readings of all stations at each site, and these results were used in the analysis to address erodability of the CMTs during service.

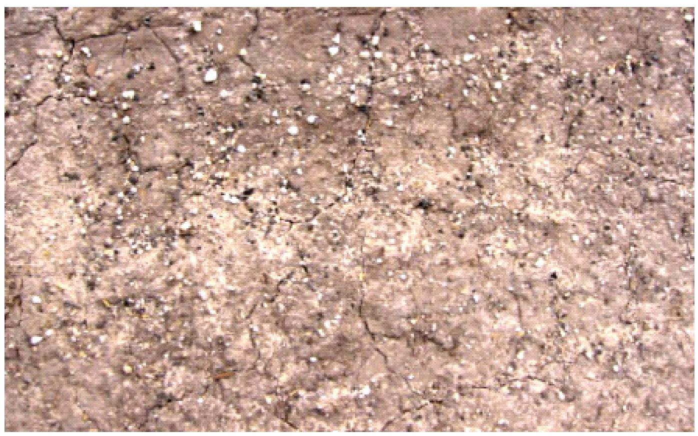
4.7.3 Shrinkage Analysis

Though free swell analysis strain tests are often used in geotechnical practice to characterize expansive soils, shrinkage or desiccation strains are considered equally important since they initiate the failure mechanisms (cracks) in expansive soils to expose large volumes of soil surface area at varying depths to saturation. If not immediately remediated, shrinkage strains in soils induced by dry environments can lead to crack propagation in both the lateral and longitudinal directions. As a result, large volumes of expansive subgrades near shrinkage cracks will have moisture access during rainy seasons and will start expanding once they are saturated. Hence, it is essential to properly characterize the shrinkage strain potentials of natural and compost amended soils.

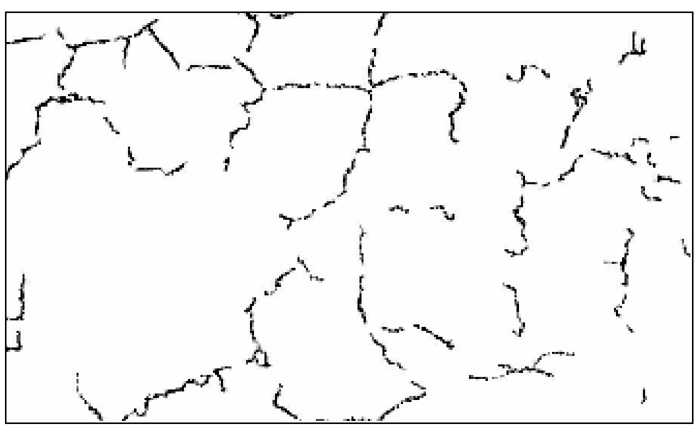
Typical shrinkage strain characterization practice is to collect soil samples and then subject them to either linear or volumetric shrinkage strain tests. These laboratory tests were not preferred in this research since the materials to be tested would be small in size and the tests would not provide any understanding of longitudinal and shrinkage strains observed in the field. This method would also lead to manual errors in the measurement of linear shrinkage strain magnitudes of soils. To rectify this error, a new digital image processing technique developed by UTA was employed.

4.7.3.1 Digital Image Analysis

Imaging software developed by Scion Corporation was adopted to analyze the shrinkage cracks. The primary image processing technique used in the research work was "thresholding". The purpose of "thresholding" is to select the pixel intensity value which separates the objects from a general background. Ideally, after "thresholding", all cracked portions would be depicted as black pixels and soil as white pixels, as shown in Figures 4.13 a and b.



(a)



(b)

Figure 4.13 Digital images (a) before (b) after the analysis

4.7.3.2 Shrinkage Cracks Calculation

The following steps describe the percent shrinkage cracks of the test plots during the field data monitoring.

1. The surface of each test plot was photographed with a high-resolution digital camera with the pictures then downloaded into a computer.
2. The photograph was opened in Paint software and saved in a .bmp format.
3. The soil picture was opened in the Scion image and the total area "A_t" of the entire sample was calculated using the "Measure" function of the Scion image software.
4. A "threshold" value was selected to view the cracked and non-cracked portions. Once the non-cracked portions had been removed, the area of the cracked portion "A_s" was measured by using the "Measure" function in the Scion image software.
5. Shrinkage was then calculated by taking the ratio or percentage of the "threshold" image in pixels (A_s) to the total area of the image in pixels (A_t).

$$\text{Shrinkage} = \frac{A_s}{A_t}$$

Due to the size of each test plot, three pictures were randomly taken to cover the entire test surface area during each site visit. Three images taken for each test plot were used to determine the average shrinkage value of the test plot. These digital photos were taken during site visits on days during which no rain was recorded at the site for one week prior to the visit. If rain events took place, the cracks were typically healed and the digital shrinkage strains would be lower. This would affect the overall statistical analysis and hence care was taken to collect the data that was representative of the shrinkage or dry conditions. The data collection and analysis of all test plots was continued for a total of seventeen months.

4.7.4 Paved Shoulder Cracking

In order to distinguish between the new and old cracks on the adjoining pavement, digital pictures of the paved shoulder were periodically taken. Old cracks had been crack sealed with a bitumen product and these can be seen in a digital photograph shown in Figure 4.14. As the paved shoulder began to deteriorate, cracks would continue to appear and propagate as well as widen. These cracks were recorded. By comparing the photographs at the same location, the severity of cracking could be estimated.

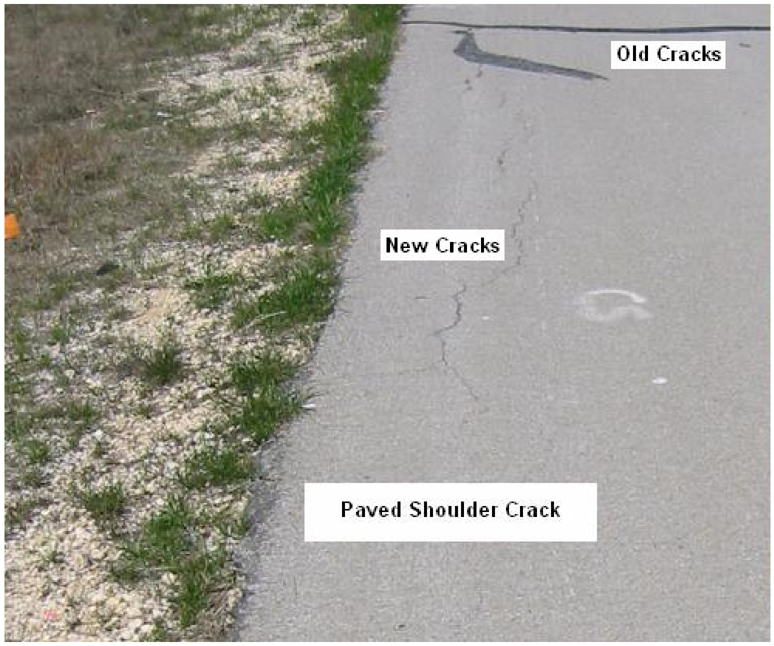


Figure 4.14 Paved shoulder cracks on the Control Plot at Stephenville site

4.7.5 Vegetation Growth

Regardless of the use of composts to amend and protect unpaved shoulders and slopes, one of the eventual goals of this amendment is to allow native vegetation to grow naturally and permanently stabilize the soils in shoulders and slopes (Tyler, 2003). In this research, an attempt was made to qualitatively assess the vegetation density in the test plots.

A digital photographic record showing the thickness of vegetation at each plot was collected and documented. A visual observation was used to compare vegetation cover and thickness at a specified plot or between several areas of each plot. These records were taken periodically. Figure 4.15 shows a typical record of vegetation growth at the Control Plot.

Figure 4.15 Vegetation growth at each test plot

4.8 Summary

This chapter provides a complete description of various steps involved in the construction of test sections in field conditions. This chapter also summarizes various field monitoring tasks used in this research to evaluate the ability of compost amended soils to serve as unpaved shoulder cover soils. Field instrumentation with moisture and temperature probes were used to collect moisture and temperature fluctuations during the monitoring period. Elevation surveys to address erosion and digital image analyses to evaluate shrinkage cracking of the test plots were discussed. These results will be statistically analyzed in subsequent chapters to evaluate the potential of compost materials for better treatment of expansive shoulder subgrades with minimal desiccation cracking.

CHAPTER 5

ANALYSIS OF FIELD PERFORMANCE TEST RESULTS: FIRST PHASE

5.1 Introduction

This chapter addresses key questions regarding the field performance of the first study phase. The effectiveness of each CMT in reducing moisture and temperature variations, erosion control, desiccation cracking, paved shoulder cracking and vegetation reestablishment are discussed. The effects of treatment depth and width are also explained. Ranking analysis based on field performance was performed to determine the most efficient field application.

5.2 Methods of Analysis

Methods of analysis consisted of statistical analysis and visual observations. In most cases, questions are answered by statistical analyses using comparison tests such as the t- test. In the t-test, the mean values of performance indices for each CMT and the Control Plot are compared. A statistical program was used to perform all analyses in this research. All statistical differences among treatments identified in this research were set at a p-value of 0.05 or less. This means that there is less than a 5% chance that the treatment means are not truly different. The following are the hypotheses used in the research.

$H_0 : \mu_1 = \mu_2$ (The means of the control and CMT sections are the same)

$H_1 : \mu_1 \neq \mu_2$ (The means of the control and CMT sections are different)

where μ_1 = Mean of the control section

μ_2 = Mean of CMT section

Once significant differences in performance indices are found, then the effectiveness of compost amendments to mitigate shrinkage cracking can be explained. However, if the statistical analyses show no significant difference between the Control Plot and other CMT plots, then it can be concluded that the CMTs and Control Plot showed similar performance. In such cases, the plot performance and compost enhancements are still evaluated by assessing the variations in magnitudes of average values of performance index parameters.

Visual observation was used to compare the performance of CMT plots when magnitudes of performance indices could not be determined. Both vegetation growth and appearance of new cracks on the paved shoulders fell into this category. Digital photographic records were taken periodically at the same test locations to record the magnitudes of performance indices at each plot. These records were then compared with photos taken immediately after construction.

5.3 Analysis of Field Data from the First Phase (April 2003-August 2004)

5.3.1 Moisture Fluctuations

Volumetric moisture contents and soil temperature were continuously recorded from April 2003 to August 2004. A typical example of the data is shown in Figure 5.1. The moisture variation was determined by finding the differences between maximum and minimum volumetric moisture contents in each month. Average values of these moisture variations are determined and used as the 'mean moisture variation' in this research. Moisture variation analysis was done by comparing the 'mean moisture variation' of every plot to the 'mean moisture variation' of the Control Plot. It should be mentioned that the analysis was also conducted on biweekly data. However, no significant difference was found.

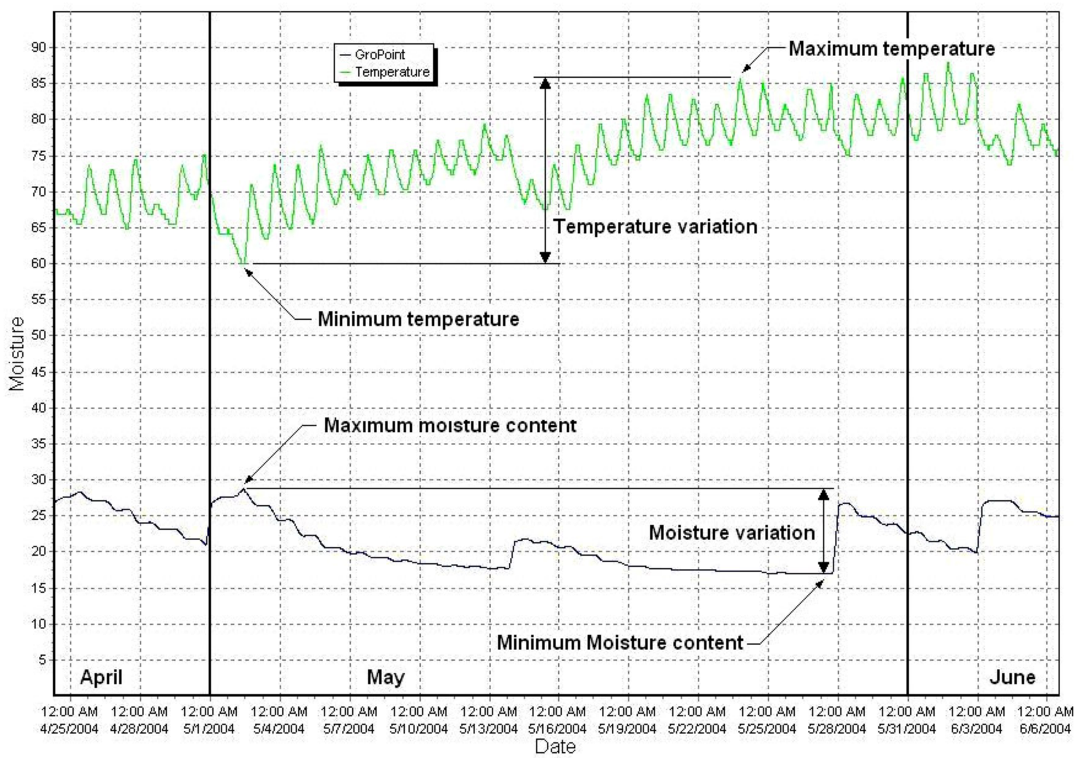


Figure 5.1 Typical temperature and volumetric moisture data

Due to the hydrophilic nature of composts, it was anticipated that plots covered with compost amended topsoils would be able to attract and retain moisture and therefore reduce moisture variations. The moisture retention was expected to reduce the desiccation cracking in the subsoil and subsequently through the pavement. However, from the moisture variation analysis, the moisture variation of the subgrade soils at the 6 inch depth does not vary significantly when compared with the moisture variation of the Control Plot. The results are shown in Table 5.1.

Table 5.1 Statistical analysis of 'Mean Moisture Variations'

Plot	**Control mean moisture variation**	**Plot mean moisture variation**	**t-value**	**Df**	**p-value 2-sided**	**Variation at 6 in depth**
CMT4-10-4	15.34	12.77	0.8384	26	0.4095	Same
CMT3-10-4	15.34	13.78	0.5023	25	0.6198	Same
CMT2-10-4	15.34	11.63	0.7412	19	0.4677	Same
CMT1-10-4	15.34	21.84	-1.7618	20	0.0934	Same
CMT4-10-2	15.34	12.68	0.8314	24	0.4139	Same
CMT3-10-2	15.34	15.13	0.0524	23	0.9587	Same
CMT2-10-2	15.34	17.35	-0.3930	24	0.6978	Same
CMT1-10-2	15.34	22.19	-1.6756	23	0.1074	Same
CMT4-5-2	15.34	15.80	-0.1333	23	0.8951	Same
CMT3-5-2	15.34	13.06	0.5827	18	0.5673	Same
CMT2-5-2	15.34	14.40	0.2436	23	0.8097	Same
CMT1-5-2	15.34	15.05	0.0732	20	0.9424	Same
CMT4-5-4	15.34	16.75	-0.4580	24	0.6511	Same
CMT3-5-4	15.34	18.43	-0.8587	23	0.3993	Same
CMT2-5-4	15.34	14.54	0.1921	21	0.8495	Same
CMT1-5-4	15.34	18.15	-0.5214	23	0.6071	Same

Although 'mean moisture content' variations are not statistically different, the CMTs' performance can be ranked by using the magnitudes of 'mean moisture variation' values recorded during the monitoring. Table 5.2 shows the 'mean moisture variations' of all plots from the lowest to the highest values. It can be noted that approximately half of all 16 plots have lesser variations than the Control Plot and the moisture variations in all plots varied from 11.6 to 22.2%. A high variability in moisture variations in certain plots is attributed to highly localized conditions, such as percent compost, compost properties, soil properties, and vegetation density. Figure 5.2 presents the results in graphical form.

Table 5.2 Sorted 'Mean Moisture Variations'

Material	**Compost**	**Width (ft)**	**Thickness (in.)**	**Mean Moisture Variation (%)**
CMT 2	DMC	10	4	11.63
CMT 4	BSC	10	2	12.68
CMT 4	BSC	10	4	12.77
CMT 3	BSC	5	2	13.06
CMT 3	BSC	10	4	13.78
CMT 2	DMC	5	2	14.40
CMT 2	DMC	5	4	14.54
CMT 1	DMC	5	2	15.05
CMT 3	BSC	10	2	15.13
CS	-	10	4	15.34
CMT 4	BSC	5	2	15.80
CMT 4	BSC	5	4	16.75
CMT 2	DMC	10	2	17.35
CMT 1	DMC	5	4	18.15
CMT 3	BSC	5	4	18.43
CMT 1	DMC	10	4	21.84
CMT 1	DMC	10	2	22.19

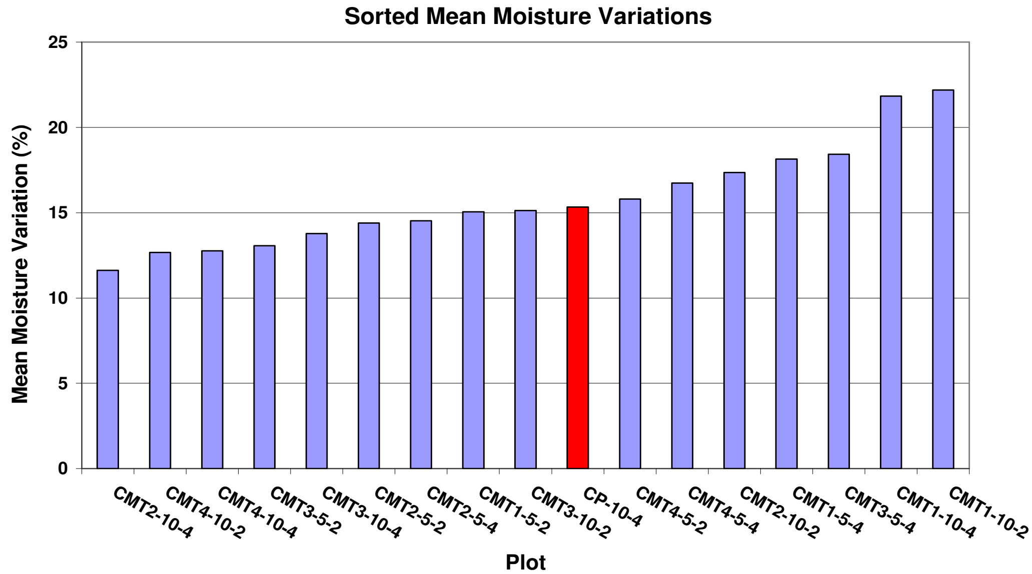


Figure 5.2 Sorted 'Mean Moisture Variations' values of present plots

The following observations can be listed from the results reported in Table 5.2 and Figure 5.2

- Biosolids Compost amended soils provided effective encapsulation when they were used to cover the test plots by 10 ft wide and 4 in. deep.
- Dairy Manure Compost amendments did not appreciably preserve the moisture content in the plots, which are attributed to low amounts of organics present in these amendments.

Another type of analysis was attempted by comparing the minimum moisture content in the test plots with respect to initial moisture contents. Table 5.3 and Figure 5.3 compare the initial moisture content in each plot with an average low or minimum moisture content. In table 5.3, plots with minimum moisture readings less than initial moisture readings are highlighted in gray. As mentioned earlier, most compost plots, except plots 3, 8, 15 and 16, did not experience any moisture losses beyond their initial compaction moisture contents. The Control Plot (17) with no compost covers experienced loss in moisture content below the initial compaction moisture content. The plots that experienced the most moisture losses were some of the Dairy Manure Compost plots indicating that this material possibly did not provide effective encapsulation of the surface. In the case of the Biosolids Compost plots, the reduction of the CMT treatment width appeared to result in higher moisture variations.

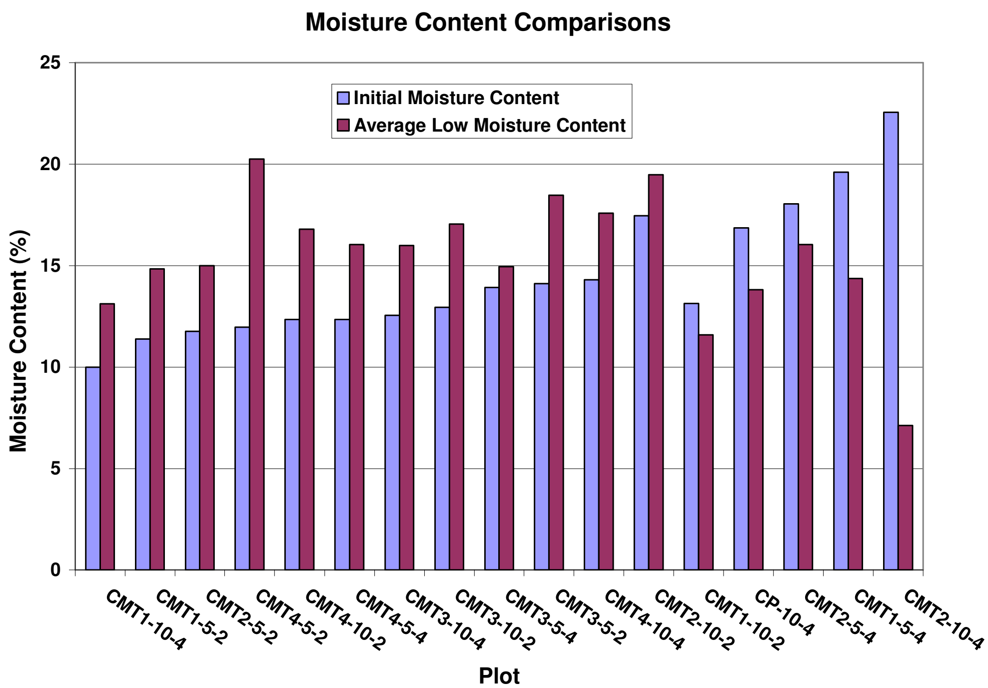


Figure 5.3 Moisture content comparisons

Table 5.3 Moisture Content Comparisons in the Control and Test Plots

Plot	Plot No.	Min. Moisture Readings @ 6 in.	Initial Moisture Readings @ 6 in.
CMT4-10-4	1	17.59	14.31
CMT3-10-4	2	15.99	12.55
CMT2-10-4	3	7.12	22.55
CMT1-10-4	4	13.12	10.00
CMT4-10-2	5	16.81	12.35
CMT3-10-2	6	17.04	12.94
CMT2-10-2	7	19.47	17.45
CMT1-10-2	8	11.58	13.14
CMT4-5-2	9	20.26	11.96
CMT3-5-2	10	18.46	14.12
CMT2-5-2	11	15.00	11.76
CMT1-5-2	12	14.84	11.37
CMT4-5-4	13	16.03	12.35
CMT3-5-4	14	14.95	13.92
CMT2-5-4	15	16.04	18.04
CMT1-5-4	16	14.36	19.61
CP-10-4	17	12.66	16.86

5.3.2 Temperature Fluctuations

Temperature variation analysis was also performed in a similar manner as moisture variation analysis. In Table 5.4, most temperature variations except on plots (CMT4-10-4 and CMT2-10-4) are not statistically different. Therefore, the CMT performance was ranked by using the average values.

Table 5.4 Temperature Variation Analysis

Plot name	CP Mean	Plot Mean	t-value	df	p-value 2-sided	Variation at 6 in. depth
CMT4-10-4	22.71	15.57	3.2770	14	0.0055	Lesser
CMT3-10-4	22.71	15.60	2.0687	14	0.0576	Same
CMT2-10-4	22.71	15.18	2.2352	11	0.0471	Lesser
CMT1-10-4	22.71	17.00	1.7986	13	0.0953	Same
CMT4-10-2	22.71	19.56	1.3365	14	0.2027	Same
CMT3-10-2	22.71	18.26	1.7451	14	0.1029	Same
CMT2-10-2	22.71	21.43	0.5169	14	0.6133	Same
CMT1-10-2	22.71	30.29	-2.1326	10	0.0588	Same
CMT4-5-2	22.71	24.88	-0.5225	14	0.6095	Same
CMT3-5-2	22.71	20.75	0.6540	11	0.5265	Same
CMT2-5-2	22.71	17.82	1.6895	14	0.1133	Same
CMT1-5-2	22.71	29.45	-2.0147	11	0.0690	Same
CMT4-5-4	22.71	23.25	-0.2160	14	0.8321	Same
CMT3-5-4	22.71	29.07	-2.1751	10	0.0547	Same
CMT2-5-4	22.71	17.32	1.2802	9	0.2325	Same
CMT1-5-4	22.71	19.91	0.7724	14	0.4527	Same

Note: df – degree of freedom as per statistical analysis

Table 5.5 and Figure 5.4 rank the temperature variations from lowest to highest. It can be noted that 11 of the 16 plots have lesser temperature variations than the Control Plot. This is attributed to the ability of composts to encapsulate thermally and hence preserve moderate temperatures at shallow depths. The compost acts like an insulator that keeps soil cool in hot weather and keeps soil warm in cold weather. As a result, rapid fluctuations in soil temperature were not recorded in the CMT plots.

Table 5.5 Sorted Temperature Variations

Material	**Width**	**Thickness**	**Temperature Variation (^oF)**
CMT2-10-4	10	4	15.18
CMT4-10-4	10	4	15.57
CMT3-10-4	10	4	15.60
CMT1-10-4	10	4	17.00
CMT2-5-4	5	4	17.32
CMT2-5-2	5	2	17.82
CMT3-10-2	10	2	18.26
CMT4-10-2	10	2	19.56
CMT1-5-4	5	4	19.91
CMT3-5-2	5	2	20.75
CMT2-10-2	10	2	21.43
CP	10	4	22.71
CMT4-5-4	5	4	23.25
CMT4-5-2	5	2	24.88
CMT3-5-4	5	4	29.07
CMT1-5-2	5	2	29.45
CMT1-10-2	10	2	30.29

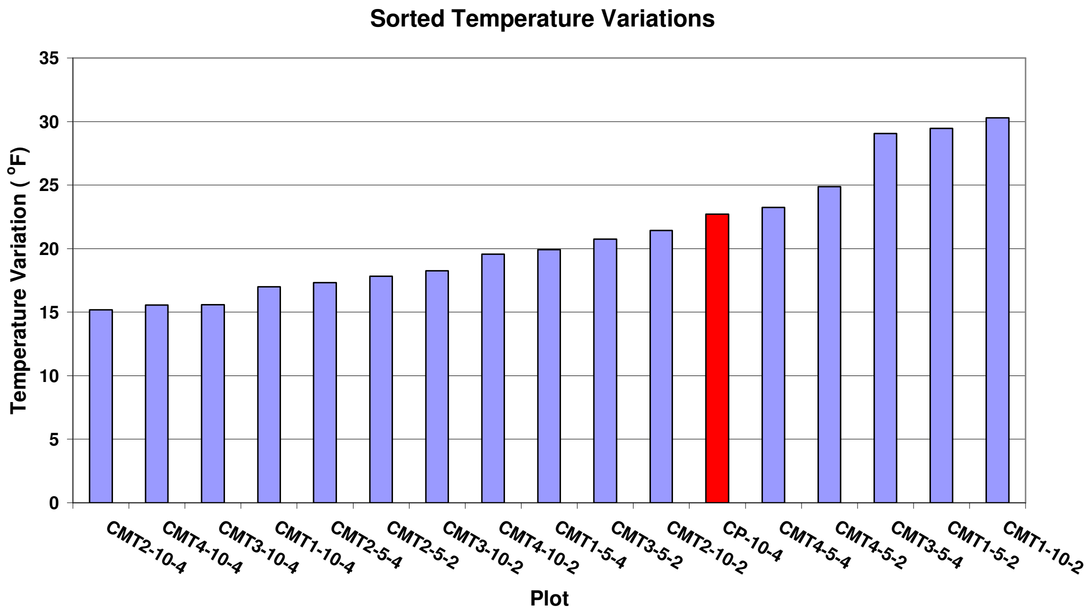


Figure 5.4 Sorted temperature variations

Tables 5.6 and 5.7, as well as Figures 5.5 and 5.6, present the effects of plot thickness and width on temperature variation. By grouping plots by width (5 and 10 feet), the effect of thickness can be clearly seen (Table 5.6 and Figure 5.5). Out of the total of 8 pairs, 7 pairs (highlighted in gray) indicate that plots with thickness of 2 inches have higher temperature variations than plots with 4 inch thickness. This indicates that the compost treatment depth has a direct influence on the temperature fluctuations.

Table 5.6 Effect of Treatment Depth on Temperature Variations

Width (ft)	Material	Thickness (in)	Temperature Variation (°F)
5	CMT1	2	29.45
	CMT2	2	17.82
	CMT3	2	20.75
	CMT4	2	24.88
	CMT1	4	19.91
	CMT2	4	17.32
	CMT3	4	29.07
	CMT4	4	23.25
10	CMT1	2	30.29
	CMT2	2	21.43
	CMT3	2	18.26
	CMT4	2	19.56
	CMT1	4	17
	CMT2	4	15.18
	CMT3	4	15.6
	CMT4	4	15.57

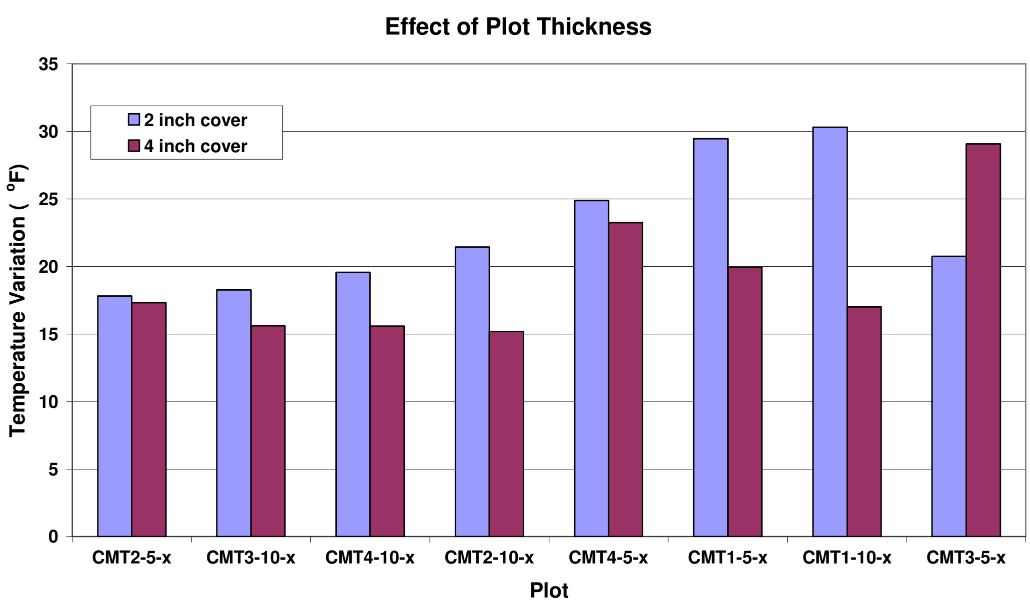


Figure 5.5 Effect of plot thickness

The effect of width in each test plot can also be explained from the following Table 5.7 and Figure 5.6. Six (6) out of the 8 pairs (highlighted in gray) indicate that the plots with width of 5 feet have higher temperature variations than of the 10 foot wide plots. Among all the test plots prepared with composts of 10 foot width, Biosolids Composts provided slightly better thermal encapsulation than Dairy Manure Composts.

Table 5.7 Effect of Shoulder Width

Thickness (in)	Material	Width (ft)	Temperature Variation (^oF)
2	CMT1	5	29.45
	CMT2	5	17.82
	CMT3	5	20.75
	CMT4	5	24.88
	CMT1	10	30.29
	CMT2	10	21.43
	CMT3	10	18.26
	CMT4	10	19.56
4	CMT1	5	19.91
	CMT2	5	17.32
	CMT3	5	29.07
	CMT4	5	23.25
	CMT1	10	17
	CMT2	10	15.18
	CMT3	10	15.6
	CMT4	10	15.57

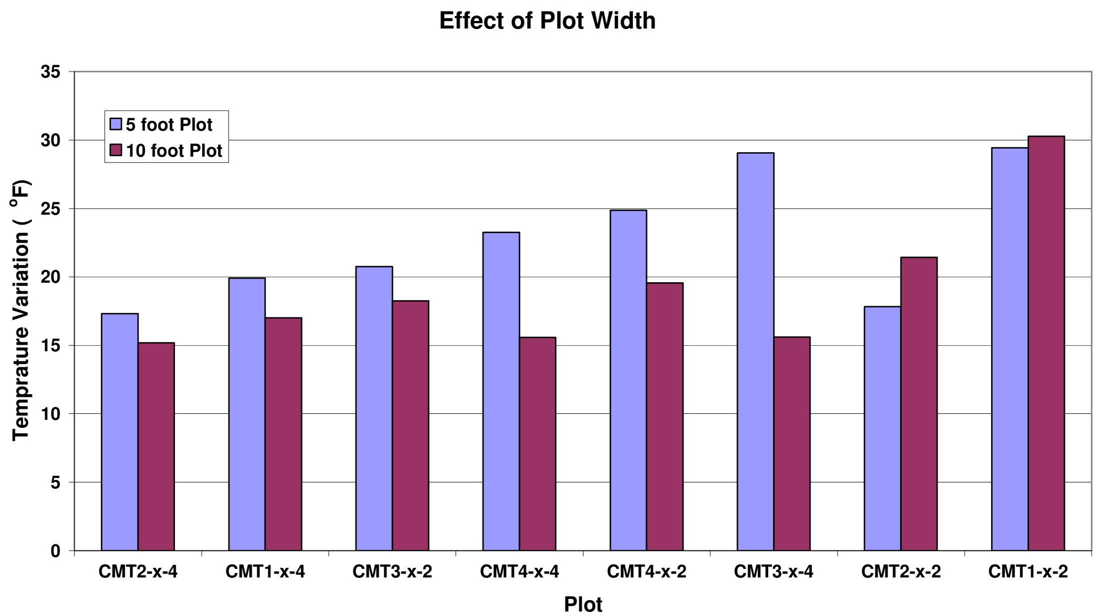


Figure 5.6 Effect of plot width

5.3.3 Erosion control

Controlling erosion is a key component in road and highway construction or rehabilitation projects. Roadside embankments, shoulders, medians, and other non-paved surfaces can be vulnerable to eroding forces such as surface runoff and storm events (Middleton et al., 2003). Controlling erosion means stopping soil movement at its source. Compost provides a physical cushion type of barrier between rainfall and the surface soil, dissipating the effect of impact energy. Figures 5.7-5.12 show the pictures of subsoil surfaces taken immediately after construction and 3 months after construction, respectively, for the three main types of treatment. It can be noted from the figures that soil erosion was a problem in the Control Plot, indicating the importance of compost to serve as protective covers. Another item to mention here is that the erosion removes topsoil, which is rich in nutrients. Hence, it reduces the ability of plants to grow in the compacted soils. A reduction in vegetation or grass growth causes further erosion.

Figure 5.7 Soil surface after construction (CONTROL)

Figure 5.8 Soil surface 3 months after construction (CONTROL)

Figure 5.9: Soil surface after construction (DMC)

Figure 5.10 Soil surface 3 months after construction (DMC)

Figure 5.11 Soil surface after construction (BSC)

Figure 5.12 Soil surface 3 months after construction (BSC)

Plot erosion is an average of erosion at all 5 spikes in each plot. Erosion at each spike can be calculated by subtracting the elevation of each spike from an initial elevation. Plot erosions are then grouped by different CMTs and averaged to determine the final surface erosion. Surface profiles for different CMTs are determined and illustrated in Figure 5.13. About half of the total erosion occurred in the first three months after construction. This could be attributed to the rearrangement of particles, heavy rains during that period and no seeding until 3 months after the construction. Subsequently, the erosion was less than 0.1 ft (1.2 in) over the last 14 months. This lowered erosion is due to the seeding of grass that took place during early Fall in 2003.

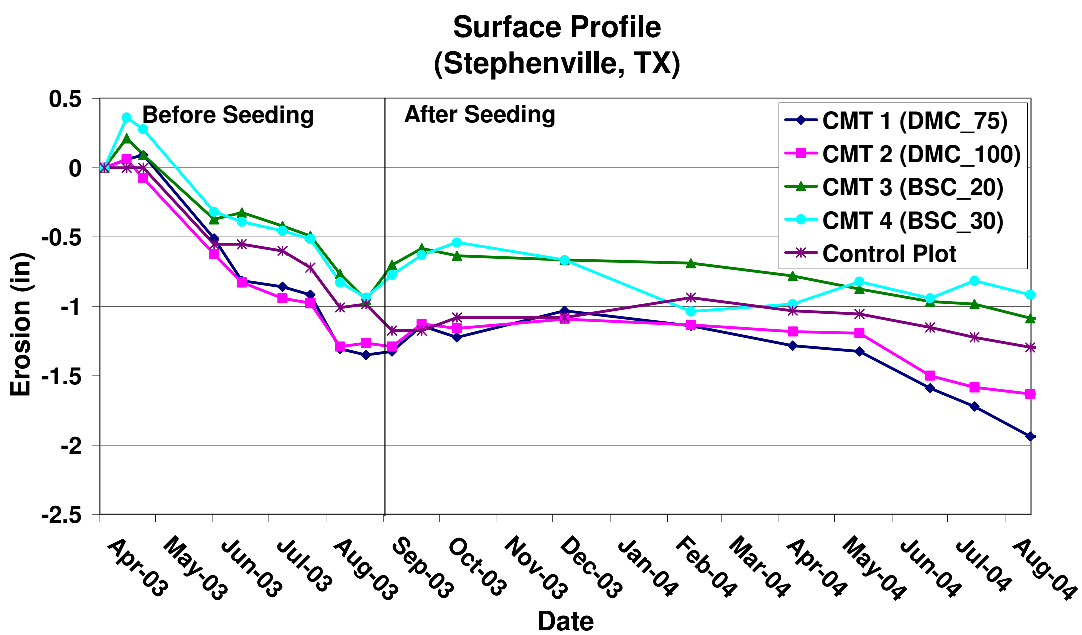


Figure 5.13 Surface profile at Stephenville site

Although the statistical analysis of the surface profiles (Table 5.8) indicated that all materials had the same elevation changes, both plots of Dairy Manure Compost manufactured topsoils (i.e. CMT 1 and CMT 2 plots), which had less fibrous materials and low vegetation, had experienced approximately 21% higher erosion than the erosion observed on the Control Plot. As a result of the high amount of fibrous materials which helps in dissipating eroding forces, both plots of Biosolids Compost manufactured topsoils (i.e. CMT 3 and CMT 4) had approximately 29% lesser erosion than the erosion of the Control Plot.

Table 5.8 Analysis of Surface Profiles

Material	Average Erosion (in)		t-value	Df	p-value
	Control Plot	CMT Plot			
DMC_75	-0.89	-1.10	1.2544	40	0.2169
DMC_100	-0.89	-1.05	1.0816	40	0.2858
BSC-20	-0.89	-0.64	-1.9259	40	0.0612
BSC_30	-0.89	-0.62	-1.9913	40	0.0532

5.3.4 Digital Image Shrinkage Analysis

Large volumes of expansive subgrades near shrinkage cracks will have moisture access during wet seasons and will start expanding once they are saturated. Hence, it is essential to properly characterize the shrinkage strain potentials of compost surface materials. Due to the size of each test plot, three digital images were randomly taken for each test plot and shrinkage results of these three images were calculated using the procedure described in Chapter 4. These results were used to determine the average shrinkage strain value of each test plot. These digital photos were taken during site visits on days during which no rain was recorded at the site in the past week to represent dry conditions. This data collection and analysis of all the test plots was continued for a total of seventeen months.

Table 5.9 and Figure 5.14 present the digital shrinkage analysis performed on the CMTs. The shrinkage strain values reported are the average values over the entire monitoring period. It can be concluded that Biosolids Compost plots (CMT 3 and 4 plots) have lesser cracking than the Control Plot. In all cases except one, the difference is statistically significant (see Table 5.9). This is attributed to the fibrous materials (woodchips) present in the BSC. These materials act like reinforcements which can withstand tensile forces generated from drying of the soil. Goldsmith (2001) also reported that root systems can increase the tensile strength of soil. On the other hand, DMC which had less fibrous materials (wood trimmings) to sustain tensile forces, experienced higher shrinkage cracking which was statistically significant in all cased except one (see Table 5.9).

Table 5.9 Shrinkage Cracking Analysis

Plot name	Compost Type	CP Mean Shrinkage	Plot Mean Shrinkage	t-value	df	2-sided p-value	Cracking
CMT4-10-4	BSC	0.1351	0.0866	3.6290	21	0.0016	Lesser
CMT3-10-4	BSC	0.1351	0.0800	3.2974	21	0.0034	Lesser
CMT2-10-4	DMC	0.1351	1.1946	-7.8313	21	0.0000	More
CMT1-10-4	DMC	0.1351	1.2516	-6.5306	20	0.0000	More
CMT4-10-2	BSC	0.1351	0.0814	3.3444	21	0.0031	Lesser
CMT3-10-2	BSC	0.1351	0.0730	4.8645	21	0.0001	Lesser
CMT2-10-2	DMC	0.1351	0.7772	-3.9127	21	0.0008	More
CMT1-10-2	DMC	0.1351	0.6408	-3.1802	21	0.0045	More
CMT4-5-2	BSC	0.1351	0.1110	0.5427	21	0.5930	Same
CMT3-5-2	BSC	0.1351	0.0723	4.3967	21	0.0003	Lesser
CMT2-5-2	DMC	0.1351	0.7762	-4.1712	21	0.0004	More
CMT1-5-2	DMC	0.1351	0.1955	-1.0351	21	0.3124	Same
CMT4-5-4	BSC	0.1351	0.0576	4.5434	21	0.0002	Lesser
CMT3-5-4	BSC	0.1351	0.0881	2.4485	21	0.0232	Lesser
CMT2-5-4	DMC	0.1351	0.7150	-3.8342	27	0.0007	More
CMT1-5-4	DMC	0.1351	0.6238	-2.6071	23	0.0158	More

Note: df – degree of freedom

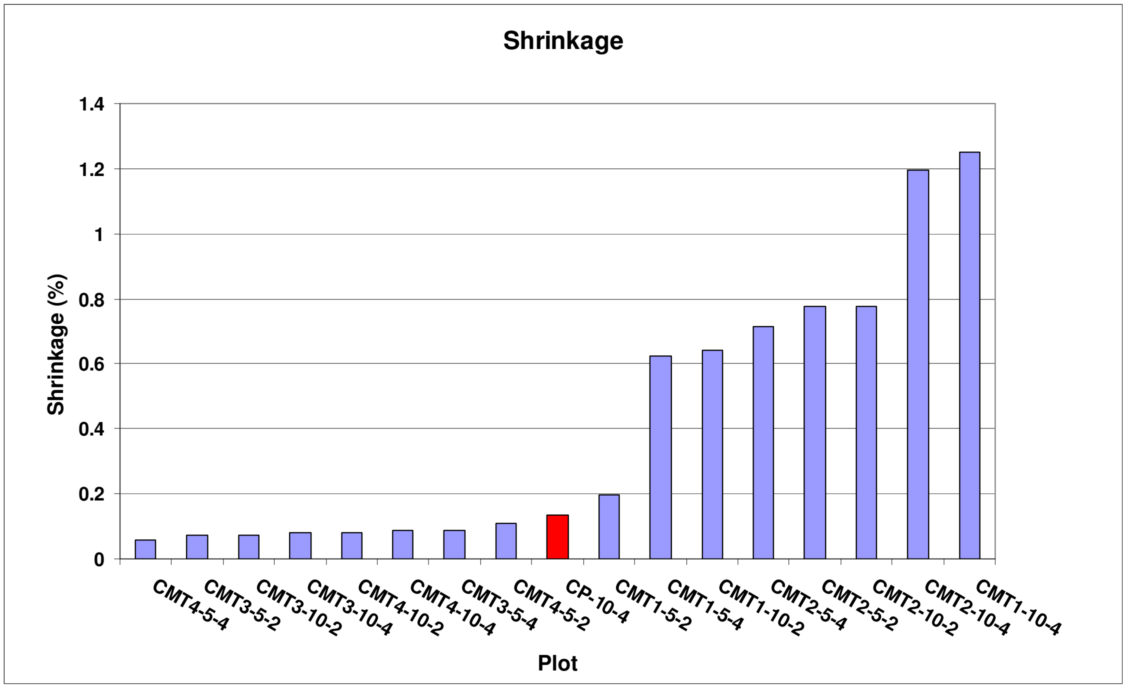


Figure 5.14 Shrinkage cracking in the test plots

Table 5.10 and Figure 5.15 also show the maximum shrinkage strain recorded in each plot during the monitoring period. All BSC plots with the exception of CMT4-5-2 experienced lesser shrinkage cracking than that of the Control Plot. This also concurs with the other CMT performances mentioned earlier by the Biosolids Composts. From this, it can be concluded that the BSC has the ability to restrain and mitigate desiccation shrinkage cracking better than the DMC.

Table 5.10 Maximum Shrinkage Strains in Test Plots

Plot	Compost	Shrinkage
CMT3-10-2	BSC	0.17
CMT4-10-4	BSC	0.17
CMT3-5-2	BSC	0.18
CMT4-5-4	BSC	0.20
CMT3-10-4	BSC	0.23
CMT4-10-2	BSC	0.23
CMT3-5-4	BSC	0.31
CP-10-4	-	0.34
CMT1-5-2	DMC	0.64
CMT4-5-2	BSC	1.04
CMT1-5-4	DMC	1.47
CMT2-10-2	DMC	1.71
CMT1-10-2	DMC	1.81
CMT2-5-4	DMC	1.93
CMT2-5-2	DMC	1.93
CMT2-10-4	DMC	2.03
CMT1-10-4	DMC	2.53

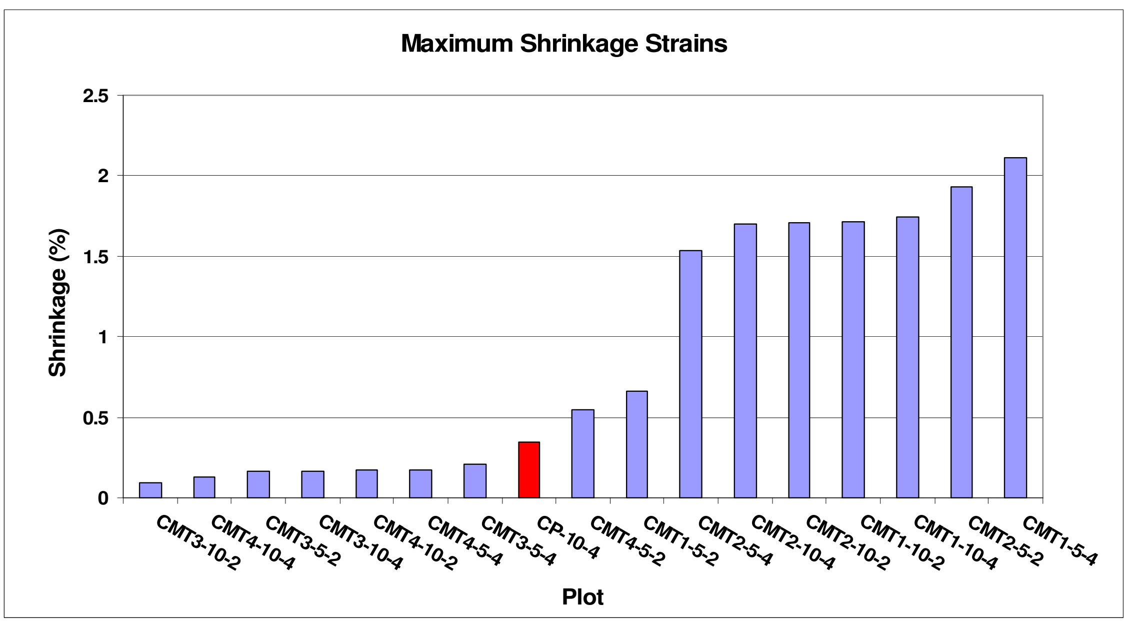


Figure 5.15 Maximum shrinkage strains

5.3.5 Pavement Shoulder Cracking

Pavement shoulder cracking can be attributed to moisture intrusion into the adjacent shoulder subgrade layers due to either desiccation cracking or shrinkage cracking movements. Less cracking on paved shoulders could be used to identify the CMT's effectiveness as an acceptable cover material. Figures 5.16 and 5.17 show a few digital images of pavement shoulder cracks adjacent to the Control Plot taken at different time periods during monitoring. In the first picture, a few longitudinal cracks can be seen. The next image, which was taken a year later, shows the widening and joining of the cracks. Due to the high amount of shrinkage cracking in the Control Plot, paved shoulders exhibited unacceptable cracking. This allowed water intrusion into the underlying subsoils, which further weakened the subgrade. As a result, the paved surface experienced further cracking and widening of existing cracks as shown in Figure 5.17.

Figure 5.16 Paved shoulder on Apr 2003

Figure 5.17 Paved shoulder on Apr 2004

Pavement crack images taken at all the other sixteen plots are presented in Appendix B. Table 5.11 presents the results of visual observations of these images on all the test plots. Cracks could be found on the plots which were treated with both composts at 5 ft. width and 2 in. thickness. Since Plots 9 to 12 have the smallest amounts of composts to retain moisture (5 feet x 2 in.), excess water was still able to infiltrate into the subgrade. Cracks in Plots 8 and 13 are most likely the propagation of cracks from Plots 9 and 12 respectively. However, no new cracks were noted in the plots treated with 10 feet or 4 inched of compost, with the exception of plots 8 and 13 mentioned earlier. Thus, compost added to a width of 10 feet or depth of 4 inches appears sufficient to eliminate pavement shoulder cracking.

Table 5.11 Paved Shoulder Cracking

Plot name	Plot No.	Compost	Visual Observation
CMT4-10-4	1	BSC	No new cracks
CMT3-10-4	2	BSC	No new cracks
CMT2-10-4	3	DMC	No new cracks
CMT1-10-4	4	DMC	No new cracks
CMT4-10-2	5	BSC	No new cracks
CMT3-10-2	6	BSC	No new cracks
CMT2-10-2	7	DMC	No new cracks
CMT1-10-2	8	DMC	New Cracks
CMT4-5-2	9	BSC	New Cracks
CMT3-5-2	10	BSC	New Cracks
CMT2-5-2	11	DMC	New Cracks
CMT1-5-2	12	DMC	New Cracks
CMT4-5-4	13	BSC	New Cracks
CMT3-5-4	14	BSC	No new cracks
CMT2-5-4	15	DMC	No new cracks
CMT1-5-4	16	DMC	No new cracks
CP-10-4	17	-	New Cracks

5.3.6 Vegetation Reestablishment

In pavement construction practice, soil compaction and topsoil removal often result in unprotected, unnourished and impenetrable ground surfaces. This can have severe effects on vegetation reestablishment, which in turn leads to higher erosion, increased runoff, and other consequences of pavement distress. Figures 5.18 through 5.20 show the visual appearances of vegetation after the initial construction of all the plots. It should be mentioned that only a small amount of vegetation can be seen on the

Control Plot, as it was prepared without any topsoil removal and compaction. However, on all the compost plots, no vegetation was observed since topsoil surfaces were disturbed as a result of removal, tilling and compaction.

Figure 5.18 Visual appearance of vegetation of Control Plot

Figure 5.19 Visual appearance of vegetation of Dairy Manure Compost plot

Figure 5.20 Visual appearance of vegetation of Biosolids Compost plot

Table 5.12 summarizes the reestablishment of vegetation on all the test plots by seeding them in early September 2003. The vegetation data was collected via digital images taken on October 10, 2003, which was approximately 6 months after the construction. Visual observation rating of vegetation growth was noted based on the denseness of the vegetation and this rating was attempted by the same researcher (author) for all the images used in this analysis.

Figures 5.21 through 5.23 show typical vegetation pictures of the CS, DMC and BSC plots, respectively. It can be seen that the Control Plot had slight vegetation growth and most DMC plots (CMT 1 and CMT 2) plots have none to slight vegetation growth on them. On the other hand, the BSC plots (CMT 3 and CMT 4) have average to high vegetation growth. The lack of vegetation in the DMC plots could result from the higher compaction density of surficial soil during the construction of those test plots.

Due to low organic content, the DMC CMTs behaved similarly to natural and untreated soils. Goldsmith et al. (2001) reported that when soil compaction levels are high, there appears to be a threshold soil bulk density value beyond which roots are unable to penetrate due to high mechanical resistant of soils (Figure 5.24).

Table 5.12 Vegetation Reestablishment on October 10, 2003

Plot name	Plot No.	Visual Observation
CMT4-10-4	1	Thick
CMT3-10-4	2	Thick
CMT2-10-4	3	Low
CMT1-10-4	4	Low
CMT4-10-2	5	Average
CMT3-10-2	6	Average
CMT2-10-2	7	None
CMT1-10-2	8	Low
CMT4-5-2	9	Thick
CMT3-5-2	10	Average
CMT2-5-2	11	None
CMT1-5-2	12	None
CMT4-5-4	13	Thick
CMT3-5-4	14	Thick
CMT2-5-4	15	Thick
CMT1-5-4	16	Thick
CP-10-4	17	Slight

Figure 5.21 Visual appearance of Control Plot

Figure 5.22 Visual appearance of Dairy Manure Compost plot

Figure 5.23 Visual appearance of Biosolids Compost plot

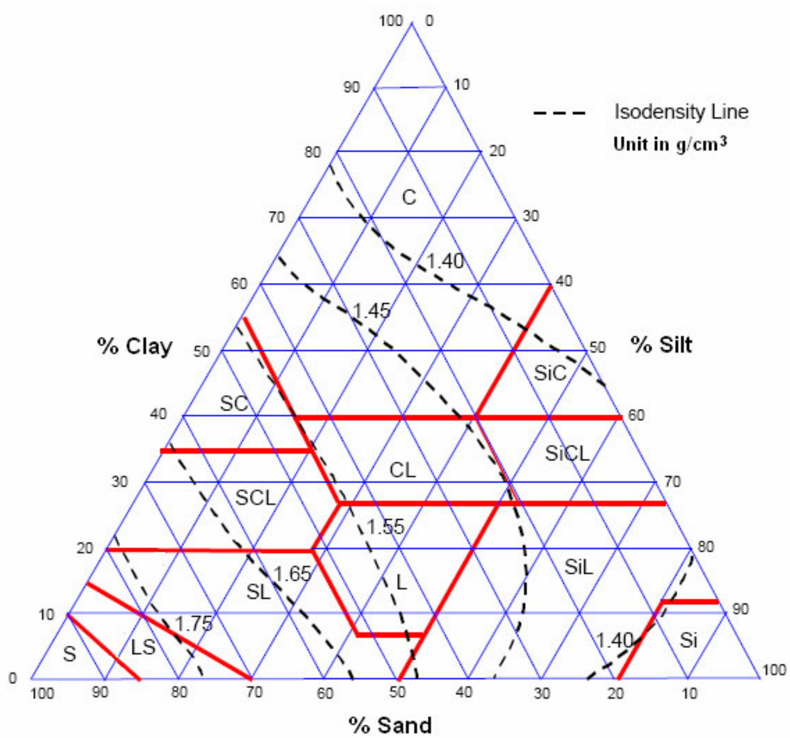


Figure 5.24 Growth-limiting bulk density textural triangle
(Modified from Goldsmith et al. 2001)

From the nuclear gauge density results conducted after the compaction of the test plots (Figure 5.25), it can be seen that the actual compaction dry density values of the test plots after construction came close to the recommended dry density values for construction. As a result, both CMT 1 and CMT 2 plots have high compaction densities (more than 90 pcf), whereas CMT 3 and CMT 4 plots have low compaction densities (less than 80 pcf). It should be noted here that the Control Plot was not recompacted and the original vegetation was allowed to grow on the same plot. Although compaction was not performed on the Control Plot, the actual density of this plot was high (from natural moisture content – dry density measurements), which might have resulted in a low amount of vegetation.

Tyler (2003) reported that in general, a compaction between 80-85 percent of the standard proctor maximum dry unit weight or density optimizes the performance of slope stability with vegetation development and growth. In the present case, this criterion did affect the vegetation growth in certain plots whose relative compactions were above 90%. Vegetation was noted on the compost test plots whose compaction densities were less than 80 pcf (relative compactions less than 85%) and not noted extensively on test plots whose compaction densities were more than 90 pcf (relative compactions more than 85%). However, with continuous seeding, one expects the vegetation growth even on the Dairy Manure Compost test plots.

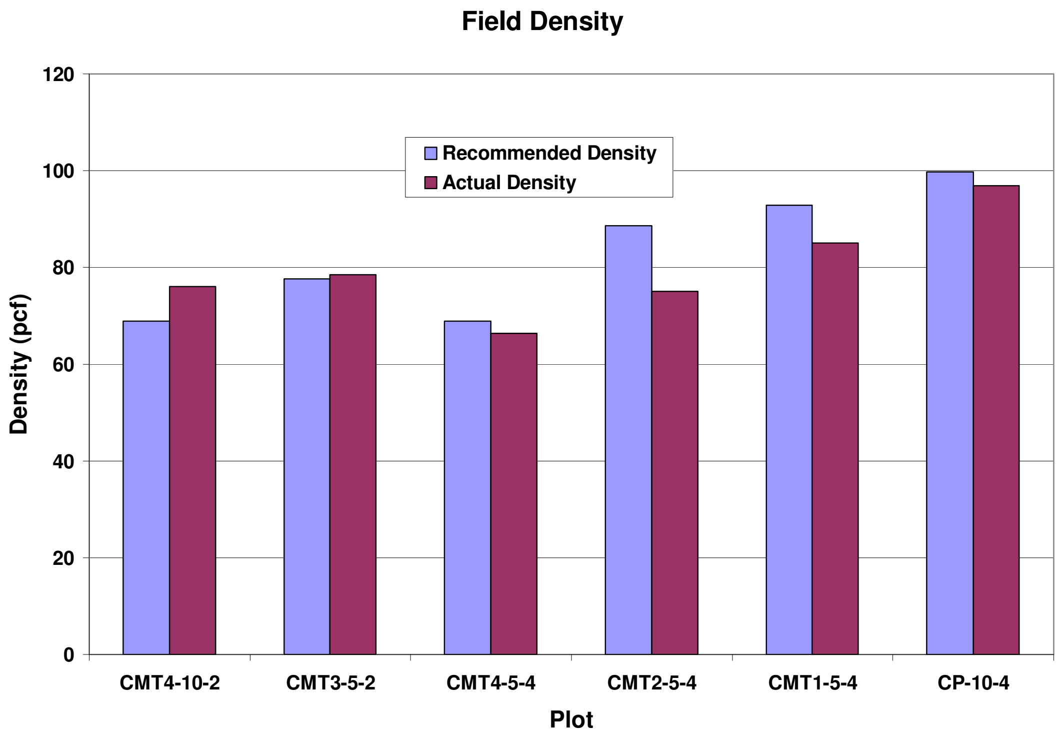


Figure 5.25 Actual and recommended field dry densities

Another reason for the lack of vegetation on the DMC (CMT 1 and CMT 2) and Control Plot is attributed to the low organic content of both the amended and top soil. ASTM standard test method for Organic Content determination (D-2974) was performed on pure and amended soils to measure the percentage of organic matter. The organic content results are presented in Table 5.13.

The maximum percentage of organics was present in BSC_30 material and the minimum percentage was present in the CS soil. The reason for the high organic percentage in BSC_30 was due to the presence of wood chips, rice husks and other organic material used in the composting process of the biosolids compost. In the case of dairy manure materials, the organic material present was low due to the limited mixing of organic fibrous material in the composting process of dairy manure (Pokala, 2003).

Table 5.13 Organic Content Percentages of Pure and Amended Soils

Soil Description	**Organic Content (%)**
CS (Control Soil)	5.92
DMC_75 (25% Control Soil, 75% DMC)	8.86
DMC_100 (100% DMC)	9.94
BSC_20 (80% Control Soil, 20% BSC)	11.76
BSC_30 (70% Control Soil, 30% BSC)	14.52

The normal practice during the construction process is to establish vegetation by seeding immediately after construction. Hence, when compost amended soils are used as cover material, seeding needs to be performed on top of the compost layers. Using both seeding and compost applications will enhance vegetation growth on test plots (Tyler, 2003).

5.3.7 Recommendations Based on Ranking Analysis

This section evaluates the overall performance of all the CMTs. The evaluation is based on moisture content and temperature fluctuations, erosion, shrinkage cracking, paved shoulder cracking and vegetation growth of all the plots. The evaluation and recommendations are shown in Table 5.14. Since paved shoulder cracking indicates the ability of CMTs to protect the integrity of roadways, more importance was given to this observation. Hence, any plots with paved shoulder cracking are not recommended for future composting applications.

It can be noted that plots treated with Biosolids Composts for 10 feet wide and 4 in. depth, both unpaved and paved shoulders performed satisfactorily with no cracking distress. Hence, both CMT3 and CMT4 are recommended from the research. Although the DMC plots are not recommended, a few of the DMC plots did not show any paved shoulder cracking. Therefore, one should not rule out the possibility of using DMCs at different dosages. Future research should explore the possibility of using DMCs at low proportions for soil amendments and then assess their performance on mitigating desiccation cracks.

Table 5.14 Evaluation and Recommendation of CMTs

Plot Name	Enhancement?						Final Recommendation
	Shrinkage	Temp Variation	Moisture Variation	Erosion	Paved Shoulder Cracking	Vegetation	
CMT1-5-2	-	X	✓	X	X	X	X
CMT2-5-2	X	✓	✓	X	X	X	X
CMT3-5-2	✓	✓	✓	✓	X	✓	X
CMT4-5-2	-	X	X	✓	X	✓	X
CMT1-5-4	X	✓	-	X	✓	✓	X
CMT2-5-4	X	✓	✓	X	✓	✓	X
CMT3-5-4	✓	X	X	✓	✓	✓	✓
CMT4-5-4	✓	X	X	✓	X	✓	X
CMT1-10-2	X	X	X	X	X	-	X
CMT2-10-2	X	✓	X	X	✓	X	X
CMT3-10-2	✓	✓	X	✓	✓	✓	✓
CMT4-10-2	✓	✓	✓	✓	✓	✓	✓
CMT1-10-4	X	✓	X	X	✓	-	X
CMT2-10-4	X	✓	✓	X	✓	-	X
CMT3-10-4	✓	✓	✓	✓	✓	✓	✓
CMT4-10-4	✓	✓	✓	✓	✓	✓	✓

Note: ✓**- Effective; X – Not Effective; - - No change.**

CHAPTER 6

FURTHER VERIFICATION OF CMT TEST PLOTS: SECOND PHASE

6.1 Introduction

The first phase of the research was conducted on a clayey soil with low plasticity (CL) from Stephenville, Texas, and hence the research results were valid for such soil type only. To extend and verify the effectiveness of compost amendments to other soil types of other districts in Texas, a further verification study was conducted. Same evaluation approaches were used in the second phase of the study.

The first part of this chapter is devoted to three additional sites' selection process and details of each site. The later part focuses on the statistical analysis of test results obtained from the second phase data collection from the Stephenville site and three new sites. This data collection of Stephenville site for three years has provided data that was used to explain the effective performance of the CMTs and possibly determine the service life of CMTs. The last part of the Chapter focuses on test results from the other three sites (Lubbock, Bryan and Corpus Christi).

Similar to the first phase, compost amended soils were evaluated for their moisture and temperature encapsulation capabilities, erosion reduction and reductions in shrinkage cracking as well as associated pavement cracking and vegetation. Ranking analysis based on field performance analysis was performed to determine the most efficient type of compost for field application. Problems experienced during the construction, data collection and analysis were also addressed. Methods of analysis were similar to those of the first phase.

6.2 Site Selection

At each site, soils from three well known pavement distress sites were sampled and classified. The classification ensured that different types of control expansive soils with distinct PI properties were used for compost application. Soil classification and basic properties of all four site soils are presented in Table 6.1. From the table, basic tests showed a high variation in Plasticity Index (PI) property, which varied from 14 to 47. Lubbock soil exhibited lowest PI value, followed by Bryan soil and Corpus Christi soil. A low value of PI is attributed to a large amount of coarse sized soil particles in this soil. A high PI is attributed to the presence of finer materials (Passing sieve No. 200) in the control soil.

Based on the Atterberg limit and particle size distributions, the control soils from Lubbock and Bryan were classified as clay with low plasticity (CL) as per the Unified Soil Classification System (USCS) and as A-6 per the AASHTO classification. The control soil from Corpus Christi was classified as clay with high plasticity (CH) as per the Unified Soil Classification System (USCS) and as A-7-6 per the AASHTO classification.

Figure 6.1 presents the locations of the three additional sites along with Stephenville, Texas site. These four distinct test sites in Stephenville, Lubbock, Bryan and Corpus Christi regions, were located in Prairies & Lakes, Panhandle Plains, Prairies & Lakes and Gulf Coast regions of the state of Texas, respectively.

Table 6.1 Soil Classification and Basic Soil Properties

Soil Properties	**Stephenville**	**Lubbock**	**Bryan**	**Corpus Christi**
Passing # 200 (%)	60.8	55.5	52.1	81.5
Liquid Limit	44	35	31	62
Plasticity Index (PI)	28	14	18	47
AASHTO Soil Classification	A-7-6	A-6	A-6	A-7-6
USCS Soil Classification	CL	CL	CL	CH

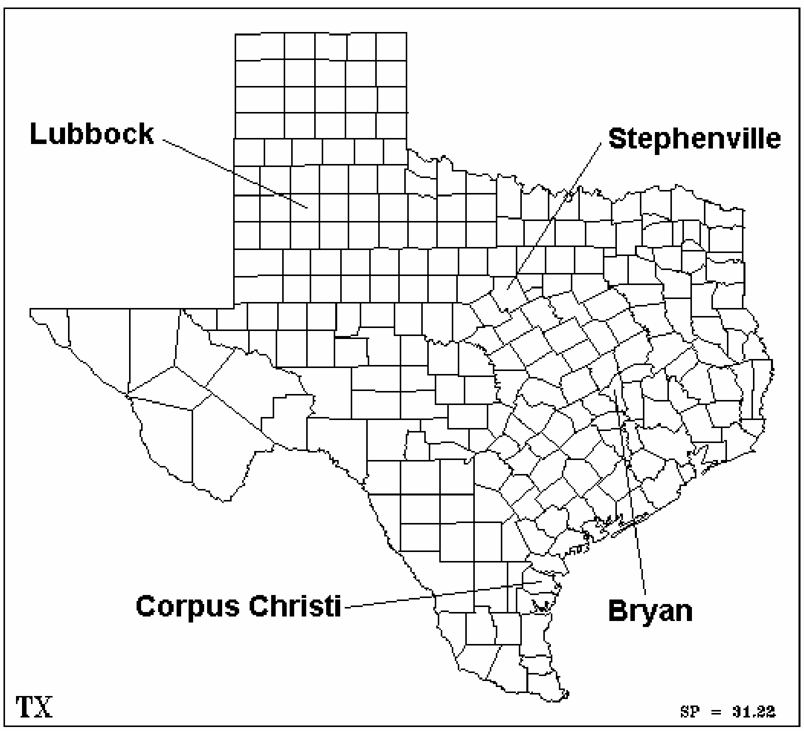


Figure 6.1 Locations of the test sites
(Source: Indiana State University)

6.2.1 Lubbock Site

Lubbock site was situated on US Highway 82 west of Crosbyton, TX. Two composts, Feedlot Compost and Cotton Burr Compost, were acquired from local sources and mixed with the control soil at 20% dry weight to form two types of Compost Manufactured Topsoils, or CMTs. The local soil was classified as clay with low plasticity or lean clay (CL) per the Unified Soil Classification System (USCS) and as A-6 as per the AASHTO classification.

6.2.2 Bryan Site

The next test site was in Bryan. It was on FM 2818 about 2 miles north of State Highway 60 on the west side of the Texas A&M University. Two compost sources were recommended for the field studies, Biosolids Compost from the City of Bryan, Texas and Wood Compost from Conroe, Texas. The local soil was classified as lean clay or CL per the Unified Soil Classification System (USCS) and as A-6 as per the AASHTO classification.

6.2.3 Corpus Christi Site

The Corpus Christi site was situated on FM 188 east of Sinton, Texas. Cow Manure Compost from San Antonio and Biosolids Compost were used as soil amendments. The control soil was classified as CH or heavy clay as per the Unified Soil Classification System (USCS) and as A-7-6 per the AASHTO classification. With January being a wet season, it was difficult to thoroughly amend compost with soil. Therefore, construction during dry season is recommended.

6.3 Test Plot Construction at Lubbock, Bryan and Corpus Christi Sites

At each test site, two CMT test plots were constructed and studied. One Control Plot (CP) with no CMT was included for comparison studies. The plots were constructed by following the design and construction methods of test plots developed for the Stephenville site. Each test plot was 50 ft. long. A transition zone of 25 ft. was used to separate the different plots in order to ensure that the adjacent compost materials did not affect the field results. Based on the recommendations from Stephenville site, a shoulder width of 10 ft and thickness of 4 in. were used in this study.

Field specifications developed for the Stephenville site were first used to design scarification subgrade depth, tilling depth, compost material to be spread over the tilled area and amount of water (in gallons) needed for the preparation of each test strip. After construction, all test sites were embedded with two moisture probes and one temperature probe. Two moisture probes were placed at 6 in. and 12 in. depths from the ground surface. Temperature probe was placed at 6 in. from the surface. These sensor data was used to study moisture content and temperature variations in subsoils. In addition, elevation surveys and digital images of paved and unpaved shoulders were recorded for further analyses and comparisons.

6.4 Analysis of Second Phase Test Results

6.4.1 Stephenville Site

6.4.1.1 Temperature and Moisture Content Data Analyses

The softening of the subgrade soils which support pavement structures often will result in cracking of pavements. The softening results from moisture intrusion coming from a cracked surface. In order to prevent the surface from being dried up, a compost amended soil was used as a cover material. The cover job is to retain soil moisture and prevent a soil surface from desiccating. To understand the effectiveness of the cover material, moisture and temperature records were collected. For the cover material to be effective, the variations of moisture content and temperature in soil should be fairly minimal or lower when compared with the variations of the control soil.

Volumetric moisture contents and soil temperature were continuously recorded from September 2004 to August 2005. Due to a shorter monitoring period, the moisture and temperature variations were determined by determining the differences between maximum and minimum sensor readings of every 15 days. This provided researchers a larger amount of data points, which resulted in a more reliable statistical analysis. Average values of these moisture variations over the entire duration of monitoring were also determined, and these values were termed the ‘mean moisture variation’ and ‘mean temperature variation’. The moisture and temperature variation analyses were attempted by comparing both ‘mean moisture variation’ and ‘mean temperature variation’ of the test plots to the same of the Control Plot. Test results of the statistical analyses are presented in Table 6.2 and 6.3.

Due to the hydrophilic nature of composts, it was anticipated that plots covered with compost amended topsoils would be able to retain moisture and therefore reduce moisture variations. However, from the moisture variation analysis, the moisture variation of the subgrade soils did not vary significantly when compared with the moisture variation of the Control Plot. The results show a similar trend as the results from the previous statistical analysis collected during April 2003 to August 2004 (Puppala et al., 2005) and described in Chapter 5.

Unlike the results of the moisture analysis, the temperature analysis showed an improvement in temperature variation. Most CMT plots especially plots with treatment width of 10 feet and thickness of 4 inches had a reduction in temperature variation. This can be attributed to the ability of composts and also the vegetation to provide thermal encapsulation and hence preserved temperatures without large fluctuations at shallow depths. Hence, the composite section of compost amended top soil with vegetation served as an insulator that keeps soil cool in hot weather and keeps soil warm in cold weather. As a result, rapid fluctuations in soil temperature were not recorded in the CMT plots.

Although the moisture analysis indicated that the control plot and CMT plots were not significantly different, another type of analysis was attempted by assessing the moisture variations in the test plots with respect to initial compaction moisture content. Table 6.4 compares the initial compaction moisture content at the time of construction in each plot with the minimum moisture content measured from September, 2004 to August, 2005. Most compost plots with the exception of plots 3, 8, 14, 15 and 16, did not experience any moisture losses beyond their initial compaction moisture contents. The Control Plot (17) with no compost covers experienced loss in moisture content below the initial compaction moisture content by three points. It should be mentioned here that four out of five plots that experienced the most moisture losses were constructed with Dairy Manure Compost (DMC) covers. This indicates that this material possibly did not have the ability to hold moisture. Biosolids Compost (BSC), on the other hand, performed better in retaining the original compaction moisture content. This is attributed to the low organic content (6.4%) of Dairy Manure compost, which is lower than that of Biosolids compost (34%). Higher the organic content, higher the ability of the material to attract and hold moistures in them.

Table 6.2 Analyses on 'Mean Moisture Variations'

	Plot Name	**CP Mean**	**Plot Mean**	**t-value**	**df**	**p-value**	**Variation**
Stephenville Moisture Content	CMT4-10-4	10.26	7.71	1.5129	42	0.1378	Same
	CMT3-10-4	10.26	11.93	-0.9358	42	0.3547	Same
	CMT2-10-4	10.26	9.48	0.3466	32	0.7312	Same
	CMT1-10-4	10.26	8.70	0.8883	42	0.3794	Same
	CMT4-10-2	10.26	7.45	1.6820	42	0.1000	Same
	CMT3-10-2	10.26	8.96	0.7532	42	0.4556	Same
	CMT2-10-2	10.26	9.02	0.6568	39	0.5152	Same
	CMT1-10-2	10.26	13.65	-1.5284	42	0.1339	Same
	CMT4-5-2	10.26	13.13	-1.5073	40	0.1396	Same
	CMT3-5-2	10.26	10.92	-0.3756	42	0.7091	Same
	CMT2-5-2	10.26	7.42	1.6501	42	0.1064	Same
	CMT1-5-2	10.26	10.82	-0.3115	42	0.7570	Same
	CMT4-5-4	10.26	12.71	-1.3536	42	0.1831	Same
	CMT3-5-4	10.26	16.54	-2.8164	36	0.0078	Higher
	CMT2-5-4	10.26	10.40	-0.0605	38	0.9521	Same
	CMT1-5-4	10.26	5.26	2.8133	42	0.0074	Lower

Note : CP – Control Plot

Table 6.3 Analyses on 'Mean Temperature Variations'

	Plot Name	CP Mean	Plot Mean	t-value	df	p-value	Variation
Stephenville Temperature	CMT4-10-4	14.60	13.09	2.2458	42	0.0300	Lower
	CMT3-10-4	14.60	8.08	10.7057	42	0.0000	Lower
	CMT2-10-4	14.60	9.56	7.0352	32	0.0000	Lower
	CMT1-10-4	14.60	11.77	3.6932	42	0.0006	Lower
	CMT4-10-2	14.60	16.94	-3.3722	42	0.0016	Higher
	CMT3-10-2	14.60	11.14	5.1891	42	0.0000	Lower
	CMT2-10-2	14.60	13.53	1.6095	42	0.1150	Same
	CMT1-10-2	14.60	N/A	N/A	N/A	N/A	N/A
	CMT4-5-2	14.60	10.52	6.0911	40	0.0000	Lower
	CMT3-5-2	14.60	14.18	0.5782	42	0.5662	Same
	CMT2-5-2	14.60	11.39	4.9024	42	0.0000	Lower
	CMT1-5-2	14.60	16.73	-2.9074	42	0.0058	Higher
	CMT4-5-4	14.60	20.64	-7.1268	42	0.0000	Higher
	CMT3-5-4	14.60	N/A	N/A	N/A	N/A	N/A
	CMT2-5-4	14.60	N/A	N/A	N/A	N/A	N/A
	CMT1-5-4	14.60	10.50	6.7254	42	0.0000	Lower

N/A – Sensor Failure; CP – Control Plot.

Table 6.4 Moisture Content Comparisons in the Control and Test Plots

Plot	Plot No.	Initial Moisture Readings @ 6 in. (Apr 2003)	Min. Moisture Readings @ 6 in. (Sep 2004-Aug 2005)
CMT4-10-4	1	14.31	14.71
CMT3-10-4	2	12.55	13.73
CMT2-10-4	3	22.55	14.31
CMT1-10-4	4	10	14.51
CMT4-10-2	5	12.35	15.10
CMT3-10-2	6	12.94	20.39
CMT2-10-2	7	17.45	20.39
CMT1-10-2	8	13.14	8.24
CMT4-5-2	9	11.96	15.88
CMT3-5-2	10	14.12	14.31
CMT2-5-2	11	11.76	15.29
CMT1-5-2	12	11.37	11.96
CMT4-5-4	13	12.35	12.37
CMT3-5-4	14	13.92	11.57
CMT2-5-4	15	18.04	14.90
CMT1-5-4	16	19.61	16.07
CP-10-4	17	16.86	13.53

Another comparison was also attempted on the moisture and temperature data (Table 6.5). The mean variations during April 2003 to August 2004 were compared to the mean variation during September 2004 to August 2005. The comparisons clearly showed the reduction of both mean variations in the last year of monitoring for all plots. This can be attributed to the thick vegetative cover developed from seeding at the site (Figure 6.2). The vegetations prevented the plot surfaces from direct exposure to heat and wind and therefore reduced the rate of moisture loss which was the main cause of desiccation cracking.

Figure 6.2 Vegetation at Stephenville site (picture taken on June 25, 2005)

Table 6.5 Comparisons of Mean Moisture and Temperature Variations

	Mean Moisture Variation		Mean Temperature Variation	
	Apr 2003 Aug 2004	**Sep 2004 Aug 2005**	**Apr 2003 Aug 2004**	**Sep 2004 Aug 2005**
CMT4-10-4	12.77	7.71	15.57	13.09
CMT3-10-4	13.78	11.93	15.6	8.08
CMT2-10-4	11.63	9.48	15.18	9.56
CMT1-10-4	21.84	8.70	17	11.77
CMT4-10-2	12.68	7.45	19.56	16.94
CMT3-10-2	15.13	8.96	18.26	11.14
CMT2-10-2	17.35	9.02	21.43	13.53
CMT1-10-2	22.19	13.65	30.29	N/A
CMT4-5-2	15.8	13.13	24.88	10.52
CMT3-5-2	13.06	10.92	20.75	14.18
CMT2-5-2	14.4	7.42	17.82	11.39
CMT1-5-2	15.05	10.82	29.45	16.73
CMT4-5-4	16.75	12.71	23.25	20.64
CMT3-5-4	18.43	16.54	29.07	N/A
CMT2-5-4	14.54	10.40	17.32	N/A
CMT1-5-4	18.15	5.26	19.91	10.50
CP-10-4	15.34	10.26	22.71	14.60

6.4.1.2 Elevation Surveys

According to the U.S. Department of Agriculture, the United States loses more than 2 billion tons of topsoil each year to erosion, mostly near the coastal regions. The detachment of topsoils can occur by the impact of rainfall or from flowing water. Damage from rainfall occurs when soil and sediment are carried away when rainwater slides down aslope and when water accumulates in drainage ditches along roads. The sediment accumulates in drainage ditches, making it impossible to store water, and the result is flooding. The erosion can also cause deterioration underneath the pavement, which often results in collapsed roads (Storey et al., 1997). The collapsed road section is likely due to the moisture intrusion into the subsoil, which could potentially lead to poor driving conditions and accidents (Figure 6.3).

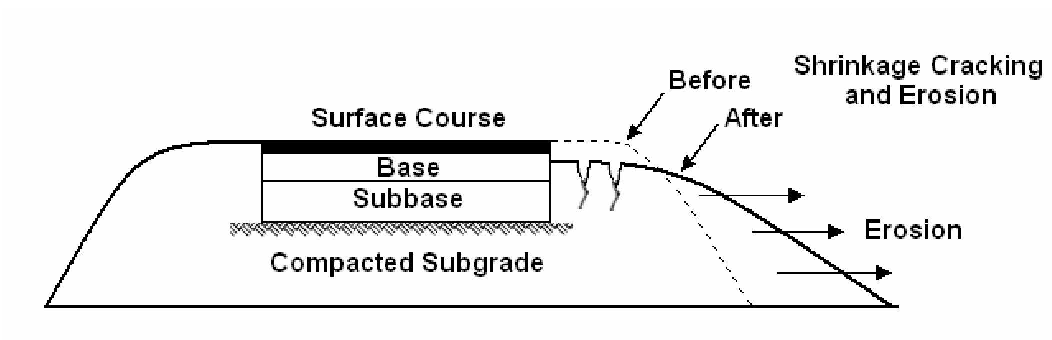


Figure 6.3 Collapsed shoulder due to erosion

Erosion also removes fertile soil rich in nutrients and organic matter, which reduces the ability of plants and grass to establish, grow and remain healthy in the soil. A reduction in plant growth and subsequent plant residue causes less soil cover, allowing the erosion process to perpetuate and become worse (Risse et al., 2001). Therefore, controlling erosion is a key component in road and highway rehabilitation projects (Middleton et al., 2003). Compost amended soil provides a physical cushion type of barrier between rainfall and the surface soil. Eroding forces from raindrops are dissipated as they hit the compost layer. As a result, less soil particles are dislodged.

Compost amendment is also used to break up the heavily compacted soils and allow water to infiltrate the soil surface and therefore reduce surface runoff.

Topographic surveys were periodically conducted during moisture and temperature data collection and these results were used to evaluate vertical movements (swell/shrinkage) of the encapsulated surface and possible erosion of the plot. Total Station instrument was used to measure the elevation of each spot in each test plot which was marked by a spike. Each plot had 5 spikes placed in both the longitudinal and transverse directions. The vertical displacements or movements were calculated by subtracting the original elevation of each spike from initial elevation surveys, which was performed at the beginning of the monitoring process immediately after the construction of test plot in April, 2003. Potential elevation changes of each plot were calculated using the average readings of all stations and these results were used in the analysis to address erodability of the CMTs during service. Figure 6.4 shows surface profiles at Stephenville site for the entire monitoring period (April 2003-August 2005).

Erosion results were grouped by different CMTs and averaged to determine the final surfacial erosion of each test plot. From the figure, it can be mentioned that there had been little or no erosion of the control and CMT plots since Aug 2004. This can be attributed to the vegetation establishment on each plot in Stephenville, Texas. Goldsmith et al. (2001) mentioned that vegetation growth of each plot generally helps to promote infiltration of water into subsoils. The process starts when rain droplets are intercepted by vegetations, funneling water down through stems or allowing water to drip slowly off leaves of the vegetation rather than directly hitting on the soil surface.

Accumulated organic litter, combined with the roughness derived from living plant stems and foliage, helps to detain water, which might otherwise leave the area as runoff, thus increasing the erosion. Organic matter that becomes incorporated into the soils also improves the capillarity of soils and enhances water retention. Therefore, the erodability of the subsoil decreases as particle size and organic matter increased with the compost amendment in the CMTs.

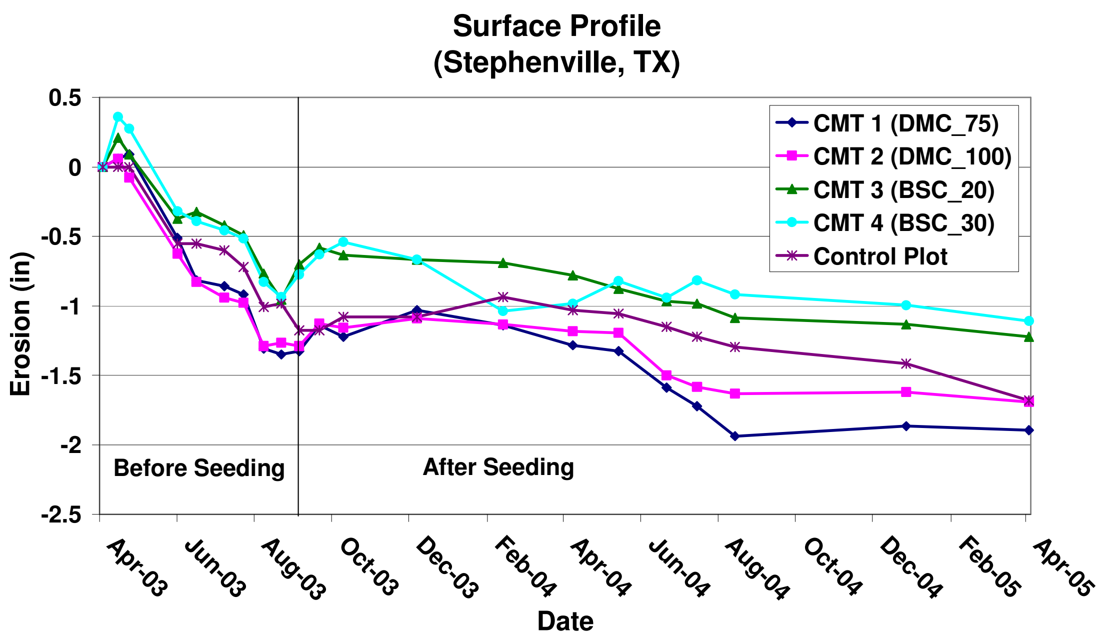


Figure 6.4 Surface profile at Stephenville site

6.4.1.3 Paved Shoulder Cracking

As mentioned earlier, paved shoulder cracking can be attributed to the moisture intrusion into the adjacent shoulder subgrade layers due to either desiccation cracking and/or erosion. Therefore, less cracking on paved shoulders could be used to identify the CMT's effectiveness as an acceptable cover material. In order to distinguish between new and old cracks on the same pavement section, all the old cracks were crack sealed with bitumen at the beginning of 2005.

Figures 6.5a, b and c present pictures of the same test plot 13, which were pictured in 2004, at the beginning of 2005 and in August 2005, respectively. As the paved shoulder began to deteriorate, cracks would continue to appear, propagate and widen. Therefore, any cracks (Figure 6.5c) extending beyond the sealed crack areas (Figure 6.5b) would be considered as new cracks.

Although mean moisture and mean temperature variations showed an improvement in the third year data collection, cracking still appeared on the same test plots. These new cracks were probably caused by crack sealant failure, which might have resulted in moisture intrusion and softening of subsoils below the paved shoulder. As a result, paved shoulder continued to deteriorate by forming new cracks as noted in Figure 6.6. Table 6.6 summarizes visual observation results of these images on all the test plots prior and after crack sealing, which supports the above observation.

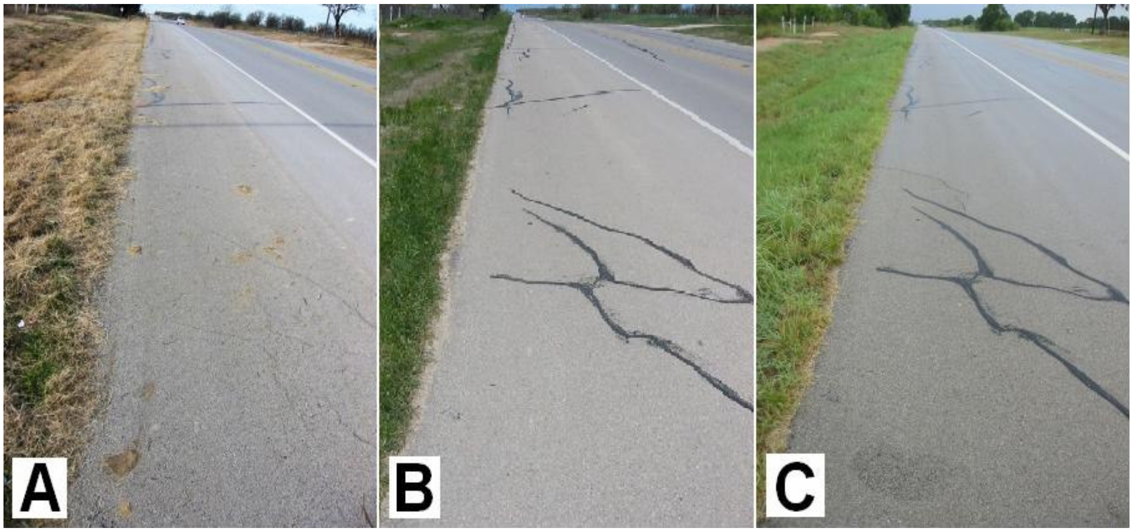


Figure 6.5 Pavement cracking on plot 13
(a) before sealant, 2004 (b) after sealant, early 2005 (c) New cracking, August 2005

Table 6.6 Visual Observations of Test Plots

Plot Name	Plot No.	Compost	Visual Observation (Before 2005)	Visual Observation (After 2005)
CMT4-10-4	1	BSC	No new cracks	No new cracks
CMT3-10-4	2	BSC	No new cracks	No new cracks
CMT2-10-4	3	DMC	No new cracks	No new cracks
CMT1-10-4	4	DMC	No new cracks	No new cracks
CMT4-10-2	5	BSC	No new cracks	No new cracks
CMT3-10-2	6	BSC	No new cracks	**New cracks**
CMT2-10-2	7	DMC	No new cracks	No new cracks
CMT1-10-2	8	DMC	**New Cracks**	**New Cracks**
CMT4-5-2	9	BSC	**New Cracks**	**New Cracks**
CMT3-5-2	10	BSC	**New Cracks**	**New Cracks**
CMT2-5-2	11	DMC	**New Cracks**	**New Cracks**
CMT1-5-2	12	DMC	**New Cracks**	**New Cracks**
CMT4-5-4	13	BSC	**New Cracks**	**New Cracks**
CMT3-5-4	14	BSC	No new cracks	No new cracks
CMT2-5-4	15	DMC	No new cracks	No new cracks
CMT1-5-4	16	DMC	No new cracks	No new cracks
CP-10-4	17	-	**New Cracks**	**New Cracks**

Figure 6.6 Shrinkage of the asphalt concrete

6.4.1.4 Summary on Third Year Stephenville Site Data

The outcome of the third year data analyses is that both CMTs provided satisfactory performance after close to three years of service in the field. The CMT plots showed similar moisture variations as the control plot and a reduction in temperature variation in majority of test plots. Eleven out of sixteen CMT plots did not experience moisture content levels below their initial compaction moisture content after the construction.

Minimal surficial erosions were measured on the CMT plots since August 2004 because of the growth of thick vegetation cover, which helped in reducing the eroding forces of raindrops and surface runoffs from pavements and winds. Despite these enhancements, some plots still experienced new paved shoulder cracking. Majority of paved shoulder cracking noted on the test sections are attributed to crack sealants applied on older cracks, which appeared to be poor. As a result, new cracks around the old cracks started appearing within months after crack sealant application. Overall, the shrinking behavior of subsoils was improved using CMTs, which resulted in enhancing the service life periods of paved shoulders and adjacent pavements with minimum maintenance problems.

In conclusion, both Biosolids and Dairy Manure Compost amendments are recommended for top soil treatments to control moisture and temperature fluctuations in subsoils and thereby reducing shrinkage cracking and erosion losses, which are the critical factors in maintaining the integrity of a pavement. Addition of further fibrous materials in the form of yard trimmings or woodchips to dairy manure is expected to increase the effectiveness of Diary Manure compost amendments.

One interesting observation from this site data is that after poor performance of the DMCs as CMTs immediately after test plot construction, they started to blend in well with top soil and thus started providing better encapsulation after the seeding process. This resulted in considerable improvements in moisture, temperature fluctuations and erosions as well as subsoil cracking and paved shoulder cracking.

6.4.2 Lubbock, Bryan and Corpus Christi Sites

6.4.2.1 Temperature and Moisture Data Analyses

Temperature and moisture variation analyses were performed in a similar fashion as the one performed for Stephenville site in the earlier section. Volumetric moisture contents and soil temperature were continuously recorded from the time of construction till August 2005. The results of the statistical analyses are shown in Tables 6.7 and 6.8. Since there are only two CMT plots in each new site, they were termed with their compost names in this dissertation.

Table 6.7 'Mean Moisture Variations' Analyses of Lubbock, Bryan and Corpus Christi Sites

	Plot Name	**CP Mean**	**Plot Mean**	**t-value**	**df**	**p-value**	**Variation**
Lubbock (Moisture)	Cotton Burr	9.29	8.38	0.4849	48	0.6300	Same
	Feedlot Manure	9.29	12.56	-1.4925	44	0.1427	Same
Bryan (Moisture)	Biosolids	12.09	15.67	-1.9753	40	0.0552	Same
	Wood Compost	12.09	14.21	-1.1090	40	0.2741	Same
Corpus Christi (Moisture)	Biosolids	13.48	11.94	0.3489	22	0.7305	Same
	Cow Manure	13.48	19.23	-1.1143	22	0.2772	Same

Table 6.8 'Mean Temperature Variations' Analyses of Lubbock, Bryan and Corpus Christi Sites

	Plot Name	CP Mean	Plot Mean	t-value	df	p-value	Variation
Lubbock (Temperature)	Cotton Burr	20.56	19.92	0.6215	48	0.5372	Same
	Feedlot Manure	20.56	16.11	4.4313	48	0.0001	Lower
Bryan (Temperature)	Biosolids	15.87	12.28	3.7480	40	0.0006	Lower
	Wood Compost	15.87	10.45	5.1507	40	0.0000	Lower
Corpus Christi (Temperature)	Biosolids	17.65	10.88	4.1035	22	0.0005	Lower
	Cow Manure	17.65	10.14	4.8721	22	0.0001	Lower

Trends similar to the ones at Stephenville site were observed for most of the CMT plots. The moisture variations of Compost plots did not vary significantly when compared with the moisture variation of the Control Plot from the same site. Most CMT plots were able to reduce their temperature variations in subsoils. Therefore, regardless of compost type, it can be mentioned that composts have abilities to encapsulate thermally and therefore reduced temperature fluctuations. While the moisture variations were statistically the same, all manure compost plots experienced higher moisture variations. This is attributed to the inability of the manure CMT to significantly reduce desiccation cracking, resulting in the moisture to seep in and evaporate out with temperature changes.

The minimum moisture contents determined for every two weeks were plotted in Figures 6.7 to 6.9. The minimum moisture contents of both compost plots at Lubbock site did not go below the initial compaction moisture contents whereas at Bryan site, the control and biosolids plots experienced losses of 7% and 2% moisture content below their initial compaction moisture contents. The Corpus Christi site was constructed during a rainy day, and hence all plots were unable to maintain compaction moisture content levels, which were higher than initial compaction moisture content level. Although all plots at Corpus Christi experienced losses in moisture contents below the initial compaction moisture content, both compost sections were able to retain more moisture during early February till early April. This indicates that compost materials used in this research were able to retain and sustain moisture and hence provided effective encapsulation of the surface.

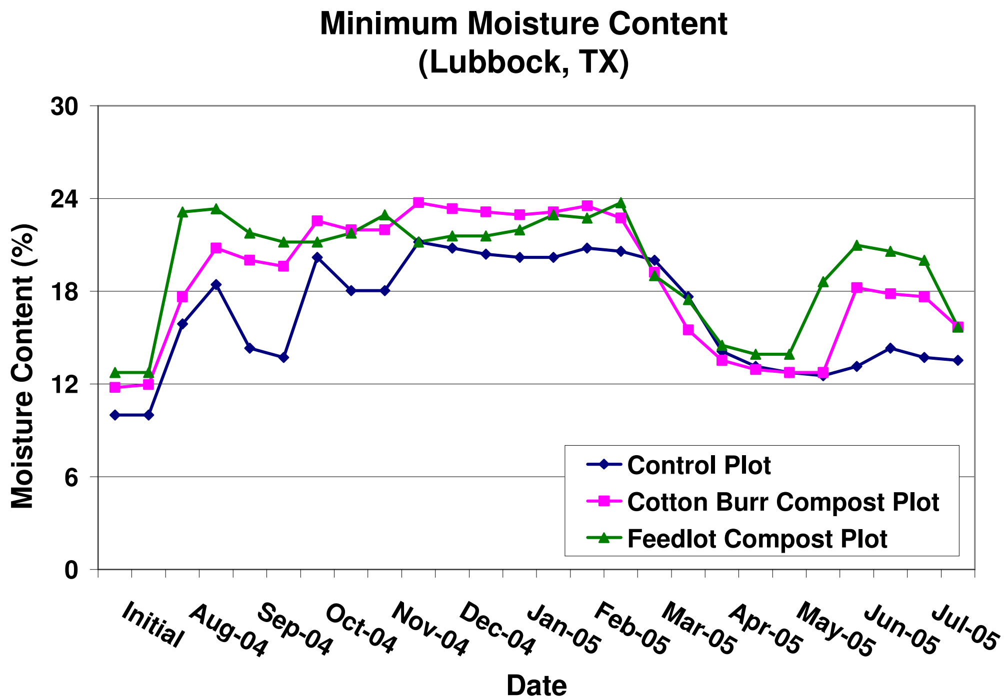


Figure 6.7 Records of minimum moisture content at Lubbock site

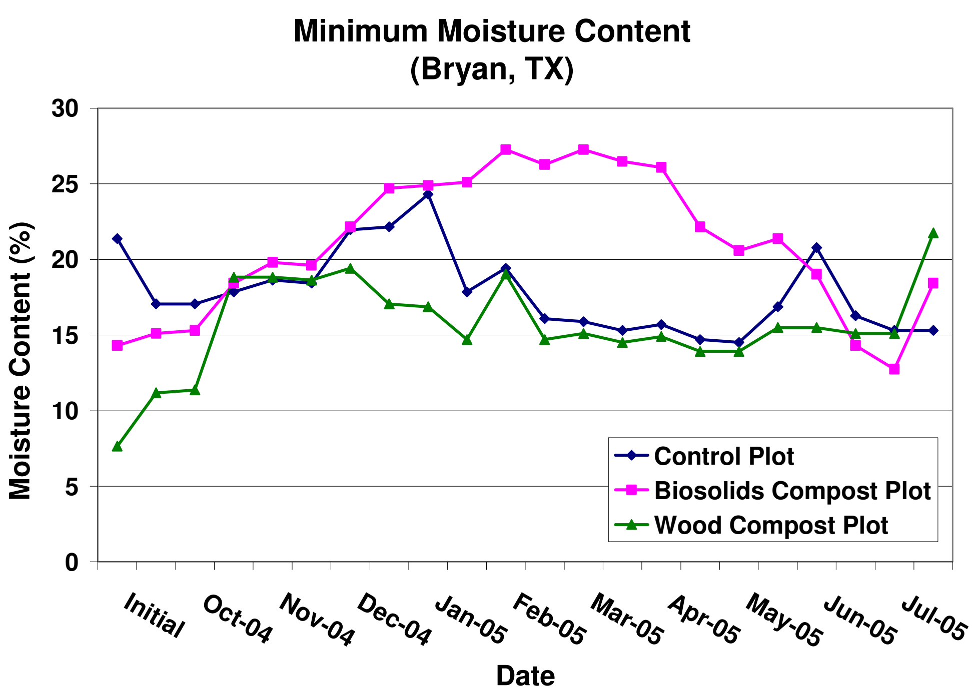


Figure 6.8 Records of minimum moisture content at Bryan site

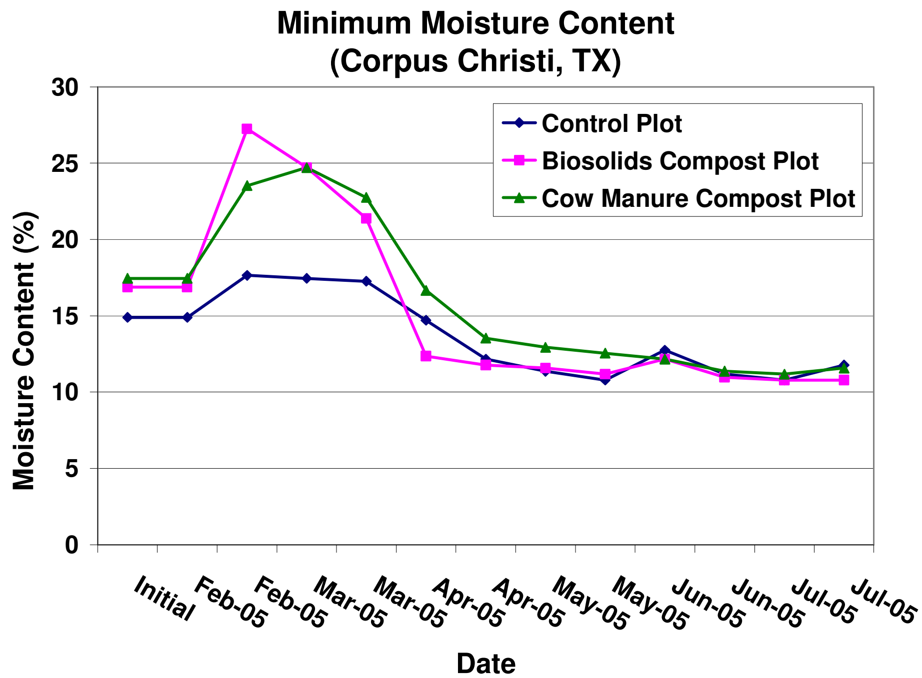


Figure 6.9 Records of minimum moisture content at Corpus Christi site

6.4.2.2 Elevation Surveys

Elevation analyses were performed by comparing the elevation data of all three sections at all three sites. These results are shown in Figures 6.10 to 6.12. From Figure 6.10, it can be mentioned that the erosions at Cotton Burr Compost and the control plots of Lubbock site were close to 0.65 inches. The highest erosion of 1 in. was recorded on Feedlot Manure Compost plot. Manure Compost has been found to have a high rate of erosion. This can be attributed to the low organic content (nutrients) that promote vegetation growth. For Bryan site (Figure 6.11), the erosions for the control, Biosolids Compost and Wood Compost plots were 0.85, 0.99 and 0.83 in respectively. Vegetation growth observations indicated that the lack of vegetation in Bryan site after compaction increased the erosion rate. Figure 6.12 indicate a swelling pattern for the control soil and Cow Manure Compost section, which are matched with the laboratory results. Both plots experienced heaving during the wet season period. Biosolids Compost plot, on the other hand, experienced erosion of 0.23 in. This erosion is considerably lesser. Nevertheless, it indicates moderate surface erosion in this plot, perhaps due to the low organic contents of this material when compared to the Biosolids compost used in Stephenville site.

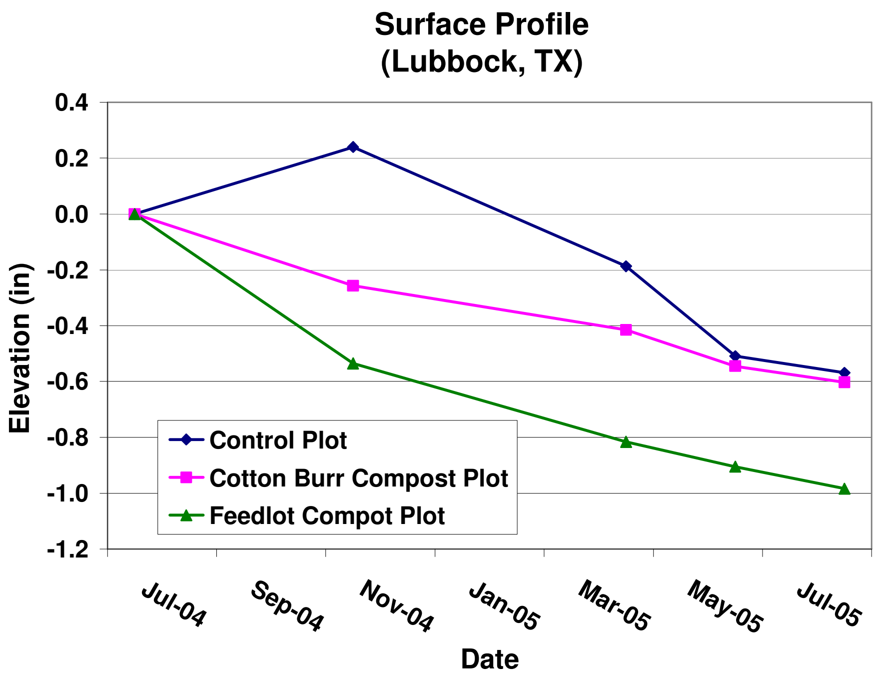


Figure 6.10 Surface profile at Lubbock site

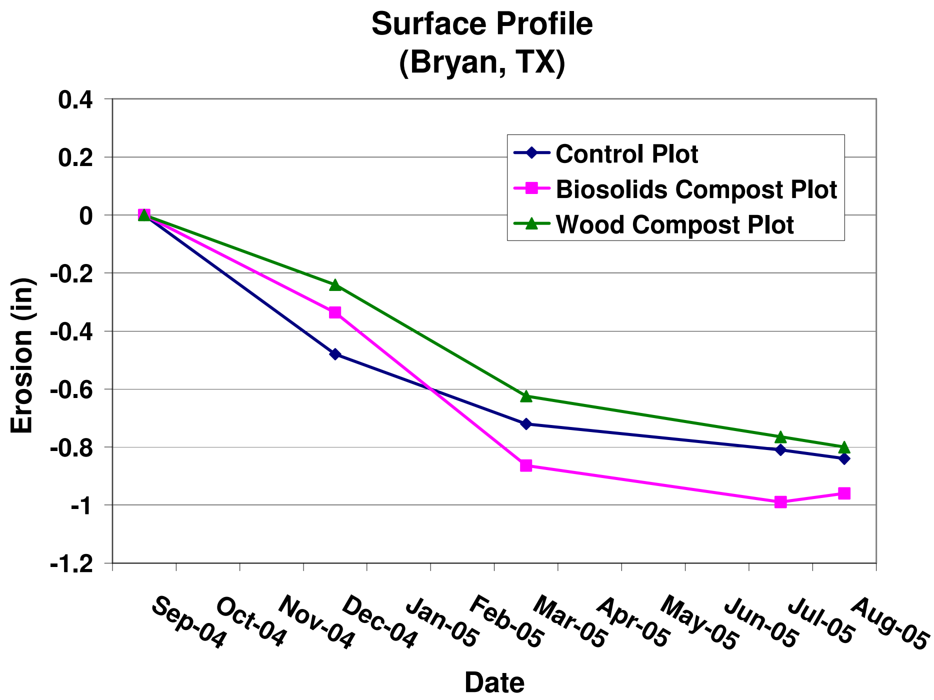


Figure 6.11 Surface profile at Bryan site

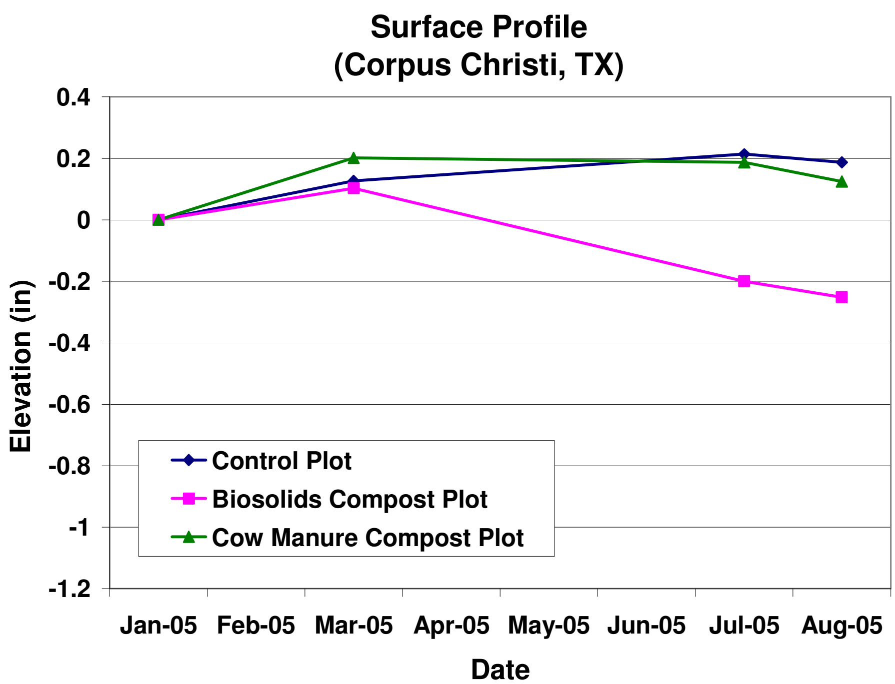


Figure 6.12 Surface profile at Corpus Christi site

6.4.2.3 Shrinkage Cracking Analysis

As mentioned earlier, cracks often appeared on unpaved shoulder subgrades or in the CMTs due to direct exposure of high temperature and wind conditions. As a result, subgrade soils near shrinkage cracks will have moisture access during rainy seasons and will soften after imbibing moisture. Hence, it is essential to properly characterize the shrinkage strain potentials of natural and compost amended soils.

Table 6.9 presents the digital shrinkage analysis performed on the CMTs by randomly imaging the plot at different locations. Each image was analyzed using Scion image software to measure the areas under shrinkage. Shrinkage strains were calculated using cracked surface to total surface area. Shrinkage strain values reported here were the average values of these random images. At Lubbock site, the highest cracking (0.77%) was found on the control soil. The Cotton Burr Compost and Feedlot Manure Compost plots showed lesser cracking. This is because of the fibers in cotton burr and also the reduced PI of compost amended soils. Hence, it can be concluded that the addition of composts at Lubbock site was beneficial.

Due to the fibrous materials in both composts from the city of Bryan and Conroe, the application of compost at Bryan site also reduced the amount of cracking. This also corresponded with the Linear Shrinkage test results. Biosolids Compost plot at Corpus Christi also showed a reduction in shrinkage cracking. On the other hand, the application of Cow Manure Compost at Corpus Christi site did not reduce the cracking. This is because of the highly plastic nature of the control soil and CMTs as seen in the laboratory test results. All three materials exhibited high swell and shrinkage strain values.

Table 6.9 Shrinkage Analysis of Lubbock, Bryan and Corpus Christi Sites

	Plot Name	**Percent Cracking**
Lubbock	Control Plot	0.77
	Cotton Burr	0.12
	Feedlot Manure	0.53
Bryan	Control Plot	0.39
	Biosolids	0.21
	Wood Compost	0.19
Corpus Christi	Control Plot	0.35
	Biosolids	0.13
	Cow Manure	0.41

6.4.2.4 Paved Shoulder Cracking

Visual observations of the pavement were studied. In order to distinguish between new and old cracks on the adjoining pavement shoulder, old cracks were first seal coated. Photos of the pavement shoulders were periodically taken and compared. Table 6.10 presents results based on the visual observations. Even though the minimum moisture content comparisons indicated that the Feedlot Manure Compost at Lubbock site was able to retain water, the material was not able to reduce desiccation cracking and erosion due to the lack of fibrous materials in the original compost. Excess moisture was able to seep in through these cracks and shoulder drop-off and therefore soften the subgrades. As a result, cracking was recorded on Dairy Manure Compost plot at Lubbock site.

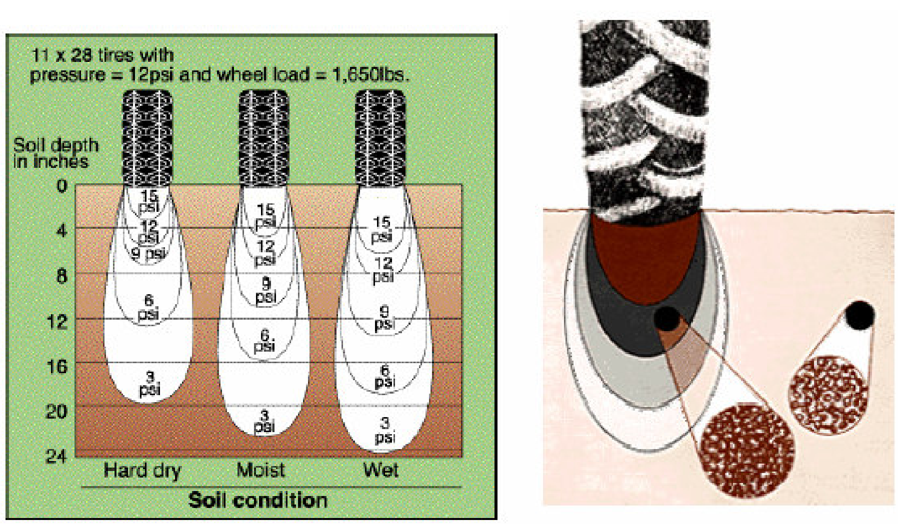
Despite the presence of fibrous materials in Biosolids and Wood composts at Bryan site, which have helped in reducing the amount of desiccation cracking at Stephenville and Lubbock sites, the plots at Bryan still experienced paved shoulder cracking. This is attributed to high erosion experienced in all test plots, which was close to 1 in. Moisture was able to seep into the pavement subgrade at the location where there was a separation of CMT shoulder and paved shoulder (due to surface erosion of unpaved shoulder subsoils) as depicted in Figure 6.3. This leads to an important observation that both erosion control and desiccation cracking prevention should be addressed in order to mitigate paved shoulder cracking. Corpus Christi site require further monitoring to evaluate any further cracking of paved shoulders.

Table 6.10 Pavement Cracking of Lubbock, Bryan and Corpus Christi Sites

	Plot Name	**Pavement Cracking**
Lubbock	Control Plot	**New cracks**
	Cotton Burr	No new cracks
	Feedlot Manure	**New cracks**
Bryan	Control Plot	**New cracks**
	Biosolids	**New cracks**
	Wood	**New cracks**
Corpus Christi	Control Plot	No new cracks
	Biosolids	No new cracks
	Cow Manure	No new cracks

6.4.2.5 Vegetation Reestablishment

In any roadside construction, one of the eventual goals of this amendment is to allow native vegetation to grow naturally and permanently stabilize subsoils adjacent to paved shoulders (Tyler, 2003). Jurries (2003) reported that compacted soil stresses the root structure of newly planted vegetation. It makes it difficult for root penetration. Thus newly established vegetation typically becomes stunted and remains smaller than vegetation established in undisturbed soil. Figure 6.13a and b show a localized compaction of soils from wheeled and tracked vehicles. The compaction can occur up to 30 in. below the soil surface. The amount of compaction is dependent up on compaction soil moisture content, soil type, and load distribution.



a b

Figure 6.13 A localized compaction of soils from wheeled and tracked vehicles (Jurries, 2003)

In this research, an attempt was made to visually determine how quickly the vegetation was reestablished in each test plot. Digital photographic records showing the denseness of vegetation of each plot were collected and documented. Table 6.11 shows a visual observation of vegetation growth at test sites. It should be mentioned that only scrapping and leveling off was performed on the control plots without compacting them. Hence, vegetation on the control plots was expected to recover faster.

At Lubbock site, the Cotton Burr Compost plot was able to show the vegetation growth as soon as the control plot started showing the vegetation. This fast growth in Cotton Burr Compost plot is attributed to high organic contents of the Compost, which provided nutrients to enhance the vegetation growth. Similar to Stephenville site, the Dairy Manure Compost plot had lower vegetation. This is attributed to two factors, high field compaction densities and low organic contents of Dairy Manure Compost.

Both Wood and Biosolids Compost plots in Bryan site increased the organic content of a control soil from 4.2% to around 16%. This, however, did not result in the reestablishment of vegetation. Similar observation was noted even on the control plot, even after more than nine months after construction. Based on the targeted field densities, researchers believed that the heavily compacted soils of few of the test plots retarded the vegetation growth. These plots include Feedlot Manure compost plot at Lubbock (compacted dry density of 103 pcf) and both compost plots at Bryan (compacted dry densities of 89 and 91 pcf), which are in low PI classification. On the other hand, high densities of high PI clays of Corpus Christi site did not show any vegetation growth related problems. Reasons for all these variations are explained in the following.

Table 6.11 Vegetation Reestablishment of Lubbock, Bryan and Corpus Christi Sites

	Construction Date	**Picture Taken On**	**Plot Name**	**Visual Observation**
Lubbock	July 20, 2004	Nov 20, 2004 (124 days)	Control Plot	Average
			Cotton Burr	Average
			Dairy Manure	Scarce
Bryan	Sep 17,04	Jul 2, 2005 (289 days)	Control Plot	Scarce
			Biosolids	Scrace
			Wood	Slight
Corpus Christi	Jan 27, 2005	Jul 2, 2005 (156 days)	Control Plot	Full
			Biosolids	Full
			Feedlot Manure	Full

Relf (1997) reported that highly compacted soils are very dense and lack pore space, which lessens water holding capacity and rooting area. For growing plants, pore sizes are more important than total pore space. Therefore, plants will have a better environment in sandy soils if porosity is low because of the increase in water retention. The converse is true for clays. High porosity clays have a high macromovement, which provides high infiltration and more water available for plants. In general, a compaction between 80 and 85 percent of the standard Proctor maximum dry density optimizes slope stability with vegetation development and growth (Goldsmith et al, 2001). The bulk density should not exceed 87.4 pcf (1.4 g/cm^3) during dry condition, otherwise the root penetration is greatly retarded (Relf, 1997). This observation was valid for both low PI clays encountered at Lubbock and Bryan sites. Construction of test plots at high PI clay site of Corpus Christi site was performed during rain, and hence all test plots on this soil were able to quickly reestablish the vegetation. Possible softening of clays due to rains and high organic contents of the materials including composts and natural soil helped in the growth of vegetation. Overall, researchers conclude that under the appropriate soil compaction density, soil type and compaction state or condition, the addition of composts result in quicker and healthier vegetation growth.

6.4.2.6 Final Recommendations

This section evaluates the overall performance of all the CMTs. The evaluation was based on shrinkage cracking, moisture content and temperature fluctuations, erosion, paved shoulder cracking and vegetation growth of all the plots. The evaluation and recommendations are shown in Table 6.12. Since paved shoulder cracking indicated the ability of CMTs to protect the integrity of roadways, more importance was given to this observation. Hence, any plots with paved shoulder cracking should be reevaluated for future compost applications.

It can be noted that a plot treated with Cotton Burr Compost, both unpaved and paved shoulders performed satisfactorily with little and no cracking distress, respectively. Hence, Cotton Burr compost is recommended for future CMT applications. Though the Feedlot Manure Compost plot in Lubbock and both Compost plots in Bryan were able to reduce desiccation cracking to a certain extent, the high erosion rate of these materials allowed extra moisture to infiltrate into subsoil layers and started weakening them. The softening of subsoil layers further caused paved shoulder cracking. Hence, Feedlot Manure Compost from Lubbock site and both composts at Bryan site are not recommended unless seeding is implemented immediately without any delays after compost amendment.

The failures at Bryan site probably resulted from lack of vegetation, which resulted in erosion and hence new cracks in pavements. The addition of Biosolids Compost at Corpus Christi site was able to enhance the quality of the existing soil and resulted in no paved shoulder cracking. Therefore, Biosolids Compost is recommended. A longer monitoring period is still needed for the researchers to evaluate the performance of Cow Manure Compost since only eight months of data collection was only possible at Corpus Christi location due to construction delays.

6.5 Summary

This chapter describes various details on data collected from moisture and temperature sensors, erosion surveys, digital image cracking studies, and visual observations of paved shoulder cracking and vegetation growth of all sixteen test plots and one Control Plot. This data was analyzed with statistical comparison tests to evaluate the effectiveness of compost amendments to reduce desiccation cracking in subsoils. The final outcome of this analysis is the recommendation of Biosolids and Cotton Burr Compost amendments to control moisture and temperature fluctuation in subsoils from surrounding environments and reduce shrinkage cracking and erosion losses. All these enhancements resulted in lesser paved shoulder cracking. Animal Manure Composts, on the other hand, resulted in erosion loss and shrinkage cracking of soils and hence resulted in adjacent paved shoulder cracking, which is similar to the problems recorded on the Control Plot with no compost amendments. The failures at Bryan site probably resulted from lack of vegetation, which resulted in erosion and hence new cracks in pavements. Hence, these materials are currently recommended. However, addition of fibrous materials during composting process is expected to enhance the performance of these materials.

Table 6.12 Evaluation and Recommendation of CMTs of Lubbock, Bryan and Corpus Christi Sites

Location	Plot Name	Enhancement?						Final Recommendation
		Shrinkage (%)	Temp Variation (Fo)	Moisture Variation (%)	Erosion (in)	Paved Shoulder Cracking	Vegetation	
Lubbock	Control	0.77	20.56	9.29	0.67	Yes	Average	
	Cotton Burr	0.12	19.92	8.38	0.68	No	Average	Yes
	Feedlot Manure	0.53	16.11	12.56	0.99	Yes	Scarce	No
Bryan	Control	0.39	15.87	12.09	0.85	Yes	Scarce	
	Biosolids	0.21	12.28	15.67	0.98	Yes	Scarce	No
	Wood Compost	0.19	10.45	14.21	0.83	Yes	Slight	No
Corpus Christi	Control	0.35	17.65	13.48	0.19**	No	Full	
	Biosolids	0.13	10.88	11.94	0.24	No	Full	Yes
	Cow Manure	0.41	10.14	19.23	0.13**	No	Full	Yes*

Note: * - Requires longer monitoring period; ** Swelling was observed

CHAPTER 7

SUMMARY OF FINDINGS AND FUTURE RESEARCH

7.1 Introduction

The research covered in this dissertation consists of both laboratory and field investigations along with statistical comparison studies to evaluate the performance of Compost Manufactured Topsoils to mitigate desiccation cracking of expansive shoulder subgrades. The following conclusions are developed from the analyses presented in Chapters 5 and 6. These conclusions are based on the majority of the trends noted in the present data. These conclusions may not be extended beyond those composts tested in this research study without proper verifications.

7.2 Summary of Findings

The following lists both major and a few specific conclusions obtained from the field study phase of this research.

7.2.1 Major Conclusions

The following lists the major conclusions obtained from this research. These are:

1. Characteristics that resulted in the best performance of CMTs in this research include cohesive strengths of amended soils and internal as well as external reinforcement interactions with organics fibers and vegetations. Composts that exhibit these characteristics provided the best enhancements

by the mitigation of shoulder cracking. Future selection of composts should include these details in the material specifications along with the required environmental and physical characteristics.

2. Based on the comprehensive field data collection and statistical comparison analysis of Stephenville site, the CMTs can be performed effectively for 2.5 years of service life. It should be mentioned here that the compost amended soils are expected to serve longer than 2.5 years. Further monitoring period beyond 2.5 years will lead to better estimation of service life of the compost amendments.
3. It can also be concluded that both Biosolids and Cotton Burr Compost amendments provided the best expansive soil property enhancements resulting in lesser shrinkage cracking of expansive shoulder subsoils than those observed from the untreated control soil. This effectiveness is verified by several types of data collected from the field studies including moisture and temperature variations as well as digital image analyses of subsoil shrinkage cracking and visual observations of paved shoulder cracking. These results indicate that the Biosolids and Cotton Burr Compost amendments lead to mitigating of shrinkage cracking in subsoils and thereby reduced paved shoulder cracking.
4. Best performance of the compost material amendments were recorded when these CMTs were constructed for a minimum of 10 ft wide and amended the top soil of atleast 4 in. thick.

5. Though Animal Manure Compost provided moderate enhancements, it should be noted here that this material performance was negatively impacted due to low amounts of fibrous or organic material in them. Hence, Animal Manure Compost treatment with fibrous material is expected to enhance its' performance in mitigating shrinkage cracking.

A few other specific conclusions were established based on the present data analysis, which are presented in the following:

7.2.2 Specific Conclusions

1. The majority of moisture and temperature variations at 6 in. shallow depth in the test plots were not statistically different when compared to those of the Control Plot at the same depth. However, most of the compost test plots showed that they had lesser moisture and temperature variations than the same of the Control Plot. This indicates the ability of composts to provide insulation to soils from surficial temperature changes and thus maintain uniform moisture levels which are expected to induce low cracking in soils.
2. Moisture content data records also showed the ability of CMTs to preserve moisture in subgrades. Moisture contents in most of the CMT plots never exceeded below the initial compaction moisture contents, indicating that the composts preserved moistures in the underlying subsoils.
3. Due to the fibrous materials, Biosolids and Cotton Burr Composts served as an erosion control blanket. Overall, Biosolids and Cotton Burr Compost plots had

lesser erosion than the Control Plot. On the other hand, Animal Manure Compost plots, due to low fibrous materials, experienced more erosion than the Control Plot.

4. The majority of the total erosion occurred within the first few months. This is attributed to lack of vegetation, heavy rain and rearrangement of CMT particles. It is recommended that seeding be done immediately after construction to prevent the early erosion loss of compost materials.

5. Biosolids and Cotton Burr Compost plots experienced lesser desiccation cracking when compared to the Control Plot. This is attributed to fibrous materials. These materials serve as natural reinforcements in the materials; hence they can withstand or resist tensile forces generated from the drying of the subsoil. The lack of fibrous materials in the Animal Manure Compost may have resulted in higher desiccation cracking.

6. Lack of sufficient organic contents or nutrients and high compaction density which inhibit the plant growth were the main causes of low vegetation on the Animal Manure Compost plots.

7. The DMC sections at the Stephenville site, which showed poor performance in the first year after construction, started providing stable support by minimizing moisture and temperature fluctuations, less erosion and enhanced vegetation growth. Existing pavement cracks at the site initiated further cracking though subsoil related soil movements are low. This leads to an important assessment that future site selection should use new pavement construction sites, if possible.

Such use will eliminate the cracks formed due to interference of moisture intrusion from the existing site conditions.

From the present analyses, erosion and desiccation cracking controls are the two important factors in preventing overall paved shoulder cracking and adjacent pavement cracking distresses. In order to prevent these two distresses, researchers recommend the following:

- Select Compost with high to moderate organic content (nutrients) to promote vegetation growth
- Addition of natural fibrous materials (woodchips or yard trimmings) to Dairy Manure compost during construction to reduce desiccation cracking
- Immediate seeding to prevent surface erosion loss
- Field compaction densities should be the lesser of 80-85% percent of the standard Proctor maximum dry density or bulk density less than 87 pcf in dry condition to facilitate vegetation growth

The above recommendations facilitate vegetetation growth in compost amended site sections, which further lead to reductions in erosion rates and surficial shrinkage cracking. In summary, by using composts in roadside shoulder construction, TxDOT can greatly reduce the amount of organic wastes going into landfills, and help in spreading composts to much needed areas of recycling applications.

7.3 Future Research

The following lists a few important future research needs:

1. Further monitoring is recommended on these test plots to address the long-term stability of compost amendments on the present test plots.
2. Cost benefit studies using long term field monitoring data should be conducted to understand the cost effectiveness of compost treated soils.
3. Potential applications for composts in different soil types and regions, with different climatic conditions should be evaluated.
4. Leachate (refers to water that emanates from these materials) collected from the field should be assessed environmentally.
5. Life pertaining to potential decomposition of the compost materials in the CMT plots should be addressed.
6. The surface runoff quality emanating from compost applied sites should be assessed over a long time.

Table 7.1 Final Recommendation

Location	Plot name	Organic Content (%)	Dry Density (pcf)	Shrinkage (%)	Temp Variation (F^o)	Moisture Variation (%)	Erosion (in)	Paved Shoulder Cracking	Vegetation	Final Recommendation
Stephenville	**Control**	**2.4**	**99.7**	**0.14**	**22.71**	**15.34**	**1.23**	**Yes**	**Average**	
	DMC_75	**5.9**	**92.8**	**0.67**	**24.16**	**19.3**	**1.94**	**No**	**Average**	**No**
	DMC_100	**6.3**	**88.7**	**0.86**	**17.93**	**14.48**	**1.63**	**No**	**Average**	**No**
	BSC_20	**11.3**	**77.6**	**0.08**	**20.92**	**15.1**	**1.11**	**No**	**Full**	**Yes**
	BSC_30	**14.2**	**68.9**	**0.08**	**20.81**	**14.5**	**0.95**	**No**	**Full**	**Yes**
Lubbock	**Control**	**2.3**	**123.5**	**0.77**	**20.56**	**9.29**	**0.67**	**Yes**	**Average**	
	Cotton Burr	**14.8**	**93.3**	**0.12**	**19.92**	**8.38**	**0.68**	**No**	**Average**	**Yes**
	Feedlot Manure	**7.9**	**103.3**	**0.53**	**16.11**	**12.56**	**0.99**	**Yes**	**Scarce**	**No**
Bryan	**Control**	**4.2**	**112.2**	**0.39**	**15.87**	**12.09**	**0.85**	**Yes**	**Scarce**	
	Biosolids	**15**	**88.7**	**0.21**	**12.28**	**15.67**	**0.98**	**Yes**	**Scarce**	**No**
	Wood	**17**	**90.9**	**0.19**	**10.45**	**14.21**	**0.83**	**Yes**	**Slight**	**No**
Corpus Christi	**Control**	**3.2**	**104.4**	**0.35**	**17.65**	**13.48**	**0.19****	**No**	**Full**	
	Biosolids	**11.5**	**91.5**	**0.13**	**10.88**	**11.94**	**0.24**	**No**	**Full**	**Yes**
	Cow Manure	**6**	**98.1**	**0.41**	**10.14**	**19.23**	**0.13****	**No**	**Full**	**Yes**

** Swelling

APPENDIX A

MOISTURE AND TEMPERATURE READINGS (FIRST PHASE)

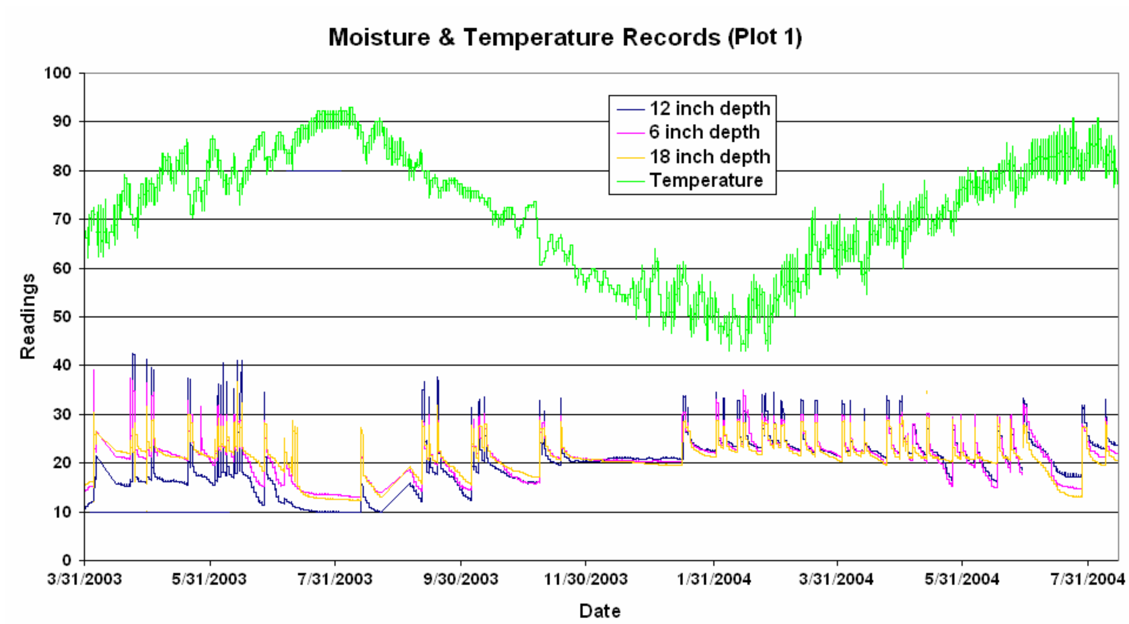


Figure A1 Plot 1 (CMT4-10-4)

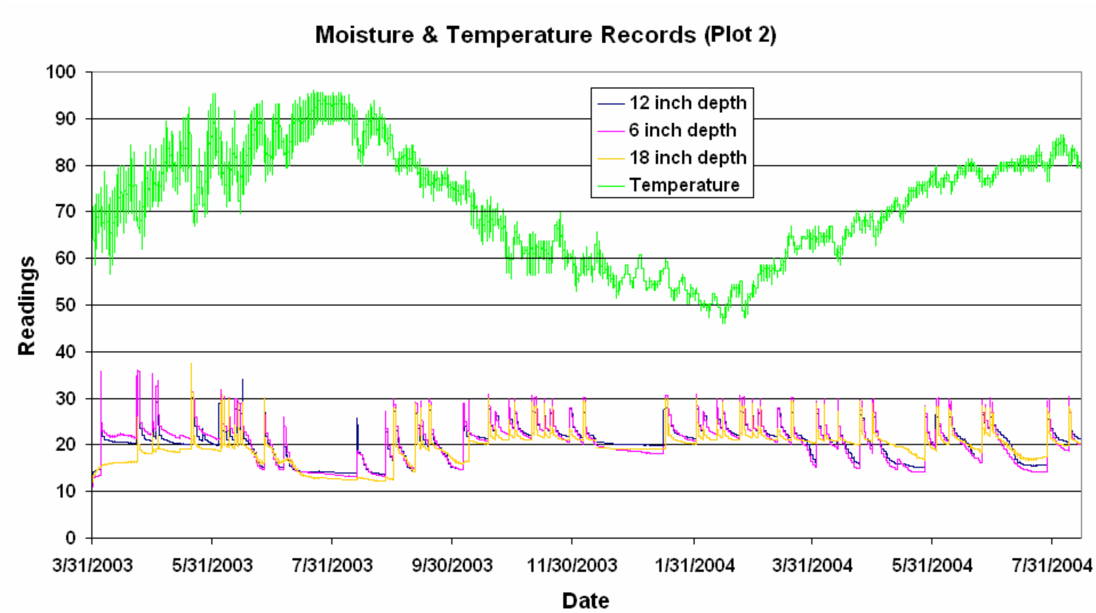


Figure A2 Plot 2 (CMT3-10-4)

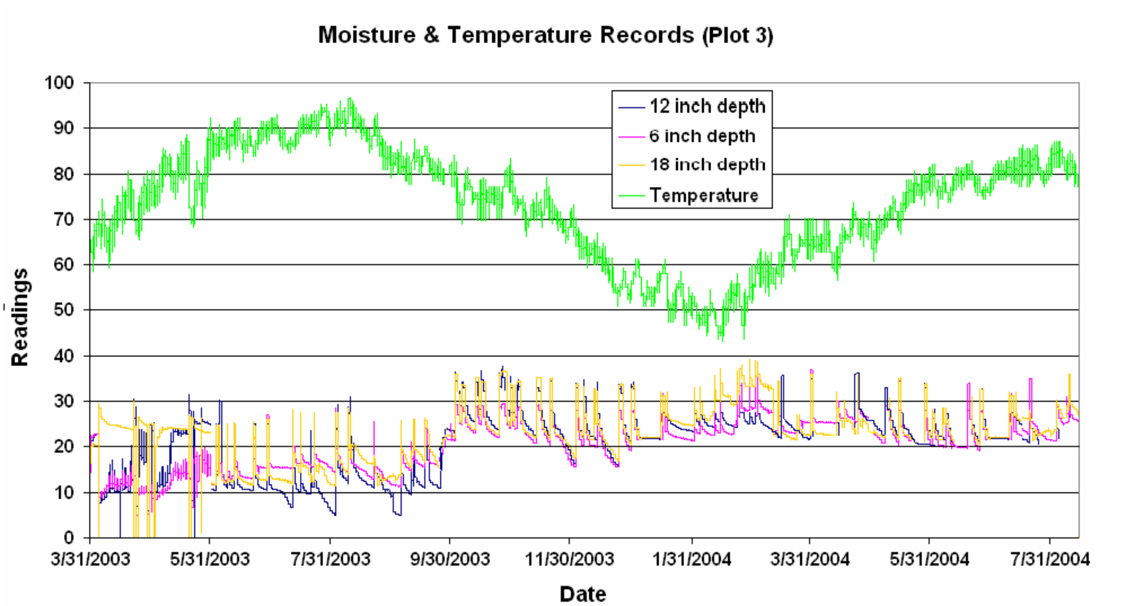


Figure A3 Plot 3 (CMT2-10-4)

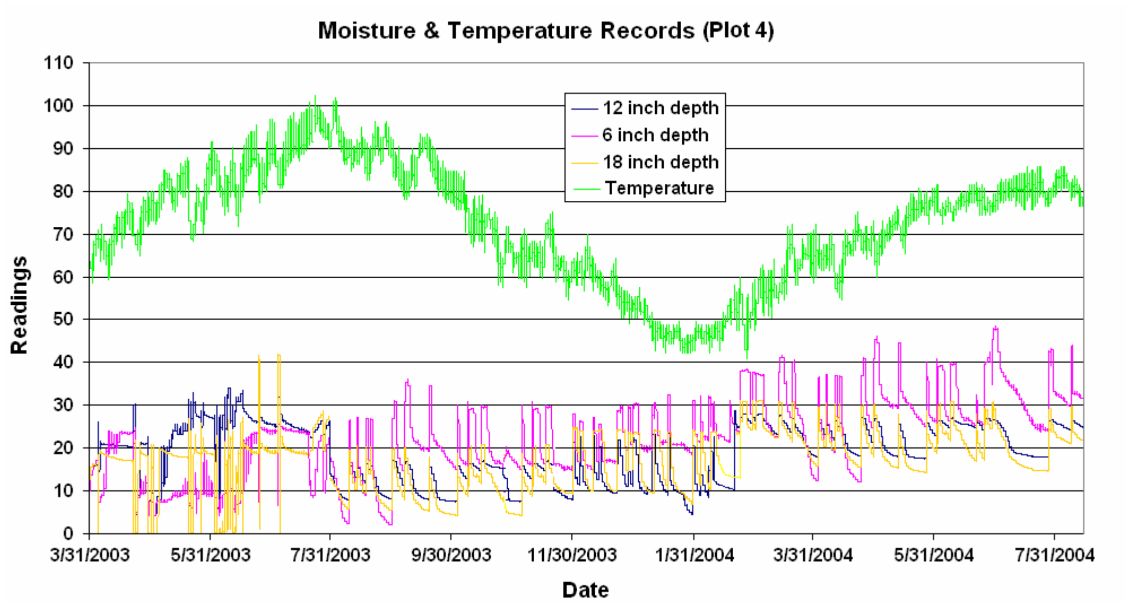


Figure A4 Plot 4 (CMT1-10-4)

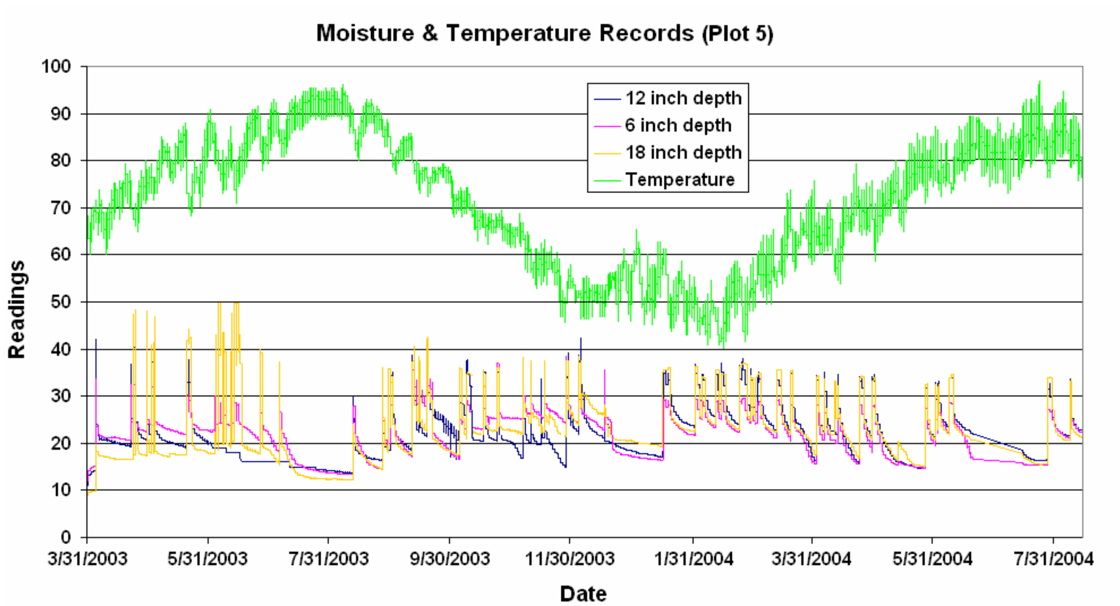


Figure A5 Plot 5 (CMT4-10-2)

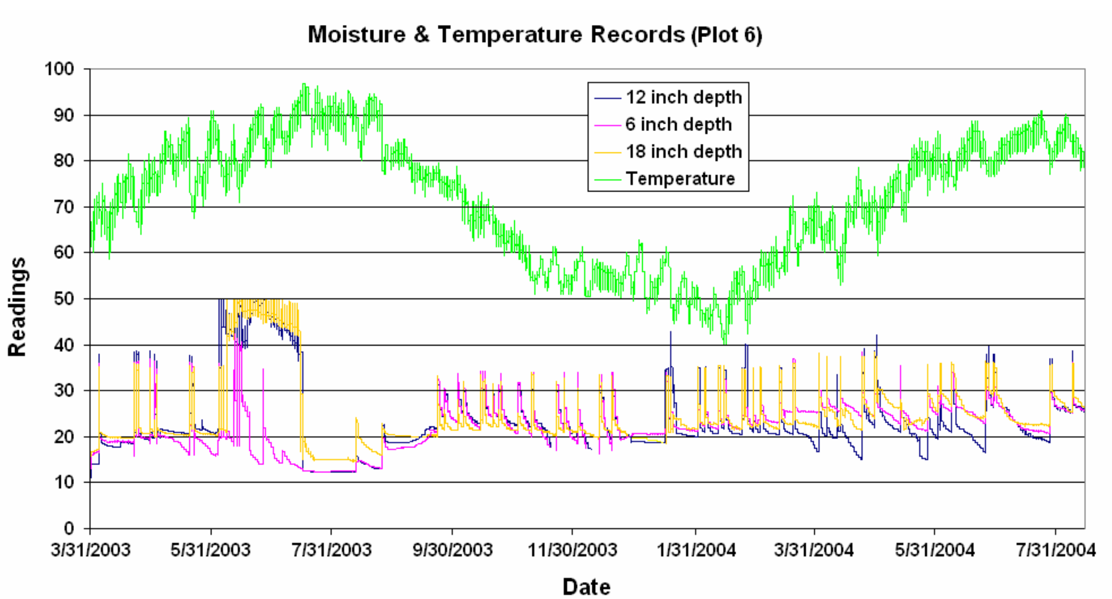


Figure A6 Plot 6 (CMT3-10-2)

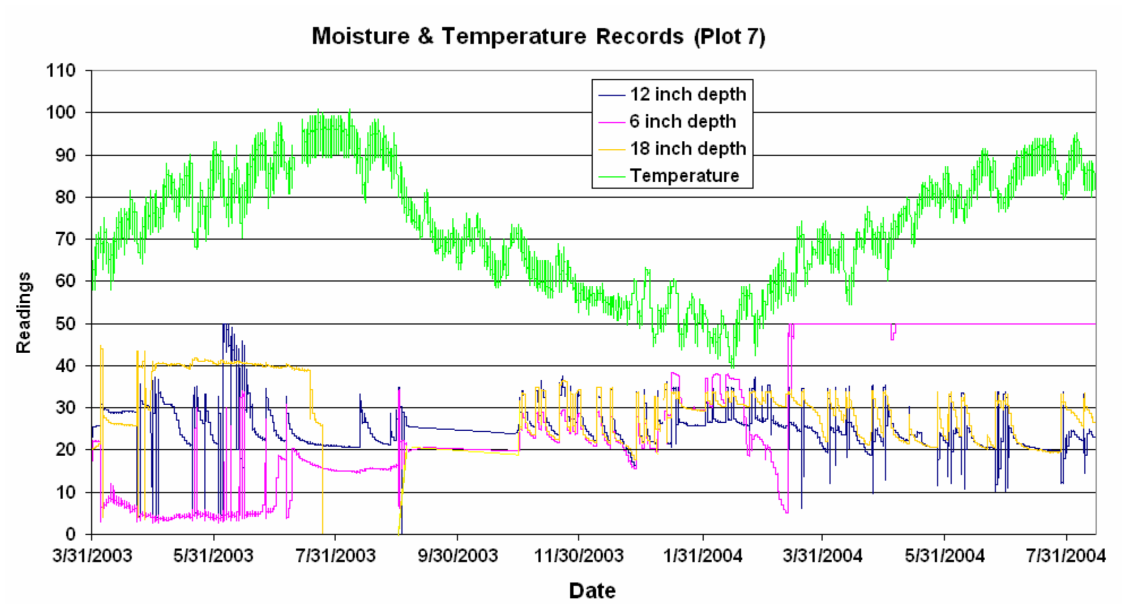


Figure A7 Plot 7 (CMT2-10-2)

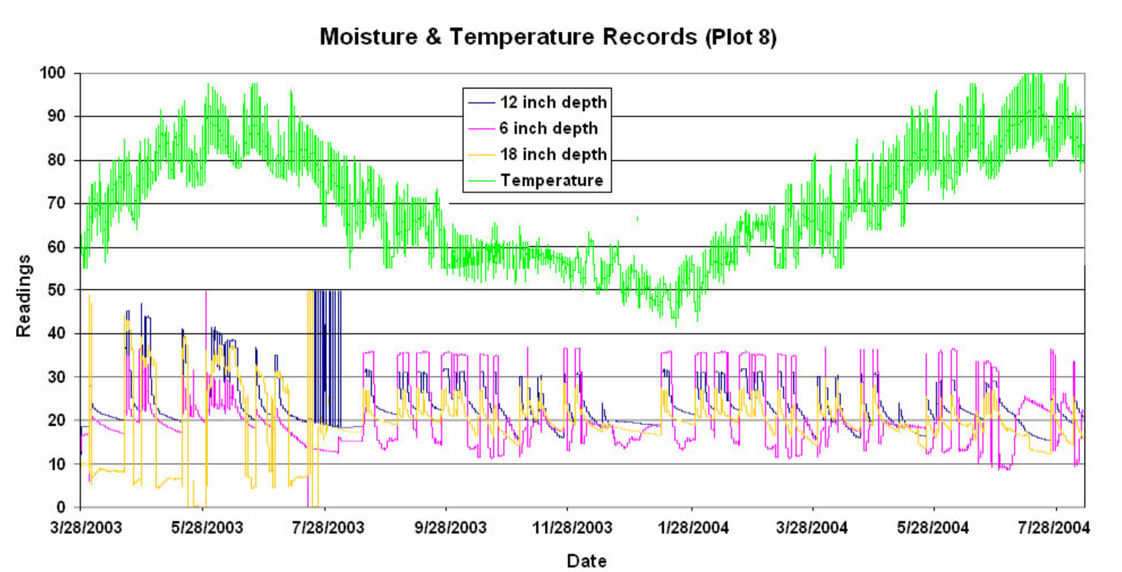


Figure A8 Plot 8 (CMT1-10-2)

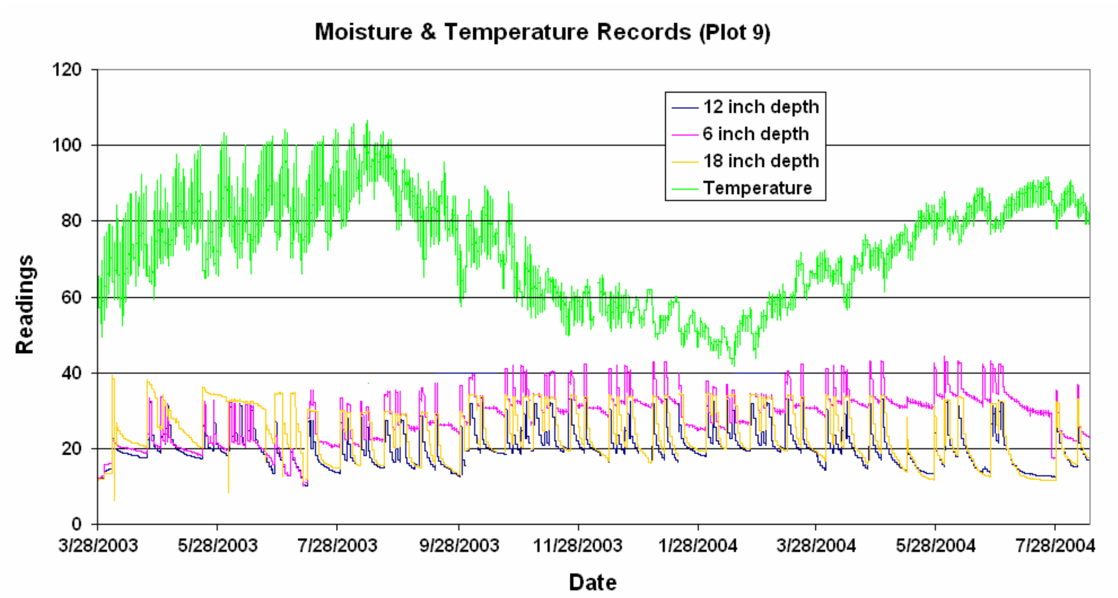


Figure A9 Plot 9 (CMT4-5-2)

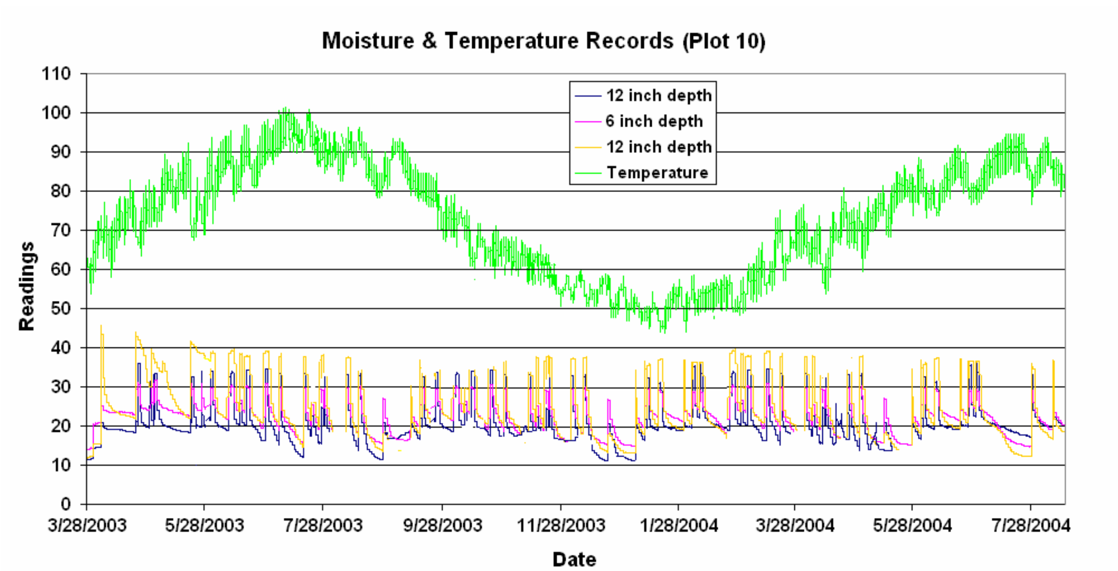


Figure A10 Plot 10 (CMT3-5-2)

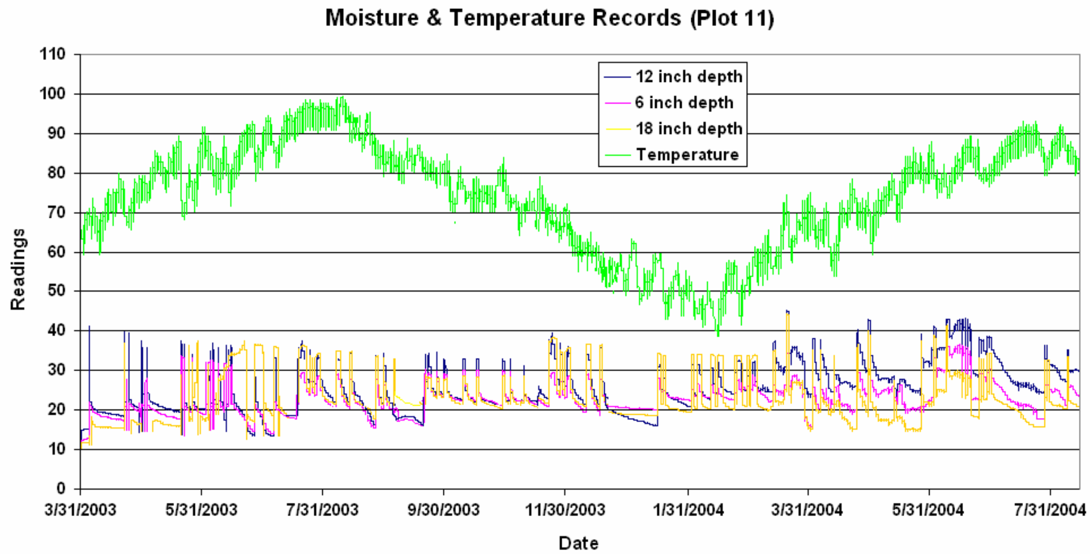


Figure A11 Plot 11 (CMT2-5-2)

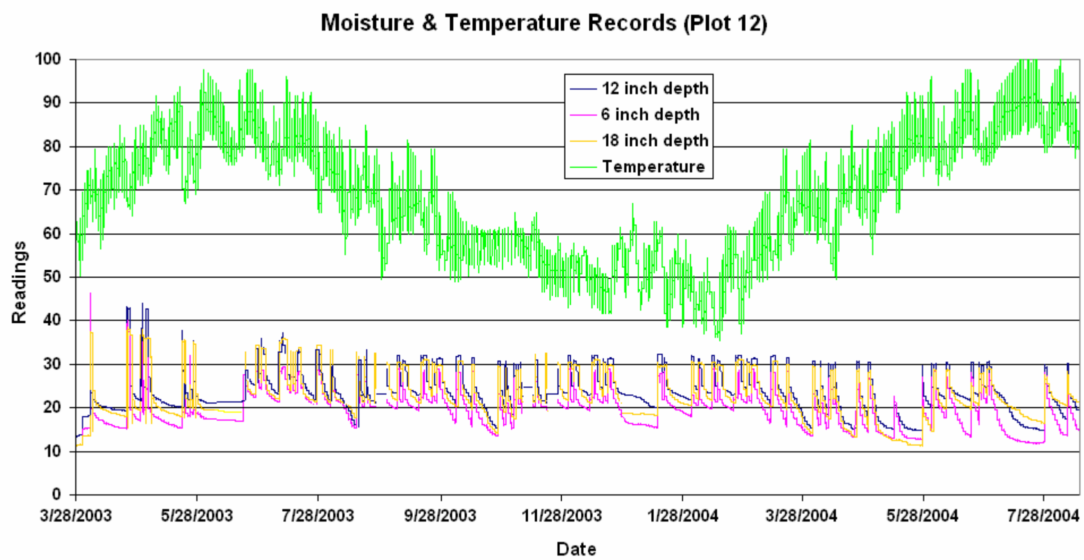


Figure A12 Plot 12 (CMT1-5-2)

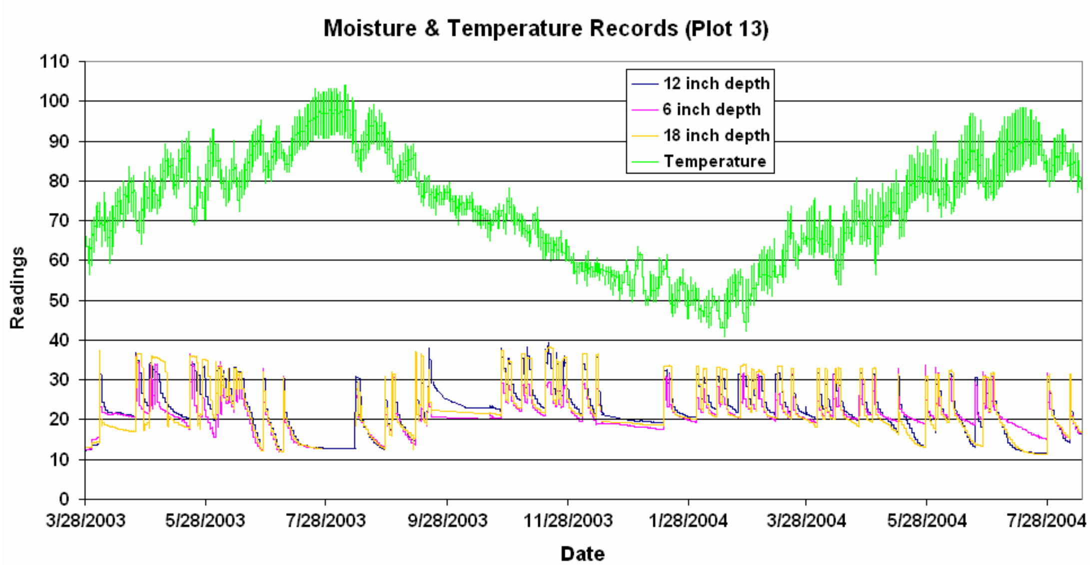


Figure A13 Plot 13 (CMT4-5-4)

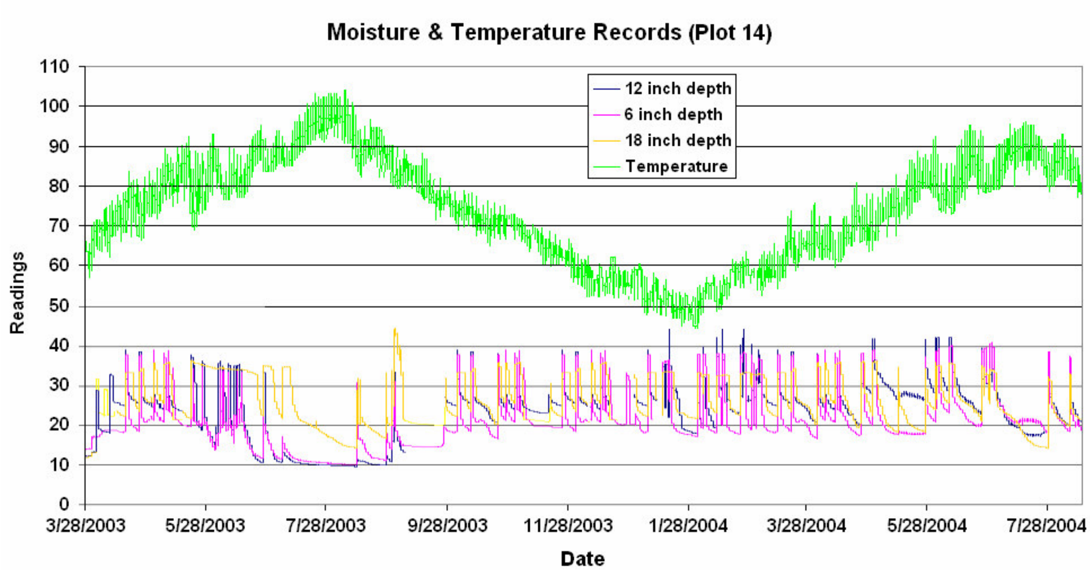


Figure A14 Plot 14 (CMT3-5-4)

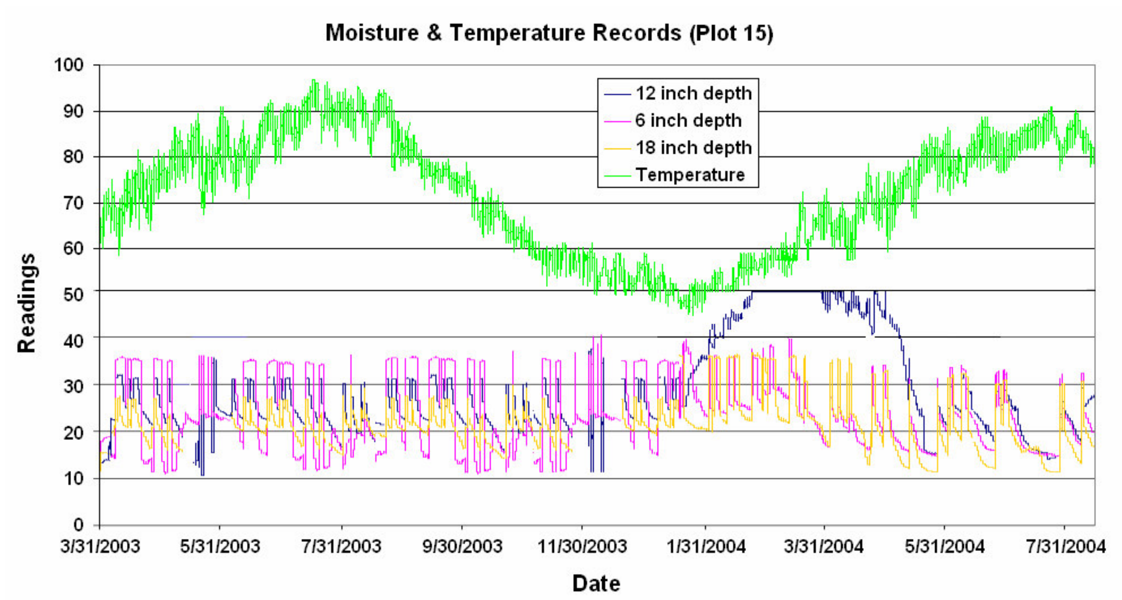


Figure A15 Plot 15 (CMT2-5-4)

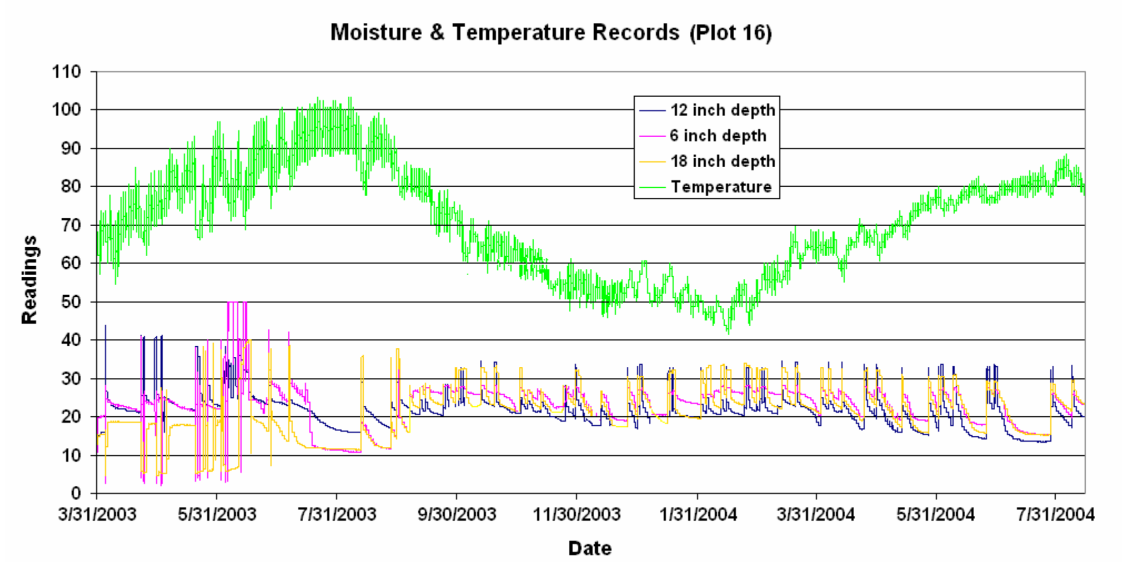


Figure A16 Plot 16 (CMT1-5-4)

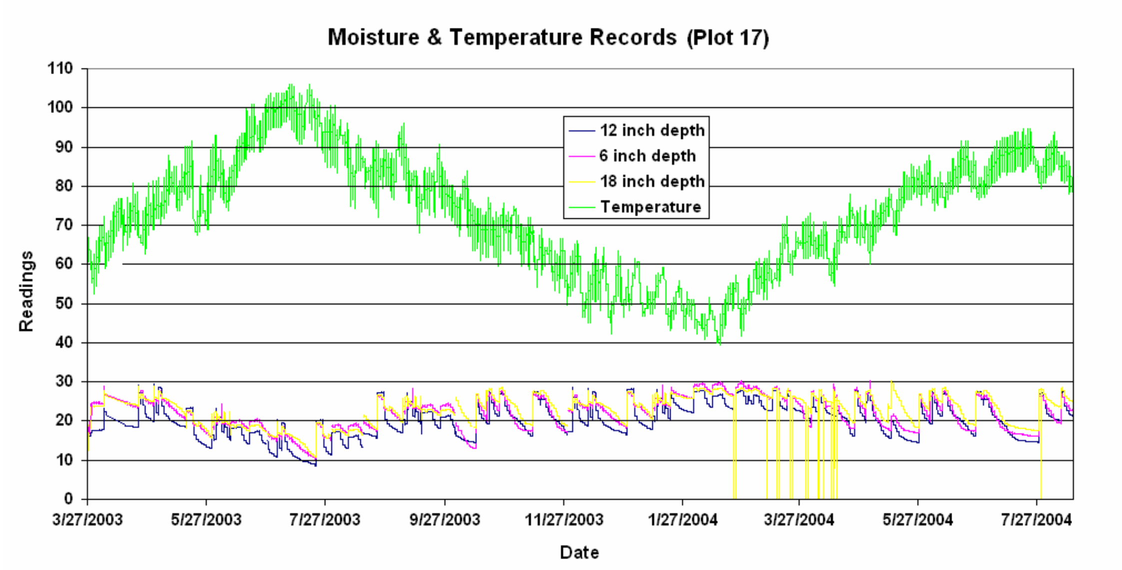


Figure A17 Plot 17 (CP-10-4)

APPENDIX B

PAVED SHOULDER CRACKING (FIRST PHASE)

Figure B1 Plot 1 (CMT4-10-4)

Figure B2 Plot 2 (CMT3-10-4)

Figure B3 Plot 3 (CMT2-10-4)

Figure B4 Plot 4 (CMT1-10-4)

Figure B5 Plot 5 (CMT4-10-2)

Figure B6 Plot 6 (CMT3-10-2)

Figure B7 Plot 7 (CMT2-10-2)

Figure B8 Plot 8 (CMT1-10-2)

Figure B9 Plot 9 (CMT4-5-2)

Figure B10 Plot 10 (CMT3-5-2)

Figure B11 Plot 11 (CMT2-5-2)

Figure B12 Plot 12 (CMT1-5-2)

Figure B13 Plot 13 (CMT4-5-4)

Figure B14 Plot 14 (CMT3-5-4)

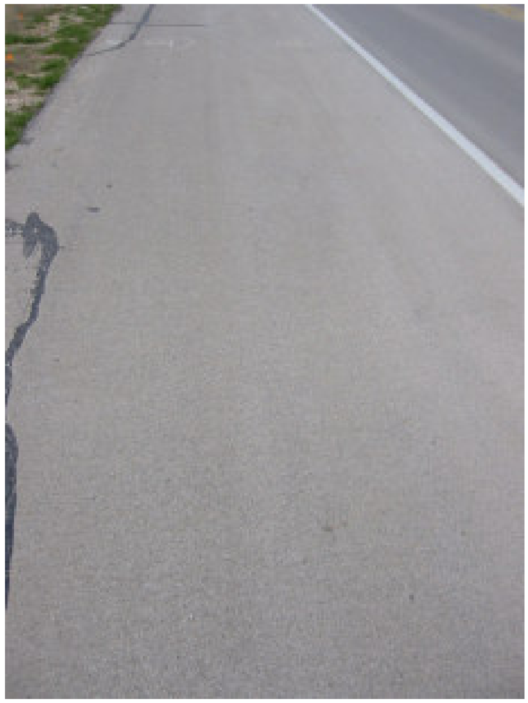


Figure B15 Plot 15 (CMT2-5-4)

Figure B16 Plot 16 (CMT1-5-4)

Figure B17 Plot 17 (CP-10-4)

APPENDIX C

VEGETATION (FIRST PHASE)

Figure C1 Plot 1 (CMT4-10-4)

Figure C2 Plot 2 (CMT3-10-4)

Figure C3 Plot 3 (CMT2-10-4)

Figure C4 Plot 4 (CMT1-10-4)

Figure C5 Plot 5 (CMT4-10-2)

Figure C6 Plot 6 (CMT3-10-2)

Figure C7 Plot 7 (CMT2-10-2)

Figure C8 Plot 8 (CMT1-10-2)

Figure C9 Plot 9 (CMT4-5-2)

Figure C10 Plot 10 (CMT3-5-2)

Figure C11 Plot 11 (CMT2-5-2)

Figure C12 Plot 12 (CMT1-5-2)

Figure C13 Plot 13 (CMT4-5-4)

Figure C14 Plot 14 (CMT3-5-4)

Figure C15 Plot 15 (CMT2-5-4)

Figure C16 Plot 16 (CMT1-5-4)

Figure C17 Plot 17 (CP-10-4)

APPENDIX D

MOISTURE AND TEMPERATURE READINGS (SECOND PHASE)

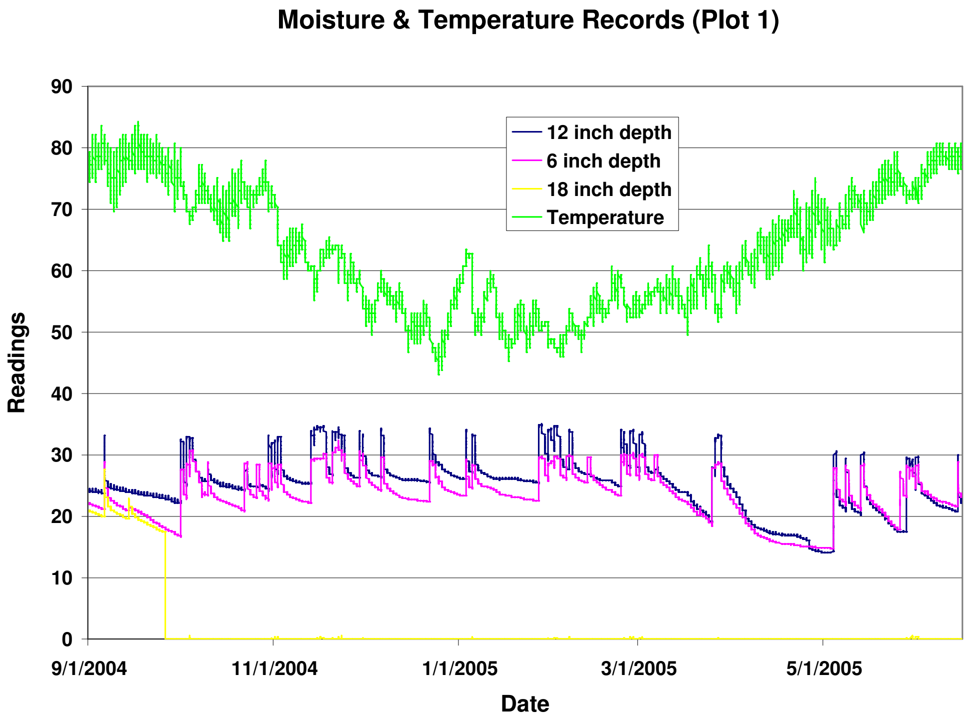


Figure D1 Stephenville Plot 1 (CMT4-10-4)

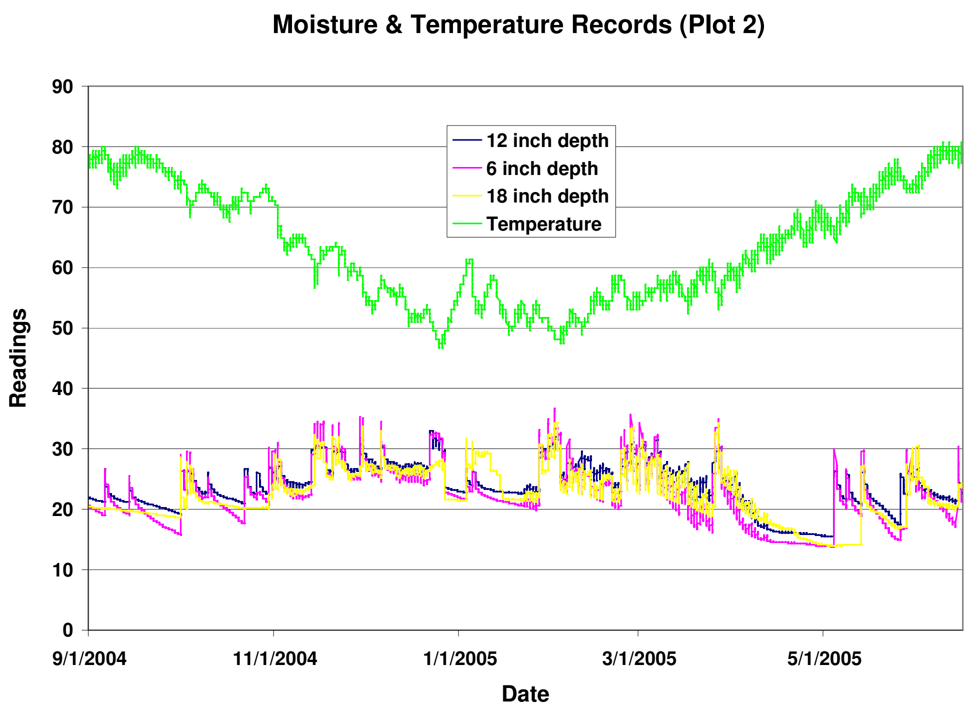


Figure D2 Stephenville Plot 2 (CMT3-10-4)

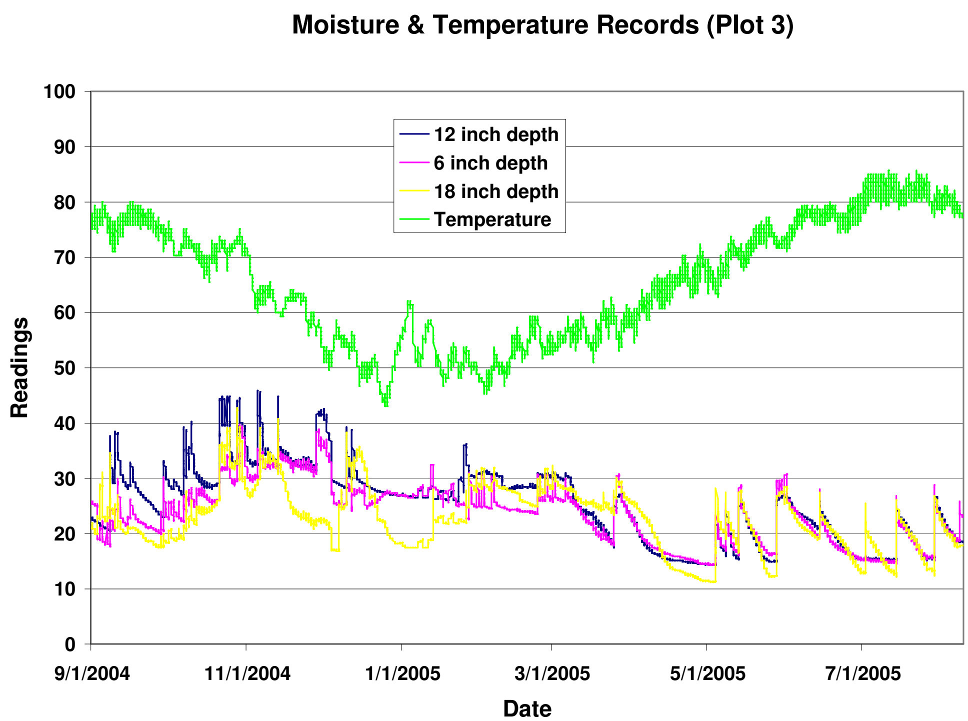


Figure D3 Stephenville Plot 3 (CMT2-10-4)

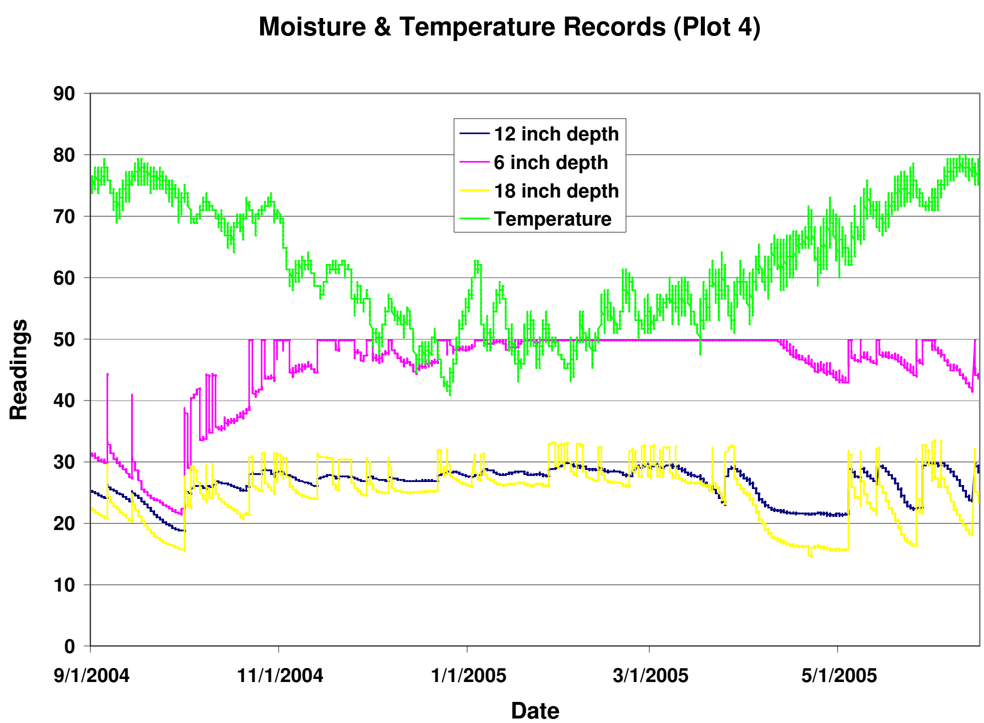


Figure D4 Stephenville Plot 4 (CMT1-10-4)

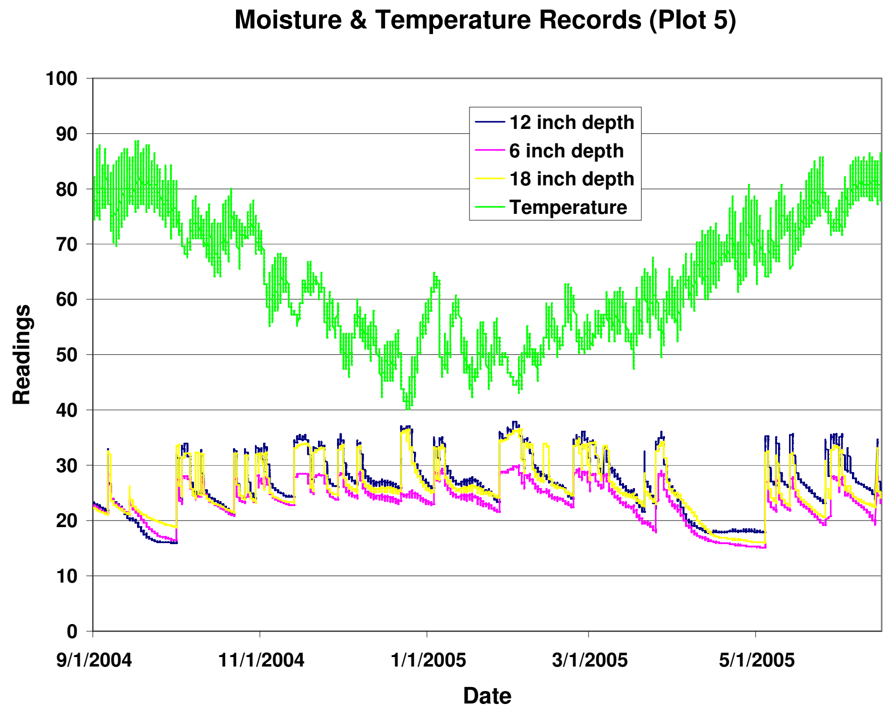


Figure D5 Stephenville Plot 5 (CMT4-10-2)

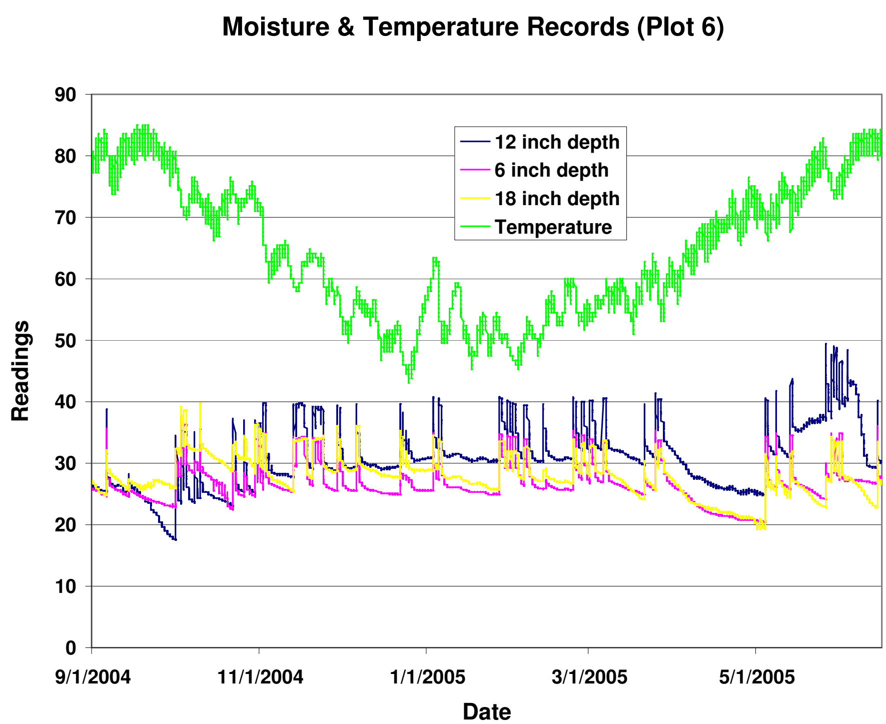


Figure D6 Stephenville Plot 6 (CMT3-10-2)

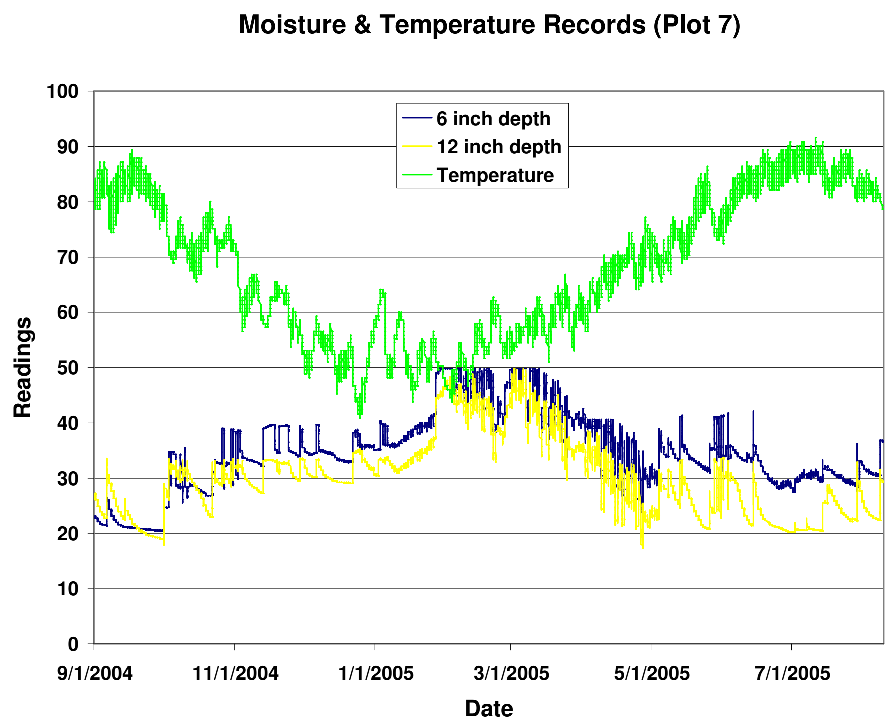


Figure D7 Stephenville Plot 7 (CMT2-10-2)

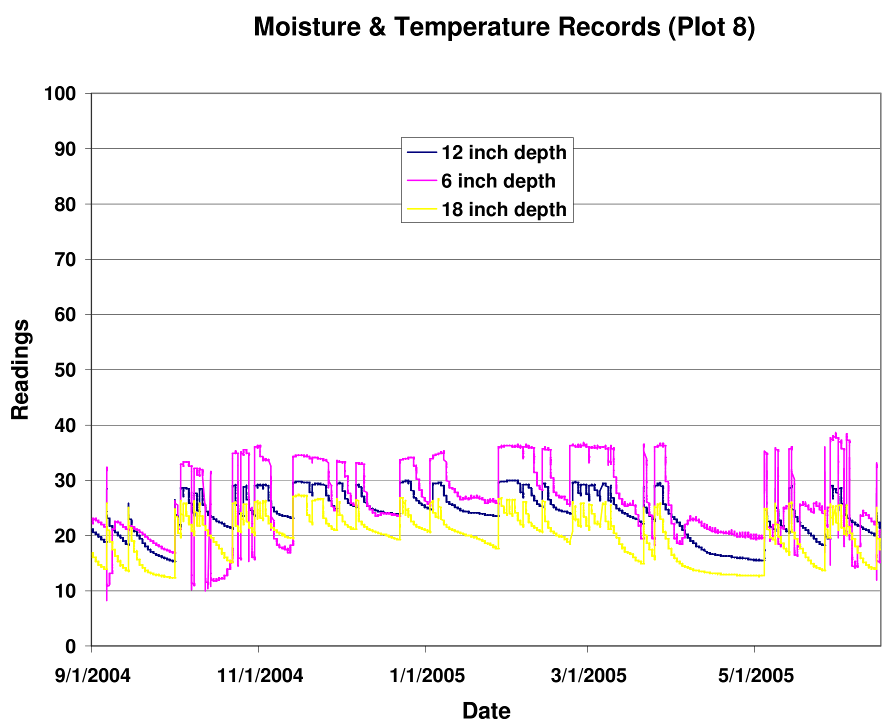


Figure D8 Stephenville Plot 8 (CMT1-10-2)

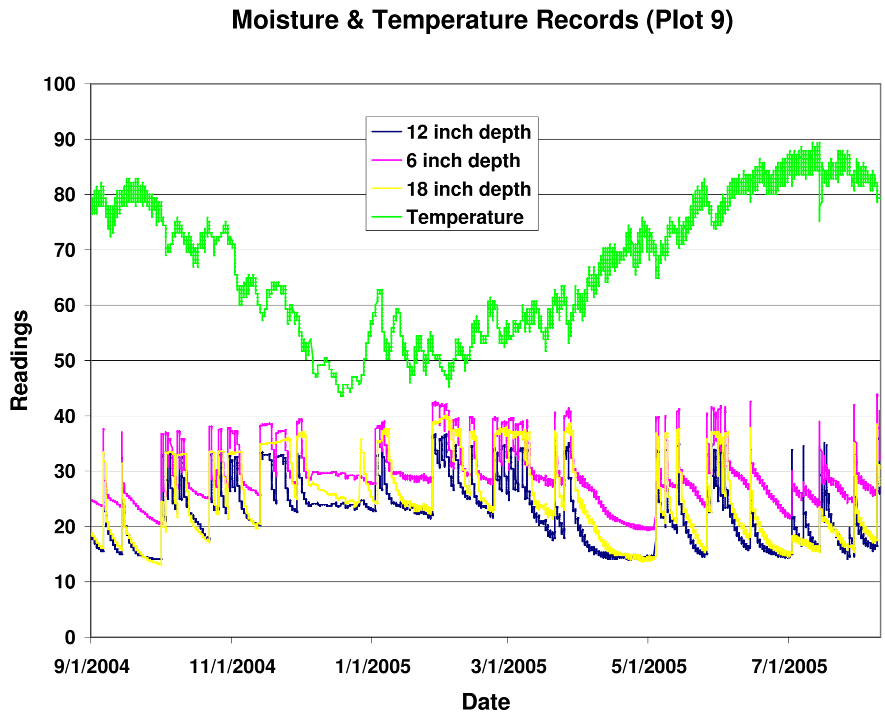


Figure D9 Stephenville Plot 9 (CMT4-5-2)

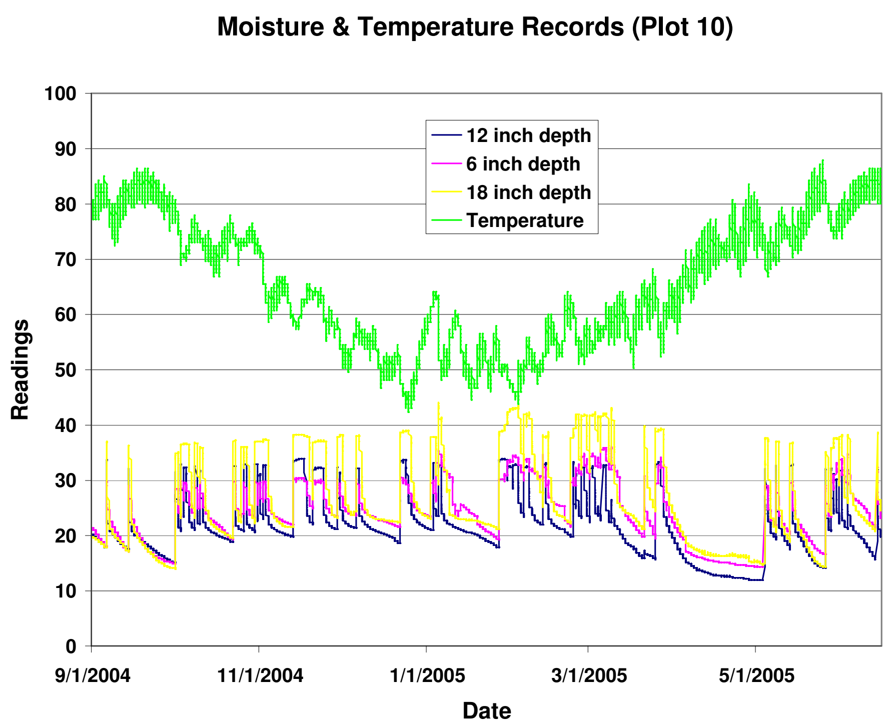


Figure D10 Stephenville Plot 10 (CMT3-5-2)

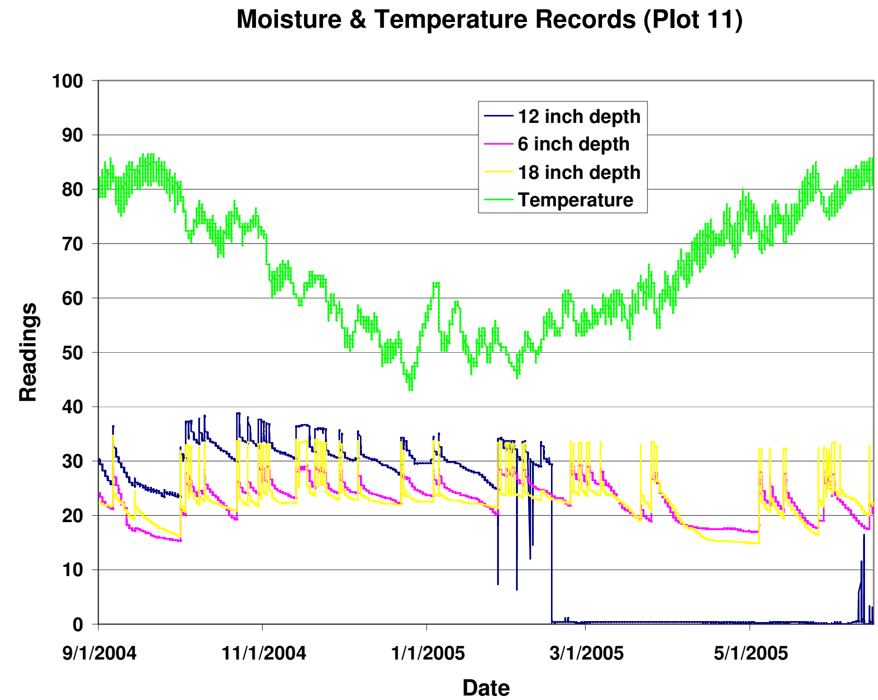


Figure D11 Stephenville Plot 11 (CMT2-5-2)

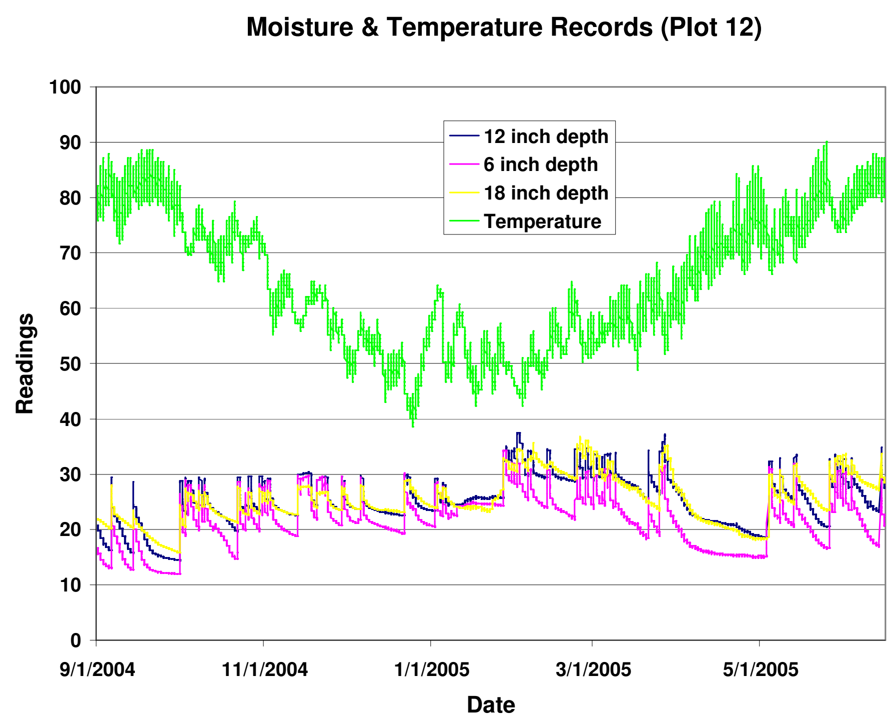


Figure D12 Stephenville Plot 12 (CMT1-5-2)

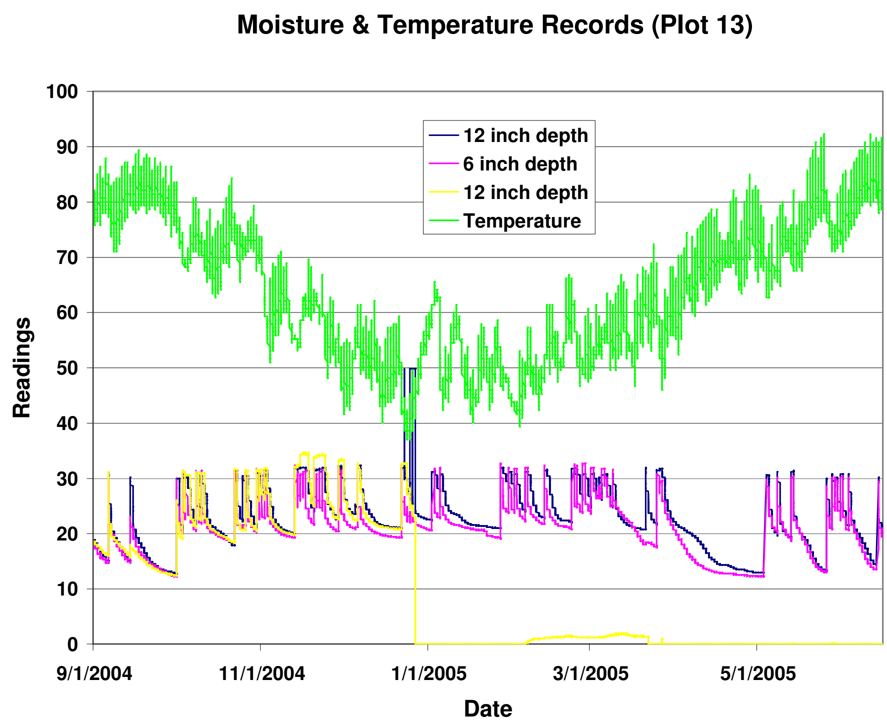


Figure D13 Stephenville Plot 13 (CMT4-5-4)

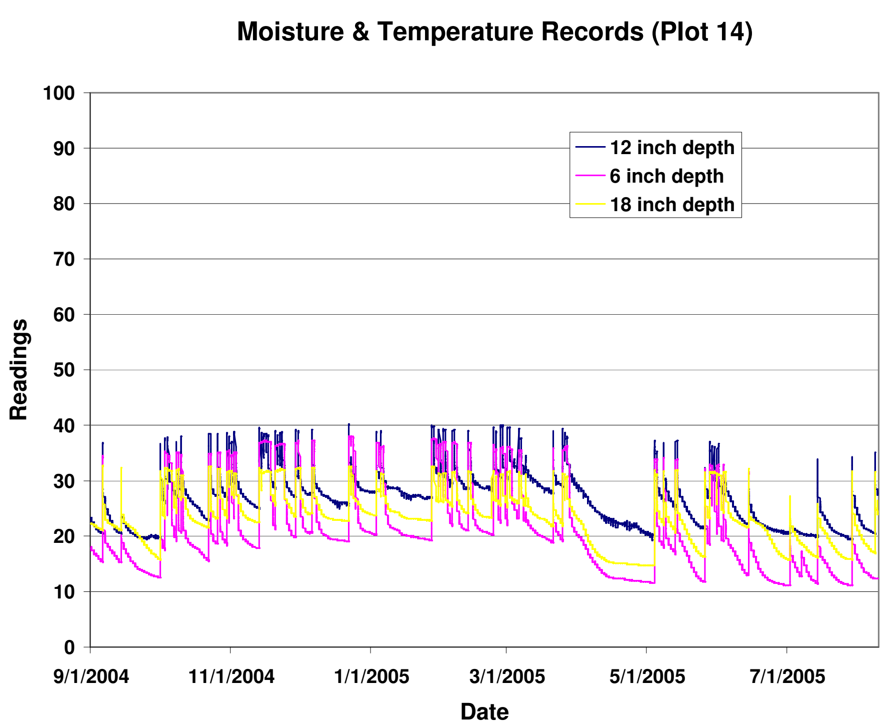


Figure D14Stephenville Plot 14 (CMT3-5-4)

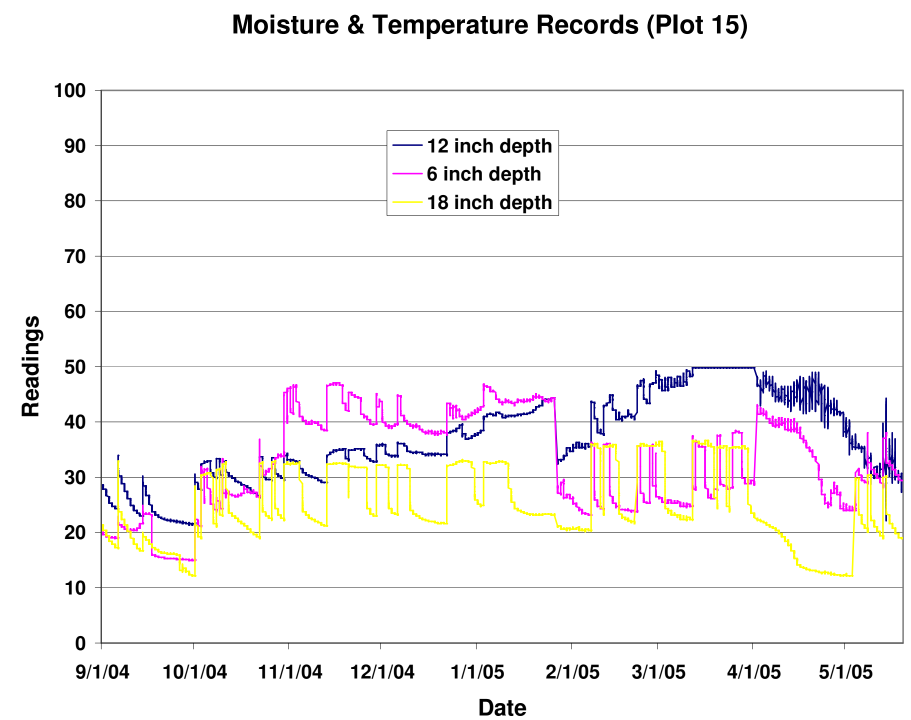


Figure D15 Stephenville Plot 15 (CMT2-5-4)

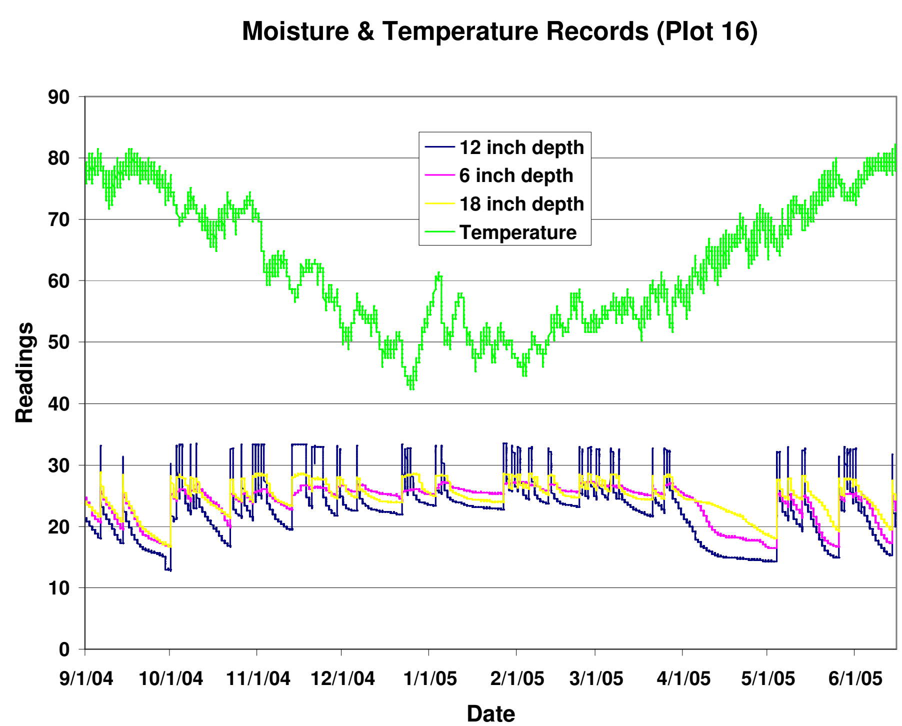


Figure D16 Stephenville Plot 16 (CMT1-5-4)

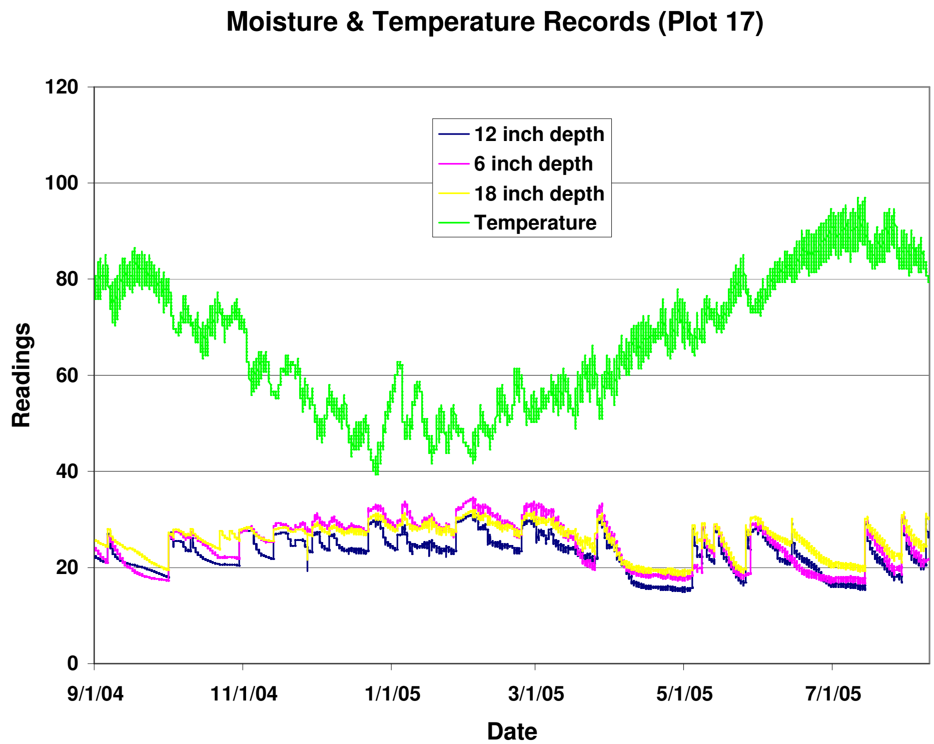


Figure D17 Stephenville Plot 17 (CP-10-4)

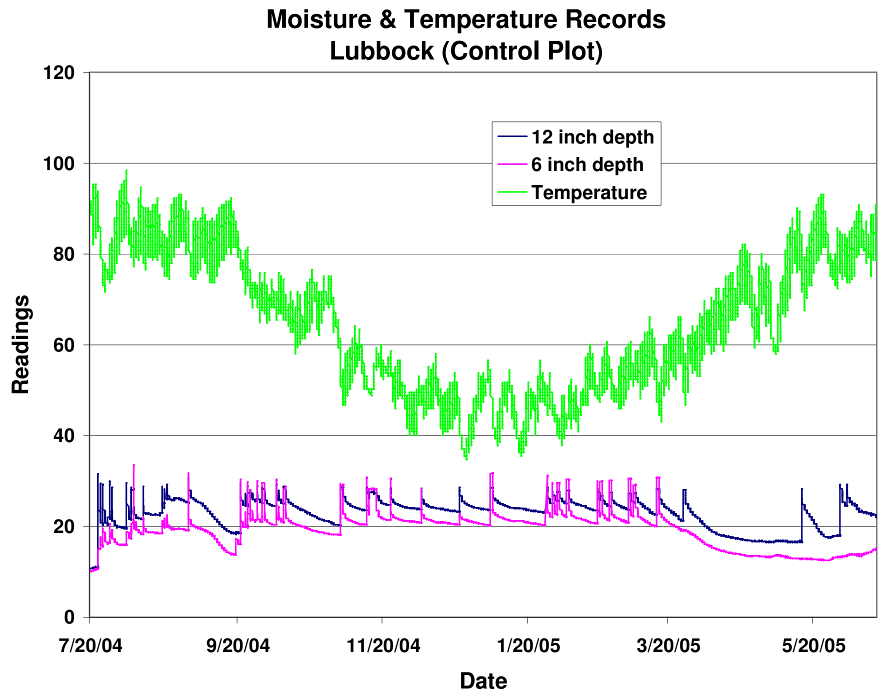


Figure D18 Lubbock Control Plot

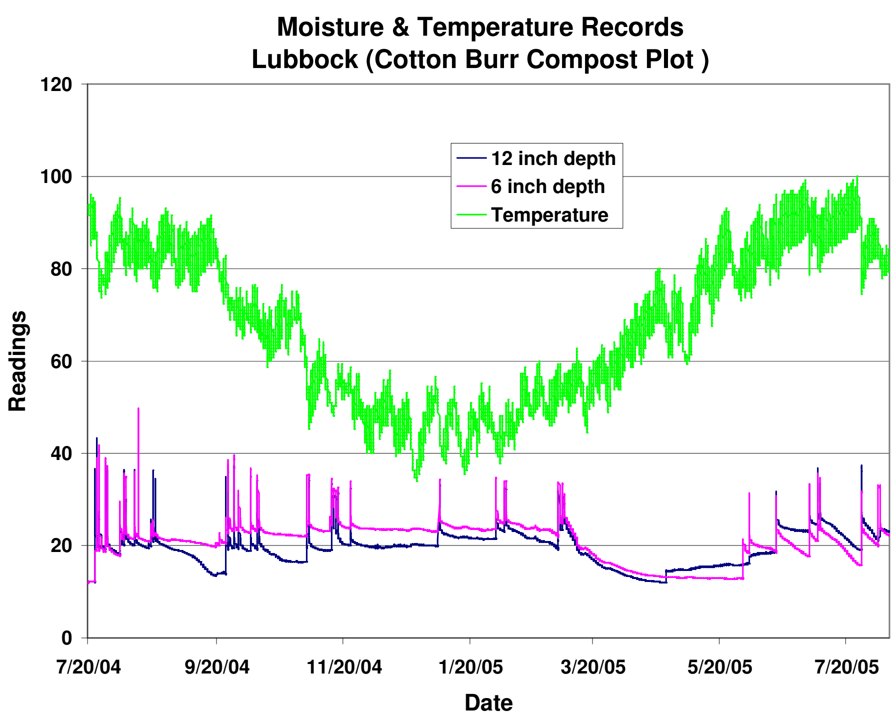


Figure D19 Lubbock Cotton Burr Compost Plot

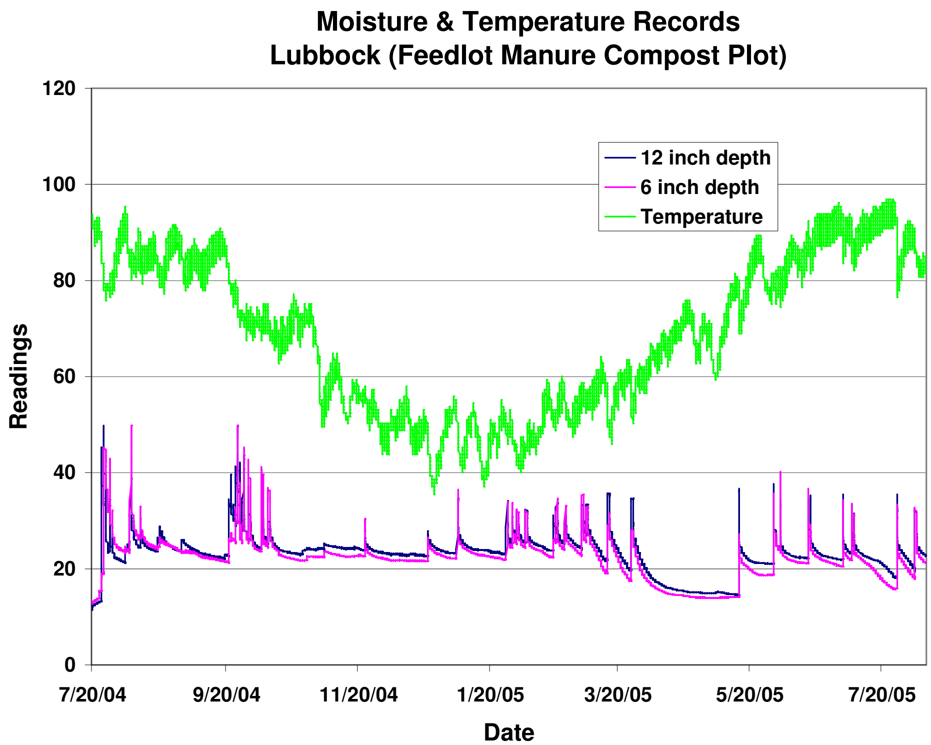


Figure D20 Lubbock Feedlot Manure Compost Plot

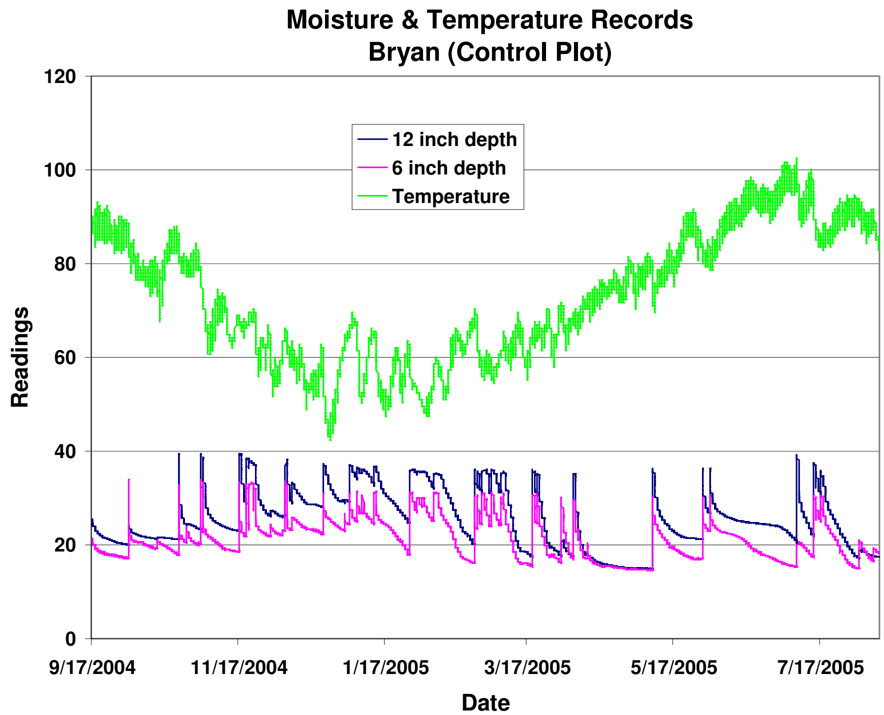


Figure D21 Bryan Control Plot

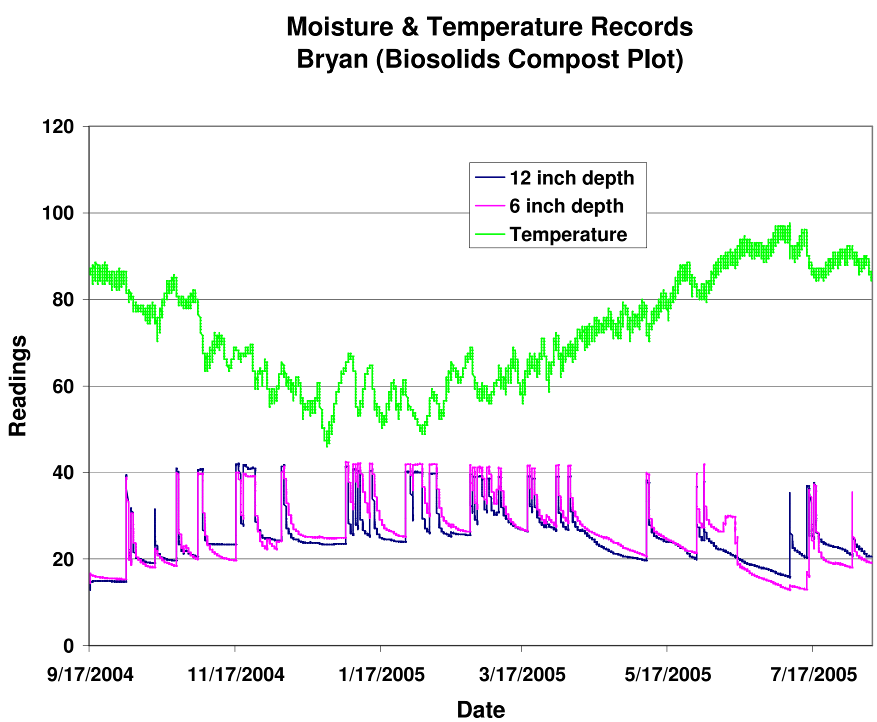


Figure D22 Bryan Biosolids Compost Plot

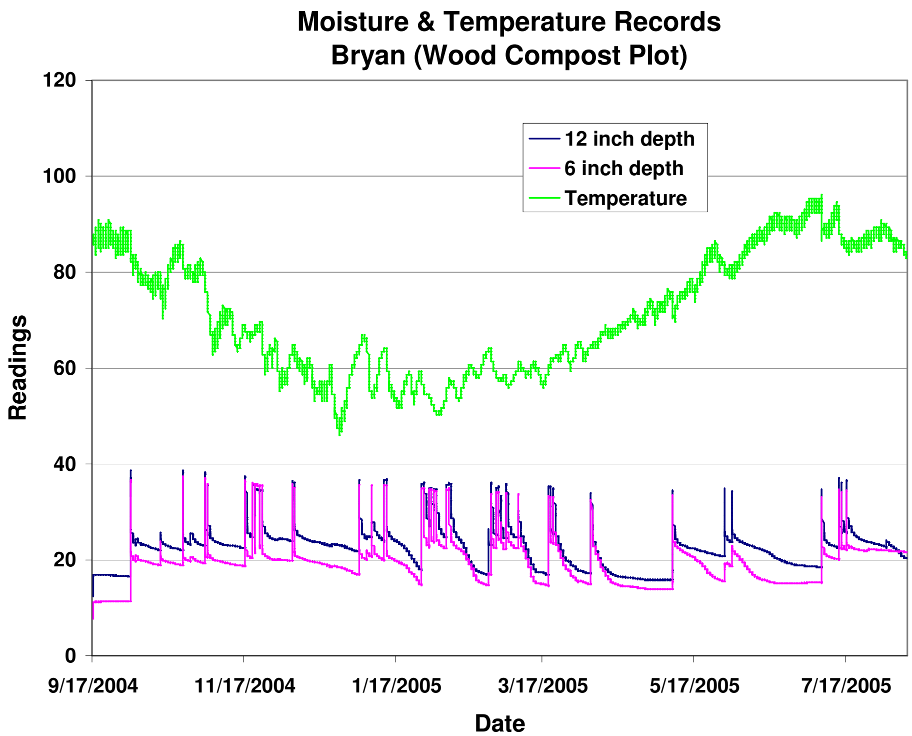


Figure D23 Bryan Wood Compost Plot

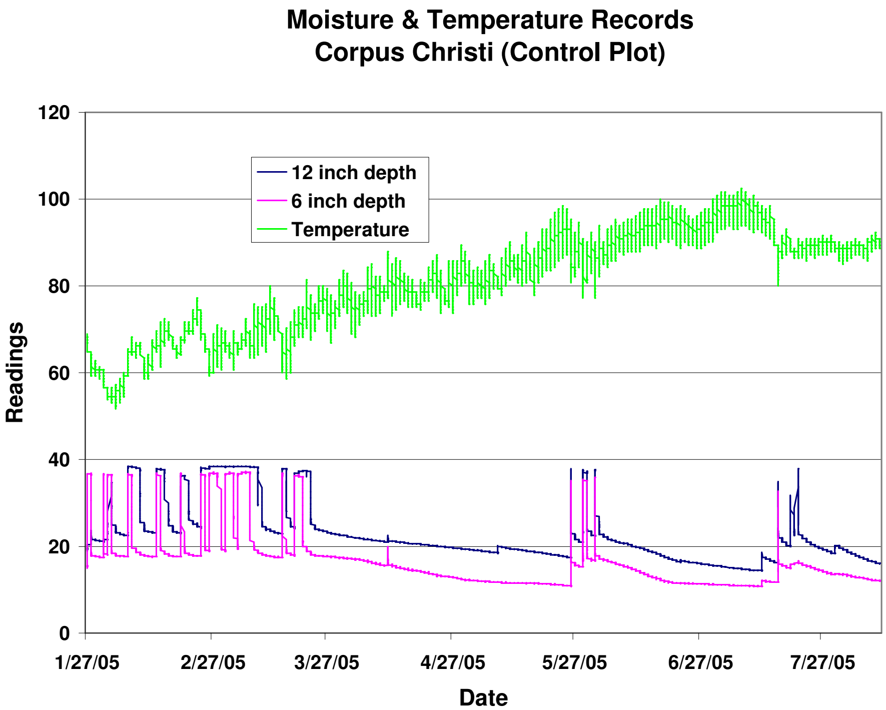


Figure D24 Corpus Christi Control Plot

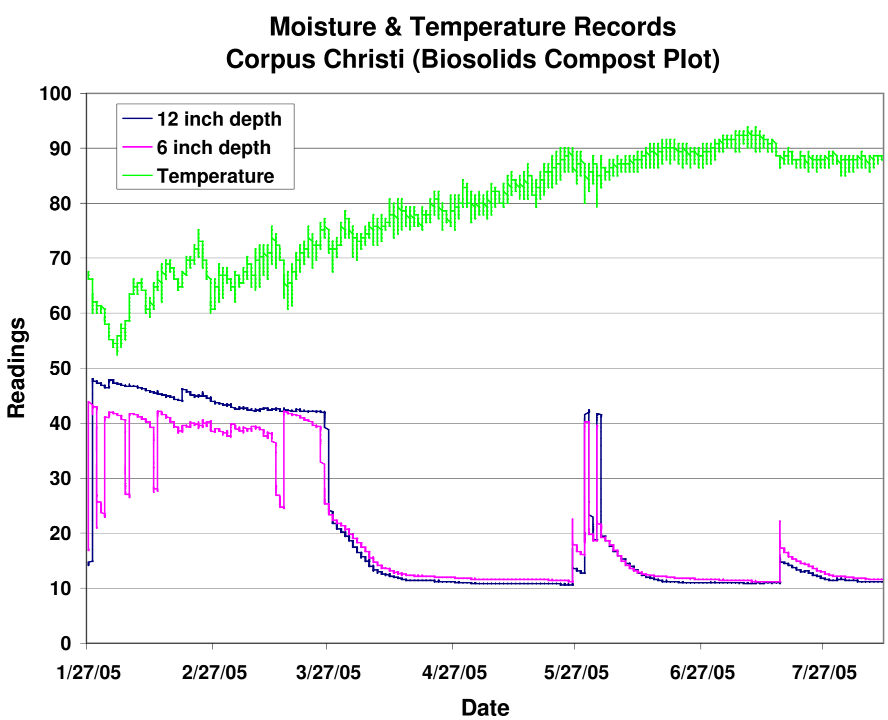


Figure D25 Corpus Christi Biosolids Compost Plot

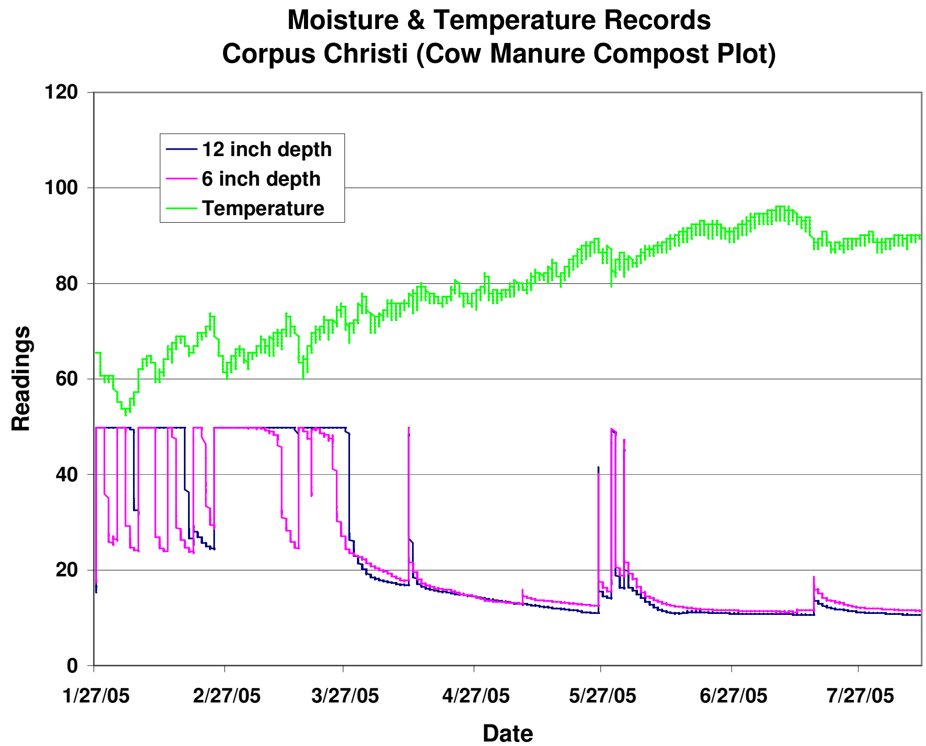


Figure D26 Corpus Christi Cow Manure Plot

APPENDIX E

PAVED SHOULDER CRACKING (SECOND PHASE)

Figure E1 Stephenville Plot 1 (CMT4-10-4)

Figure E2 Stephenville Plot 2 (CMT3-10-4)


Figure E3 Stephenville Plot 3 (CMT2-10-4)


Figure E4 Stephenville Plot 4 (CMT1-10-4)

Figure E5 Stephenville Plot 5 (CMT4-10-2)

Figure E6 Stephenville Plot 6 (CMT3-10-2)

Figure E7 Stephenville Plot 7 (CMT2-10-2)

Figure E8 Stephenville Plot 8 (CMT1-10-2)


Figure E9 Stephenville Plot 9 (CMT4-5-2)


Figure E10 Stephenville Plot 10 (CMT3-5-2)


Figure E11 Stephenville Plot 11 (CMT2-5-2)


Figure E12 Stephenville Plot 12 (CMT1-5-2)

Figure E13 Stephenville Plot 13 (CMT4-5-4)

Figure E14 Stephenville Plot 14 (CMT3-5-4)

Figure E 15 Stephenville Plot 15 (CMT2-5-4)

Figure E 16 Stephenville Plot 16 (CMT1-5-4)

Figure E 17 Stephenville Plot 17 (CP-10-4)

Figure E 18 Lubbock Control Plot

Figure E 19 Lubbock Cotton Burr Compost Plot

Figure E 20 Lubbock Feedlot Manure Compost Plot

Figure E 21 Bryan Control Plot

Figure E 22 Bryan Biosolids Compost Plot

Figure E 23 Bryan Wood Compost Plot

Figure E 24 Corpus Christi Control Plot

Figure E 25 Corpus Christi Biosolids Compost Plot

Figure E 26 Corpus Christi Cow Manure Plot

APPENDIX F

VEGETATION (SECOND PHASE)

Figure F1 Stephenville Plot 1 (CMT4-10-4)

Figure F2 Stephenville Plot 2 (CMT3-10-4)


Figure F3 Stephenville Plot 3 (CMT2-10-4)


Figure F4 Stephenville Plot 4 (CMT1-10-4)


Figure F5 Stephenville Plot 5 (CMT4-10-2)


Figure F6 Stephenville Plot 6 (CMT3-10-2)

Figure F7 Stephenville Plot 7 (CMT2-10-2)

Figure F8 Stephenville Plot 8 (CMT1-10-2)

Figure F9 Stephenville Plot 9 (CMT4-5-2)

Figure F10 Stephenville Plot 10 (CMT3-5-2)


Figure F11 Stephenville Plot 11 (CMT2-5-2)


Figure F12 Stephenville Plot 12 (CMT1-5-2)


Figure F13 Stephenville Plot 13 (CMT4-5-4)


Figure F14 Stephenville Plot 14 (CMT3-5-4)

Figure F15 Stephenville Plot 15 (CMT2-5-4)

Figure F16 Stephenville Plot 16 (CMT1-5-4)

Figure F17 Stephenville Plot 17 (CP-10-4)

Figure F18 Lubbock Control Plot

Figure F19 Lubbock Cotton Burr Compost Plot

Figure F20 Lubbock Feedlot Manure Compost Plot

Figure F21 Bryan Control Plot

Figure F22 Bryan Biosolids Compost Plot

Figure F23 Bryan Wood Compost Plot

Figure F24 Corpus Christi Control Plot

Figure F25 Corpus Christi Biosolids Compost Plot

Figure F26 Corpus Christi Cow Manure Plot

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BIOGRAPHICAL INFORMATION

Napat Intharasombat has been a Doctoral research assistant at the University of Texas at Arlington, Texas, USA since May 2003. His PhD research was funded by the Texas Department of Transportation (TxDOT). The research focused on the use of compost manufactured topsoils as a preventive measure to mitigate desiccation cracking in expansive soils.

He received a Masters Degree in Civil Engineering from the University of Texas at Arlington, Texas, USA. His research was on the Ettringite formation in lime treated sulfate soils. He also received a Bachelor Degree in Civil Engineering from Chulalongkorn University, Bangkok, Thailand. His main interests are ground modifications and slope stabilizations.