# LIFE CYCLE ASSESSMENT OF BIO-MATERIAL STABILIZED EXPANSIVE SOILS

by

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ABSTRACT

LIFE TIME ASSESSMENT OF BIO-MATERIAL

STABILIZED EXPANSIVE

SOILS

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Pavement cracking is one of the major maintenance works that requires millions of dollars in repair costs annually. Pavement cracks are formed due to moisture and temperature fluctuations in the soil. Stabilization of pavement shoulder subsoil with the addition of compost material was studied for preventing pavement cracks. Eight different compost materials with three major feed stock sources such as biosolids, wood waste, and animal manure were investigated in this research. Compost treatment studies were performed at four different test sites located in various regions of the state of Texas.

Laboratory experiments were conducted completed compost manufactured topsoil's (CMTs) to determine their physical and compaction characteristics as well as engineering properties such as linear shrinkage and free swell properties. Test sections were prepared with CMTs as shoulder covers and these sections were instrumented with temperature and moisture probes underneath the CMT cover. Elevation surveys and digital images of the CMTs and the adjacent pavement sections respectively were periodically obtained.

Statistical analyses were performed on the maximum monthly moisture and temperature variations of CMTs and Control section were conducted. Elevation survey data and the digital images of the sites were collected and analyzed to determine soil erosion loss and magnitude of pavement cracking, respectively. Overall, it was concluded that both biosolids and wood based composts were effective; while the manure based compost was not effective in mitigating pavement cracking. These findings were based on moisture variation, elevation survey, and digital image analyses. Surface soil samples were collected from the CMTs and laboratory experiments such as organic content (OC), cation exchange capacity (CEC), and total soil suction studies were performed at various time periods. Three kinds of models were analyzed for simulating the degradation of the soil properties with time and it was found that the measured data fitted well when an exponential decay model was used. The equations developed from these models were used to determine the service life of the compost treatment. The average of the service life predicted based on the OC, CEC and total soil suction results was taken as the service life of the compost treatment. The service life of the biosolids and wood based compost was 5 to 6 years while the manure based compost had a service life of 4 to 5 years.

Cost analysis was performed in order to compare cost effectiveness between CMTs, seal coating, and crack sealing. It was concluded that CMTs were recommended over seal coat and crack sealing maintenance techniques based on the costs, quality control issues and benefits of compost treatment in promoting environmental recycling efforts. Future research needs in this area are also summarized.

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# CHAPTER 1

# INTRODUCTION

## 1.1 Introduction

All pavements though appropriately designed would in due course require some sort of maintenance work. This maintenance work is due to the different stresses that are endured by the pavement due to the different environmental and traffic loading effects on it. The pavement distress could be categorized into Surface Defects, Surface Deformation, Cracking, and Potholes. Pavement cracking occurs when the stresses caused by the environmental and traffic loads are greater than the fatigue or tensile strength (Patrick Lavin., 2003). The Texas Department of Transportation (TxDOT) has been experiencing considerable amount of pavement cracking in areas having expansive soils. If these cracks are left unattended it would lead to the intrusion of rainwater into the base and sub-base layers weakening the soil layers. In many cases the soil on the unpaved shoulder which is exposed to the environment is subjected to the swelling and shrinkage effects, leading to the formation of cracks on the soil surface which propagates onto the pavement causing pavement cracks. The normal preventive maintenance activities are pavement sealers, crack filling, and surface treatment. It can be observed from normal practice that there is almost no treatment done on the unpaved soil shoulder, which is one of the major factors contributing to pavement cracking. Therefore it is important to maintain the structural integrity of the unpaved shoulder soil, in order to sustain the roadways and pavement structures from cracking (Booze-Daniels et al., 2000).

**Figure 1-1 Longitudinal and transverse cracks on SH 180**

A number of treatment methods have been carried out on the shoulder subgrade soils to prevent cracking. There are certain disadvantages of using such treatments such as cost, effectiveness, suitability to expansive soils, and etc. One particular research that was funded by the Texas Department of transportation (TxDOT) was the application of a mixture of compost and local control soil on the unpaved shoulder surface. The short term effectiveness of the compost amendment in preventing pavement cracking was evaluated (Napat et al., 2005). However the long term effectiveness and the life time of the compost amendments has yet to be addressed. Hence the current research study involves the determination of the long term effectiveness, and development of models for the prediction of the life time of compost treatments.

## 1.2 Research Objectives

Several state departments have set goals for the composting and recycling of municipal solid waste. These goals would be achieved by locating suitable markets for the application of these recycled materials. One of these markets is the transportation department. There has been increased use of recycled materials in the transportation industry in the recent years. Since the regulations for the disposal of municipal solid waste is becoming more and more stringent, there has been an increase in the number of composting facilities (Shelburne et al., 1998). In 2003 the Texas Department of Transportation was the largest market for the use of compost in the nation (Rhonda Sherman., 2003). Compost is mainly used as mulch, blended with shoulder soil, erosion control, fertilizer enhancement, and soil amendments.

The application of compost on the highway shoulders have been studied by many researchers. Highways, road embankments, and other engineering projects are no longer limited just by their strength limits. Nowadays revegetation and erosion control are also major design factors such as geotechnical ones (De Ona et al., 2005).

This study involves the selection of compost from different source materials, and mixed with wood chips and fibers. These composts were obtained from locally available sources and mixed at fixed ratios determined from a previous study (Napat et al., 2005). The engineering characteristics of the compost amended soil were determined from various laboratory experiments. The different laboratory experiments that were conducted on the samples were Atterberg limits, sieve analysis, specific gravity, linear shrinkage, free swell, Procter compaction (standard), and organic content. These parameters were used in the field implementation of the compost amendment on the pavement shoulder at Tyler-TX, and Yoakum-TX. Field studies included in this research were temperature, elevation, digital imaging, and moisture readings which were recorded to evaluate the performance of the compost amendment. The temperature and moisture readings were used to determine the ability of the compost amended soils to reduce the temperature and moisture fluctuations. The elevation and digital imaging was used to measure the amount of erosion and monitor any development of cracks on the pavement shoulder.

The research also included laboratory studies to investigate the parameters which would predict the life time of the compost amendments. Four different parameters which were cation exchange capacity (CEC), suction, organic content (O.C), and pH were measured. Four different sites which are located at Stephenville, Corpus Christi, Yoakum, and Tyler were analyzed in this research.

Samples were collected once every month from each of the test sites and the different laboratory test mentioned earlier were conducted. The data collected from the Stephenville and Corpus Christi sites would be used to predict the models for determining the effective service life of the compost amendment. The data from the Yoakum and Tyler sites would be used to validate the models that are produced from the results of the previous two sites. Cost analysis between other treatment types and the application of compost amended top soil would be analyzed and reported. The fulfillment of this research would provide an approximate estimate on the service life of the compost treatment, while encouraging the recycling of municipal solid waste. This would provide a positive impact on the environment and encourage the use of compost for further highway applications.

## 1.3 Organization of the Dissertation

This dissertation is made up of 7 chapters

Chapter 1 consists of a brief introduction on pavement cracking, research objectives, and the outline of the dissertation on how it would be presented.

Chapter 2 provides the background and history of compost and its different sources, the different parameters that would be measured and analyzed, application of compost, and process of degradation. Pavement cracking and the different treatment methods that are used to prevent it would also be discussed

Chapter 3 provides a brief overview of the different laboratory experiments and the procedures involved with it. Results obtained from the laboratory tests prior to the field implementation of the compost amended soil would also be presented.

Chapter 4 consists of the field implementation of the compost amended soil sections at the various sites and also the field instrumentation of those respective sites. The sampling procedure and the field data collected during each field visit is briefly explained in this chapter.

Chapter 5 provides the analysis of the results that was collected from the field. It involves statistical data analysis of the field results collected and provides the effectiveness of the treatment methods.

Chapter 6 consists of the laboratory tests done on the samples collected periodically from the field visits. The results are analyzed and the service life prediction model is presented in this chapter.

Chapter 7 provides a brief summary and conclusion of the overall research studies conducted and future recommendations.

# CHAPTER 2

# LITERATURE REVIEW

## 2.1 Introduction

This chapter includes a brief overview of compost, and its engineering application. Since a number of different types of compost have been used in this research, it is required to have a good understanding on the composting process and the different kinds of materials that are composted. The United states Environmental Protection Agency (USEPA) has numerous regulations on the materials that could be composted and also on the applications of the end products of composting which would be explained in this chapter. It would also include the different types of pavement distress problems that are encountered and their current remedial procedures. Applications of the parameters such as cation exchange capacity, organic content, and suction would also be explained in this chapter.

## 2.2 Compost

Municipal solid waste could be defined as the type of waste that consists of the typical house hold waste and sometimes includes commercial waste collected from a particular area. The most optimum solutions for the reduction and management of the MSW are ranked as follows (USEPA)

1. Source Reduction
2. Composting

3. Landfill

The total amount of MSW generated by the United States of America in 2006 was 251 million tons. Out of these 21 million tons of municipal solid waste was recycled by composting. The energy equivalent of saving 21 million tons of MSW is equal to 2.5 billion gallons of gasoline (USEPA). It was seen that there was an increase in the community composting facilities from 3227 to 3470 facilities (USEPA). Composting can be defined as the degradation of organic material under controlled conditions into useful end products. The degradation of organic matter can be carried out in aerobic and anaerobic conditions. Composting degrades the organic matter by aerobic degradation.

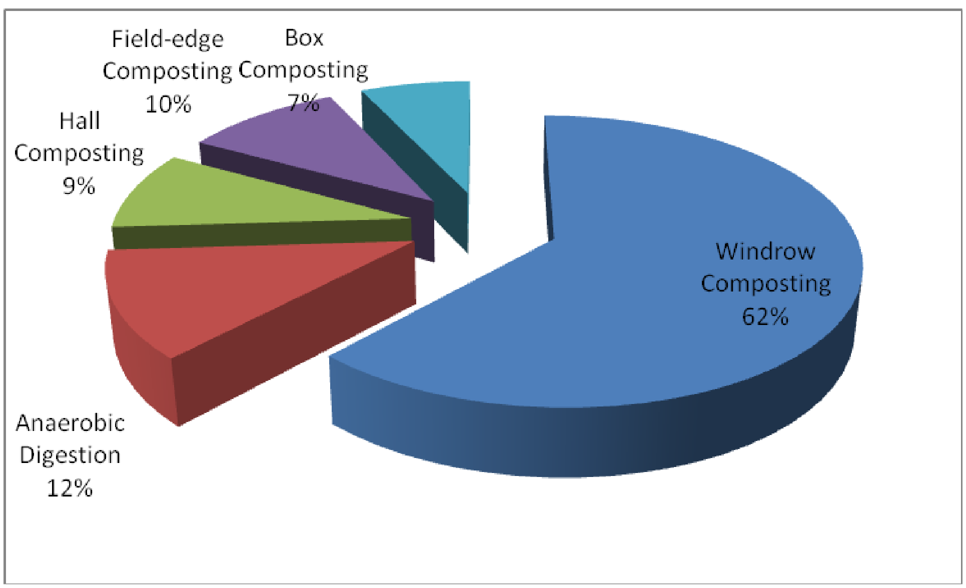



**Figure 2-1 Types of composting methods followed in switzerland, 2000 (Ludwig, 2003)**

Data show that composting has the lowest use of resources per gram of waste compared to incineration and land filling (Marchettini N., et al. 2006). Composting could be done by different methods such as seen in Figure 2-1 (Ludwig C., et al. 2003). It can be noted that the most common composting process done is by windrow composting. All the compost used in this research was prepared by the windrow composting process. During the composting process the raw materials (organic) are converted into humus and useful end products by the various micro organisms that act on it. Previously there were not many composting facilities because of the lack of a lucrative market for the usage of the end product produced by composting. Nowadays due to the many restrictions placed on landfills and the bans placed on certain materials that can be dumped in a landfill there is a search for an efficient way for the disposal of these materials.

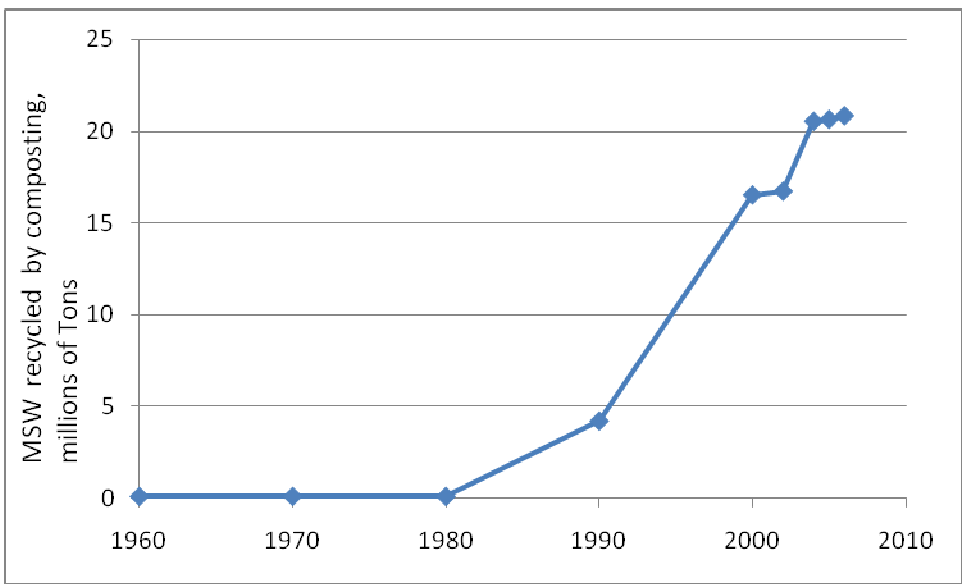



**Figure 2-2 Trend in the percentage of municipal solid waste recycled by composting (USEPA)**

Composting is beginning to prove as a resourceful as well as an energy efficient way for the disposal of these materials. It can be observed from Figure 2-2 that more and more percentage of the municipal solid waste recycled is done by composting (USEPA). The composted waste material is turned into useful products that can be used in landscaping, erosion control, highway construction, agriculture, and many other applications.

The United States Environmental Protection Agency has regulated some organic material not suitable for composting. Compost are classified into two types class A and class B compost based on their quality, process conditions, pathogens present, vectors attraction characteristics, odor, etc. Class A compost is the only type of composed that is allowed to come into contact with the public. There are special rules that are to be followed when the source of the compost is biosolids from the waste water treatment plants given by the 40 CFR part 503 of the Clean Water Act (USEPA). The type and efficiency of the waste water treatment plants greatly determines the quality and quantity of the biosolids produced, which directly affects the quality of the compost produced. There are stringent sampling techniques that are specified by the USEPA that have to be followed during the composting process. The samples are collected at the appropriate intervals and checked for pathogens and vector attraction properties and then classified. All the compost that is used in this research is class A compost.

## 2.3 Windrow Composting

Windrow composting is one of the most popular processes by which composting are done. There are many methods by which windrow composting is done by all of them follow the same basic principle. The organic matter is arranged into rows of long piles called as windrows by trucks and frond end loaders. The typical size of the windrow is 2–6 m at the base and 1–3 m at the top which depends on the equipment, type of waste, and the weather (Kuhlman L.R. 1989). There are a lot of factors that affect the quality of the compost which are described in the sections below.

*2.3.1 Particle Size*

One of the major factors that effect compost quality is the particle size of the waste material. The MSW is usually grinded and shredded into smaller particles in order to facilitate the aeration of the compost pile. The surface area of the organic material is increased by grinding the waste material hence decreasing the particle size making it more accessible to the microorganisms acting on it (USEPA, 2008). A homogenous mixture of waste material is prepared by shredding, and the pile insulation capacity to maintain the temperature generated is also improved (USEPA, 2008). The optimum size of the grinded particles should be 1-3 inches (Tchobanoglous G., et al 1977). If the size of the particles is too small then it could inhibit the air flow through the pile leading to anaerobic conditions (Kuhlman L.R. 1989).

*2.3.2 Mixing and Turning*

In order to prevent the waste material being composted from caking, drying, and air channeling the pile has to be turned at regular predetermined time periods (Tchobanoglous G., et al 1977). Turning frequency could be daily, weekly or monthly depending on the type of waste material that is being composted and also on the judgment of the operator. The turning frequency for the same kind of waste material could vary depending on the seasons (Kuhlman L.R. 1989). It was found that that the degradation of Aspergillus fumigates was found to be much higher in the piles which were turned weekly when compared to the ones which were turned monthly (Fischer J.L., et al. 1998).

*2.3.3 Air Requirement*

The waste material in the windrows has to receive a certain amount of air in order to carry the aerobic degradation of the waste material into humus. The addition of bulking agents such as wood chips and newspaper shreds are added to the waste material to increase the aeration capacity (USEPA 2008). Air with at least 50 % of the initial oxygen concentration has to reach all the parts of the compost pile (Tchobanoglous G., et al 1977). In some cases where the windrows are significantly larger a series of pipes are laid below the waste material before it is placed and air is supplied through those pipes (Rhyner C.R., at al.1995). Aeration also helps in the control of the temperature that is built up in the interior of the windrows (Kuhlman L.R. 1989). The amount of oxygen required for the aerobic decomposition of organic waste could be calculated from the following equation (Tchobanoglous G., et al 1977).

$$C_aH_bO_cN_d + 0.5(ny + 2s + r - c)O_2 \rightarrow nC_wH_xO_yN_z + sCO_2 + rH_2O + (d - nx)NH_3 \qquad 2.1$$

*2.3.4 Moisture Content*

Moisture content is one of the major factors that control the biological degradation process that takes place in the composting process. The microorganisms that thrive in the compost pile require a sufficient amount of moisture in order to survive (Tchobanoglous G., et al 1977). The application of moisture to the waste material also helps to bring down the temperature inside the pile. The water also helps to carry the substances around and also makes the nutrients available to the microorganisms (USEPA, 2008). Both the initial and final moisture content of the compost pile helps in the determination of the quality of the compost produced. The initial moisture content can vary from 45-75% with the optimum values ranging between 50 and 65%. The optimum water content is determined from several variables such as volatile solids, turning frequency, temperature, and rainfall pattern. The final moisture content of the completed end product should never be less that 40% (Kuhlman L.R. 1989).

*2.3.5 Temperature*

The temperature of the compost pile has to be maintained between 45 and 55˚C. The optimum temperature of the compost pile depends on the type and variety of microbes that are acting on the waste material. It was determined that the temperature had to be maintained between 50 and 55˚C at the initial stages of decomposition and then between 55 and 60˚C (Tchobanoglous G., et al 1977). The temperature at the interior of the compost pile can reach up to 140˚C. It leads to the development of anaerobic conditions if the temperature of the compost pile is not properly maintained (USEPA, 2008). The microorganisms are very active at a particular range of temperature. Cold temperatures greatly reduce the rate at which the microbes degrade the organic matter, though they do not stop off the reaction completely.

*2.3.6 Carbon-nitrogen Ratio*

The carbon-nitrogen ratio (C/N) plays an important role in the composting process. The waste material can typically be distinguished into two types green and brown, the green material is high in nitrogen and the brown material is high in carbon. Grass clippings, manure and food waste are the green material whereas wood chips and dry leaves could be categorized as the brown material. There has to be a delicate balance between the nitrogen and the carbon for optimum composting efficiency (USEPA, 2008). If the amount of nitrogen is too low then it is difficult for the build up of temperature which deters the degradation process. If the amount of nitrogen is too low then addition of substances such as urea is recommended (Kuhlman L.R. 1989). If the nitrogen content is too high, then the temperature gets hot killing all the microorganisms in the compost pile. It has been found out that a typical C/N ratio at the start of the composting process would be 30/1. As the composting progresses the carbon in the waste material is converted into $CO_2$ therefore reducing the C/N ratio. The finished compost should have a C/N ratio of 10/1 (Trautmann N., Cornell University).

*2.3.7 Respiratory Quotient, RQ*

The respiratory quotient can be used to determine what type of biological reaction is taking place. The respiratory quotient is given as follows

$$RQ = \frac{O_2 including \cdot CO_2}{O_2 consumption} \qquad 2.2$$

If the RQ > 1 than it indicated an anaerobic degradation since the amount of $CO_2$ being formed is more than it is supplied. If the RQ < 1 than it indicates an aerobic reaction since the amount of oxygen used is less than that which is supplied (Tchobanoglous G., 1977).

*2.3.8 Pathogen Control*

Pathogen control is a very important quality parameter for the composted end product. Based on this there are federal regulations that direct the applications of the compost for different uses (USEPA 40 CFR part 503, 2008). All the harmful pathogens could be eliminated by maintaining the compost pile between 60 and 70˚C for about one day (Tchobanoglous G., 1977).

*2.3.9 Size of Compost Pile*

The size of the compost pile influences many factors. If the pile is too large the interior of the pile become anaerobic due to lack of oxygen resulting in unpleasant odor and vector attraction problems. The application of moisture to the compost piles becomes difficult if they are too large. If the windrows are too small then they would be subjected to weather effects, and would also require a greater land area for the same amount of compost applied as a bigger windrow (Kuhlman L.R. 1989).

## 2.4 Applications of Compost

Currently there has been an increase in environmental awareness on recycling waste material. One of the main recycled materials that are being used is compost. Compost provides a better land fill space utilization by diverting the organic matter away from the landfills. It also converts the waste material by using virtually no external energy into useful end products. Compost was found to be the most efficient in recovering eMergy from municipal solid waste when compared to incineration and land filling (Marchettini N., 2006). Compost has been used as a fertilizer and conditioner by farmers for a very long time. Nowadays compost is being used in a lot of other different applications such as erosion control, soil reclamation, bio-filters, landscaping, weed control, soil amendments, reestablishing wetlands, etc. One of the major markets for the application of compost is the state department of transportations (DOTs).

In 1999 the Texas Department of Transportation (TxDOT) implemented a project to improve the vegetative growth by manufacturing topsoil with compost. The site was constructed in Stephenville along SH 108 10 miles north of Stephenville. It was noted that the vegetative growth on the sections treated with compost showed marked improvement in germination (U.S. composting council). TxDOT selected another site which was constructed in 1968. The site was chosen because there had been no sign of any vegetative growth for the past 30 years. The site showed good vegetative growth after it was treated with compost (U.S. composting council). In 2003 TxDOT was the largest market for compost in the nation out of all the government agencies (Sherman R. 2003). In 2003 the TxDOT agency used 300,000 cubic yards of compost in various applications related to roadway maintenance and construction (Sherman R. 2003). This utilization of this huge amount of compost was due to some program specialists in the Texas Commission on environmental Quality (TCEQ).

In order for the different states that use compost to have any similarity between them there has to be a basic compost specification which has to be followed. This kind of specification would help in promoting the applications and use of compost in highway construction and other markets. Table 2-1 provides some of the compost specifications and the typical range of values that are being used by the department of transportations (Alexander, 2001).

Table 2-1 Compost properties used by Department of Transportation

| **Parameter** | **Range of values** | **Typical range** |
|---|---|---|
| pH | 5 – 8.5 | 5.5 – 8.5 |
| Organic matter (%) | 35 – 60 | 35 – 55 |
| Soluble salts (dS/m) | < 3 – 10 | <4 |
| Moisture content (%) | 35 – 60 | 35 – 55 |
| C:N | < 6-30:1 | < 10-20:1 |
| Inert (%) | < .3 – 1 | < 1 |
| Particle Size (inches) | < ½ - 1 | < ½ - 1 |

Adapted from Alexander, 2001.

Compost has also been used for the control of air pollution. There is severe odor problems associated with waste water treatment plants due to the aeration of sewage. Recently there has been some development of bio-filters based on compost to remove the odor causing compounds. Compost was packed in plastic spheres providing adsorption and biodegradation within the compost matrix contained within (Boswell J. 2004). The residual effect of compost application on crop growth and soil properties were studied. It was observed that the compost application increased the soil electrical conductivity which could be related to the cation exchange capacity (Bahman E., 2004).

Nowadays the design and construction of highways not only depend on their strength, geological and geotechnical aspects, but also on their environmental impact. Soil erosion is one of the major environmental impacts that is caused by highway development. Soil erosion is affected by many factors such as the characteristic of the soil, geology of land, vegetation, and weather patterns. Vegetation provides a positive effect on soil erosion by firmly holding the soil together and increasing the permeability of the soil thus preventing surface runoff (De Ona., 2005). Vegetation plays an important role in erosion control, but the properties and slope of an embankment are not suitable for vegetation. This study involves the application of two kinds of amendments to the soil surface in trying to improve the suitability of the embankments for vegetative growth.

Two kinds of soil amendments such as compost and sludge were used in this research. The slope of the embankments were 3:2 to 2:1, since they are the most commonly used embankment slopes in highway construction. The average rainfall at the test location was 219 mm. The embankment material was made of sand or sand silt mixtures. The sludge dosage was 60, 80, and 100t/ha while the compost dosage was 40, 60, and 80 t/ha. The sludge dosage was based on previously done agricultural work, while the compost dosage was based on cost of application. The cost of compost application was made equal to that of the sludge application cost. The sludge and compost were applied onto the surface directly without any mixing.

A total of fourteen different test sections were created with seven sections adjacent to each other for the 3:2 slope and 2:1 slope. The dimensions of the plot were 4 m × 5 m. Vegetative cover and soil erosion were the two parameters that were observed. The soil erosion was measured using the universal soil loss equation given below

$$A = R \times K \times L \times S \times C \times P \qquad 2.3$$

Where,

A = soil loss, t/ha per year

R = Rainfall erosivity index, J/cm $\div$ $m^2$/hr (51.10)

K = Soil erodibility factor, t/$m^2$ per h $\div$ ha/J per cm (0.3362)

L = Slope length (0.41)

S = Slope factor (2:1 → 18.57), (3:2 → 31.96)

C = Cropping factor

P = conservation practice factor (0.90)

It was observed that for the 2:1 slopes the sludge treatment and the compost treatment increased vegetative cover by 30 and 54% respectively. Similarly for the 3:2 slopes the sludge and compost treatment increased vegetative cover by 56 and 54% respectively. It was noted that for the 2:1 slope the efficiency of the sludge and the compost treatment are almost similar. It was observed for the 2:1 slope the soil loss was 71.57 t/ha per year for the control section and 46.85 t/ha per year for the section that was treated with 80 t/ha of compost. The 3:2 slopes had a soil loss of 70.51 t/ha per year while the lowest soil loss of 9.93 t/ha per year were observed on the 60 t/ha of sludge dosage test section.

The cost analysis was done by comparing the sludge application, compost application, and embankment revegetation. The cost of the application of the treatments were calculated using the transportation cost, irrigation cost, drying cost, and the cost savings done by saving space in the landfills. The cost of application of the sludge treatment would be € 152.68/ dry metric ton compared to that of €39.05/ dry metric ton of compost. It was found out that traditional hydro seeding would cost €50,000 /ha while the application of compost or sludge would only cost €3000/ha.

Compost has been used to prevent soil erosion by applying compost in the form of blankets and filter berms in steeper slopes. Compost blankets can be defined as the direct application of the compost on the soil surface ranging form 1 – 3 inches in depth as can be seen in Figure 2-3 (a). Compost blanket is usually applied in slopes that are lower than 4:1 (Risse, University of Georgia). The blankets are typically applied on steeper slopes using pneumatic blowers where the spreaders are not accessible. It is recommended that the compost be applied 3 feet over the shoulder of the compost or carried into existing vegetation in order to prevent rill formation (Risse, University of Georgia).

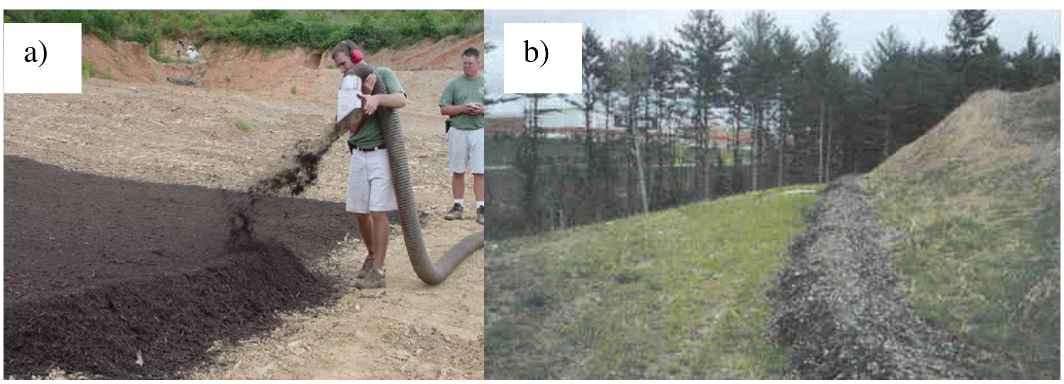



**Figure 2-3 (a) Application of compost blanket, (b) Compost filter berm at the end of a steep slope**

Compost filter berms are used in steeper slopes where there is higher erosion potential. Typically the compost filter berm is placed at the base of the slope, but in cases where the slope is steep it is recommended that another filter berm is placed at the shoulder of the slope with a compost blanket in between the berms as shown in Figure 2-4. In times of heavy rainfall and erosion events the berm allows the water and runoff to flow through it while filtering out the soil particles, thus preventing soil loss. This filtering property of the berm also causes the decrease in the velocity of the runoff, hence decreasing the erosion potential further. The compost filter berm is constructed in the form of a windrow or a trapezoidal structure usually. Typically the compost used in the construction of a compost filter berm should consist of a higher fraction of coarser particles, unless the objective of constructing a compost filter berm is for vegetation (Risse, University of Georgia).

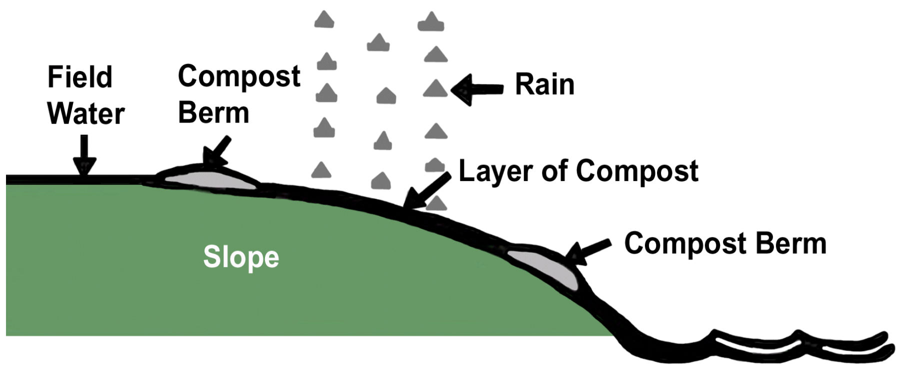



**Figure 2-4 Schematic of a compost filter berm (USEPA)**

A study was conducted on the application of compost to expansive subsoils to prevent shoulder cracking. This study included two types of compost Biosolids Compost (BSC) and Dairy Manure Compost (DMC), which were applied to the soil in both pure and mixed form. Several parameters were measured in order to study the effect of compost on mitigating the shoulder cracking, such as swelling, shrinking, strength, moisture and temperature fluctuation, erosion, and runoff quality. The moisture and temperature fluctuations were measured in order to study the effect of compost on the encapsulation effect on the soil sub layers. The shear strength of the compost amended soil was measured by following the ASTM D3080. The soil was compacted at the optimum dry density and the wet of optimum dry density. The wet of optimum was described as the moisture content at 95% of the maximum dry density. T he shear strength of the soil was found by using three different confining pressures of 14, 28, and 42 psi. The results of the shear strength of the different compost amended soils are shown in Table 2-1.

**Table 2-2 Shear strength of compost amended soils**

| Soil | Optimum moisture content | | Wet of optimum moisture content | | Shear Strength | |
|---|---|---|---|---|---|---|
| | Cohesion c, psi | Friction Angle θ, ° | Cohesion c, psi | Friction Angle θ, ° | Cohesion c, psi | Friction Angle θ, ° |
| S_CS | 17.1 | 3.0 | 12.2 | 2.5 | 17.8 | 12.9 |
| S_CMT 1 | 15.5 | 21.0 | 12.4 | 13.0 | 21.1 | 15.7 |
| S_CMT 2 | 8.5 | 26.0 | 6.0 | 23.0 | 15.6 | 12.2 |
| S_CMT 3 | 20.8 | 22.5 | 17.4 | 19.0 | 26.9 | 22.4 |
| S_CMT 4 | 16.8 | 23.5 | 16.1 | 19.5 | 23.2 | 21.2 |

Adapted from (Intharasombat, 2005), CMT 1- 75% DMC, CMT 2- 100% DMC, CMT 3- 20 % BSC, CMT 4- 30% BSC.

It can be noted that the friction angle of the control soil is very similar to that of clayey soil since it is very low. It can be observed that both the DMC compost and the BSC compost provided higher friction values, which was due to the coarse nature of the compost amended soils. The addition of bulking agents while composting such as wood chips and yard trimmings would have contributed to the coarse nature of the compost amended soils (Intharasombat, 2005). The main objective of this research was to determine the optimum dimensions for the compost amended sections. The test site was located on SH 108 10 miles north of Stephenville, Erath county, TX. Sixteen different test sections were built altogether. Two widths (10ft and 5ft) and two depths (2 inches and 4 inches) were selected for this project. A total of sixteen different test sections were constructed with different combinations of compost dosage, widths and depths. The length of each test plot was 50 ft and a 25 ft of transition zone was left between each section.

**Table 2-3 Composition of the test plots**

| Plot | Plot Name | Material | Shoulder width (ft) | Thickness (in) |
|---|---|---|---|---|
| 1 | S_CMT4-10-4 | BSC | 10 | 4 |
| 2 | S_CMT3-10-4 | BSC | 10 | 4 |
| 3 | S_CMT2-10-4 | DMC | 10 | 4 |
| 4 | S_CMT1-10-4 | DMC | 10 | 4 |
| 5 | S_CMT4-10-2 | BSC | 10 | 2 |
| 6 | S_CMT3-10-2 | BSC | 10 | 2 |
| 7 | S_CMT2-10-2 | DMC | 10 | 2 |
| 8 | S_CMT1-10-2 | DMC | 10 | 2 |
| 9 | S_CMT4-5-2 | BSC | 5 | 2 |
| 10 | S_CMT3-5-2 | BSC | 5 | 2 |
| 11 | S_CMT2-5-2 | DMC | 5 | 2 |
| 12 | S_CMT1-5-2 | DMC | 5 | 2 |
| 13 | S_CMT4-5-4 | BSC | 5 | 4 |
| 14 | S_CMT3-5-4 | BSC | 5 | 4 |
| 15 | S_CMT2-5-4 | DMC | 5 | 4 |
| 16 | S_CMT1-5-4 | DMC | 5 | 4 |
| 17 | S_CP-10-4 | CS | 10 | 4 |

Adapted from (Intharasombat, 2005)

Temperature and moisture probes were installed in each of these test sections and the data measured was recorded in the data logger that was buried along with the probes. The data was downloaded once every three months via a notebook computer.

Elevation surveys were conducted during every site trip. Shrinkage cracking was analyzed by taking high resolution digital images and appraising the pictures using software to determine the percentage of cracks developed. The ratio of the cracked area to that of the total area was determined as the percentage cracking.

The moisture reading over a month period was taken and the maximum moisture content and the minimum moisture content values were recorded. The difference between the maximum and minimum moisture contents were recorded as the moisture variations. The average of all the moisture variations for the period of data collected was taken as the mean moisture variation of that particular test plot. The mean moisture variation for all the seventeen different test sections was determined. A t-test analysis was conducted between the data sets of each test sections and it was checked to see if there was any significant moisture variation between each test section. Similar data analysis was done with the temperature readings. The results showed that the moisture readings were not significantly different from each other, so a ranking analysis was conducted based on the magnitude of the mean moisture variation between the test sections. It was observed that the biosolids compost was the most effective in reducing the moisture fluctuations when it was applied as 10ft wide and 4 inch deep sections. The 20% BSC dosage was found to be the optimum dosage for the moisture encapsulation effect. The DMC compost was found to be not effective in providing effective moisture encapsulation, which was attributed to the presence of low organic content (Intharasombat, 2005).

**Table 2-4 Application of Compost by various DOT's**

| 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 |

Adapted from (Intharasombat, 2005)

Table 2-4 presents the various applications of compost by the different departments of transportation. It can be observed that none of the applications include treatment for preventing pavement cracking.

## 2.5 Pavement Distress

Pavements undergo different types of stresses that would induce minor defects into them. These are caused by the varying traffic loading, temperature fluctuations, moisture fluctuations, and sub grade movements. The different types of pavement distresses are raveling, rutting, cracking, formation of pot holes, and depressions, etc. Most of this pavement distress if they are identified earlier can be repaired and maintained. The different types of maintenance work that are done in case of pavement distress are as follows

1. Sealers or sealcoats
2. Crack filling
3. Surface treatments

Cracking is of two type's transverse and longitudinal cracking. The transverse cracking can be defines as a crack that is perpendicular to the traffic direction. If the transverse cracks are not sealed immediately it would lead to the formation of parallel cracks near it. If the crack is wider it would lead to the intrusion of moisture into the crack thus leading to failure of the pavement surface. The transverse cracks are caused mainly due to the temperature variations. When the thermal stresses that are developed exceed the tensile strength of the pavement then the transverse cracks are formed. Longitudinal cracks are the one that occur parallel to the direction of traffic flow. They can be caused by both load or non-load stresses. Usually the cracks induced by traffic load stresses are at the center of the pavement (Lavin P.G. 2003). These types of cracking can also be caused by reflective cracking. The unpaved shoulder soil is subjected to the extreme elements. In such cases due to the seasonal and daily temperature moisture fluctuations cracks are developed in the soil surface. Due to the fluctuations the soil undergoes swelling and shrinkage alternatively causing the surface to crack. These surface cracks slowly propagate towards the pavement and continues below the pavement surface. As time goes by these cracks are propagated upwards onto the pavement surface leading to cracks.

Basically in order to prevent such kind of crack formation it is necessary to lower the moisture and temperature fluctuation. In this research compost is mixed with the control soil to determine its effectiveness in controlling the fluctuations. It is assumed that compost being hydrophilic in nature, it would tend to absorb the water onto itself and create a capillary moisture barrier. This would prevent the moisture fluctuations whereby preventing the pavement cracking. The presence of the bulking agents in the compost such as wood chips would also help to further prevent the soil surface from cracking by interrupting the path of the cracks.

In order to study the effect of the compost in preventing the pavement cracking test locations were selected in the area shown in Figures 2-3 and 2-4. These locations were selected because of the presence of a moderate amount of longitudinal and transverse cracking.

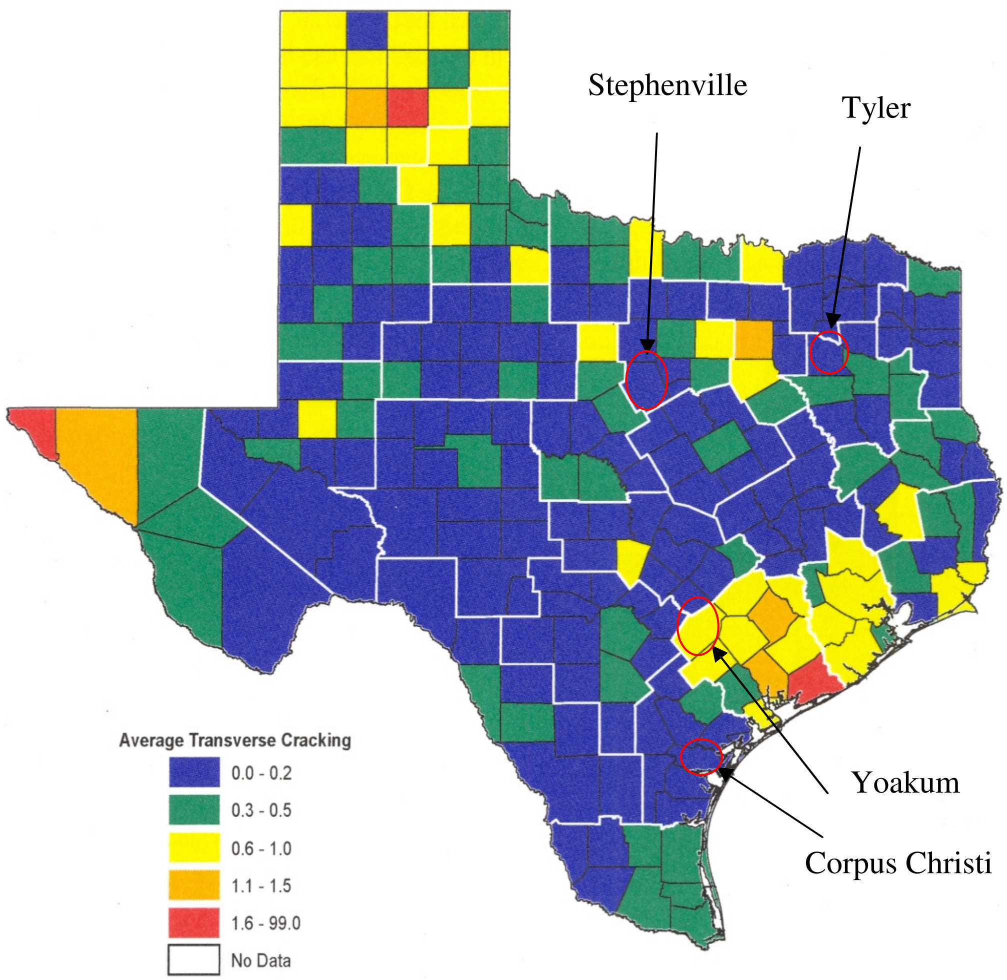



**Figure 2-5 Average transverse cracks in Texas, 2005 (PMIS 2004-2005)**

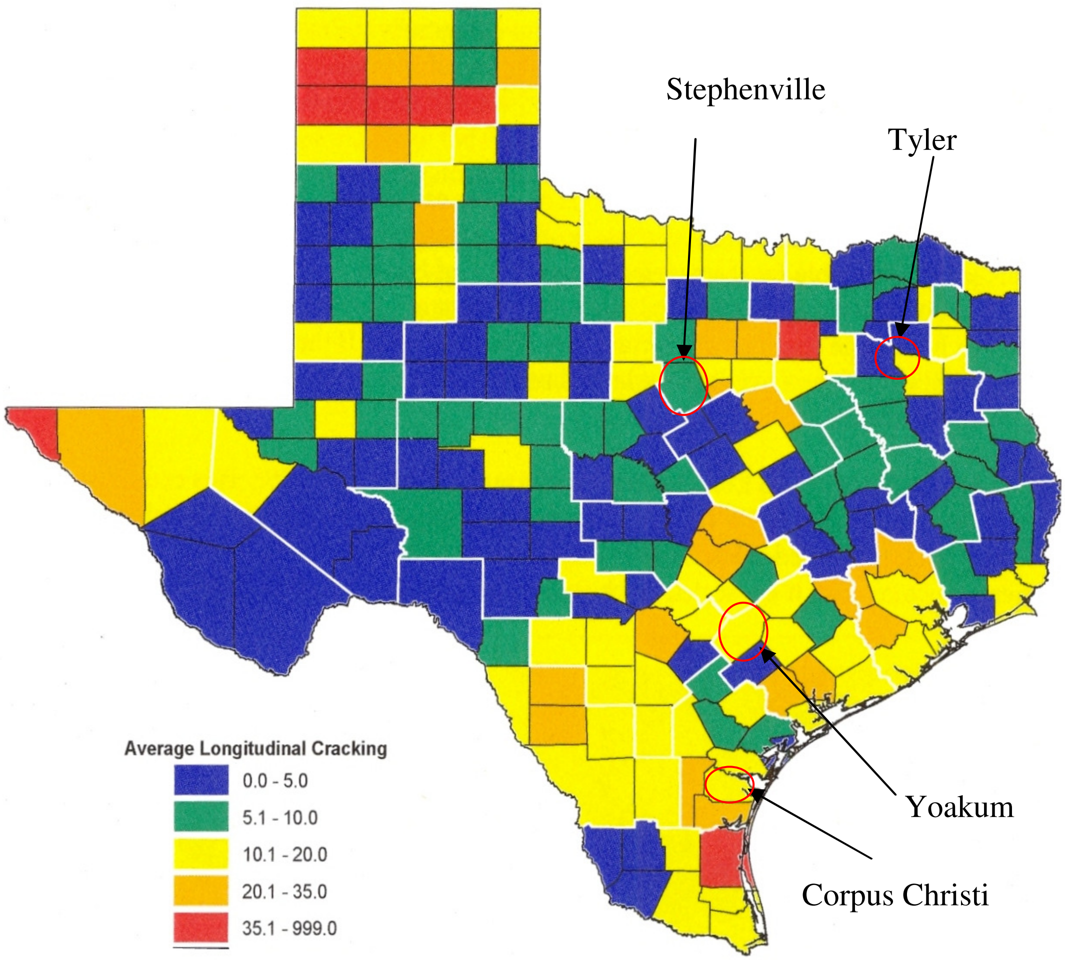



**Figure 2-6 Average longitudinal cracking in Texas, 2005 (PMIS, 2004-2005)**

# CHAPTER 3

# LABORATORY STUDIES

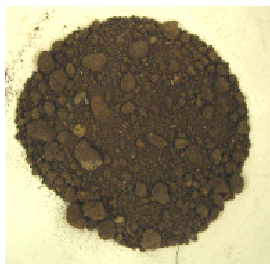
## 3.1 Introduction

Different compost materials were used in the construction of the compost treated sections. The compost material was bought from locally available sources. Several laboratory tests were conducted on the soil and the compost material before it was selected for field implementation. This chapter includes the procedure for the tests that were conducted on the samples that were collected periodically from the field since field implementation. The compost administered top soil is termed as Compost Manufactured Topsoil's (CMTs). The processes and the sources of the compost material differed from each other. The description of each compost material that was used is described below.

## 3.2 Compost Source Materials

Compost could be defined as the end product resulting from the aerobic decomposition of organic matter under thermophilic conditions (Kuhlman, 1989). It requires certain conditions to result in the production of quality compost. There are many federal regulations regarding the materials that are allowed to be composted, based on the safety of the composting process and application of the finished composted product.

**Table 3-1 Compost Used at the different test sites.**

| | | | | |
|---|---|---|---|---|
| **Stephenville** |  | Dairy Manure Compost<br><br>Organic Content 10% |  | Biosolids Compost<br><br>Organic Content 41% |
| **Corpus Christi** |  | Cow Manure Compost<br><br>Organic Content 18.0 % |  | Biosolids Compost<br><br>Organic Content 45.0 % |
| **Tyler** |  | Wood Compost 3<br><br>Organic Content 40.2 % |  | Wood Compost 4<br>Organic Content 34.6 % |
| **Yoakum** |  | Wood Compost 1<br><br>Organic Content 32.6 % |  | Wood + Biosolids Compost 1<br>Organic Content 28.3 % |

Due to restrictions on the solid waste materials that can be disposed of in landfills, there has been a steady increase of composting facilities. This increase could also be due to the realization of compost as a useful end product. The only disadvantage of this process is that only biodegradable products could be composted. All the compost materials that are used in this research were prepared by a process called as windrow composting. The different types of compost that were used in the test sites are shown in Table 3-1.

## 3.3 Laboratory Experiments

Soil samples from all the four different test sites were collected from the unpaved shoulders. The test sites were located adjacent to known high pavement distress areas. The ratio of compost to control soil was determined from a previous investigation carried out by TxDOT (research project 0-4573). The mixture of the compost and the control soil is termed as Compost Manufactured Topsoils (CMTs). The laboratory experiments were conducted on the control soil, compost material, and the mixture of compost and control soil.

The percentage of compost used in the preparation of the CMTs was based on the dry weight of the compost. The percentages of compost that were used in each of the test sections are provided in Table 3-2. The percentage of compost used at the Corpus Christi, Yoakum and Tyler sites were determined from the efficiency of the different compost dosages tried out at the Stephenville test sections.

**Table 3-2 Compost and Control soil percentages of the CMTs at each site**

| Location | Designation | Percents of Constituents |
|---|---|---|
| Stephenville | **CS** | Pure Control Soil |
| | **S_DMC_1** | 100 % Dairy Manure Compost |
| | **S_DMC_2** | 75 % Dairy Manure Compost and 25% Control Soil |
| | **S_BSC_1** | 30 % Biosolids Compost and 80% Control Soil |
| | **S_BSC_2** | 20 % Biosolids Compost and 70% Control Soil |
| Corpus Christi | **C_CMC_1** | 30 % Cow Manure Compost and 70% Control Soil |
| | **C_BSC_3** | 30 % Biosolids Compost and 70% Control Soil |
| Yoakum | **Y_WC_1** | 30 % Wood Compost and 70% Control Soil |
| | **Y_WBSC_1** | 30 % Wood + Biosolids Compost and 70% Control Soil |
| Tyler | **T_WC_2** | 30 % Wood Compost and 70% Control Soil |
| | **T_WC_3** | 30 % Wood Compost and 70% Control Soil |

S_XXX_X: Stephenville, TX; C_XXX_X: Corpus Christi, TX; Y_XXX_X: Yoakum, TX; T_XXX_X: Tyler, TX

Both the compost and the control soil was oven dried and then the required quantity was weighed using an electronic weighing balance and then mixed thoroughly until they were uniformly mixed. Then the appropriate quantity of water was calculated using the desired water content and added to the soil compost mixture which was further mixed until they were approximately homogeneous. The laboratory experiments on the CMTs were carried out on the samples prepared from this soil compost mixture.

*3.3.1 Experiments Conducted Before Field Implementation*

The following laboratory experiments were carried out before the implementation of the compost amendments to study the characteristics and suitability of the treatment. The moisture content of the soil was determined by the Tex-103-E TxDOT procedure. The liquid limit of the soil was conducted as per the Tex-104-E

TxDOT procedure. The plastic limit of the soil was determined using the Tex-105-E TxDOT procedure. The plasticity index of the soil was obtained using the Tex-106-E TxDOT procedure. The plasticity index provides us with the expansive property of the soil. The linear shrinkage of the soil was determined using the Tex-107-E TxDOT procedure. The linear shrinkage test conducted on the control soil and the CMTs were used to determine the effectiveness of compost treatment. The particle size analysis of the soil was done by following the Tex-110-E TxDOT procedure. The results from the procedure were used to classify the soil from the different test sites. The moisture-density relationship of the soil was determined using the Tex-114-E TxDOT procedure. The optimum water content was determined from this procedure. This water content was used in the preparation of the CMTs during the field construction. The results that were obtained from these experiments are presented in the following tables.

**Table 3-3 Control soil properties at the different compost test sections**

| **Soil Properties** | **Stephenville**† | **Corpus Christi**† | **Yoakum** | **Tyler** |
|---|---|---|---|---|
| Passing # 200 (%) | > 35 % | 81.5 | 58.6% | > 35% |
| Liquid Limit | 44 | 62 | 63 | 42.5 |
| Plasticity Index (PI) | 28 | 47 | 43 | 30 |
| AASHTO Soil Classification | A-7-6 | A-7-6 | A-7-5 | A-7-5 |
| USCS Soil Classification | CH | CH | CL | CH |

† Napat et al., 2005

**Table 3-4 Engineering properties of the different CMTs at each test section**

| Property | Stephenville | | |
|---|---|---|---|
| | Control Soil | S_DMC | S_BSC |
| PI | 28 | 18 | 37 |
| Organic Content (%) | 3.2 | 6 | 11.5 |
| Max. Dry Density (pcf) | 104.4 | 98.1 | 91.5 |
| Opt. Moisture Content (%) | 15.9 | 20.3 | 21.9 |
| Free Swell (%) | 11.4 | 24.6 | 31.2 |
| Linear Shrinkage (%) | 14 | 6 | 10.7 |
| **Property** | **Corpus Christi** | | |
| | **Control Soil** | **C_BSC_3** | **C_CMC_1** |
| PI | 47 | 28 | 33 |
| Organic Content (%) | 3.2 | 6 | 11.5 |
| Max. Dry Density (pcf) | 104.4 | 98.1 | 91.5 |
| Opt. Moisture Content (%) | 15.9 | 20.3 | 21.9 |
| Free Swell (%) | 28.7 | 27.4 | 16.1 |
| Linear Shrinkage (%) | 18.0 | 16.1 | 15.9 |
| **Property** | **Yoakum** | | |
| | **Control Soil** | **Y_WBSC_1** | **Y_WC_1** |
| PI | 26.0 | 19.8 | 24.7 |
| Organic Content (%) | 3.6 | 9.8 | 10.6 |
| Max. Dry Density (pcf) | 100.75 | 82.73 | 93.46 |
| Opt. Moisture Content (%) | 17.4 | 22.5 | 17.9 |
| Free Swell (%) | 24.6 | 18.9 | 27.3 |
| Linear Shrinkage (%) | 15.9 | 11.2 | 12.3 |
| **Property** | **Tyler** | | |
| | **Control Soil** | **T_WC_3** | **T_WC_2** |
| PI | 30.0 | 27.0 | 24.4 |
| Organic Content (%) | 4.0 | 19.0 | 13.5 |
| Max. Dry Density (pcf) | 107.2 | 78.4 | 85.9 |
| Opt. Moisture Content (%) | 13.8 | 22.5 | 21.8 |
| Free Swell (%) | 10.1 | 6.4 | 5.4 |
| Linear Shrinkage (%) | 16.3 | 10.7 | 7.8 |

Table 3-4 provides the engineering properties of the different test sections at each site. It can be noted that the addition of compost to the control soil in all the cases leads to a reduction in the P.I. of the amended soil. It can be said that the expansive property of the soil is decreased by the addition of the compost material. It can also be noted that the free swell of the compost amended soil is greater than that of the control soil in most cases. This is due to the presence of organic matter present in the compost and its hydrophilic nature. It adsorbs and is capable of storing more amount of water within itself thus leading to the higher swell property. The bar linear shrinkage values are found to be lower for the compost amended soil than that of the control soil. This is attributed to the presence of fibrous material and wood chips that are present in the compost. The wood chips tend to provide a slightly higher strength to the soil and prevents the propagation of shrinkage cracks in the soil surface. It is also noted than the optimum dry density of the compost amended soil is lower than the control soil. This is due to the nature of the compost material which is loosely packed and contains a significantly amount of air void. Therefore it can be concluded that the compost amendment provides a positive impact on the control soil. This conclusion was verified by analyzing the temperature and moisture fluctuations recorded by the field instrumentation which is presented in the following chapters.

*3.3.2 Experiments Conducted After Field Implementation*

Samples were collected from the field once in every two to three weeks. The soil samples were collected from each test section by random sampling. Grab samples were collected from four locations in each test sections and mixed together to form a representative sample. This was done in order to minimize the heterogeneous characteristic of the soil. The following tests such as Cationic Exchange Capacity (CEC), suction, Organic Content (O.C), and pH were conducted on these representative samples. The detailed experimental procedure for each of the tests is provided in the following sections.

3.3.2.1 Cation Exchange Capacity

Cation Exchange Capacity (CEC) is defined as the capacity of the soil to hold cations. The CEC depends on the amount of clay or organic matter that is contained in the soil. Soils that have large amounts of clay or organic matter in them tend to have a higher CEC. The CEC can also be termed as an indicator that shows the water holding capacity of the soil. Agriculturists usually add organic matter to improve the quality of the soil and to increase the crop yield from their farm soils. The intrinsic reason for adding organic matter is that it increases the CEC of the soil. This increase in CEC results in higher water holding capacity and the nutrients that are added to the soil are held more firmly by the soil. The same principle is employed in the treatment sites. Compost (organic matter) is added to the soil in order to increase the quality (CEC) so that it improves the water holding capacity of the soil. There are several procedures for the determination of the cation exchange capacity; the procedure given by Chapman, 1965 was followed in this research. This method was selected since it involved simple equipment which was readily available and cost effective procedure. The only disadvantage with this method is that it over predicts the CEC values for acidic soils, but since the soils being tested were known not to be acidic the CECs were obtained using this procedure.

- 25 grams of soil was taken in a 500 mL Erlenmeyer flask
- 125 mL of 1 M $NH_4OAc$ was added, mixed well, and left to stand for 16 hrs as shown in Figure 3-1 (a).
- A 5.5 cm Buchner funnel was taken with filter paper. The filter paper was moistened and the soil was transferred into it simultaneously applying suction as shown in Figure 3-1 (b). If the filtrate was not clear, it was filtered again.
- Four 25 mL additions of $NH_4OAc$ were added to the sample allowing it to filter through. Suction is applied appropriately such that the soil does not crack creating preferential pathways as shown in Figure 3-3 (a) and (b).
- Add eight separate additions of 95 % ethanol to wash away the excess $NH_4OAc$ as shown in Figure 3-2 (a).
- Remove the funnel and place it in a fresh flask before adding eight separate additions of 1M KCl to extract the $NH_4$ adsorbed onto the soil particles as shown in Figure 3-2 (b).
- Discard the soil and transfer the lechate to a 250 mL flask making it up to 250 mL by adding additional 1 M KCL solution.
- Determine the concentration of the $NH_4$ ion in the extracted lechate.

$$CEC = \frac{NH_4^{\ +}}{18} \text{(meq/100gms)} \qquad 3.1$$

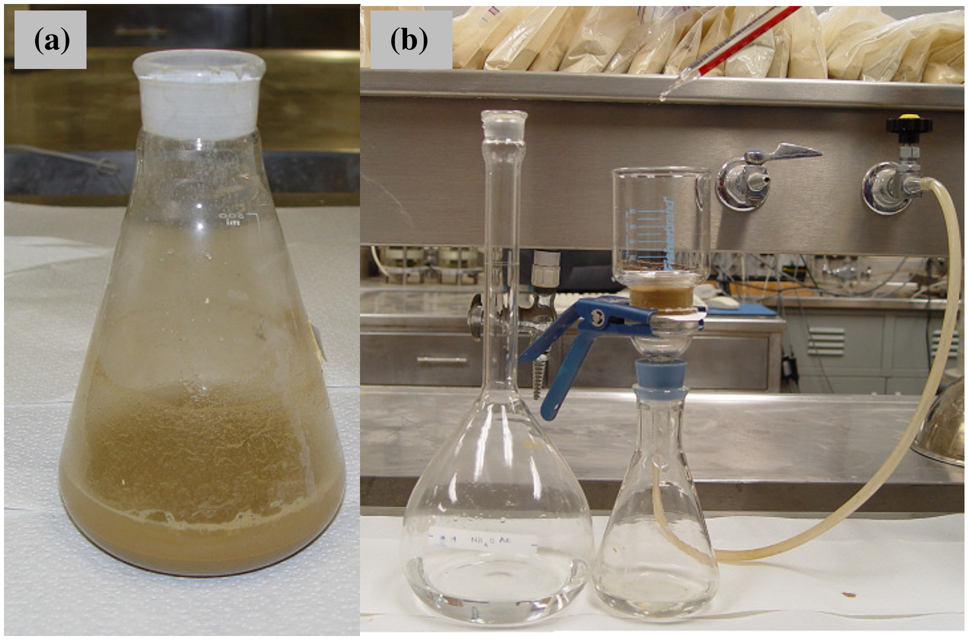



**Figure 3-1 (a) Soil soaking in $NH_4OAc$, (b) 25 mL additions of $NH_4OAc$**

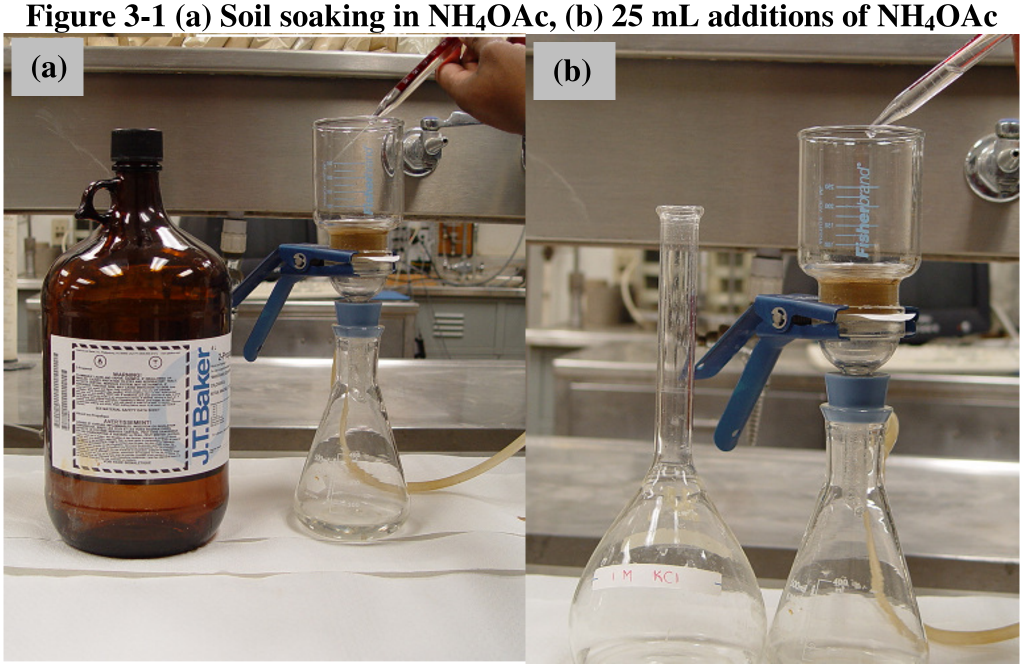



**Figure 3-2 (a) 25 mL additions of ethanol, (b) 25 mL additions of KCl**

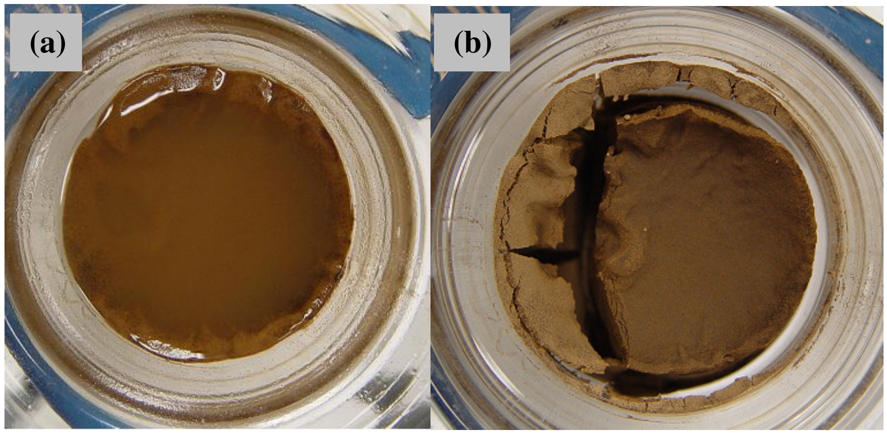



**Figure 3-3 (a) Appropriate stage for addition of solution, (b) cracked soil under vacuum suction**

3.3.2.2 Organic Content

The organic content (OC) of the soil samples collected from the different compost amended plots were determined using the ASTM standard test (D-2974). The organic matter present in the soil helps to hold water and other nutrients within it. The soil organic matter is an important parameter which is determined by farmers to evaluate the crop growth potential of the soil. The organic content of the soil is increased by adding the different composts. Hence the capacity of the amended soil to hold a large quantity of water within itself can be measured from the organic content of the compost material. The organic content of the compost slowly decreases due to the gradual aerobic degradation of the compost material, and also due to the washout of the compost material during significant rainfall events. The organic content therefore acts as a clear indicator of the amount of compost that is still present in the amended soils.

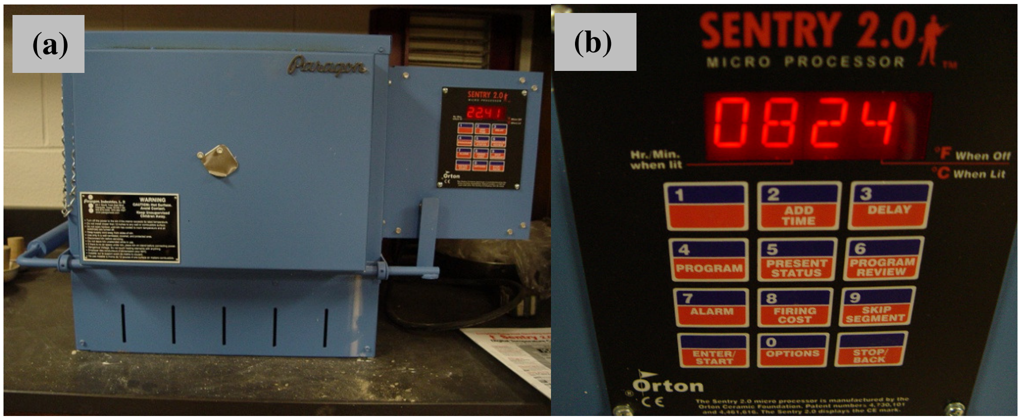



**Figure 3-4 (a) Oven used for O.C. determination, (b) Programming module**

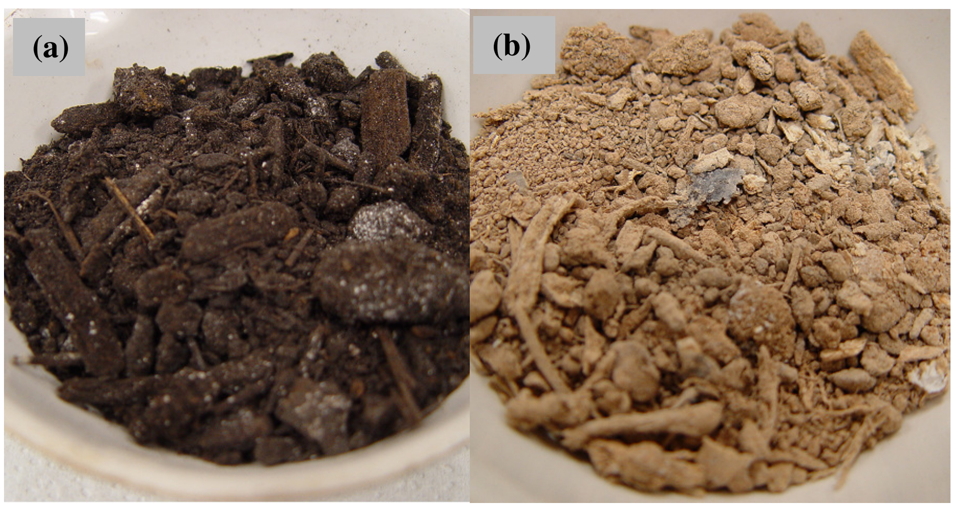



**Figure 3-5 (a) Compost before firing, (b) Compost after firing**

The furnace that was used for the determination of the organic content of the compost amended soils is shown in Figure 3-4 (a). The oven could be programmed for the final temperature, rate of temperature increase, holding duration, and cooling time. The module through which the furnace was controlled is shown in Figure 3-4 (b). The compost is heated for 24 hrs at 440˚C and then the O.C is determined using the ash content. The compost material before firing and after firing in the oven is shown in Figure 3-5 (a) and (b).

The organic content was determined using the following procedure.

- Oven dried soil sample which has been dried for 24 hrs was taken and weighed, A grams.
- The soil sample was placed in a muffle furnace at $440^{o}$ C.
- It was heated until the weight of the soil remains constant.
- The soil sample was then allowed to cool and then the weight of the soil sample was again measured, B grams.
- The organic content was calculated by the following equation

$$O.C = \left(\frac{A-B}{A}\right)\times 100,\ \% \qquad 3.2$$

3.3.2.3 Soil Suction

Soil suction could be defined as the attractive force on the soil water exerted by the soil particles. The soil suction depends on many factors such as type of particle packing, compaction density, water content, and soil particle size. Soil suction could be said to be inversely proportional to the water content and directly proportional to the density of the soil. During the compost amendment of soil the particles are packed loosely with each other due to the presence of wood chips in the compost. Therefore the soil suction reduces as it is inversely proportional to the void ratio. The organic material present in the compost is hydrophilic in nature and thus able to hold more quantity of water therefore reducing the soil suction. The organic material in the compost amended soil degrades as time increases due to which the soil suction also changes with time. The soil suction was measured by following the Lytton's filter paper method (Lytton, 2001) provided as follows

- CMT mixture collected from the field was compacted to a sample size of 2.8 inch in diameter and 1 inch in height, The samples were prepared at optimum moisture content and dry unit weight conditions of the corresponding standard Proctor test.
- The compacted soil sample was taken in an air tight container which was placed in a temperature bath.
- The Schleicher and Schuell No. 589-WH filter paper is used in this procedure as the calibration curve for the respective filter paper is available.
- A small piece of plastic was gently placed on the top surface of the soil sample and the filter paper was kept on top of the plastic piece so that the filter paper and the soil sample were not in contact with each other.
- The edge of the filter paper was bent a little so that the removal of the filter paper would be easier at the end of the experiment
- Then the container was tightly sealed and carefully placed in the temperature bath which was maintained at room temperature.
- The setup was kept in the temperature bath until it reached equilibrium conditions. This usually would take up to 7 – 10 days.

- The temperature fluctuations in the bath was not more than ± 1° C.
- After equilibrium conditions were reached the container was taken out of the temperature bath.
- A weighing balance that could measure up to 0.0001 g was used to measure the weight of the filter paper.
- Care was taken such that the filter paper was exposed to the lab environment for the shortest possible time.
- The weight of the filter paper was measured in the weighing balance.
- After this step the wet filter paper was dried in the oven for at least 10 hrs till the weight of the filter paper remained constant.
- Then the dry weight of the filter paper was measured and from this the moisture content of the filter paper was measured.
- The suction values were obtained by using the calibration chart that was provided in Fig 3.1

## 3.4 Summary

The results from the experiments that are mentioned above are presented and analyzed in the following chapters. The results obtained from the cation exchange capacity, suction and organic content would be used in the development of a model to predict the service life time of the compost treatment. The engineering properties which were obtained from the laboratory experiments mentioned in section 3.3.2 were used in the design of the test sections. The quantity of compost, water, scarifying depth, tilling depth, level of compaction applied was determined from these experiments.

However the efficiency of this design had to be verified by field studies. The next chapter deals with those field studies and the construction of the test sections.

# CHAPTER 4

# FIELD CONSTRUCTION OF TEST SECTIONS

## 4.1 Introduction

This chapter deals with the field construction of the test sites. Chapter four explains various parameters that were measured in order to design the construction of the test section and estimate the various quantities of materials required for the construction of test plots in the field. Several parameters were measured in order to determine the efficiency of the compost treatment in the prevention of pavement cracking. Several parameters were measured using field sensors and stored in site by using data loggers. These results were downloaded into a computer and they were then statistically analyzed to address the efficiency of different compost treatments for different site conditions. The instrumentation of the test section and the sample collection procedure are explained in this chapter.

## 4.2 Test Location

The location of the test sections are presented in Figure 4.1 and they are: Stephenville; Corpus Christi, Yoakum, Tyler, Texas

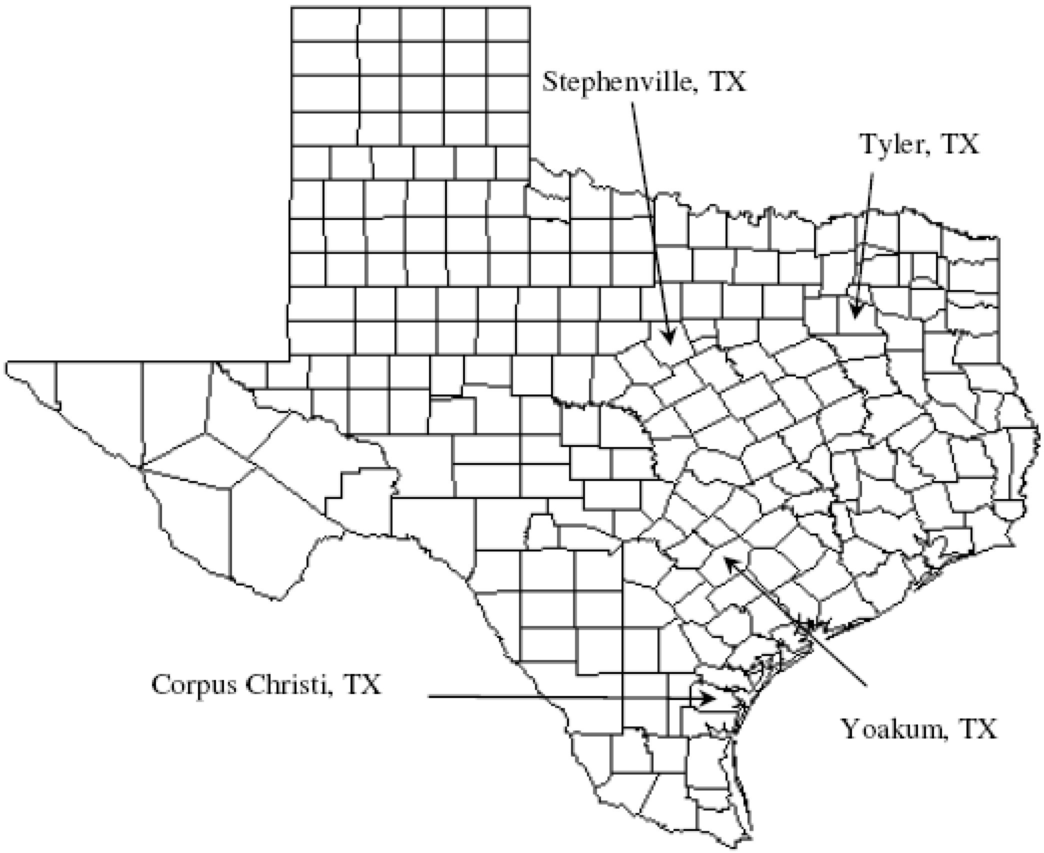



**Figure 4-1 Location of all the test sites**

The test sites were selected in such that the soil property at each location was different from each other and site environmental conditions were varied from humid to relatively low humid conditions. Texas Department of Transportation identified low traffic roads that had significant pavement distress symptoms. The test sites were constructed adjacent to these pavements along with an untreated Control section in order to compare the data from each section with the control section to address the efficiency of the different treatments. It was ensured that none of the test sections were located in a depression or low elevations, which otherwise would have been influenced by the ponding of rain water. In case of any treatment failures determined based on moisture readings, it cannot be clearly attributed to the materials used since it could be due to the ponding of water.

Soil samples were collected from each test site by the Texas Department of Transportation once the site location was selected. A part of the soil sample that was collected was received by us at the research lab in the University of Texas at Arlington. Several laboratory tests were conducted in the laboratory such as swelling, shrinking, shear strength, etc. The samples were prepared by mixing the control soil from each of the test location with the compost material which was procured from compost producers locally available near the test locations. The compost dosage was based on the results from the laboratory tests conducted on the lab compost amended soils complimented by the results from a previous research study that was conducted by Puppala A.J. et al, 2004. This study involved sixteen different test sections of varying dimensions such as 10 ft and 5 ft in widths, and 4 in. and 2 in. in depths.

Two types of composts, biosolids compost and dairy manure compost were used in this study. The test section dimensions and the compost dosage that was applied to each test section are shown in Table 2-3. The results from an earlier research project 5-4573 showed that the optimum dimensions of the test plot that yielded effectiveness of compost amendment in mitigating cracking were 50 feet in length and 10 feet in width with a thickness of 4 inches, while the optimum compost dosage was found to be 20%.

A follow-up implementation study was conducted by installing compost amended soil sections at four test sites located throughout the state of Texas. The dimensions of all the test sections were the same. The research project 5-4537 conducted by Intharasombat addressed the short term effectiveness and the determination of the optimum dimensions for these new test sites.

In order to study the long term effectiveness of the compost treatment and to find the service life of the compost amendments, four compost sections from the Stephenville, TX site with the optimum dimensions were selected for further monitoring. The Stephenville test section was located in state highway SH108, 10 miles north of Stephenville, TX.

Three other sites from implementation studies are also considered for further validation studies. These include Corpus Christi, Yoakum and Tyler sites. The Corpus Christi, TX test site consisted of two compost amended test sections and one control section. This test site was selected also for its geological location. The test site was located near to the coast, so the results from this site could be used to check the effectiveness of the compost amendments in diverse geological environments. The Corpus Christi site was located on state highway SH 188, 12 miles east of Sinton, TX. The Yoakum, TX site is located on state highway SH 1395, 2 miles north west of the intersection between state highways SH 1395 and SH 859. The Tyler, TX site was located on state highway SH 97, 1 mile south of the intersection between state highway SH 97 and interstate highway IH-10.

A typical compost treatment section on a two lane state highway is shown in Figure 4-5. It consists of 50 foot long treatment sections with a 25 foot buffer zone in between. The buffer zone is constructed in order to prevent any cross contamination between treatment sections at the time of construction due to the use of heavy equipment. The treatment was done on the soil adjacent to the pavement shoulder.

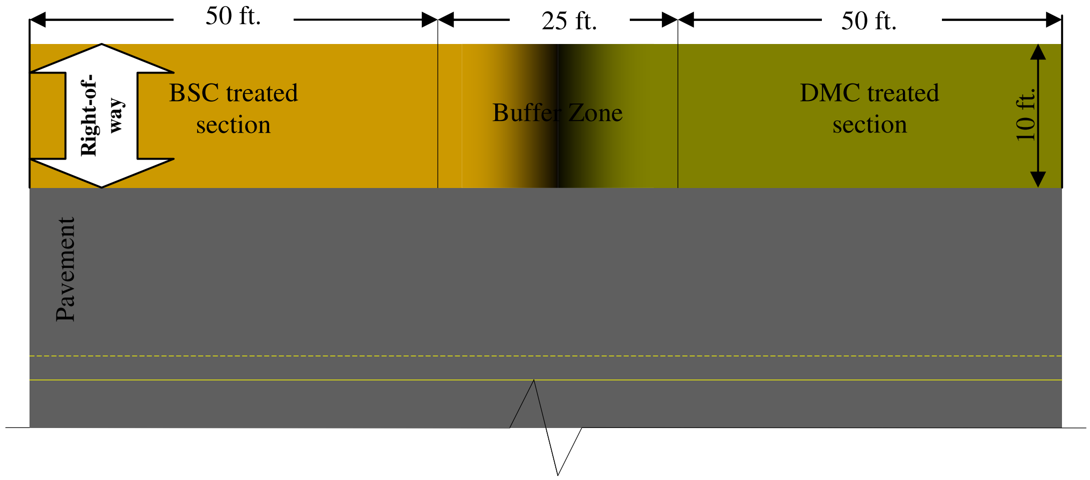



**Figure 4-2 A two lane state highway showing the typical 4 in. deep compost treated section and Buffer Zone.**

## 4.3 Treatment Design

In this research the combination of the site top soil with the different composts were referred to as Compost Manufactured Topsoils (CMTs). The treatment design of the CMTs involved the calculation of the scrapping depth, tillage depth, volume of compost, and volume of water required. The scrapping depth could be defined as the depth to which the on site soil had to be removed after scarification of the vegetative cover. The tillage depth could be defined as the depth up to which the site soil after scrapping had to be tilled in order to be mixed with the compost material to achieve the design compost dosage. All these design values were based on tests that were conducted in the lab, and on the site soil and compost properties.

Standard proctor tests were conducted on the site soil collected previously from the test sections at the design compost dosages. The optimum dry unit weight and the optimum water content values were determined from the proctor tests. The density and water content of the site soil and the compost procured were measured on site just before field construction with the use of a nuclear density gauge. Since the use of the nuclear density gauge required highly specialized hazardous training the readings were directly recorded and supplied by the TxDOT personnel on site. The calculation of the various design parameters are explained more clearly in the section below.

Length of treatment section, ft = L

Width of treatment section, ft = W

Depth of treatment, ft = D

Volume of treatment (ft$^3$), $V = \text{L} \times \text{W} \times \text{D}$

Dry unit wt of compost, $\rho_{dry,compost}$, pcf = $\dfrac{\rho_{moist,compost}}{1+\dfrac{w_{compost}}{100}}$

Water content of compost, $\% = w_{compost}$

Water content of site soil, $\% = w_{soil}$

Water content of CMT required, $\% = w_{CMT}$

Weight of available site soil, lbs, $W_{soil,available} = V \times \rho_{site,soil}$

Design compost dosage, $D_c$ = 30 %

Total dry CMT, lbs, $W_{CMT}$ = V × $\rho_{dry,CMT}$

Dry compost required, lbs, $W_{dry,compost} = W_{CMT} \times \frac{D_C}{100}$

Compost required, lbs, $W_{compost} = \dfrac{W_{dry,compost}}{1 + \dfrac{w_{compost}}{100}}$

Weight of dry soil required, lbs, $W_{dry,soil} = W_{CMT} - W_{dry,compost}$

Weight of soil required, lbs, $W_{soil} = \dfrac{W_{dry,soil}}{1 + \dfrac{w_{soil}}{100}}$

Scrapping depth, inch = $\left( \dfrac{W_{soil,available} - W_{soil}}{\rho_{site,soil} \times Length(ft) \times width(ft)} \right) \times 12$

Tilling depth, inch = Depth of treatment – Scrapping depth

Volume of water required, gallons = $V_{water}$

$$W_{water}, lbs = \left( W_{dry,CMT} \times \frac{w_{CMT}}{100} \right) - \left( W_{dry,compost} \times \frac{w_{compost}}{100} \right) - \left( W_{dry,soil} \times \frac{w_{soil}}{100} \right)$$

$$V_{water} = \frac{W_{water}(lds)}{\rho_{water}(lds/ft^3)} \times \frac{7.48 gallons}{ft^3}$$

All these design steps were incorporated into an excel sheet for ease of calculations. A sample calculation of the design parameters are shown in Table 4-1.

**Table 4-1 Calculation of design parameters**

| Description | Quantity | Unit |
|---|---|---|
| Length of treatment section, L | 50 | ft |
| Width of the treatment section, W | 10 | ft |
| Depth of treatment, D | 4 | in |
| Volume of treatment | 166.667 | ft3 |
| | | |
| Bulk density of compost | 35 | pcf |
| Compost moisture content | 30 | % |
| Dry density of compost | 26.9231 | pcf |
| | | |
| Bulk density of soil | 104.975 | pcf |
| Moisture content of soil | 10.5 | % |
| Dry density of soil | 95 | pcf |
| Mass of available soil | 17495.8 | lb |
| | | |
| Bulk density of CMT | 92.9 | pcf |
| Compost dosage | 20 | % |
| Dry density of CMT | 72 | pcf |
| Moisture content of CMT | 29 | % |
| Mass of dry CMT | 12000 | lb |
| Scrapping depth | 1.6 | in |
| Tilling depth | 2.4 | in |
| Mass of dry soil | 9600 | lb |
| Mass of soil required | 10608 | lb |
| Mass of dry compost required | 2400 | lb |
| Mass of compost required | 3120 | lb |
| Volume of compost required | 3.30 | CY |
| Volume of water required | 209.94 | Gallons |

Construction details of compost section are already presented by Intharasombat (2005) and hence these details are not presented here. Construction details of a typical validation site i.e. Yoakum site was presented in the following. Construction details of other validation sites, Tyler and Corpus Christi are similar and hence not presented in this Chapter.

## 4.4 Yoakum, TX site construction

The general layout of the test site in Yoakum, TX is shown in Figure 4-6. The test site was marked into the various treatment sections and buffer zones with marking paint before the start of the construction. The buffer zones were constructed so that there was no cross contamination between the compost material that was used between two adjacent treatment sections. The vegetative cover over the treatment sections were removed to a certain extent using the grader.

**Figure 4-3 Yoakum, TX test site before field construction**

Before scarifying the top soil to the design depth, the density of the site soil was measured using a nuclear gauge. The density measurements were recorded at more than three locations randomly selected over the treatment section and the mean of the soil density was taken. The nuclear gauge was used to measure both moisture content and dry unit weight of the soil at the site. Both unit weight and the moisture content of the compost material were measured by taking readings on the compost stockpile with a nuclear gauge. It was noted that more number of readings for the compost material was required in order to get a stable reading. This was due to the fact that in order to obtain an accurate reading the probe which was inserted had to be closely packed around the material which was being examined. Since compost had a relatively higher void ratio than the soil it required more number of measurements.


**Figure 4-4 Grader used for scarifying top soil layer**

Once the soil and compost properties were measured, the top soil was scrapped off till the design scrapping depth by the motor grader as shown in Figure 4-7. The scrapped soil was moved away from the treatment section and then the soil was tilled up to the design tilling depth using the mechanical tiller.

**Figure 4-5 Unloading of compost from the truck**

The compost material was brought to the test site using the TxDOT truck. The quantity of compost that was required to be mixed with the tilled soil was then calculated based on the soil and compost properties using the excel spreadsheet. The calculated amount of compost was then carefully placed on the test section in short piles by visual observation as shown in Figure 4-8. Then the compost material was spread on top of the tilled soil using the motor grader as shown in Figure 4-9. The layer of compost was mixed into the top soil by again using the tiller. A number of passes were made by the tiller over the compost soil mixture in order to ensure a uniformly mixed layer as shown in Figure 4-10.

**Figure 4-6 Application of a compost layer over the tilled site soil**

**Figure 4-7 Tiller used for mixing the soil and compost**

The required quantity of water that was needed to achieve the optimum dry density was calculated using the steps shown in the previous section. The rate of water flow from the water truck was calculated by observing the time required to fill up a container of know volume. The required amount of water was applied to the CMTs by carefully monitoring the time and making sure that it was evenly distributed through out the treatment section in the calculated time as shown in Figure 4-11.

**Figure 4-8 Application of water onto the CMT**

The treated sections were compacted using a smooth drum roller as shown in Figure 4-12. The density of the compacted CMT section was measured by the nuclear gauge once the roller had completed a single pass. Further passes were made by the roller till the design density of the treatment sections was achieved.

**Figure 4-9 Compaction of the CMT using smooth drum roller**

One of the completed compost treated sections in the Yoakum, TX test site is shown in Figure 4-13.

**Figure 4-10 Completed CMT section**

After compaction of the test section holes were dug on the soil layer in order to place the temperature and moisture probes. The typical method by which the holes were dug is shown in Figure 4-14. Two moisture probes and a temperature probe were installed in each of the compost treated sections and also on the control section. The moisture probes would measure the volumetric moisture content of the soil surrounding the probe up to 4 inches. The moisture and temperature readings were measured every 30 minutes and the data was stored in a data logger that was buried along with the sensors. The data logger was covered in a plastic bag with small holes made for the cables that were to be connected to the moisture and temperature probes. This was done in order to protect the terminals of the battery that was connected to the data logger. Once the loggers were placed in the ground it was further protected by an inverted plastic container to protect it from the surface loading from mowers, etc.

**Figure 4-11 Digging holes for the moisture and temperature logger**

The moisture probes were placed at 6 inches and 12 inches from the top soil surface. Small trenches of about 1 inch width and 2 inches in depth were dug along the surface of the soil layer to route the cable from the sensors to the data logger. After installation the area around the sensors were compacted using a manual hand tamper. A schematic of the arrangement of the moisture and temperature sensors in the CMT is shown in Figure 4-15.

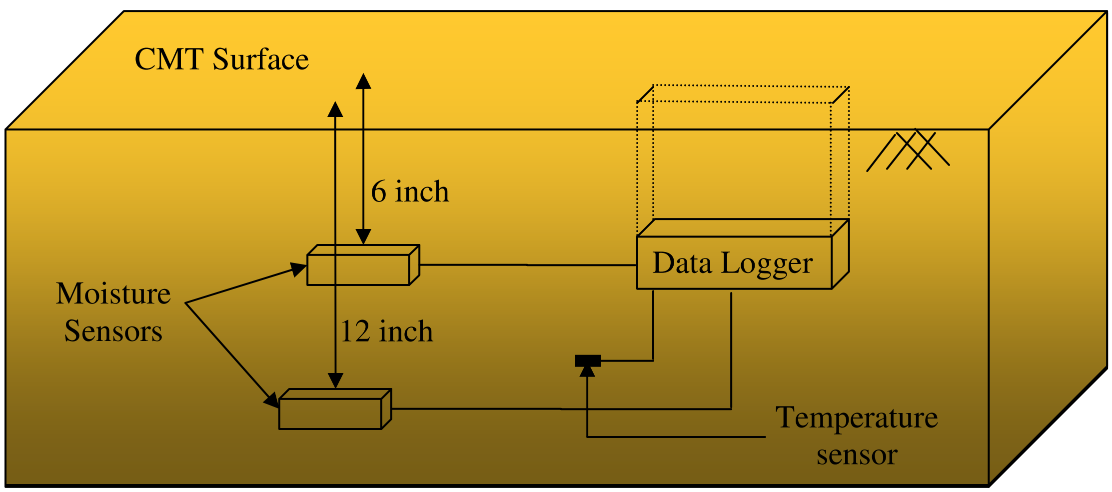



**Figure 4-12 Arrangement of moisture and temperature sensors in the CMT**

4.5 Moisture and Temperature sensor

The measurement of the volumetric moisture content by the moisture probes were based on electro magnetic wave propagation. There are two methods based on electromagnetic wave propagation such as Time Domain Reflectrometry (TDT) and Time Domain Transmissometry (TDT). In this research the determination of moisture content was based on TDT principles. This involves the measurement of time for an electromagnetic wave to propagate through the probe length. This propagation time is based on the moisture content of the soil. The more the moisture content of the soil, the longer time it takes for the electromagnetic wave to propagate through the probe length. The type of moisture probe, temperature probe and the data logger that were installed in the test sections are shown in Figure 4-16.

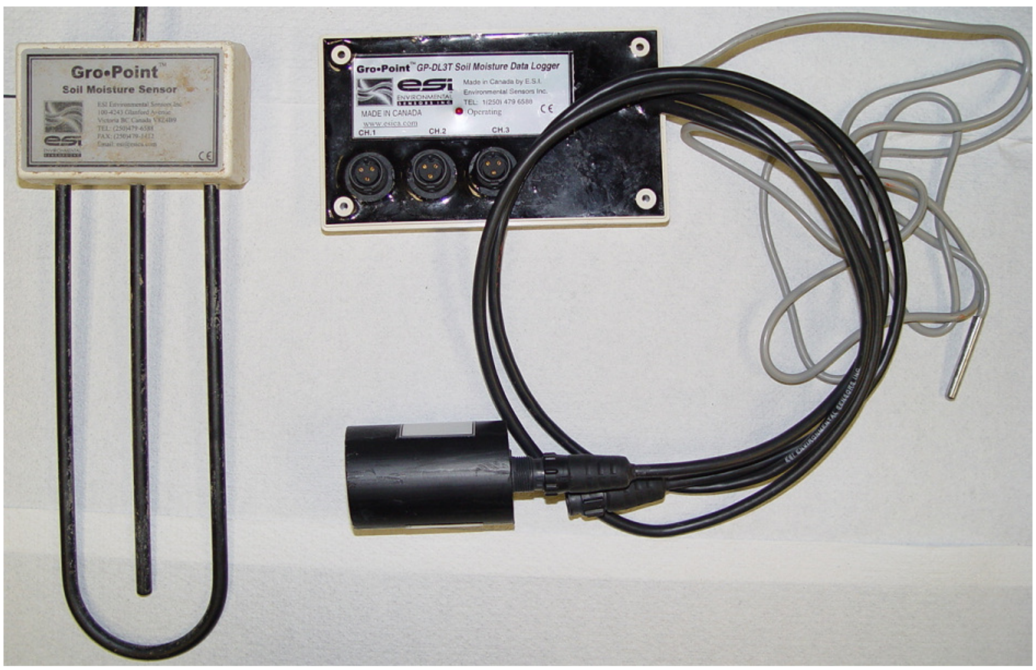



**Figure 4-13 Moisture probe, temperature sensor, and data logger**

The moisture probe could be oriented in either horizontal or vertical alignment. The horizontal alignment is recommended for probes that are buried at shallow depths. The basic principle of this method is the determination of the relative permittivity of the material which is related to the moisture content. The relative permittivity of a material is otherwise called as the effective dielectric constant (Friedman, 1998). The volumetric moisture content is usually calculated from the relative permittivity based on empirical relationships. The relative permittivity of the material is found out by the equation given below (Blonquist, 2005).

$$K_a = \left(\frac{ct}{L}\right)^2$$

Where,

c = Speed of light, m/s

t = time of propagation, sec

L = Length of probe, m

Gravimetric water content = volumetric water content/Bulk specific gravity.

4.6 Moisture and Temperature Data

The moisture and temperature readings were measured every 30 minutes and they were stored in the data logger. The data logger had a capacity to store values for up to six months at the rate at which the data was collected. The battery life of the data logger was approximately two (2) years and hence needed very little maintenance. The moisture sensor measured the moisture content of around four inches on all sides of the probe. Two million pulses were generated every second and the average moisture content reading was displayed based on TDT. The temperature and moisture content data would be used to determine the effectiveness of the compost treatment in the encapsulation of the soil moisture content. The temperature and moisture data readings were downloaded from the data logger with the help of software that was provided along with the logger. The data was downloaded during each field visit which was at a frequency of once every three weeks. The mean moisture variation and mean temperature variation were calculated from the data downloaded. These observations were used in determining the effectiveness of treatment.

### 4.7 Elevation Surveys

Elevation surveys were conducted at each field visit. The initial elevation survey was conducted at the completion of field construction. A suitable reference point was located near the test site. The reference point was selected in such a way that the elevation change of the point would be negligible. A telephone post and a sign post whose base was encased in concrete were selected at the Yoakum, TX test site. The elevation survey readings were recorded periodically. The survey points were located both in the shoulder unpaved soil section and also on the edge of the paved shoulder. The survey points in the unpaved shoulder section would be used for the determination of any erosion that takes place. The amount of erosion would be compared between the compost treated sections and the control section, and the effectiveness of compost in preventing soil erosion could also be determined.

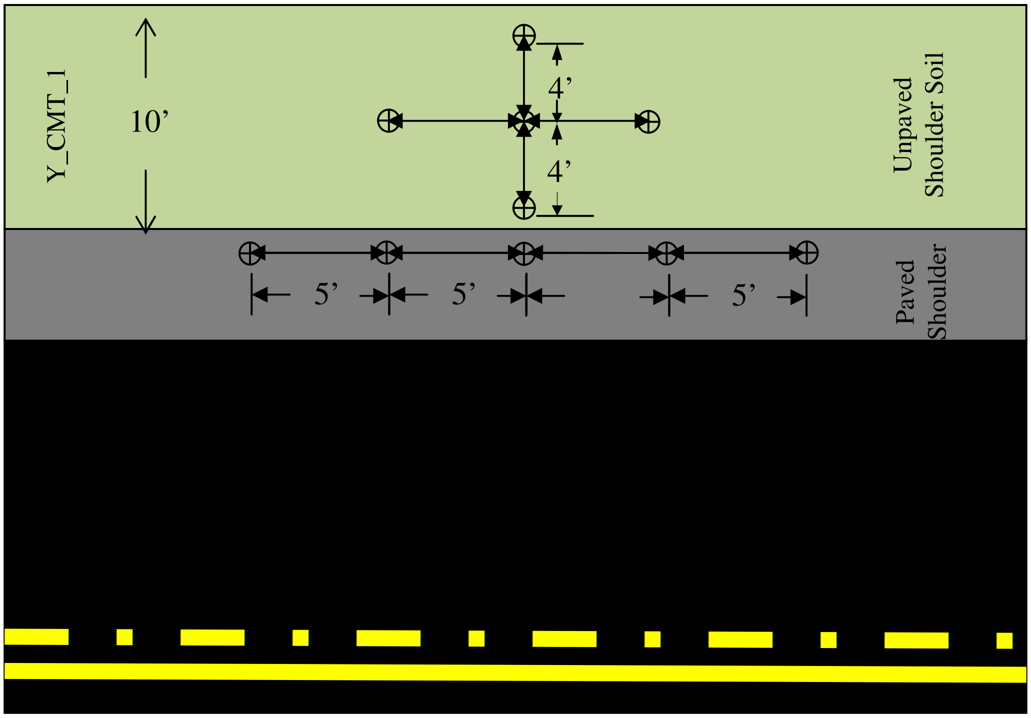



**Figure 4-14 Survey points on the unpaved shoulder soil and the paved shoulder for each CMT**

The survey points at the edge of the paved shoulder would help in identifying the vertical movement of the roadway. The vertical movements between the compost treated sections could be compared to determine the effectiveness of the compost treatment in preventing the vertical movements of the pavement structure. The survey points were located in the field as shown in Figure 4-18.

## 4.8 Pavement Cracking Analysis

After completion of the site construction, the paved shoulder section adjacent to the CMTs were divided and marked equally into five parts. Digital images of each part of the paved shoulder were taken using a high resolution camera. The pictures of the respective parts were attempted to be taken from the same height, angle, resolution, and time of day in order to produce similar image representations during each field visit. All these precautions were applied while taking the digital images in order to compare the shrinkage cracks of each section with time. The shrinkage crack of a particular section would be calculated each month. Any increase in the shrinkage crack would mean that the pavement structure is undergoing stress due to the pavement movement. If the cracking amount is negligible then we can assume that the compost treatment is effective in preventing the pavement shoulder cracking. A typical digital image that is taken during each field visit is shown in Figure

The digital images are analyzed by using image analysis software. The digital images are converted into .bmp format in order to be accessible by the software. The digital images are opened by using the open tab in the menu as shown in Figure 4-19. The number of total pixels in the image is measured using the measure function in the analyze menu. The number of pixels measured in this stage is noted down as $A_T$. Now an appropriate threshold value is selected in such a way that there is a clear distinction between the cracked and uncracked portion as shown in Figure 4-20. The uncracked portion is removed by using the eraser tool available in the software as shown in Figure 4-21. Now the area of the cracked portion is again measured using the measure function in the analyze menu. This area is noted down as $A_c$. Now the shrinkage crack percentage is calculated by taking the ratio between the cracked area and the total area.


**Figure 4-15 Digital image of the paved shoulder**

**Figure 4-16 Digital image after selection of appropriate threshold**

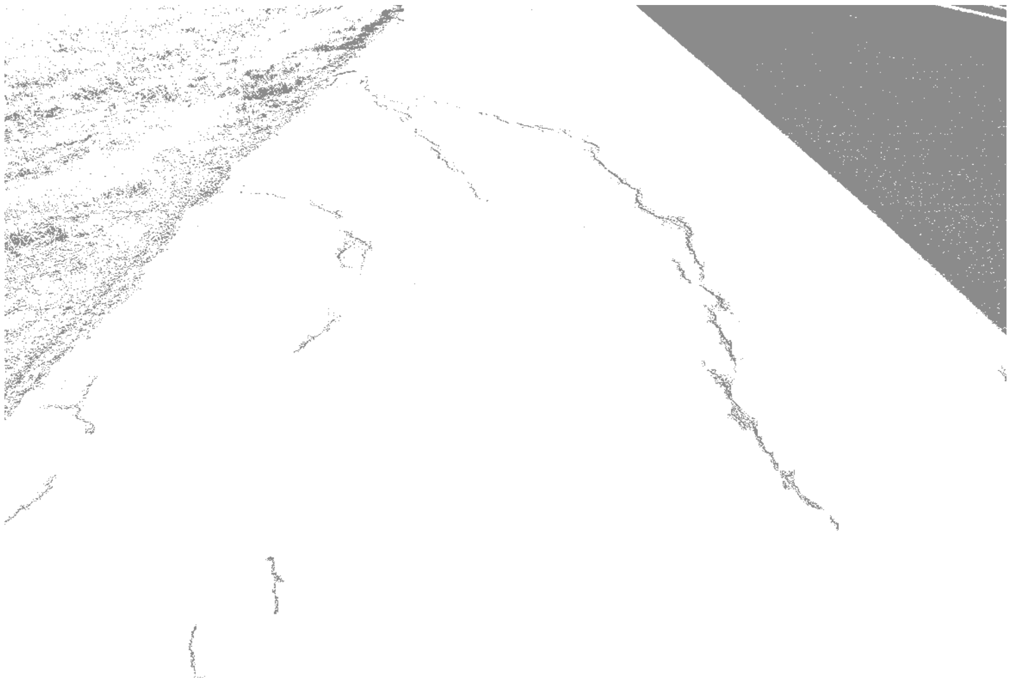


**Figure 4-17 Digital image after clearing the uncracked portion**

## 4.9 Site Description

All the test sections were of the same dimension which was 10 feet in width and 4 inches in depth. The different types of composts that were used in the various test sections are described in the sections below

### *4.9.1 Biosolids Compost*

The biosolids compost is made by composting the sludge from the waste water treatment plants. Previously this material was spread over waste lands directly for agricultural and highway construction purposes. Due to the hazardous nature of these materials in their raw state and the amount of pathogens in them, the USEPA had put forth stringent regulations on the disposal of the sludge from waste water treatment plants. Composting provides a very efficient and lucrative market for the disposal of these materials. The compost based on sludge used in this research is of the class A classification which is safe for public exposure. Wood chips were added to the sludge to act as bulking agents in aiding the composting process. The trade name of the biosolids compost used in this research is “Dillo Dirt”. This compost was used in Stephenville and Corpus Christi, TX and it should be noted that these are not same type.

*4.9.2 Dairy Manure Compost*

Dairy manure compost is prepared from the manure that is produced by the animals in the dairy farms. The manure is prepared into a semi solid solution and the organic solids are removed from the solution by basic filtration techniques. The solids retained are then dried and used as the feed stock for the composting processes. The dairy manure compost is significantly lower in pathogen count and is easier to manage and produce. Dairy manure compost was used in Stephenville site and cow manure compost was used in the Corpus Christi site. Both the manure composts used were different as these materials were obtained from locally available compost producers.

*4.9.3 Wood Compost with Biosolids*

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). The Aquazime compost facility produced the compost by composting wood chips from the cities of Wharton and Bay City. The wood chips were composted with grease-trap waste and septage to produce compost that has similar characteristics to that of the bio-solids compost. The New Earth facility produces the compost from sawdust and bio-solids. Wood Compost-1 and Wood + biosolids compost-1 were used in the Yoakum, TX test site.

*4.9.4 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, conserves water, reduces erosion, and lessens or eliminates the need for fertilizer (CIWMB, 2002). This compost was produced by windrow composting. The final composted product was mixed with an equal amount of fresh wood chips and brought to the site to be applied to the soil. Wood Compost-2 and Wood Compost-3 were used in the Tyler, TX test site.

## 4.10 Summary

Four sites, Stephenville, Corpus Christi, Tyler and Yoakum test sites in the state of Texas were constructed with different locally available compost amended shoulders and these sites were instrumented and monitored for various time periods. The results from the Stephenville test site, the site that was built more than five years ago were used to determine the long term efficiency of the compost treatment and to develop service life models. Both moisture and temperature data were used to evaluate the effectiveness of the compost amendment treatment and the parameters such as cationic exchange capacity or CEC, organic content or O.C, and field suction were studied and used to develop the service life model.

Service life model which is developed with the Stephenville test site would be validated with the models developed with the Corpus Christi data. It can be seen that the compost that was used for the Stephenville and Corpus Christi test sites have similar sources of feed stock. The biosolids compost used in Stephenville is same as the biosolids compost used in Corpus Christi. The Dairy Manure compost and the Cow Manure compost are assumed to behave similarly since the feedstock for the compost were animal manure even though they had their sources from different farms. Field effectiveness details are covered in the next chapter.

# CHAPTER 5

# FIELD RESULTS

## 5.1 Introduction

This chapter describes the field results that were collected periodically since the time of field construction. The field results include the moisture content data, temperature data, elevation survey results, and shrinkage cracking analysis. The moisture and temperature readings were recorded in order to determine the moisture encapsulation effect of the compost amended soils. The analysis of the moisture and temperature readings was done by using statistical methods. The t-test analysis was done in order to determine if the mean moisture and temperature variations of the treated sections were significantly different from that of the untreated control section. The elevation survey data was used to determine any significant soil loss due to the environmental factors. The shrinkage cracking analysis was done in order to document and compare any significant pavement cracking between the treated and untreated sections. Analysis of these results is presented in the following subsections.

## 5.2 Moisture and Temperature Data Analysis Method

The temperature and moisture data were recorded by the sensors that were installed in the ground at the time of field implementation. The measurements were made every 30minutes and were stored in the data logger that was buried along with the sensors. The data was downloaded using software at each field visit. A typical moisture and temperature readout downloaded from the data logger is shown in Figure 5-1. Definitions of moisture variation and temperature variation are presented in the figure and these variations are determined for the statistical analyses.

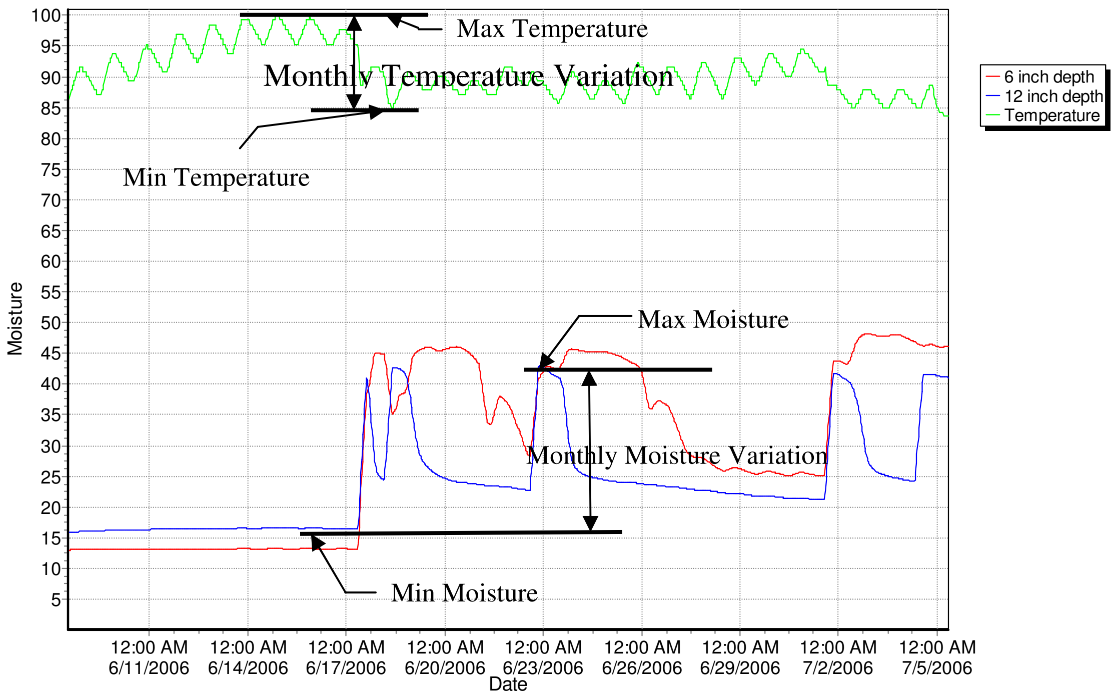



**Figure 5-1 Typical temperature and moisture data**

The downloaded moisture and temperature readings are separated into parts based on monthly intervals. The data is downloaded in a .dat file format by the software, which can be opened with excel. The maximum and minimum moisture readings are noted down from the excel files. The difference between the two readings is taken as the monthly mean moisture variation. The absolute mean moisture variation is calculated by taking the average of the entire monthly mean moisture variation over the period through which the data was collected. The designations of the different CMTs used in this research are shown in Table 5-1.

**Table 5-1 Average mean moisture variation of the different test sections**

| Test Site Location | Compost Used | Designation |
|---|---|---|
| Stephenville | Control | S_CS |
| | 100 % Dairy Manure Compost | S_DMC_1 |
| | 75 % Dairy Manure Compost | S_DMC_2 |
| | 30 % Biosolids Compost | S_BSC_1 |
| | 20 % Biosolids Compost | S_BSC_2 |
| Corpus Christi | Control | C_CS |
| | 30 % Biosolids Compost | C_BSC_3 |
| | 30 % Cow Manure Compost | C_CMC_3 |
| Yoakum | Control | Y_CS |
| | 30 % Wood + Biosolids Compost | Y_WBSC_1 |
| | 30 % Wood Compost | Y_WC_1 |
| Tyler | Control | T_CS |
| | 30 % Wood Compost | T_WC_2 |
| | 30 % Wood Compost | T_WC_3 |

The designation referred to in Table 5-1 describes the type of compost used and the source of the compost. The term S_DMC_1 for example can be explained as follows, the term S stands for the location and in this case Stephenville. DMC_1 is the term that is used to describe the Daily Manure Compost (DMC) and the dosage of compost that is used in that particular test section as shown in Table 5-1. The terms "BSC, DMC, CMC, WBSC and WC" describes the type of feedstock source of the compost. The various feed stock sources are as listed below

- BSC - Biosolids Compost
- DMC - Dairy Manure Compost
- CMC - Cow Manure Compost
- WBSC - Wood + Biosolids Compost
- WC - Wood Compost

From this section onwards the compost sections would be represented by the terms explained in Table 5-1.

## 5.3 Statistical Analysis

The statistical analysis of the data collected from the field was done by using the t-test. The t-test is generally used in order to determine whether the means of two different groups are significantly different from each other. The t-test could be defined as a statistical hypothesis test of which if the null hypothesis is true then the set has a student's t-distribution. The null hypothesis generally is assumed to be such that the means of the two sets that are being measured is not significantly different from each other. In this research the hypothesis were predetermined as follows

$\mu_o \Rightarrow \mu_{CMT} = \mu_{CS}$, The mean moisture variation of the compost treated and untreated sections are the same (null hypothesis).

$\mu_o \Rightarrow \mu_{CMT} < \mu_{CS}$, The mean moisture variation of the treated section is significantly lower than the mean moisture variation of the control section (alternate hypothesis).

In some of the data sets the number of samples between the two sets that were analyzed was not equal. In this case the degrees of freedom were calculated by taking the sum of the number of samples of the two sets and subtracting 2 from it. The unequal number of samples in the sets resulted from sample loss due to adverse conditions in the field. The data sets represent the mean monthly moisture variation of a particular test section for the entire time the data was collected. If the mean moisture variation of the treated sections were lower than that of the control section then it would mean that, the compost treatment on the top soil has a desirable effect on controlling the moisture fluctuation.

In case the null hypothesis was found to be true then the magnitude of the average moisture variation was taken and compared. In case the magnitude of the values was not significant enough to be compared, then the shrinkage crack analysis data was compared between the treated and untreated sections. The shrinkage crack analysis was calculated from the high definition digital images that were taken periodically during each field visit. The shrinkage crack analysis also helped in the identification of any new crack development and to determine the extent of crack formation.

## 5.4 Moisture Data Analysis

The mean moisture variation was calculated from the difference in the maximum and minimum moisture readings. The time periods were divided into monthly intervals and the mean of all the monthly moisture variation is termed as the mean moisture variation. The Stephenville test sections had the largest amount of moisture data incorporated into the analysis. Previously collected moisture data for the Stephenville test sections were available through a research conducted by Intharasombat in 2005. Hence the data obtained from the previous researcher was combined with the newly downloaded data and the t-test analysis was conducted on the total data. Table 5-2 shows the number of months of data that was used in the statistical analysis at each test site. The mean moisture variations of all the test sites are provided in Table 5-3 and Figure 5-2.

**Table 5-2 Time period for which experimental data was collected**

| Test Site Location | Number of months of Data used in statistical Analysis |
|---|---|
| Stephenville†† | 24 |
| Stephenville | 30 (Total – 54) |
| Corpus Christi | 30 |
| Yoakum | 18 |
| Tyler | 19 |

†† Data collected by Intharasombat 2005.

The t-test analysis was conducted on the data collected from both the moisture probes located at 6 inch and 12 inch depths, respectively. The moisture probe located at the 6 in. depth would have been subjected to the environmental conditions at the surface and hence do not represent sufficient amounts of moisture variations from underlying soils. Hence, this data was not included in t-test analysis.

**Table 5-3 Average mean moisture variation of the different test sections**

| Designation | Average Monthly Mean Moisture Variation |
|---|---|
| S_CS | 12.75 |
| S_DMC_1 | 11.58 |
| S_DMC_2 | 10.35 |
| S_BSC_1 | 9.76 |
| S_BSC_2 | 8.31 |
| C_CS | 15.56 |
| C_BSC_3 | 10.06 |
| C_CMC_1 | 17.6 |
| Y_CS | 27.65 |
| Y_WBSC_1 | 20.4 |
| Y_WC_1 | 20.4 |
| T_CS | 11.38 |
| T_WC_2 | 8.84 |
| T_WC_3 | 10.6 |

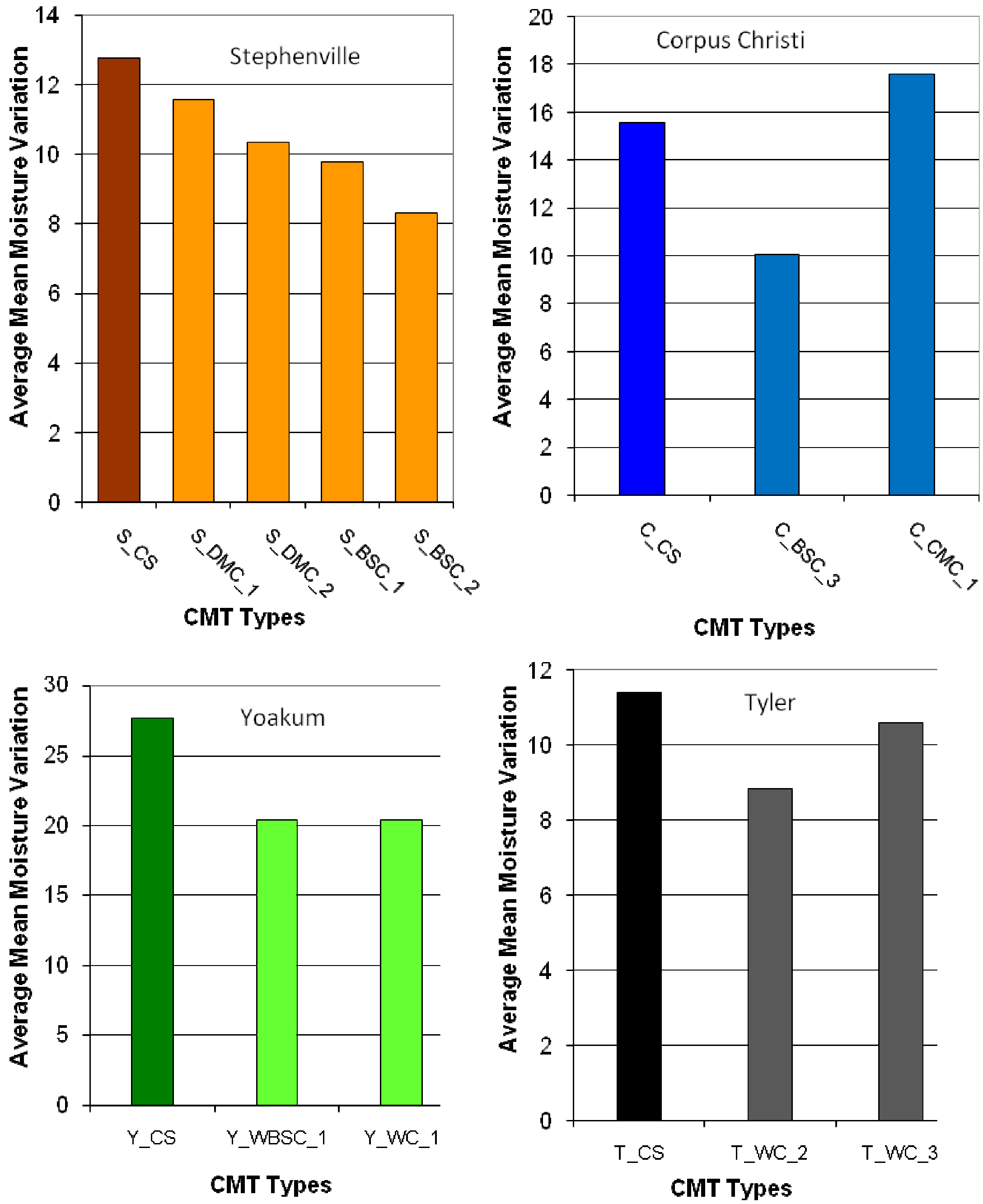



**Figure 5-2 Mean moisture variation of the different CMTs**

In Figure 5-2 the different test locations are differentiated by the different sets of colors. The darkest shade of a particular color represents the control section of that particular test site. It can be seen that in the Stephenville, Tyler and Yoakum test sites the mean moisture variation of the treated sections are lesser than that of the untreated section. In is observed that in the Corpus Christi site the C_CMC_1 test section has more moisture variation than the control sections, while all the other CMTs have lower moisture variations comparatively. Since the magnitude of the mean moisture variations cannot be used to determine if they are significantly different from each other, statistical analysis was conducted on the values recorded. The t-test was selected as the statistical model that was going to be applied to determine the significant differences between the treatments.

*5.4.1 Stephenville Moisture Data*

The monthly moisture variation of all the four different compost treated sections and the control section is given in table 5-4. It can be generally noted that the moisture variation of all the compost treated section in the Stephenville; TX site has a lower moisture variation than that of the control section. It should be noted that the S_CMT 1a actually had the control top soil completely removed and replaced with pure manure compost. Statistical analysis was conducted on the moisture readings recorded from the sites in Stephenville. Two sample sets with one of them being the control set data was selected at each single trail and the t-test conducted. The t-test results that were obtained are presented in Table 5-5.

**Table 5-4 Moisture variation data from the Stephenville, TX test site**

| Dates | Monthly Moisture Variation | | | | |
|---|---|---|---|---|---|
| | S_CS | S_DMC_1 | S_DMC_2 | S_BSC_1 | S_BSC_2 |
| Dec-05 | | 14.51 | 11.96 | | 14.31 |
| Jan-06 | | 18.04 | 13.53 | 13.72 | 14.51 |
| Feb-06 | | 7.84 | 12.55 | 8.43 | 12.75 |
| Mar-06 | | 3.14 | 4.31 | 10.39 | 3.33 |
| Apr-06 | | 4.51 | 4.31 | 14.5 | 2.35 |
| May-06 | | 9.02 | 3.33 | 14.31 | 7.06 |
| Jun-06 | 17.05 | 16.47 | 11.74 | 8.43 | 11.76 |
| Jul-06 | 5.88 | 5.68 | 5.09 | 5.49 | 1.76 |
| Aug-06 | 13.72 | 15.88 | 12.54 | 7.84 | 10.19 |
| Sep-06 | 13.92 | 13.52 | 9.8 | 4.5 | 11.37 |
| Oct-06 | 14.3 | 15.29 | 11.56 | 6.86 | 12.15 |
| Nov-06 | 9.8 | 11.37 | 6.66 | 6.66 | 7.64 |
| Dec-06 | 7.84 | 10.58 | | | 9.6 |
| Jan-07 | 7.45 | 10.78 | | | 5.49 |
| Feb-07 | 10.2 | 11.77 | 3.92 | | 3.72 |
| Mar-07 | 8.23 | 11.56 | 8.82 | 8.8 | 13.72 |
| Apr-07 | 9.6 | 11.18 | 9.61 | 11.37 | 9.21 |
| May-07 | 11.76 | 10.4 | 8.23 | 9.21 | 8.03 |
| Jun-07 | 14.11 | 11.96 | 7.84 | 9.6 | 10.39 |
| Jul-07 | 17.05 | 16.86 | 8.43 | 4.9 | 11.17 |
| Aug-07 | 10.19 | 12.35 | 8.23 | 6.07 | 8.82 |
| Sep-07 | 11.37 | 8.62 | 8.43 | 2.35 | 9.8 |
| Oct-07 | 10.58 | 12.55 | 9.8 | 9.8 | 4.7 |

It can be observed that the p value for the t-test conducted between the S_DMC_2 and the control section is 0.004. The significance level that is "α" was set as 0.05 for all the t-test analysis that was conducted. If the level is 0.05, then the results are only 5% likely to be as significant as just seen, given that the null hypothesis is true. Hence if the p-value is less than 0.05 then the null hypothesis is to be rejected. This means that for the p value mentioned above, the mean moisture variation of the treated section S_DMC_2 is lesser than that of the control section. Similarly the mean moisture variation of the S_BSC_1 and S_BSC_2 were found to be significant lower than the control section, with p-values of 0.0003 and $6.9\times10^{-6}$ respectively. If the moisture variation is low then the swelling and shrinkage of the soil underneath the pavement would also reduce, leading to significant reduction in pavement cracking.

**Table 5-5 Statistical t-test results on the Stephenville, TX moisture variation data**

| Section | Control plot mean moisture variation | Mean moisture variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| S_DMC_1 | 12.75 | 11.58 | 92 | 0.167 | 1.393 | same |
| S_DMC_2 | 12.75 | 10.35 | 94 | 0.004 | 2.939 | lesser |
| S_BSC_1 | 12.75 | 9.76 | 91 | 0.0003 | 3.702 | lesser |
| S_BSC_2 | 12.75 | 8.31 | 95 | $6.9 \times 10^{-6}$ | 4.76 | lesser |

The higher moisture variation in the S_DMC_1 could be due to the application of compost without any mixing. Since compost material has a higher void ratio, it has high permeability characteristics. Therefore in the S_DMC_1 test section the top compost layer for 4 inches would have let water pass through it being permeable causing the higher moisture fluctuations. The other CMTs in the Stephenville test site had the compost being added to the top soil at certain percentages compost dosages. Hence the soil particles would have filled up the voids leading to a compost amended soil section with lower permeability. Therefore the compost material in the CMTs would have been able to absorb the moisture to itself, since having a high affinity to water. The biosolids compost contained wood chips as a bulking agent. The decrease in the moisture fluctuation of the sections treated with the biosolids compost could also be attributed to its fibrous nature.

*5.4.2 Corpus Christi Moisture Data*

The data from the Corpus Christi test site sections were downloaded onto the computer and the mean moisture variation was calculated as mentioned in the previous section. The monthly moisture variation data calculated from the moisture readings downloaded is presented in table 5-6.

The t-test results are presented in Table 5-7. It can be seen that the biosolids compost was effective in reducing the moisture variation, whereas there was no significant difference in the moisture variations between the cow manure compost and the control section. It could be said that the biosolids compost is more effective than the manure compost since the same kinds of trends are observed both in Stephenville and Corpus Christi. It could be understood that due to the absence of any fibrous material in the manure compost might have contributed to the larger moisture variations in the present results. The presence of wood chips in the biosolids compost would have likely increased its effectiveness in decreasing the moisture variation.

**Table 5-6 Moisture variation data from the Corpus Christi, TX test site**

| Dates | *Monthly Moisture Variation* | | |
|---|---|---|---|
| | *C_CS* | *C_BSC_3* | *C_CMC_1* |
| Aug-05 | | | 0.19 |
| Sep-05 | | | 30.98 |
| Oct-05 | | | 27.45 |
| Nov-05 | | | 25.68 |
| Dec-05 | | 1.76 | 1.37 |
| Jan-06 | 14.11 | 1.96 | 2.16 |
| Feb-06 | 1.96 | 1.96 | 1.764 |
| Mar-06 | 21.37 | 0.78 | 0.98 |
| Apr-06 | 2.745 | 0.58 | 0.98 |
| May-06 | 37.45 | 25.68 | 28.03 |
| Jun-06 | 38.03 | 24.5 | 27.25 |
| Jul-06 | 14.9 | 22.74 | 28.82 |
| Aug-06 | 10.14 | 0.588 | 10.1 |
| Sep-06 | 22.7 | 2 | 26.07 |
| Oct-06 | 15.7 | 2.5 | 22.94 |
| Nov-06 | 3.7 | 2.7 | 3.92 |
| Dec-06 | 19.2 | 3.5 | 24.5 |
| Jan-07 | 10.2 | 8.23 | 17.06 |
| Feb-07 | 11.37 | 13.92 | 17.84 |
| Mar-07 | | 17.84 | 20 |
| Apr-07 | | 18.53 | 20 |
| May-07 | 15.1 | 20.39 | 23.52 |
| Jun-07 | 20.19 | 20.19 | 29.6 |
| Jul-07 | 21.38 | 17.05 | 21.37 |
| Aug-07 | 21 | 16.9 | 20.78 |
| Sep-07 | 21.8 | 19.4 | 21.8 |
| Oct-07 | 22.35 | 19.2 | 21.8 |
| Nov-07 | 2.9 | | |

**Table 5-7 Statistical t-test analysis on Corpus Christi, TX data**

| Section | Control plot mean moisture variation | Mean moisture variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| C_BSC_3 | 15.56 | 10.06 | 58 | 0.014 | 2.51 | lesser |
| C_CMC_1 | 15.56 | 17.6 | 64 | 0.237 | 1.19 | same |

### *5.4.3 Tyler Moisture Data*

The monthly moisture variation of the different compost treated sections in the Tyler, TX test site are presented in Table 5-8. It can be observed from the table that the moisture variations of both the treated sections are lower than that of the control section. The t-test analysis was done on the data sets and is presented in Table 5-9. It was seen that the moisture variations of T_WC_2 was significantly lower than the untreated section, and the T_WC_3 was similar to the control section. This is due to the lower PI of the T_WC_2 compost amended section than the T_WC_3 as seen from the laboratory tests that were conducted as shown in Table 3-4. Since both the compost was of the same type it was expected that the treated sections would have the same efficiency. In order to further probe this issue the shrinkage crack analysis of these test sections would be used to determine the efficiency of the compost treatment.

**Table 5-8 Moisture variation data from Tyler, TX test site**

| *Dates* | *Monthly Moisture Variation* | | |
|---|---|---|---|
| | *T_CS* | *T_WC_2* | *T_WC_3* |
| May-06 | 0.58 | 0.78 | 2.15 |
| Jun-06 | 3.13 | 3.13 | 0.39 |
| Jul-06 | 4.7 | 4.9 | 1.37 |
| Aug-06 | 18.23 | 3.52 | 0.58 |
| Sep-06 | 16.47 | 7.45 | 1.76 |
| Oct-06 | 17.05 | 24.11 | 7.45 |
| Nov-06 | 8.62 | 18.43 | 3.13 |
| Dec-06 | 18.43 | 10.19 | 18.43 |
| Jan-07 | 6.07 | 11.17 | 5.68 |
| Feb-07 | 6.86 | 11.76 | 7.05 |
| Mar-07 | 11.76 | 14.5 | 17.64 |
| Apr-07 | 12.16 | 13.52 | 15.3 |
| May-07 | 11.76 | 14.31 | 16.86 |
| Jun-07 | 14.9 | | 13.33 |
| Jul-07 | 17.25 | | 15.49 |
| Aug-07 | 4.7 | | 3.13 |
| Sep-07 | 17.64 | | 15.6 |
| Oct-07 | 14.5 | | 13.72 |

**Table 5-9 Statistical t-test analysis of the Tyler, TX data set**

| Section | Control plot mean moisture variation (%) | Mean moisture variation (%) | Degree of Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| T_WC_2 | 11.38 | 8.84 | 17 | 0.048 | 2.12 | lesser |
| T_WC_3 | 11.38 | 10.60 | 12 | 0.366 | 0.94 | same |

*5.4.4 Yoakum Moisture data*

The monthly moisture variations that were recorded at the test site in Yoakum, TX are presented in Table 5-10. The t-test analysis was done on the moisture readings and the results are shown in Table 5-11. It could be seen that both the compost had lower moisture variation when compared to the control section. It has to be noted that both the compost were mixed with an equal part of wood chips before they were bought to the construction site. Hence, the presence of wood chips seems to play a vital role in the reduction of the moisture variations. This could be due to the fibrous nature of the wood chips and also due to its water absorption characteristic.

**Table 5-10 Moisture variation data from Yoakum, TX test site**

| *Dates* | *Monthly Moisture Variations* | | |
|---|---|---|---|
| | *Y_CS* | *Y_WC_1* | *Y_WBSC_1* |
| June-06 | 49 | 35.68 | 33.13 |
| Jul-06 | 49 | 34.9 | |
| Aug-06 | 40.58 | 16.07 | 1.76 |
| Sep-06 | 31 | 31.4 | 30.78 |
| Oct-06 | 24.3 | 26.3 | 23.9 |
| Nov-06 | 30.6 | 13.1 | 8 |
| Dec-06 | 21.2 | 23.5 | 24.7 |
| Jan-07 | 26.29 | 14.9 | 17.8 |
| Feb-07 | 2.35 | 2.94 | 6.47 |
| Mar-07 | 31.6 | 16.7 | 25.7 |
| Apr-07 | 26.29 | 13.13 | 21.96 |
| May-07 | 21.17 | 16.86 | 25.49 |
| Jun-07 | 22.94 | 19.41 | |
| Jul-07 | 17.84 | 19.21 | 23.13 |
| Aug-07 | 22.15 | 21.96 | 22.35 |
| Sep-07 | 31.37 | 22.7 | |
| Oct-07 | 22.4 | 18.2 | |

**Table 5-11 Statistical t-test analysis conducted on the Yoakum, TX data set**

| Section | Control plot mean moisture variation | Mean moisture variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| Y_WBSC_1 | 27.65 | 20.40 | 12 | 0.036 | 2.36 | lesser |
| Y_WC_1 | 27.65 | 20.41 | 16 | 0.001 | 4.01 | lesser |

## 5.5 Temperature Data Analysis

The temperature data was analyzed in the same way as that of the moisture readings. The time period was separated into monthly intervals, and the minimum and maximum temperatures were recorded. The difference between them is referred to as the mean temperature variation. The average of the monthly temperature variations are presented in Figure 5-3. It can be observed from Figure 5-3 that the temperature variation of both the treated sections in Yoakum and Tyler, TX are significantly more than that of the untreated section. In both the Stephenville and Corpus Christi test site the temperature variation of all test sections other than the S_DMC_2 do not show any significant difference with the control section. Since statistical analysis is required to interpret the data t-test was conducted on the recorded temperature readings. The hypothesis was formulated to check whether the temperature fluctuations of the treated sections were lower than that of the untreated sections. The temperature was recorded at a depth of 12 inches and stored in the data logger. The readings were downloaded periodically during each field visit.

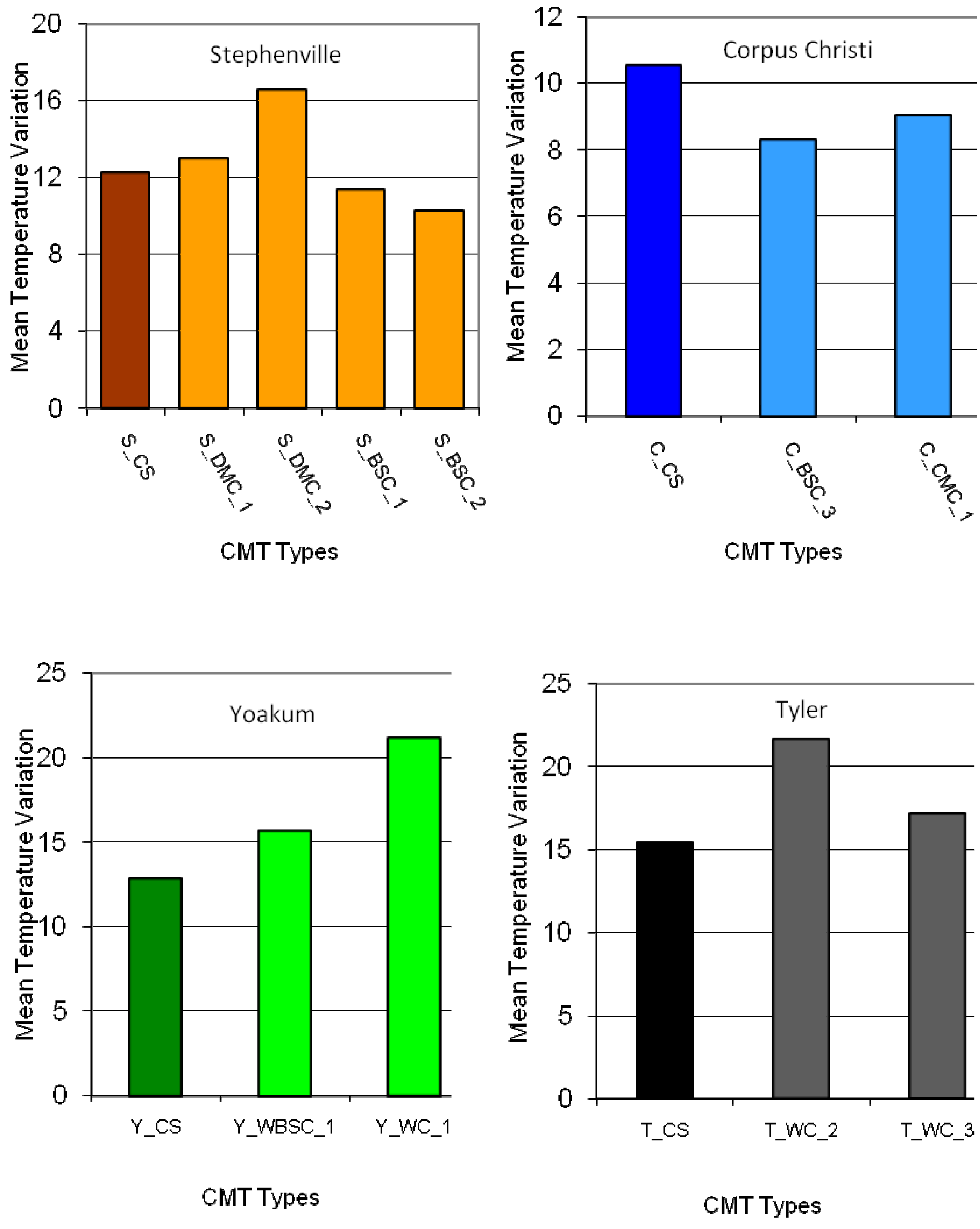



**Figure 5-3 Mean temperature variation of the different CMTs**

*5.5.1 Stephenville Temperature Data*

The t-test results of the temperature variation data of the Stephenville, TX test sections are presented in Table 5-12. It can be seen that the temperature variation of the manure compost that was used in S_DMC_2 was found to be higher than that of the untreated section. It was seen that the moisture variation for the same section was significantly lower than that of the control section; hence shrinkage cracking analysis results would have to be used in this case to determine the effectiveness of that particular compost treatment.

**Table 5-12 Statistical t-test analysis on Stephenville, TX temperature data**

| Section | Control plot Temperature moisture variation | Mean Temperature variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| S_DMC_1 | 12.21 | 12.98 | 92 | 0.254 | 1.148 | same |
| S_DMC_2 | 12.21 | 16.56 | 94 | 0.000 | 3.55 | greater |
| S_BSC_1 | 12.21 | 11.31 | 91 | 0.367 | 0.906 | same |
| S_BSC_2 | 12.21 | 10.23 | 95 | 0.145 | 1.47 | same |

*5.5.2 Corpus Christi Temperature Data*

It could be seen from the temperature readings that the magnitude of the temperature variations of the compost treated sections were lower than that of the control section. The t-test results show that there is not a significant difference in the temperature fluctuations between the treated and untreated sections.

**Table 5-13 Statistical t-test analysis on Corpus Christi, TX temperature data**

| Section | Control plot Temperature moisture variation | Mean Temperature variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| C_BSC_3 | 10.54 | 8.29 | 51 | 0.130 | 1.53 | Same |
| C_CMC_1 | 10.54 | 9.01 | 51 | 0.218 | 1.24 | Same |

### *5.5.3 Tyler Temperature Data*

The t-test analysis of the temperature variations of the Tyler, TX test sections are presented in Table 5-14. It can be observed that the section T_WC_2 has a higher temperature variation than the control section, though the moisture variation is significantly lower than the control section. Hence further investigation of this section through the shrinkage crack analysis is required to determine its effectiveness in preventing cracking. The second section does not show any significant difference.

**Table 5-14 Statistical t-test analysis on Tyler, TX temperature data**

| Section | Control plot Temperature moisture variation | Mean Temperature variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| T_WC_2 | 15.39 | 21.6 | 34 | 0.000 | 11.83 | greater |
| T_WC_3 | 15.39 | 17.14 | 29 | 0.246 | 1.22 | same |

### *5.5.4 Yoakum Temperature Data*

The t-test results of the temperature variation data of the Yoakum, TX test sections are presented in Table 5-15. It can be noted that both the treated sections show higher temperature variation than the control section. It has to be noted that both the Yoakum and Tyler test sites compost had their feedstock source as wood waste. From the t-test results of the Yoakum and Tyler test sites it can be said that the wood waste compost is not efficient in lowering the temperature fluctuation even though they are efficient in decreasing the moisture fluctuations.

**Table 5-15 Statistical t-test analysis on Yoakum, TX temperature data**

| Section | Control plot Temperature variation | Mean Temperatur e variation | Degree Freedom | One sided p-value | T-value | Conclusion |
|---|---|---|---|---|---|---|
| Y_WBSC_1 | 12.78 | 15.61 | 29 | 0.034 | 2.22 | greater |
| Y_WC_1 | 12.78 | 21.15 | 32 | 0.000 | 5.37 | greater |

It can be seen from the t-test analysis of the monthly temperature variations that there is no significant difference between the compost treated and untreated sections. This can be due to the location of the temperature probe. Since there is only one thermocouple, it was placed at a depth of 6 inch next to logger box. As a result temperature changes are not clear or evident in the present study. Vegetation growth at the surface at all sections might have opened up the soil surface and hence resulted in similar temperatures in all sections.

## 5.6 Shoulder Soil Erosion

The erosion potential of each site was determined by the elevation survey that was conducted during each field visit. The elevations of the particular points were recorded and compared with a immovable reference point. The difference in elevation readings were recorded as the amount of soil erosion that had taken place. There were two kinds of elevation surveys that were conducted. The erosion potential of the treated sections were determined by placing the survey points on the unpaved shoulder soil surface as shown in Figure 4-14. The average of the five points that were spread out on the soil surface was reported as the elevation value each month.

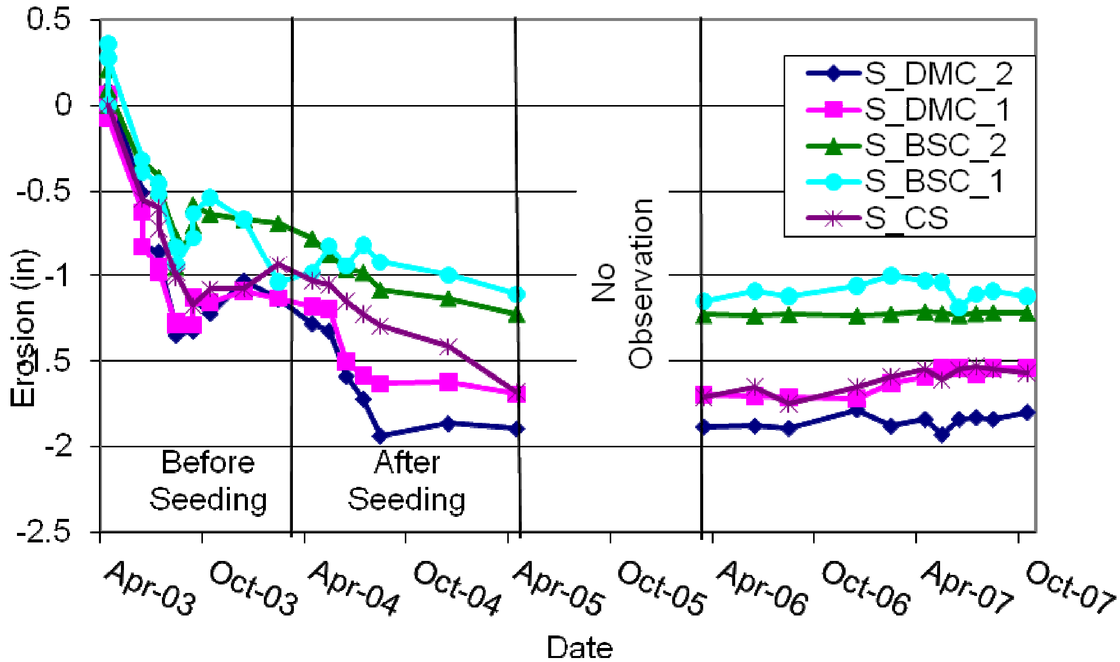



**Figure 5-4 Elevation profile of the Stephenville, TX test site**

The elevation profile of the Stephenville test site is shown in Figure 5-4. It can be noted that at the initial stages just after the site construction there had been some significant loss of the compost amended soil. This was due to the fact that the site was not seeded after construction. It can be observed that the elevation readings had stabilized after seeding due to vegetative growth. Hence it is important that the site be seeded right after construction to protect the compost amended top soil from washing out. The growth of vegetation helps in the soil particles to be held tightly to each other and also gives protection against environmental factors, since a kind of microclimate is created at the surface of the soil layer (De Ona, 2005). This formation of a micro climate helps in the reduction of the temperature and moisture variations of the treated soil sections.

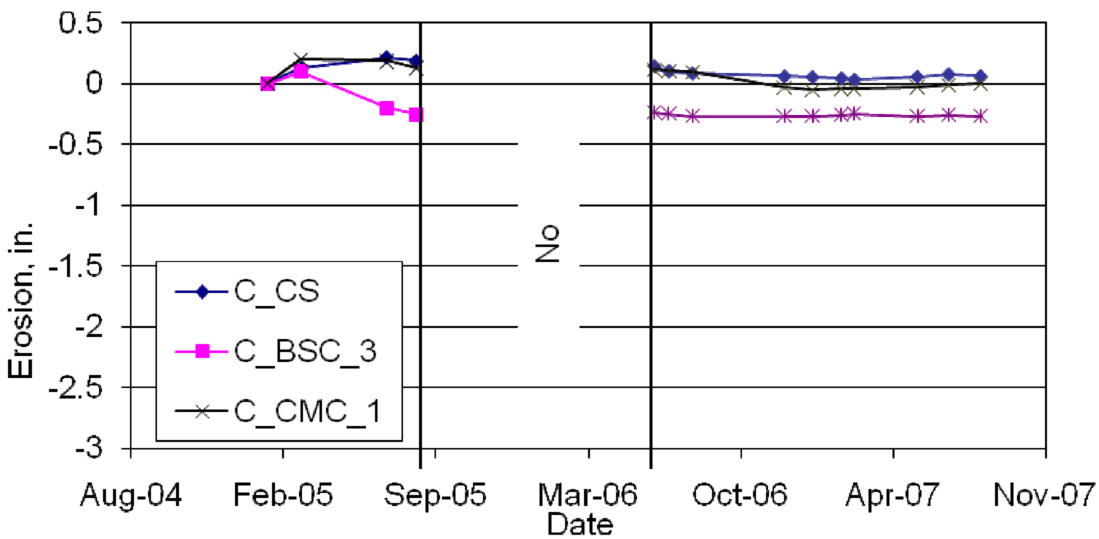



**Figure 5-5 Elevation profile of the Corpus Christi, TX test sections**

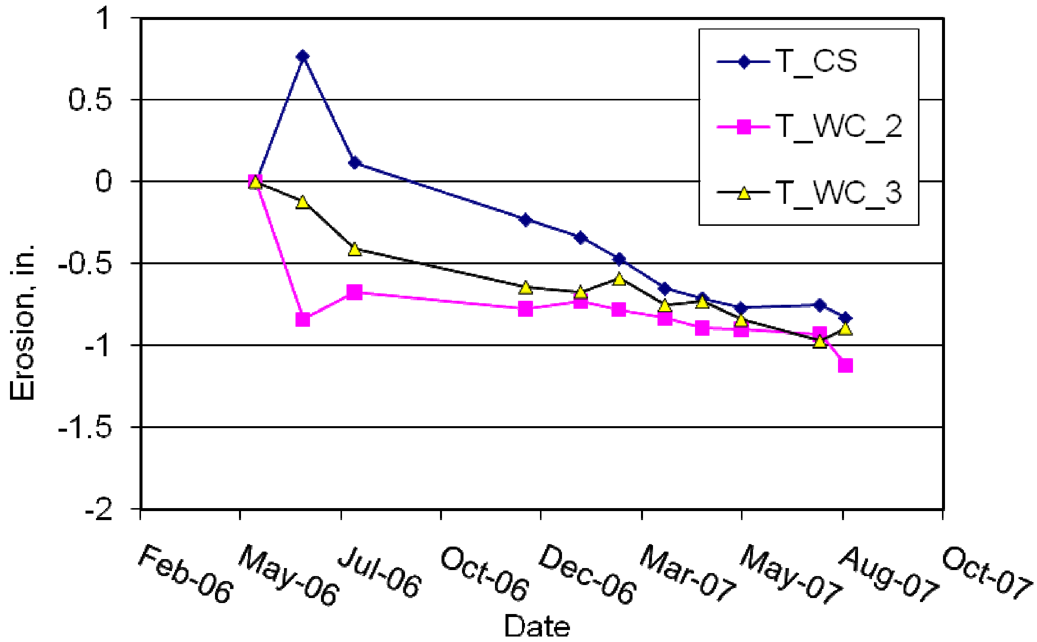



**Figure 5-6 Elevation profile of the Tyler, TX test sections**

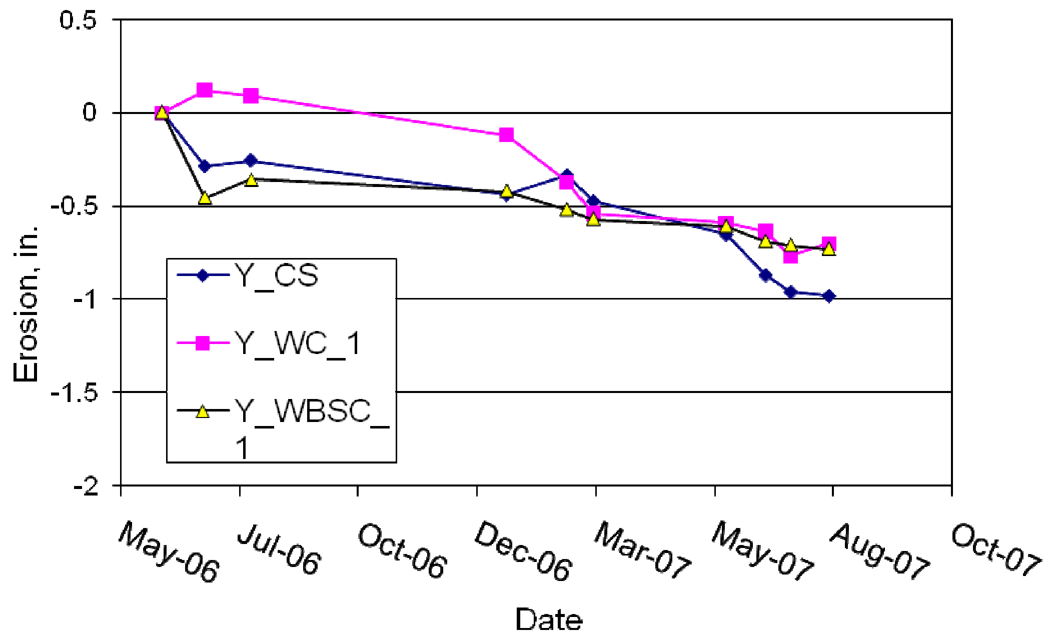



**Figure 5-7 Elevation profile of the Yoakum, TX test sections**

It can be observed from Figures 5-5, 5-6, and 5-7 that there is more erosion during the stage right after construction and it slowly stabilizes. This early erosion is again due to the exposure of the compost treated soil surface directly to the environment. As the compost was rich in nutrients it enhanced the growth of a vegetative cover as time increased, hence reducing the erosion potential of the soil surface. Hence the application of the compost treatment not only reduces the moisture and temperature fluctuations but also reduces the erosion potential of the soil surface.

## 5.7 Pavement Shoulder Cracking Analysis

The shrinkage cracking analysis was calculated from the high resolution pictures of the treatment section. The shoulder pavement that is adjacent to the treated soil layer is divided into equal parts to accommodate proper coverage during the digital imaging. The divisions are clearly marked using paint on the road surface and it is made sure that each portion is photographed during each field visit. The digital images are analyzed using computer software. The images are converted from jpeg format to bitmap as the software uses only bitmap format. The number of pixels of the required section in the photograph was calculated. Then a particular threshold value is selected and then the portions that do not contain any cracks were completely removed. Finally only the cracks was left over which were identified by black pixels. The number of black pixels was calculated. The area of cracking is the number of black pixels divided by the total number of pixels. The percentage cracking was calculated just after the site was calculated, and any new cracking was identified by the increase of this value. The percentage cracking of the treated section was compared to that of the control section to determine the effectiveness of the compost treatment in mitigating the pavement cracking. The results of the pavement cracking are presented in Table 5-16 and Figure 5-9.

**Table 5-16 Pavement shoulder crack percentage of the different test sections**

| Designation | Percentage Pavement Shoulder Cracking |
|---|---|
| S_CS | 0.73 |
| S_DMC_1 | 0.36 |
| S_DMC_2 | 0 |
| S_BSC_1 | 0 |
| S_BSC_2 | 0.08 |
| C_CS | 0.12 |
| C_BSC_3 | 0.04 |
| C_CMC_1 | 0.13 |
| Y_CS | 0.41 |
| Y_WBSC_1 | 0.18 |
| Y_WC_1 | 0.11 |
| T_CS | 0.23 |
| T_WC_2 | 0 |
| T_WC_3 | 0 |

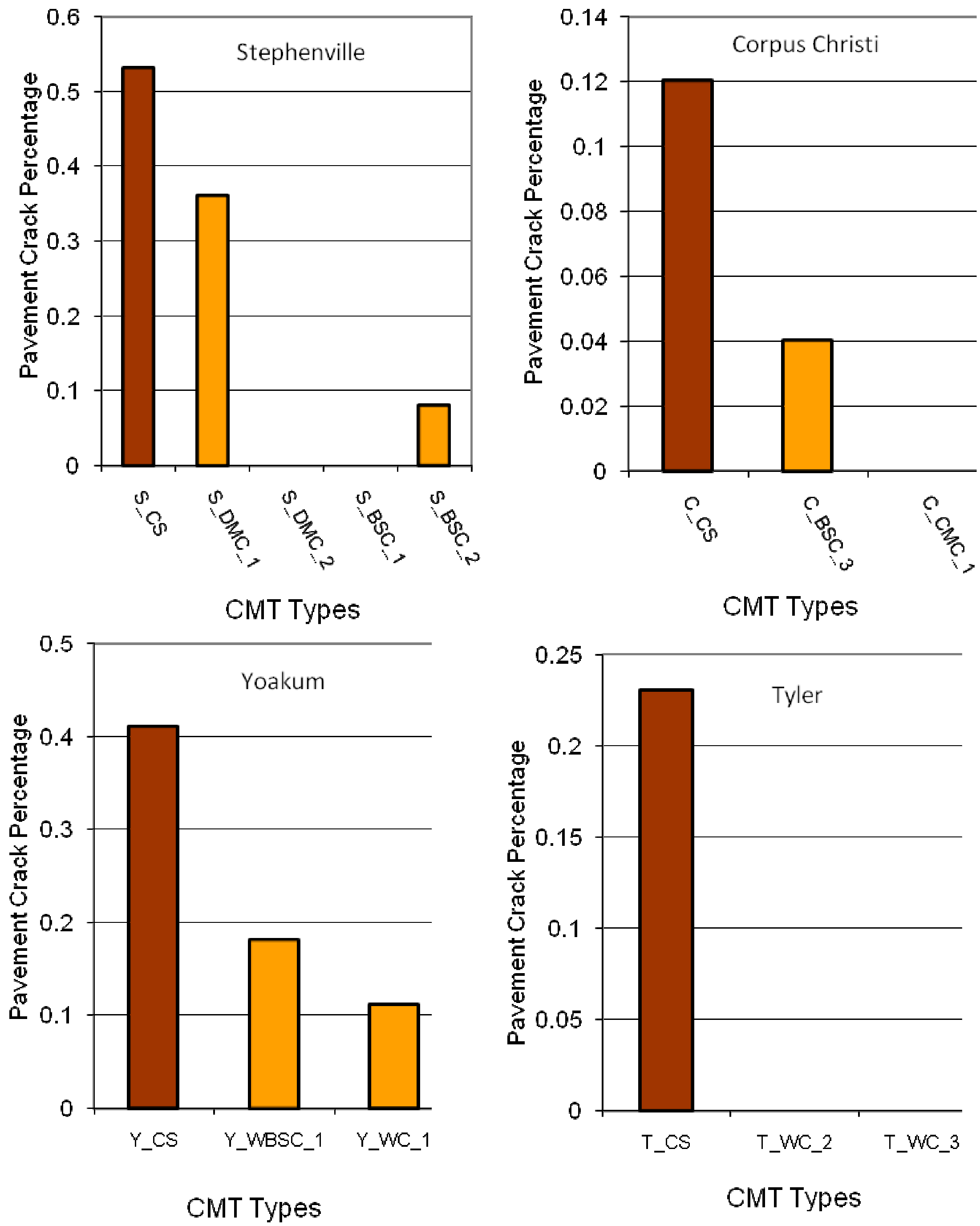



**Figure 5-8 Pavement shoulder crack percentage of the different test sections**

It can be seen from Figure 5-9 that all the compost treatments were effective in reducing the pavement cracking. It can be noted that the compost treated sections in Yoakum, TX show approximately half of the crack percentage of the respective control section. The cracks that were seen on the Y_WBSC_1 were due to the extension of the cracks from the untreated soil. The site setup was such that the Y_WBSC_1 section was on one end, while the Y_WC_1 section was in between the Y_WBSC_1 and the control section. Hence the cracks that were formed on the Y_WBSC_1 was found to originate from the untreated soil that was next to it on one side. The cracks on the Y_WC_1 section was the extension of old cracks that was present on the pavement shoulder at the time of construction. Hence the cracks on the treated section on the Yoakum, TX site was not due to the defect of the compost treatment. The treated section in the Tyler, TX site showed no cracks on the section. The untreated section had new cracks on it indicating that the wood compost that was used in Tyler, TX was found to be effective in mitigating the pavement cracking. All the treated sections in the Stephenville, TX site except the S_DMC_1 section showed absence or negligible amount of cracking when compared to the control section. It was observed that the S_DMC_1 test section proved to be not effective from analyzing all the parameters measured in that section. The remaining test sections at the Stephenville test site showed negligible or no cracking when compared to the cracking in the control pavement section.

## 5.9 Summary

It was seen that the parameters that were measured in the field for the S_DMC_1 Section was almost similar in all aspects to that of the control section on the Stephenville, TX test site. It has to be noted that this section did not involve any type of mixing the compost with the soil since the compost dosage was 100% DMC. Though the temperature variation of the S_DMC_2 site was found to be higher than the control section, it was found to be effective in reducing the moisture variation and the pavement cracking. Hence it can be said that the application of 100% compost of any type would prove not to be effective in reducing the pavement cracking. It was seen that the treated sections both in Yoakum and Tyler, TX had a higher temperature variation than the control section. From the moisture variation data and the percentage pavement shoulder cracking it was seen that the compost treatment proved to be an effective method to reduce the pavement cracking even though they had a higher temperature variation. It was observed from the Corpus Christi, TX test site that the cow manure compost was not effective in preventing the shoulder cracking. Hence from both the Stephenville and Corpus Christi data it was seen that the animal manure composts were not effective in reducing the pavement cracking. Comparing the statistical analysis results, digital imaging, and elevation survey results it was seen that the wood compost was the most efficient in preventing the shoulder cracking. The effectiveness of the different compost treated sections based on the parameters that were measured are provided in Table 5-17.

**Table 5-17 Effectiveness of compost treatment based on different parameters**

| Test Section | Moisture Variation Analysis | Temperature Variation Analysis | Elevation Survey Analysis | Shrinkage Cracking Analysis |
|---|---|---|---|---|
| S_DMC_1 | ✗ | ✗ | ✓ | ✗ |
| S_DMC_2 | ✓ | ✗ | ✓ | ✓ |
| S_BSC_1 | ✓ | ✗ | ✓ | ✓ |
| S_BSC_2 | ✓ | ✗ | ✓ | ✓ |
| C_BSC_3 | ✓ | ✗ | ✓ | ✓ |
| C_CMC_1 | ✗ | ✗ | ✓ | ✗ |
| Y_WBSC_1 | ✓ | ✗ | ✓ | ✓ |
| Y_WC_1 | ✓ | ✗ | ✓ | ✓ |
| T_WC_2 | ✓ | ✗ | ✓ | ✓ |
| T_WC_3 | ✗ | ✗ | ✓ | ✓ |

✓ Effective in preventing shoulder cracking based on that particular parameter

✗ Not effective in preventing shoulder cracking based on that particular parameter

# CHAPTER 6

# ANALYSIS OF LABORATORY RESULTS AND SERVICE LIFE PREDICTION MODEL

## 6.1 Introduction

This chapter deals with the laboratory tests that were conducted on the samples that were collected from the field. In order to determine the parameters which could determine the life of the compost treatment several laboratory tests were conducted on the samples collected from the field. These tests included Cation Exchange Capacity (CEC), Organic Content (O.C), and Total Soil Suction. The soil samples were collected from all the four test sections from Stephenville, Corpus Christi, Yoakum, and Tyler from the state of Texas during site visits. These samples were subjected to the above mentioned laboratory tests.

The samples that were collected from the Stephenville, TX site was the most comprehensive set of all the test data sets based on the length of the data collection. Hence the data from the Stephenville site was first used in the development of the 'life prediction' model that would be applied for the determination of the service life of the compost treatments for the mitigation of the pavement shoulder cracking. The model developed based on the Stephenville data set was then applied to the data sets that were collected from the other treatment sections. The developed models were also used to determine the service life of their own respective test section.

It is important to understand the characteristic of the compost material in order to predict the service life of the compost treatment on the shoulder soil. In order to comprehend the nature of the composted material in soils, it would be effective to learn about soil organic matter initially. The organic content of soil is usually referred to as soil organic material in the agronomy field. The organic content of the soil can be defined as the vast number of carbon compounds that are found in the soil structure. The organic matter in the soil can be divided into two groups as follows (Lewandowski, 2002)

- Stabilized organic matter
- Active fraction of the organic matter

The stabilized portion of the organic matter includes the highly decomposed and stable material which make up about third to a half of the soil organic matter(Lewandowski, 2002). The active fraction of organic matter refers to the part which is being degraded by the plants and microbes and used up for plant growth, and others (Lewandowski, 2002). The stabilized organic matter is able to absorb up to six times its own weight in water.

It is a known fact that the compost is a highly organic rich matter. Hence when we add compost to the soil it results in the increase of the organic content of the soil. Compost being an organic compound is bio-degradable in nature. There are two basic processes by which any bio-degradation process takes places which are known as the aerobic and anaerobic degradation processes (Metcalf and Eddy, 2003).

Aerobic degradation can be defined as the break down of the organic compounds in the presence of oxygen (Metcalf and Eddy, 2003). The anaerobic degradation is the process by which the organic material is degraded in the absence of oxygen (Biomass, 2008). The microbes that are involved in both processes are totally different from each other. Anaerobic degradation can be identified by the release of a strong unpleasant odor during the process due to the formation of methane. An example of anaerobic degradation is the breakdown of organic material that is dumped into landfills, where oxygen is absent for microbial respiration.

In this research the compost was mixed with the soil in such a way that the soil compost blend extended to a depth of only 4 inches from the surface. It has to be noted that the compost is a highly porous medium and when mixed with the soil decreases the overall density of the soil. This was observed from the proctor density curves of the compost amended soil and the control soil. Hence it can be assumed that the compost amended soil layer would be highly aerated and unlikely to support any anaerobic degradation in the soil surface (Qasim, Oral Communication). The microorganisms involved in the degradation of the organic material present in the compost include facultative and strict aerobic bacteria, fungi, and actinomycetes (Huang, 2000).

## 6.2 Sample Collection

The samples were collected from the test sections periodically during each field visit. The samples were collected from the field using the random sampling technique. The test section was divided into forty equal sub sections which were 5 ft in length and 2.5 ft in breadth each. These sub sections were not marked out in the field but were located by measuring with a tape from the corners of the whole treatment sections at the time of field visit. The samples were collected from 5 to 6 sub sections at each CMT that was randomly selected. The soil surface was scraped off to remove any vegetative growth before the compost amended sample collection. About 300 grams of soil was collected from each sub section and it was made sure that the sample collection depth never exceeded 4 inches.

Soil samples thus collected from the field was brought to the lab and mixed together homogeneously and then divided into four parts. Then one of these parts was selected for conducting O.C. or organic content, cationic exchange capacity or CEC, and the total suction experiments. Details of the experimental procedures are given in Chapter 3. The time period through which the soil samples were collected for each of the treatment locations are presented in Table 6-1.

**Table 6-1 Time period of sample collection**

| **Site Location** | **Months of Sample Collection.** |
|---|---|
| Stephenville, TX | 54 |
| Corpus Christi, TX | 34 |
| Yoakum, TX | 24 |
| Tyler, TX | 25 |

## 6.3 Laboratory Results

Three parameters were obtained for predicting the service life of the compost treatment on the shoulder soils to prevent the shoulder pavement cracking. These parameters were based on the biological, chemical and mechanical properties of the compost amended soils. These are:

- Organic Content, O.C (Biological and Chemical)
- Cation Exchange Capacity, CEC (Chemical Property) and
- Total Soil Suction (Mechanical Property)

*6.3.1 Stephenville Results*

Results from the laboratory tests performed on the Control and compost amended soil samples collected from the Stephenville test site are presented in this section. Since the time period of sample collection for the Stephenville site is the most comprehensive, this data was used to develop the model for the service life prediction.

6.3.1.1 Organic Content

The organic content of a soil plays a major role in determining the soil quality of the particular soil. The physical and chemical characteristics of the soil vary depending upon the organic content of a soil. The addition of organic matter to the soil results in the increase in the water holding capacity of the soil and also decreases the evaporation of water from the soil (UMN, 2005).

The organic content of the soil depends upon two factors which are the addition of organic matter to the soil and the decomposition of the organic matter present in the soil. Hence compost was mixed with the top soil to enhance the water holding capacity and to prevent loss of water from the soil. As we know that organic material degrades with time compost which is highly organic in nature degrades with time. Hence by measuring the organic content of the soil with time and comparing it with the organic content of the control soil we would be able to determine the amount of compost that is remaining in the soil. The organic content of the test sections in the Stephenville site are shown in Figure 6.1.

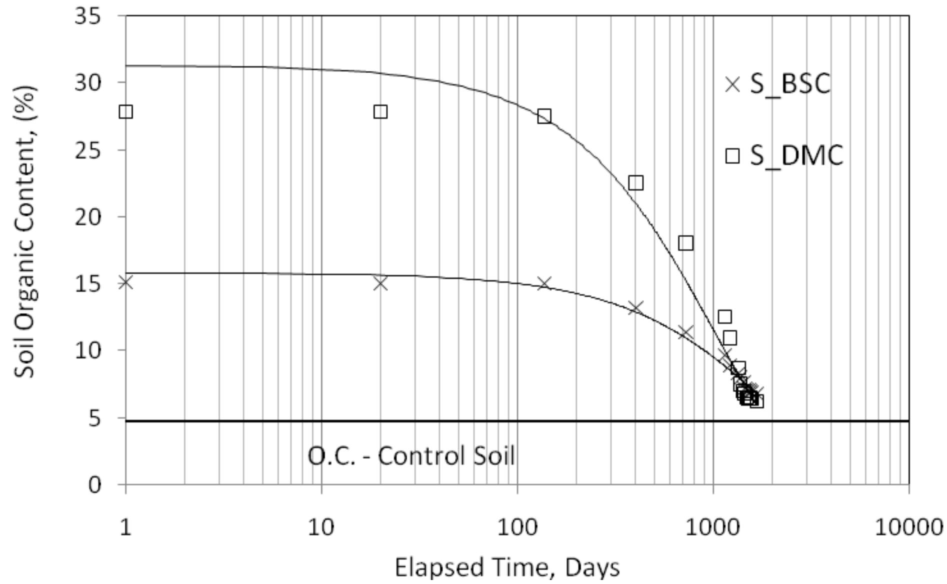



**Figure 6-1 Trend of organic content at the Stephenville, TX test site**

Figure 6-1shows that there is a gradual reduction of the organic content of the compost treated sections with the elapsed time period. The decrease in the OC of the CMTs are due to biological processes such as the aerobic degradation of the compost by the microorganisms present in the soil, and physical processes like water runoff and erosion due to wind and water. The reduction in the OC cannot be modeled as a purely biological process because of the influence of the physical and environmental processes which directly affect the OC of the soil.

It can be seen that the OC of the untreated soil is 3.9. It is assumed that as the OC of the CMTs reach 3.9, then the CMTs have reached the initial original Control soil state rendering the compost ineffective and the longevity finished. Therefore a threshold value of approximately 5%-7% above the Control soil OC is proposed to provide a reasonable reapplication timeframe of the compost treatment. Based on the plotted points and the steep downward drop of the curves shown in

Figure 6 in the Appendix, it can be seen that the OC values of the CMTs have almost reached the OC value of the Control soil.

#### 6.3.1.2 Cation Exchange Capacity (CEC)

Cation Exchange Capacity (CEC) is defined as the capacity of the soil to hold cations. The CEC depends on the amount of clay or organic matter that is contained in the soil (Camberato, Clemson Univ.). The CEC also depends on the type of minerals that are present in the soil. It was observed that the soil that has mixed mineralogy and the destruction of organic matter resulted in the decrease of the CEC (Dowling, 1984). Soils that have large amounts of clay or organic matter in them tend to have a higher CEC; for example, sandy soils have very low CECs while organic clays have high CECs. On average the organic matter of the soil contributes 49% of the CEC of the soil (Thompson, 1989). The CEC can also be termed as an indicator that shows the water holding capacity of the soil. It can be observed from Figure 6-2 that as the clay percentage and the organic matter percentage increases there is an increase in the CEC of the soil (Hepper, 2006).

Agriculturists usually add organic matter to improve the quality of the soil and to increase the crop yield from their farm soils. The intrinsic reason for adding organic matter is that it increases the CEC of the soil. This increase in CEC results in higher water holding capacity and the nutrients that are added to the soil are held more firmly by the soil. The same principle is employed in the treatment sites. Compost (organic matter) is added to the soil in order to increase the quality (CEC) so that it improves the water holding capacity of the soil. Thus, the higher the CEC, the better the efficiency of the treatment in preventing the swelling and shrinking of the subgrade soil.

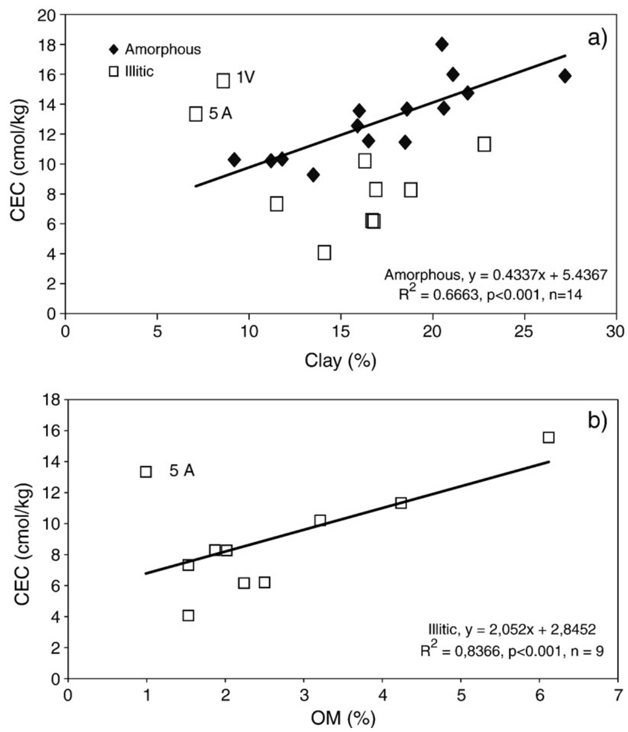



**Figure 6-2 CEC with different clay and organic matter percentage (Hepper, 2006)**

Figure 6-3 shows that the CEC values of the Biosolids and Dairy Manure CMTs at the time of field implementation were 133 and 137 meq/100 gms respectively. A gradual decrease in the cationic exchange capacity can be observed with time. This decrease in the CEC is due to the decrease in the organic content of the compost in the compost treated sections. This is due to the gradual washout of the compost material in the soil at particular heavy rainfall events and also due to the biodegradable nature of the compost material. Thus this decrease in the organic matter results in the observed lower CEC values with time, which in turn reduces the water holding capacity of the treated soil leading to swelling and shrinking related problems in the soil under the pavement.

The CEC of the Control soil was found to be 96 meq/100gms (red horizontal line). Based on the plotted points and the steep downward drop of the curves, it can be seen that the CEC values of the treated sections have almost reached the CEC value of the control soil.

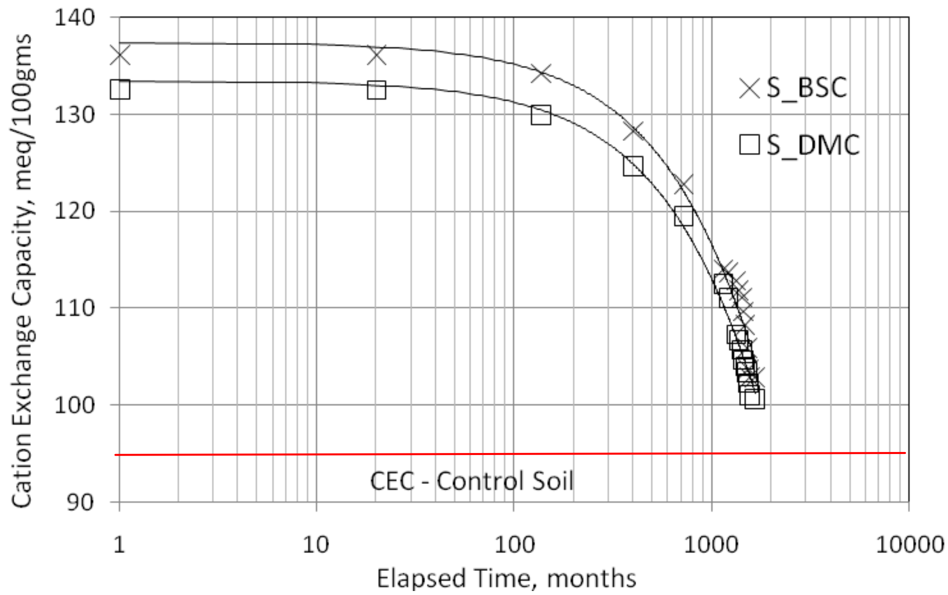



**Figure 6-3 Trend of CEC from the Stephenville, TX test site**

6.3.1.3 Total Soil Suction

The attraction that the soil exerts on the water is termed soil suction and manifests itself as a tensile hydraulic stress in a saturated piezometer with a porous filter placed in intimate contact with the water in the soil. The magnitude of the attractive force that soil above the water table exerts on the water is governed by the size of the voids. The addition of compost to the soil results in the formation of macro structures within the soil. Hence this results in the creation of larger voids within the soil compost mixture resulting in the higher water holding capacity of the mixture. The larger the voids and the higher the moisture content within the soil matrix the lower are the suction values. Hence due to the addition of the compost the voids and the moisture holding capacity are increased immediately after field implementation. As time increases theoretically the organic matter would decompose and break down into finer particles thus densifying the soil matrix. Hence as the organic material decompose the suction values would increase and at the end of their service life reach the suction values of the control section.

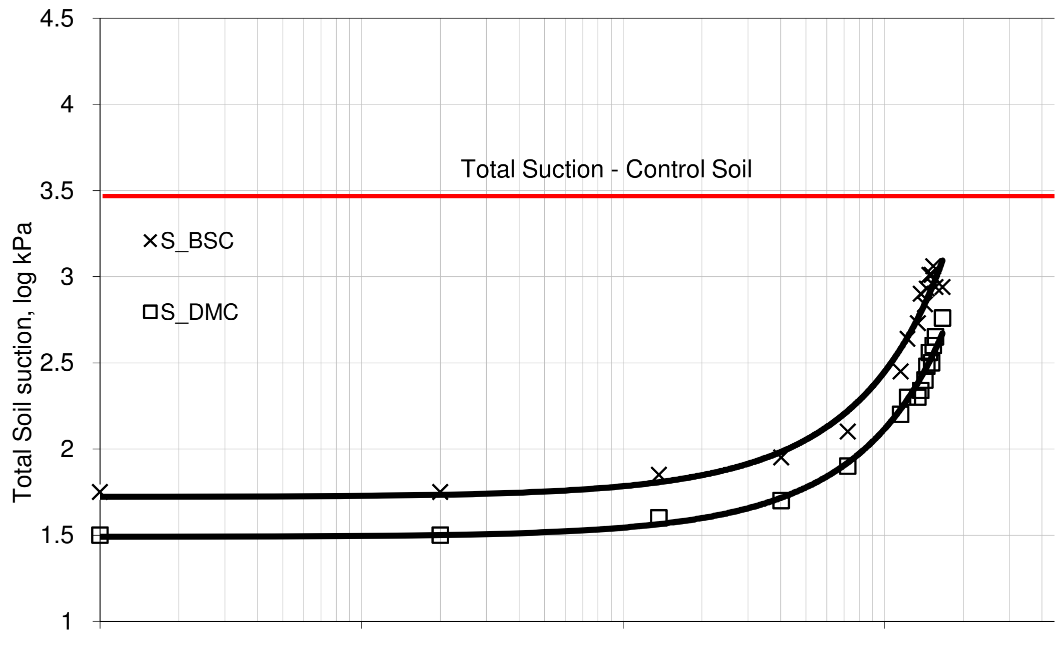



**Figure 6-4 Trend of total soil suction from the Stephenville, TX site**

Figure 6-4 shows that the suction values gradually increased as the time increased. The suction values were approximately 1.4 log kPa for the DMC CMT and 1.7 log kPa for the BSC CMT at the time of field implementation. The soil samples obtained from the field were compacted at the same moisture content (OMC) every time for the total suction measurements. The suction values were observed to increase with the reduction in the organic content. This was due to the presence of the woodchips and other organic matter that were in the compost material. The organic material present in the soil resulted in the higher air-to-water ratio, thus resulting in lower suction values. As the organic matter started degrade and wash away from the treatment sections due to natural reasons, the suction values started increasing. It is noted that the values at the present time period are approximately 3.1 log kPa which is close to the untreated suction value of 3.5 log kPa.

*6.3.2 Corpus Christi Results*

This section presents the laboratory results from the samples that were collected from the test sections located in the Corpus Christi test site. All the three parameters were measured from the soil samples collected.

6.3.2.1 Organic Content

Figure 6-5 shows that the initial OC of the Biosolids Compost and the Cow Manure Compost CMTs at the time of field implementation were 11.5 and 6.3 % respectively. The Control soil had an organic content of 3.1%. It is observed from the figure that the organic content shows a decreasing trend as the time increases. This is due to the biodegradation and washing out of the compost material over time. It can be seen that the OC of the CMTs gradually reduce and tend to reach the OC of the Control soil. From the figure it is noted that the lowest organic content value measured for the Biosolids Compost CMT is 6.5% while the organic content value for the Cow Manure Compost CMT is 4.5%. The reduction in the OC cannot be modeled as a purely biological process because of the influence of the physical and environmental processes which directly affect the OC of the soil. It can be seen that the OC of the untreated soil is 3.2.

It is assumed that as the OC of the CMTs reach 3.2, then the CMTs have reached the initial original Control soil state rendering the compost ineffective and the longevity completed. Therefore a threshold value of approximately 5% - 7% above the Control soil OC is proposed to provide a reasonable reapplication timeframe of the compost treatment. It also has to be noted that the rate of degradation of organic matter reduces with time as biological degradation depends on the concentration of organic matter available for breakdown. This can be observed from figure 22 in the appendix as the organic content remains the same from 750 – 1000 days.

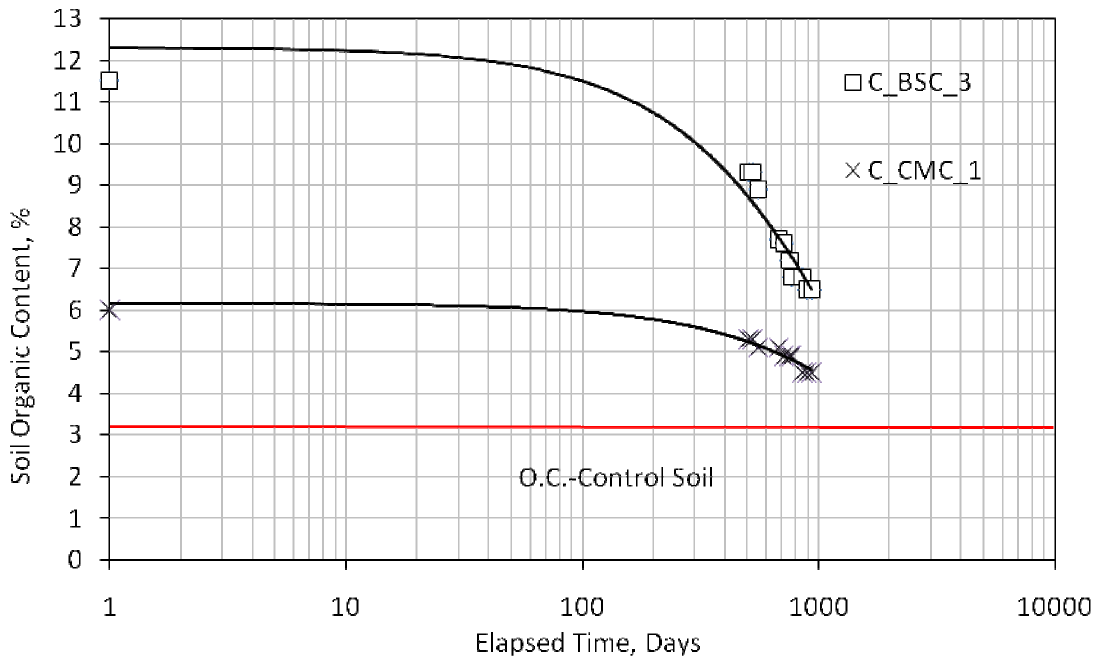



**Figure 6-5 Trend of organic content from the Corpus Christi, TX site**

6.3.2.2 Cation Exchange Capacity

Figure 6-6 shows that the CEC values of the CMTs measured periodically over time shows a decreasing trend. The initial values of the CEC for the Biosolids Compost and the Cow Manure Compost CMTs are 110 and 96.4 meq/100 gms. The decreasing trend in the CEC values is due to the reduction in the organic content of the treated sections as the time increases. The reduction in organic content is due to the washout and biological degradation of the compost in the treated sections. The Control section in this site has a CEC value of 44 meq/100 gms. Studying the decreasing trend in the CEC values, the effective life span of the composts would be the time taken for the CEC values of the CMTs to reach a threshold value obtained from the CEC value of the Control soil using a suitable factor of safety. The lowest value of CEC for the BSC and the Cow Manure Compost are around 70 and 65 meq/100 gms. Based on the plotted points and the steep downward drop of the curves, it can be seen that the CEC values of the treated sections have not reached the CEC value of the Control soil.

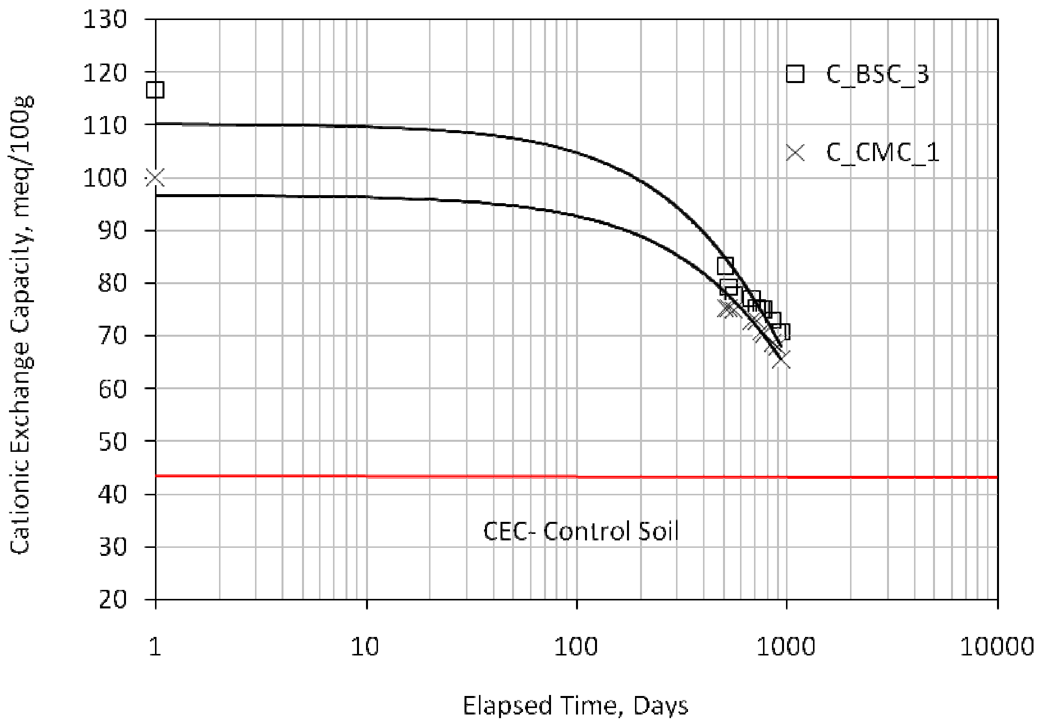



**Figure 6-6 Trend of CEC from the Corpus Christi, TX site**

6.3.2.3 Total Soil Suction

Figure 6-7 shows that the initial suction of the Control soil was 3.5 log kPa, the Cow Manure CMT was approximately 1.6 log kPa, and the Biosolids CMT was 2.2 log kPa. The Figure shows a generally increasing trend as the time increases since field implementation. This is due to the loss of the organic matter and a reduction in the moisture holding capacity resulting in lower moisture contents and higher suction. The highest monitored suction for the Cow Manure CMT is 2.7 log kPa, 3.2 log kPa for the Biosolids CMT, and for the Control soil is 3.5 log kPa. Therefore it is necessary to further monitor the suction values of the CMTs to predict the effective life of the treatment system.

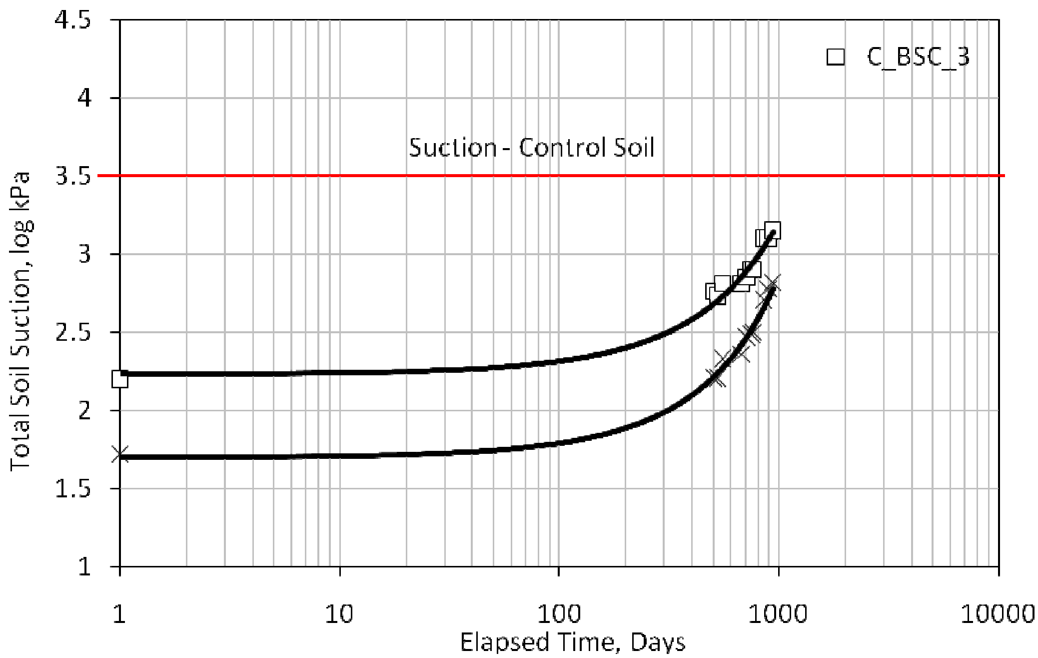



**Figure 6-7 Trend of total soil suction from the Corpus Christi, TX site**

*6.3.3 Yoakum Results*

This section presents the laboratory results obtained from the samples collected from the test sections in the Yoakum, TX test site. The soil samples were collected during each field visit.

6.3.3.1 Organic Content

The organic content tests were conducted on the same batch of samples on which the CEC experiments were done. Figure 6-8 shows that the organic content of the CMTs are decreasing as the time increases. The organic content of the Y_WC_1 CMT has decreased from 10.5% to 10.2%. The organic content for the Y_WBSC_1 CMT has decreased from 9.9% to 9.4%.

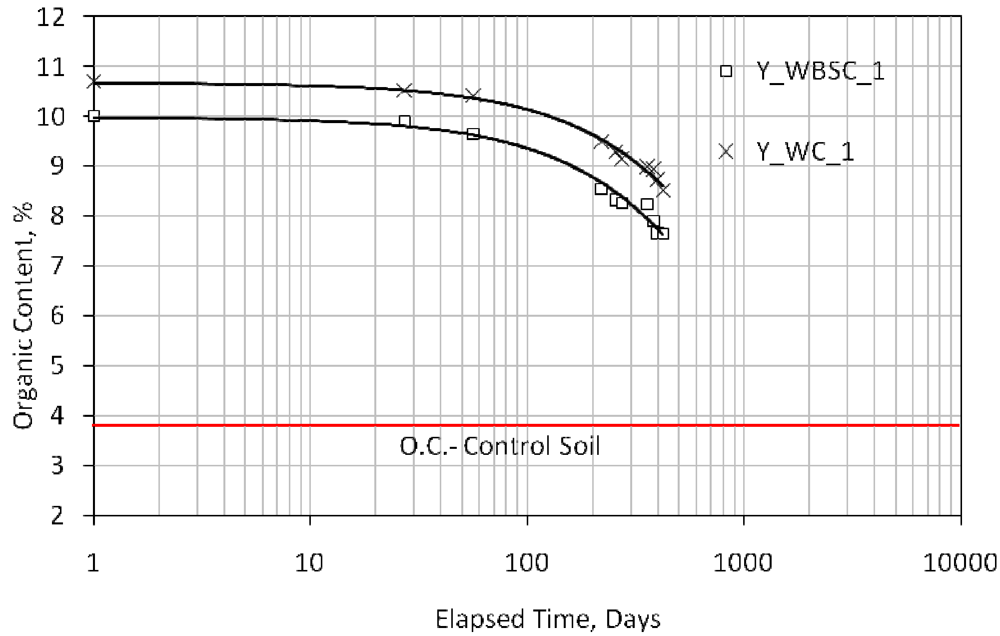



**Figure 6-8 Trend of organic content from the Yoakum, TX site**

It can be noted that there has been minor change in the organic content of the treated sections CMTs since field implementation. This is due to the gradual washout and bio-degradation of the organic material that were present in the compost material that was used for the treatment. It is noted that there has been no significant decrease in the organic content with the increase in time. This is due to the relatively short monitoring period. It can be seen that the OC of the untreated soil is 3.7. It is assumed that as the OC of the CMTs reach 3.7, then the CMTs have reached the initial original Control soil state rendering the compost ineffective and the longevity finished. Therefore a threshold value of approximately 5%-7% above the Control soil OC is proposed to provide a reasonable reapplication timeframe of the compost treatment.

6.3.3.2 Cation Exchange Capacity

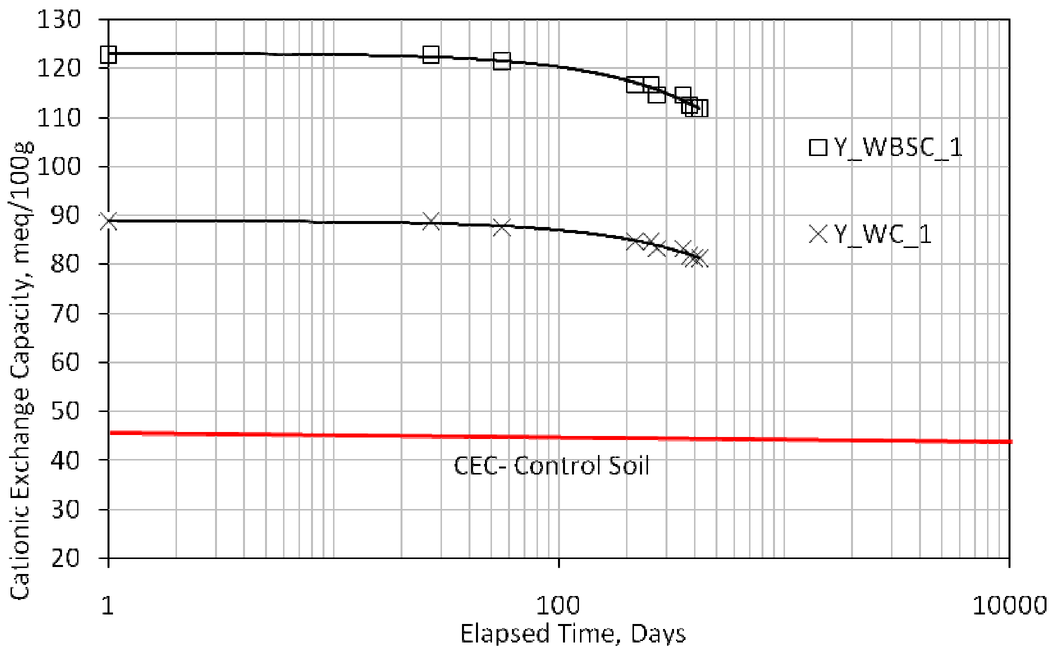



**Figure 6-9 Trend of CEC from the Yoakum, TX site**

Figure 37 in the Appendix shows that the CEC displays a decreasing trend with the increase in time. This is due to the loss of organic matter from the topsoil layer due to erosion and biodegradation. The CEC of the Y_WBSC_1 CMT decreased from 122 to 110 meq/100gms while the Y_WC_1 CMT decreased from 90 to 80 meq/100gms. Based on the collected data, it can be concluded that not enough time has elapsed nor data collected to predict the compost longevity in the soil.

6.3.3.3 Total Soil Suction

1. Figure 6-10 shows that the suction values of the CMTs show an increasing trend with time. The suction for the Y_WBSC_1 CMT has increased from 1.7 to 2.2 log kPa and for the Y_WC_1 CMT has increased from 1.6 to 2.1 log kPa. The increase in the suction values is due to the loss of organic matter present in the treated sections. The reduction in the organic content is due to

the gradual washout of the compost material from the soil and the biodegradation of the compost material. Both CMT suction values are starting to increase with an upward turn toward the initial Control soil value of 3.4 log kPa. The available data cannot be accurately interpreted for prediction of the life of the compost treatment due to the short monitoring time.

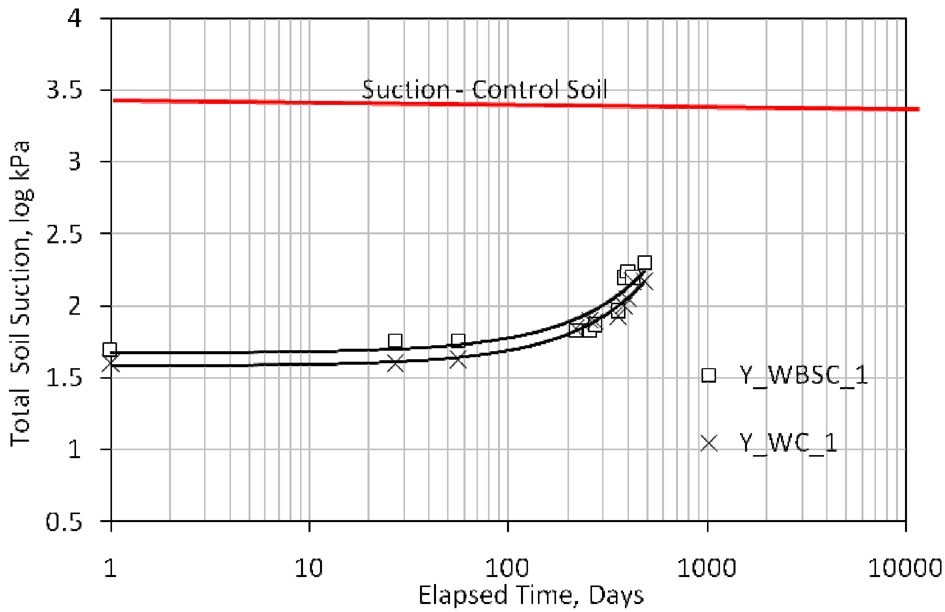



**Figure 6-10 Trend of total soil suction from Yoakum, TX site**

*6.3.4 Tyler Results*

This section presents the laboratory results of the soil samples collected from the Yoakum, TX test site

6.3.4.1 Organic Content

Figure 6-11 shows that the organic content of the CMTs are decreasing with time. The organic content of the T_WC_3 Compost CMT has decreased from 18% to 15%. The organic content for the T_WC_2 has decreased from 13% to 10%. This initial loss in organic matter is due to rainfall events immediately after the field implementation when there was no vegetative cover. It can be seen that the OC of the untreated soil is 4.5. It is assumed that as the OC of the CMTs reach 4.5, then the CMTs have reached the initial original Control soil state rendering the compost ineffective and the longevity finished. Therefore a threshold value of approximately 5%-7% above the Control soil OC is proposed to provide a reasonable reapplication timeframe of the compost treatment.

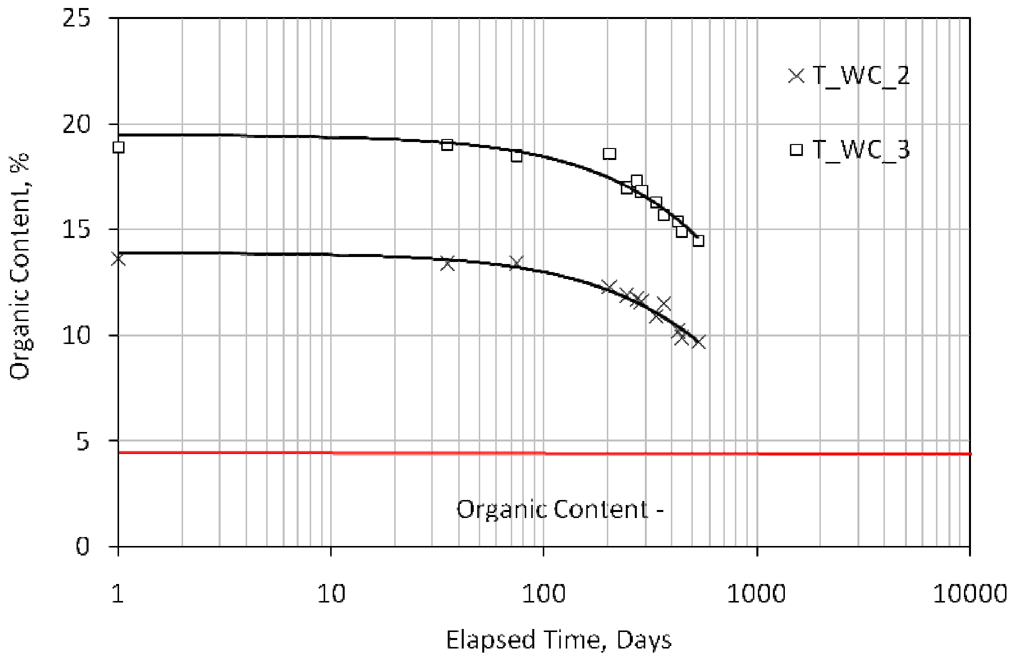



**Figure 6-11 Trend of organic content from Tyler, TX site**

6.3.4.2 Cation Exchange Capacity

Figure 29 in the Appendix shows that the CEC values of the CMTs displays a decreasing trend with time. It is noted that the CEC values of the T_WC_3 decreased from 111 to 106 meq/100gms and the T_WC_2 decreased from 96 to 90 meq/100gms within 1 yr since the field implementation. The Control section in this site has a CEC value of 47 meq/100 gms. It can be seen that the CEC values for the CMTs have decreased minimally since the time of field implementation due to the short duration of data collection.

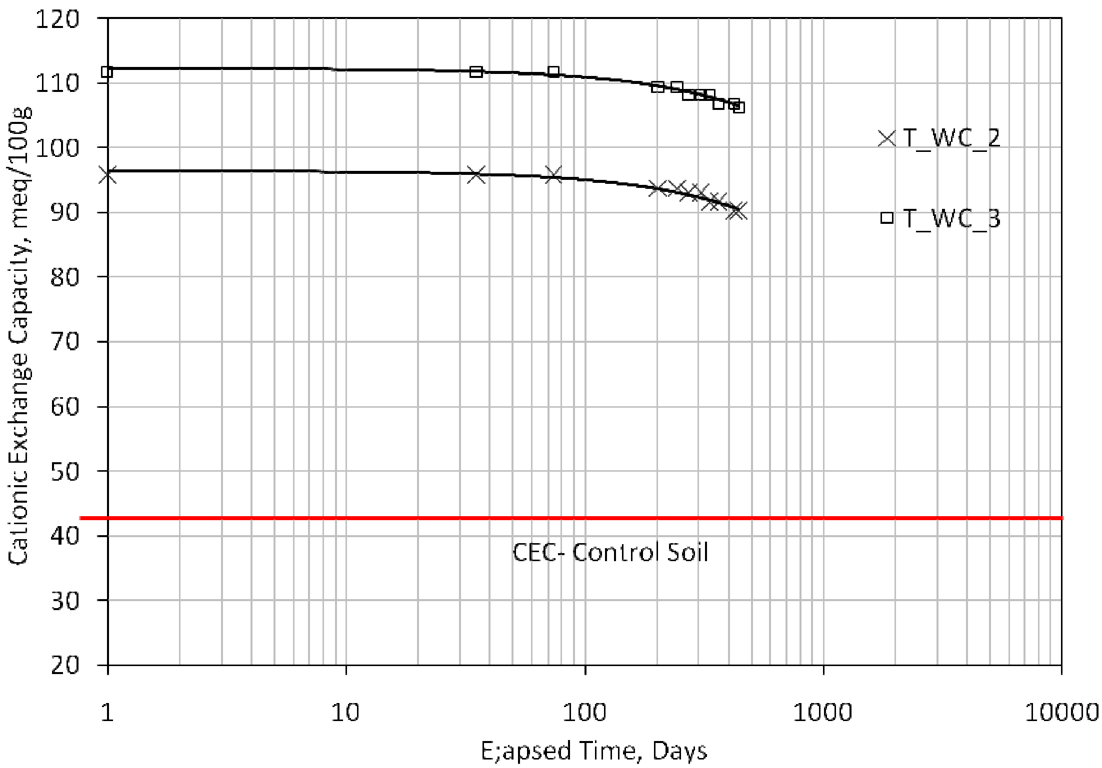



**Figure 6-12 Trend of CEC from Tyler, TX site**

6.3.4.3 Total Soil Suction

Figure 31 in the Appendix shows that the suction values of the CMTs show an increasing trend as the time increases. The suction increased from 1.5 to 1.9 log kPa for the T_WC_3 CMT and from 2.2 to 2.6 log kPa for the T_WC_2 CMT. Both CMT suction values are starting to increase with an upward turn toward the initial Control soil value of 3.4 log kPa.

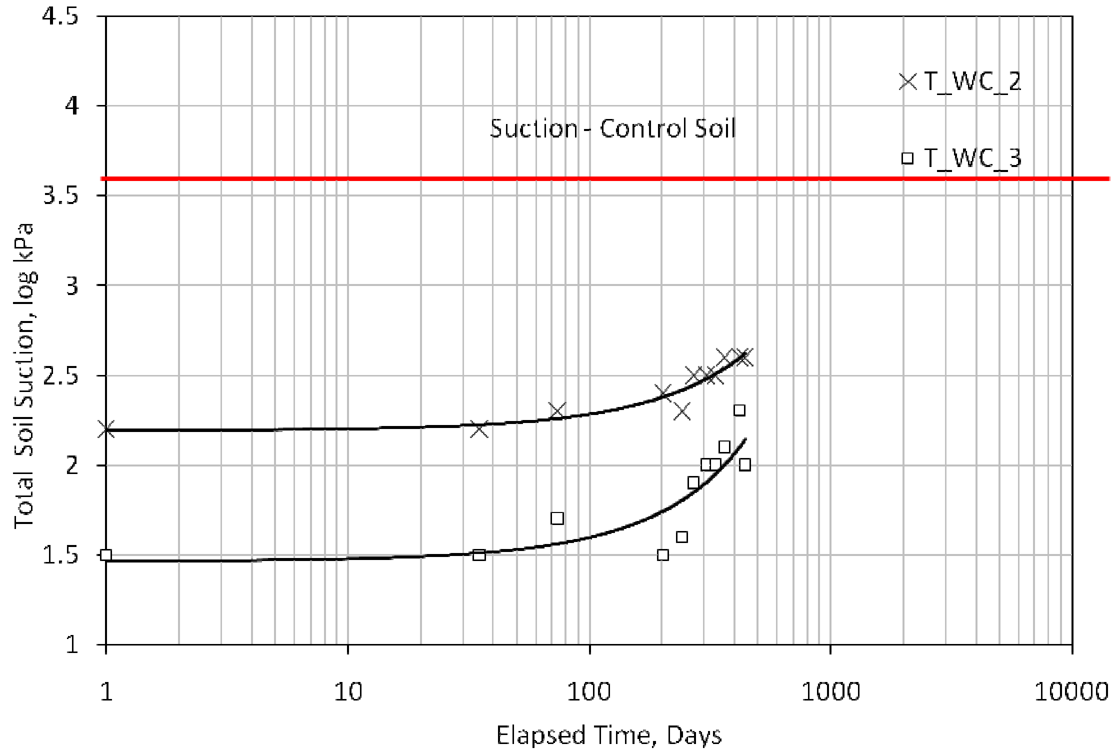



**Figure 6-13 Trend of total soil suction from Tyler, TX site**

<u>6.4 Service Life Model</u>

The data collected from the Stephenville, TX test location would be used in the development of the model, since it has the longest period of data collection. The model developed based on this data would be applied to the other data sets and the service life of their respective test section calculated. It is known that the compost is made up of highly degraded organic matter. Once the compost is added to the soil the organic content of the soil is increased due to the high OC of compost. Since it is organic in nature it is subjected to bio-degradation with time. Hence based on the degradation of the organic content the effectiveness and presence of the compost material in the treatment section can be determined.

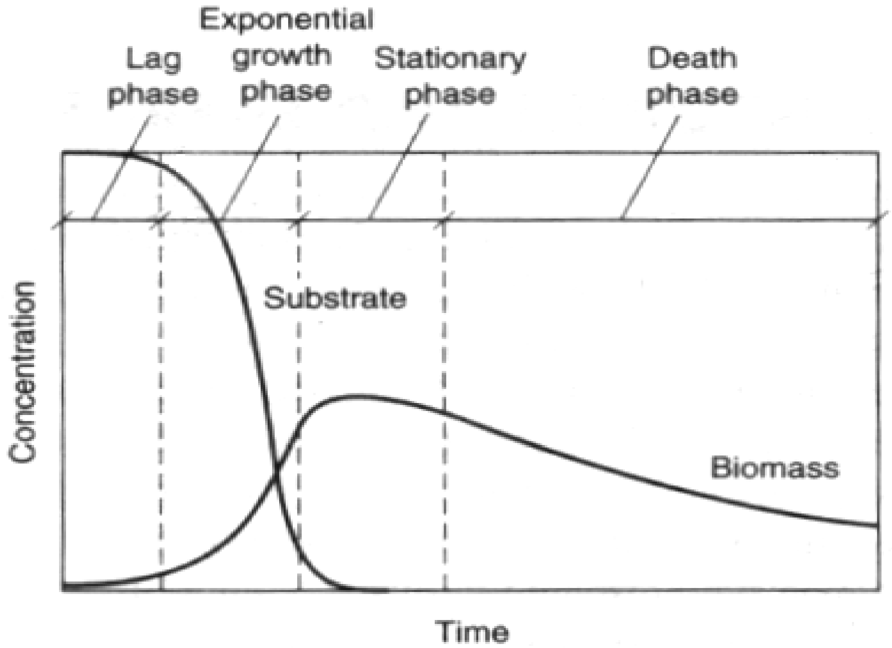



**Figure 6-14 Typical degradation of organic material in a batch process (Metcalf and Eddy, 2003)**

The degradation of the organic material in the soil compost mixture can be considered to be similar to that of the batch process in water treatment processes. The organic material is introduced into the soil and then compacted. There is no addition of further fresh organic material into the system since field implementation. The organic material is further decomposed by the micro organisms that are present in the mixture and then after significant decomposition, the micro organisms start dying or decomposing themselves.

From Figure 6-14 it can be seen that there is a lag phase where the decomposition of the organic matter is at the lowest rate. This is due to the colonization of the microbes that is required for the efficient decomposition of the organic matter (S. Kuo, 2004). It can be seen that during the exponential growth phase there is an exponential decay of the decomposition of the organic matter due to the microbial consumption. Then after the exponential decay there is a stationary phase followed by the death phase where the microbial population is destroyed. The stationary phase is due to the lack of food (organic matter) for the various microbial colonies.

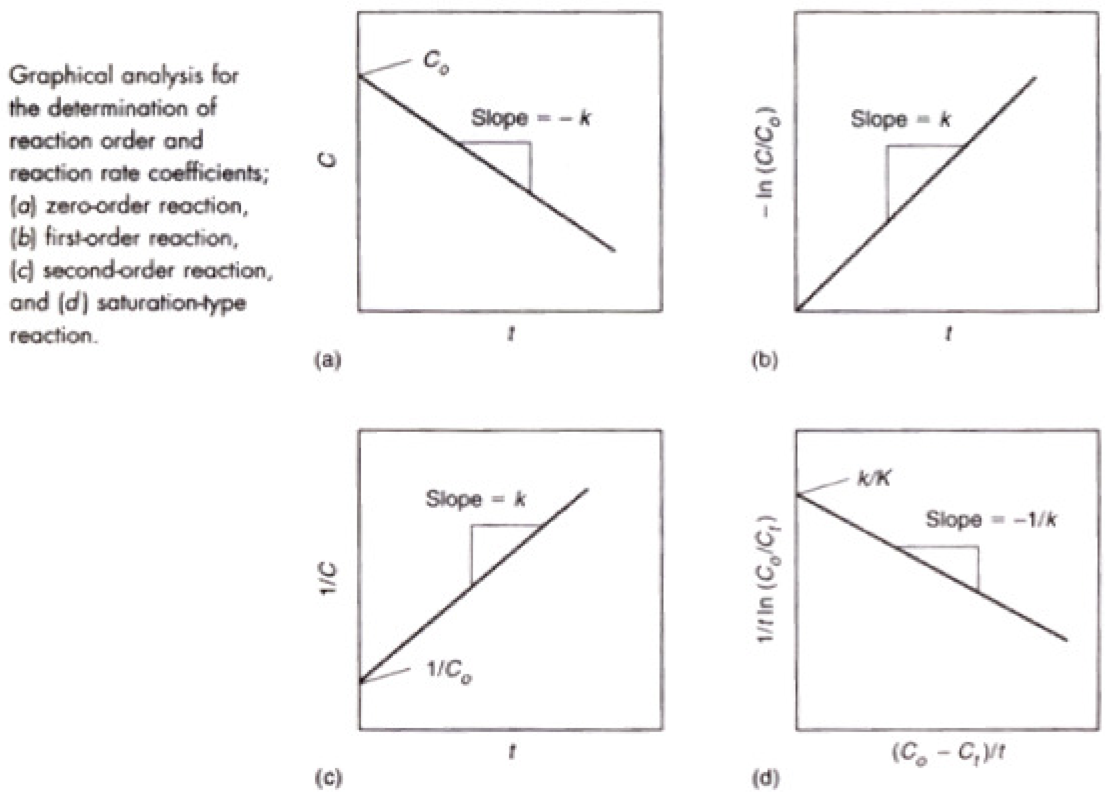



**Figure 6-15 Graphical analysis for the determination of the reaction order (Metcalf and Eddy, 2003)**

In the natural environment the organic matter would degrade for a number of reasons including mortality rate of the microbial organisms and photo oxidation of certain kinds of organic materials. The rate of organic material degradation depends upon many factors such as degradability of the material, proportion of organic material in the mixture, aeration rate, temperature, and time of reaction. It is unlikely that the rate of degradation of one system can be applied to that of another due to the variability in the conditions and material characteristics. it is extremely difficult to derive a deterministic model that takes into account all the complex physicochemical and biological interactions involved in the compost deterioration (Huang, 2000).

There have been many studies that involve the determination of the optimum conditions and requirements for the degradation of organic material, but only a very few studies had been reported on the degradation models and kinetics (Huang, 2000). Hence a simplistic approach was followed for the development of the model on the assessment of the life cycle of the compost treatment. The typical rate at which natural and radioactive decay occurs is through first order kinetics (Metcalf and Eddy, 2003). Three kinds of model were looked into for the suitability of applying it towards determining the service life of the compost treatment. These are:

- Linear Rate of Degradation Model
- Exponential Decay Model
- Second Order kinetics Model.

In order to determine which model the Stephenville data set follows, the graphical analysis procedure using statistical methods was followed (Metcalf and Eddy, 2003). It can be seen from Figure 6-15 that the measured data can be fitted with different kinds of graphs and the ones that provided best match with the measured data was considered for life assessments.

*6.4.1 Linear Rate of Degradation Model*

If the plot between the organic content and the elapsed time forms a straight line then it implies that the measured data set is applicable to be fit with the linear rate of degradation model. This model assumes that the rate of degradation is independent of the amount of organic matter remaining that is being degraded. It is observed that from figure 6-16 that the $r^2$ value of the linear degradation model is 0.99. The $r^2$ value is the adjusted coefficient of determination and it indicates how good the model fits the data. The $r^2$ value can be used to determine the goodness of fit of a model.

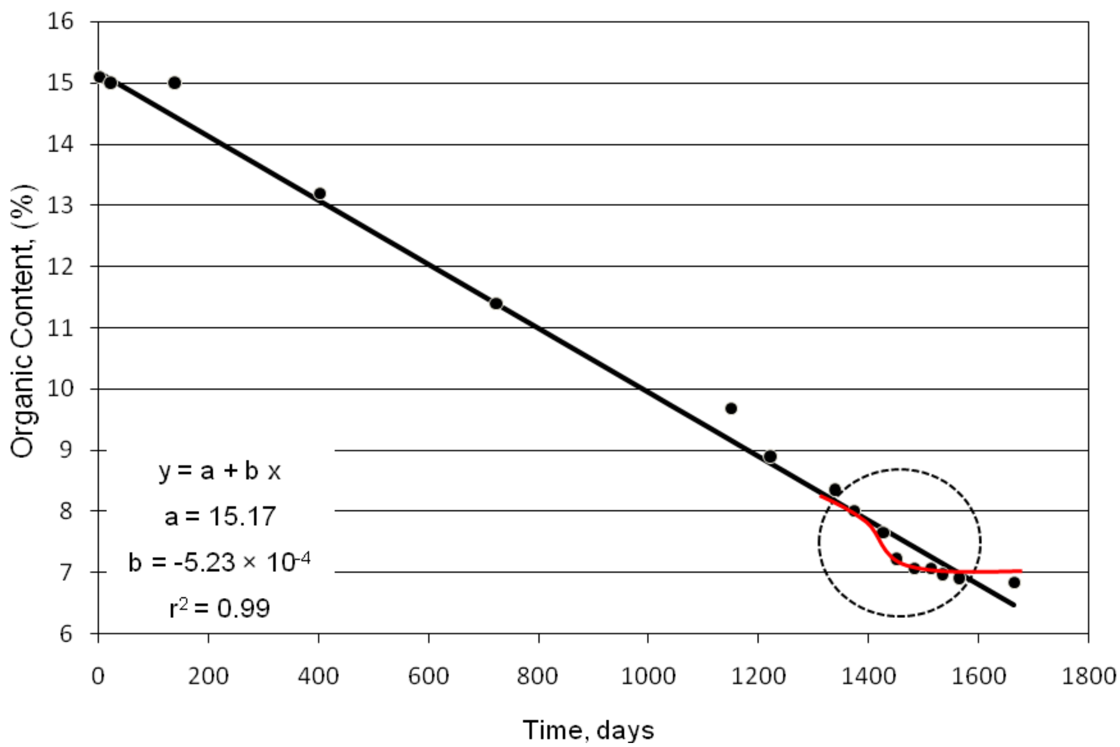



**Figure 6-16 Linear rate of degradation model**

Though the $r^2$ value is 0.99 as seen from figure 6.16, this model was considered not suitable for simulating the organic content degradation data from the Stephenville site. It can be observed from the highlighted portion of the figure that the degradation rate of the organic matter has reduced drastically and is starting to become stable. This is caused due to the amount of organic content reaching almost the recalcitrant organic content. As the compost is added to the soil and the organic content increased subsequently, there would be a small portion of that organic matter content that would never be degraded even after a very long time (S. Kuo, 2004). This portion of the organic content that never degrades is called as the recalcitrant organic content. Hence as the organic content reaches the recalcitrant level and starts to stabilize, the linear degradation models constant rate does not epitomize the bilinear rates of degradation. Hence this model was not considered for the life rate assessments.

*6.4.2 Exponential Degradation Model*

This model assumes that the rate of degradation of the organic material follows an exponential rate and then as it approaches the initial organic content, the rate decreases rapidly and becomes a constant. The graphical method was used to determine the applicability of this model to the laboratory results. This is done by calculating the ratios of the organic content with respect to time to that of the Initial organic content value ($C/C_o$). Then a graphical plot between the negative natural logarithmic value of the organic content ratios versus the time at which the organic content values were measured is plotted. If the plot between $-\ln(C/C_o)$ versus time is linear, then it indicates that the data follows an exponential rate of degradation. C is the organic content at any time and $C_o$ is the initial organic content at the time of field installation.

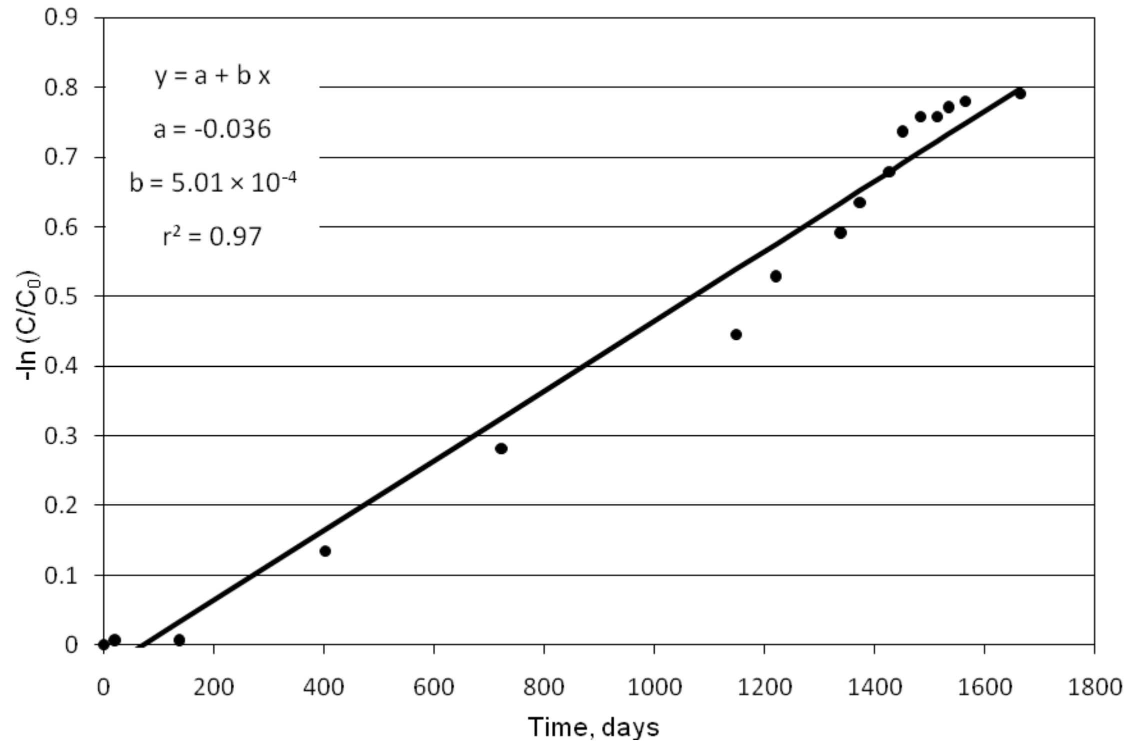



**Figure 6-17 Exponential degradation rate model**

This model follows the typical type of organic material degradation as shown in Figure 6-14. There is initially a lag phase where the microbes colonize to degrade the organic matter (S. Kuo, 2004). The results from the Stephenville soil tests show a negligible lag phase since the microbes would have already colonized during the composting process. After the initial lag phase the organic materials were degraded exponentially.

Even though the degradation was exponential it took place through a number of years since the compost material was already made up of stabilized organic material. It can be seen from Figure 6-17 that the $r^2$ value of the plot between $-\ln(C/C_o)$ and time is 0.98. Hence it was found that this model would be well suitable for the application of the data from the compost treated sections to model the degradation of the organic matter.

*6.4.3 Second Order Kinetics Model*

According to this model the rate of the organic material degradation is proportional to the square of the organic content or the product of two reactants. The order of the reaction controls how the reactant concentration affects reaction rate. If the plot between 1/C and time results in a straight line then it shows that the data follows second order reaction rate equations. In the plot between the reciprocals of the organic content and the time it resulted in a straight line with an $r^2$ value of 0.95.

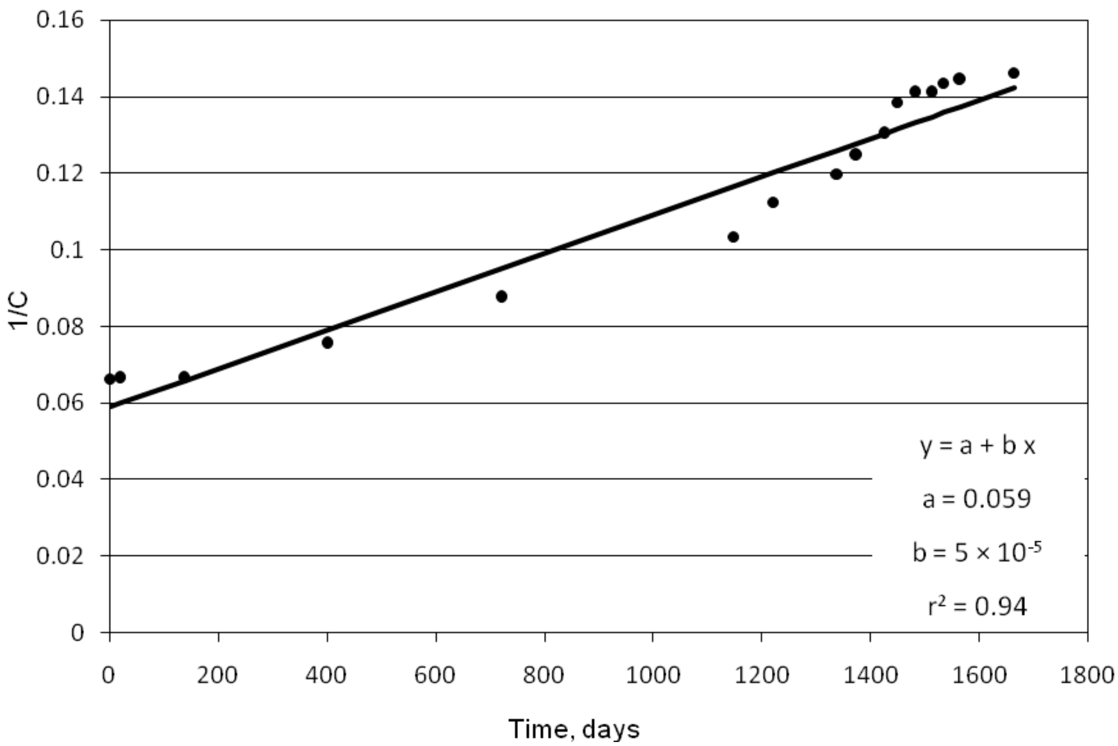



**Figure 6-18 Second order kinetics model**

It can be seen from Figures 6-17 and 6-18 that both the first order model and the second order model fit the data well. Typically any biological degradation process is modeled as following first order kinetics (Qasim S., Oral Communication.). The assumptions associated with modeling the data as a second order kinetics model is highly complex when compared to that of the first order kinetics model. It was also seen from the literature review that the degradation of compost is typically modeled as a first order kinetics model. Hence based on the complexity of using a second order kinetics model and the literature review, the first order kinetics model was used to model the data obtained from the laboratory results.

The following figures in the next section represent the modeling of the organic content, cation exchange capacity, and suction based on the exponential decay model. The exponential decay model is typically represented as follows

$$C_t = C_o e^{-kt}, \quad 6.1$$

Where,

$C_t$ = Organic content at any time "t", (%)

$C_o$ = Initial organic content, (%)

$k$ = degradation rate constant, $day^{-1}$

$t$ = Elapsed time since field implementation, days

It can be seen from figure 6-19 that the CEC and suction are dependent on the organic content. Hence the model developed for the degradation of the organic material in the compost treated sections would be applicable to the CEC and the suction values. The modeling results for all the test sections are presented in section 6.5.

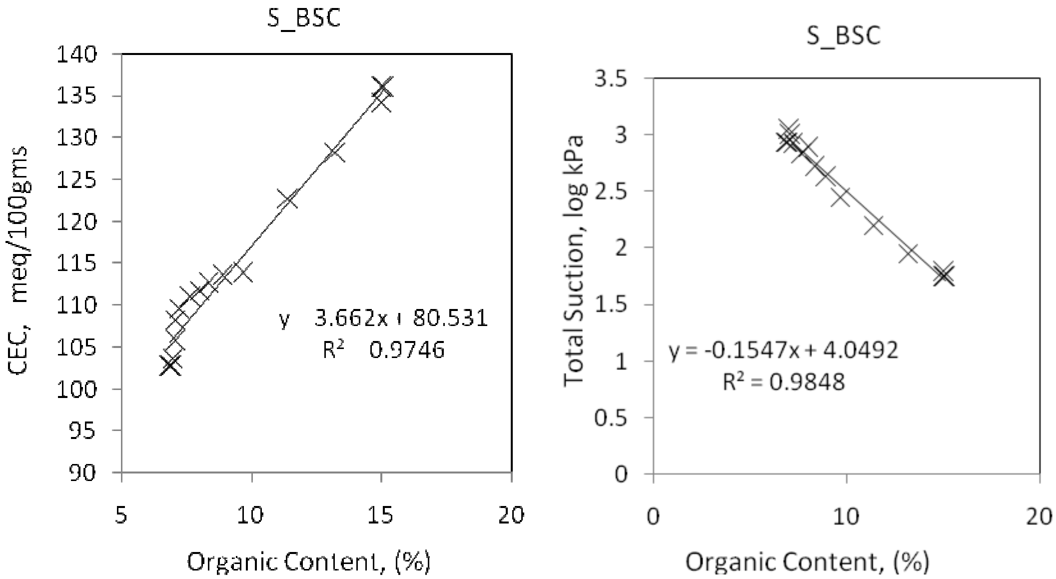



**Figure 6-19 Correlation between CEC and suction with O.C at the S_BSC test site**

## 6.5 Modeling Results

Three kinds of models were assessed to determine the applicability of the laboratory results obtained from the samples collected from each treatment section to determine the service life of the compost treatment. The exponential degradation model was found to have the best goodness of fit with the laboratory results measured. Since the cation exchange capacity was directly proportional and the total suction was inversely proportional to the organic content of the treated sections, the exponential model was applied to the measured values respectively. Hence the results from the Stephenville, Corpus Christi, Yoakum and Tyler test sites were fitted into the model and the results are presented in the following sections.

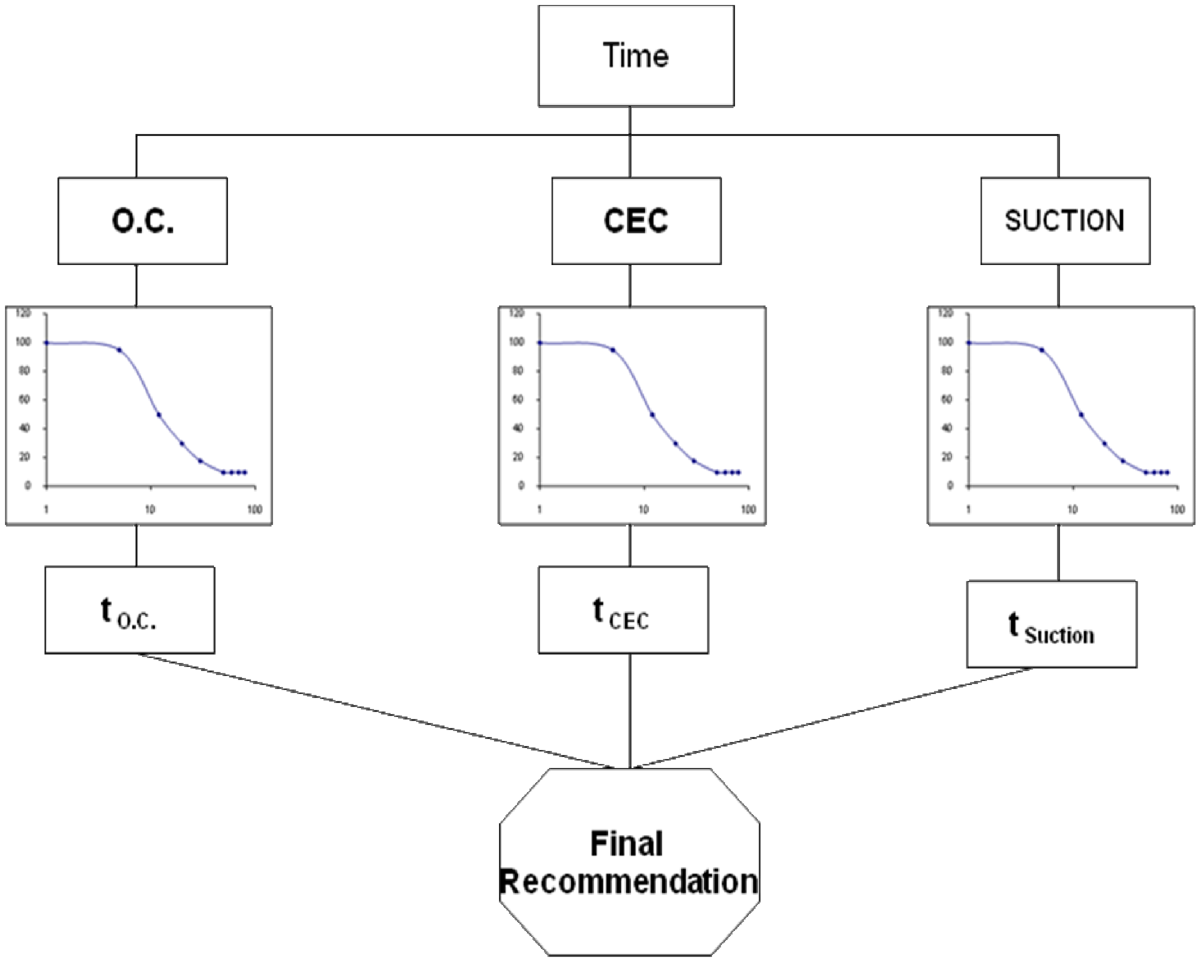



**Figure 6-20 Flow chart for determination of average service life**

Figure 6-20 describes the process which would be followed to determine the average service life of the different compost treated sections. The laboratory results of each parameter namely organic content, cation exchange capacity, and total suction would be fit with the exponential decay model. The models thus developed would be used to come up with three separate service life times based on their respective parameters. The average of the three service lives would be considered as the final recommended service life of that particular compost treated section.

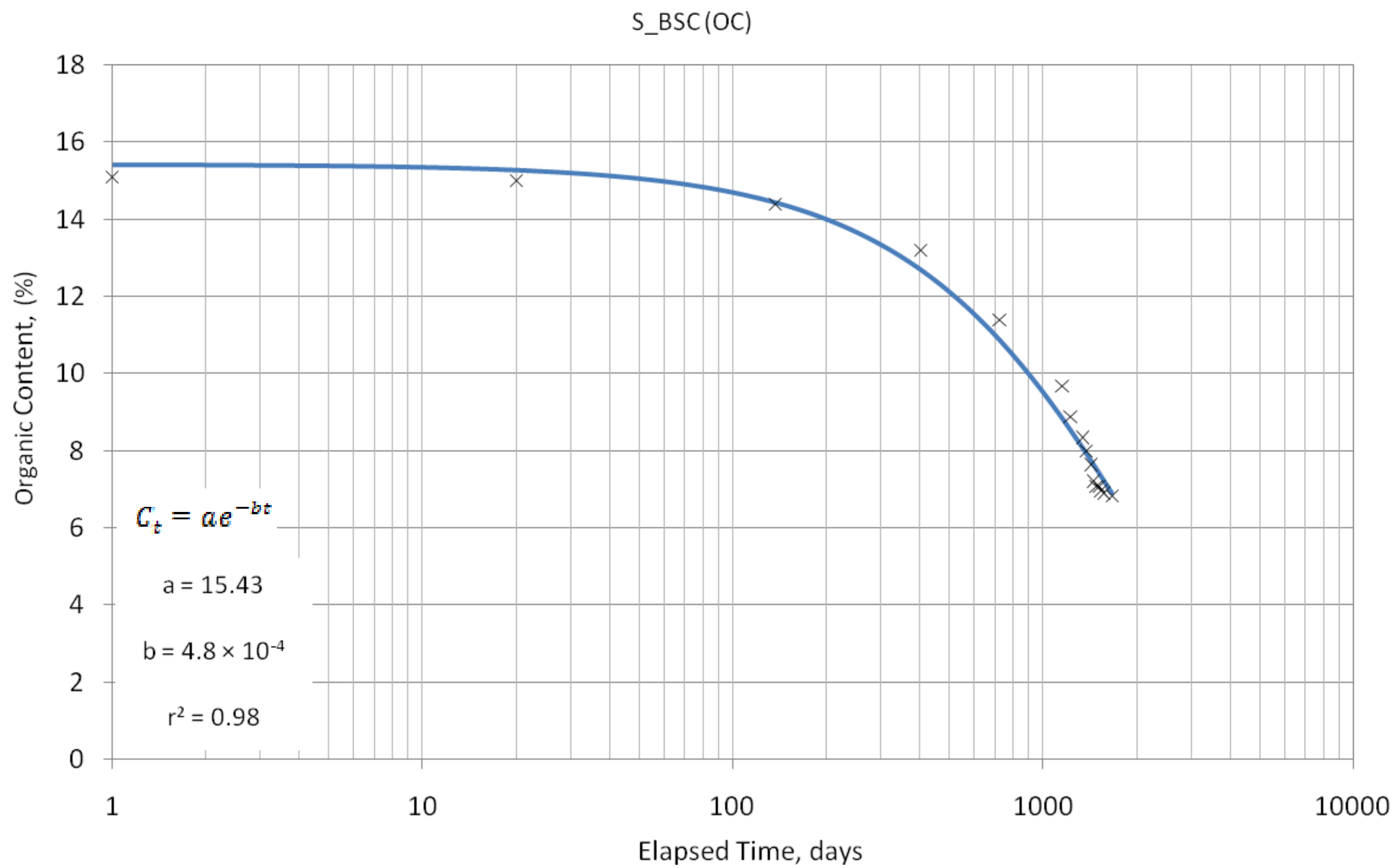



**Figure 6-21 Modeling of O.C. results from S_BSC section**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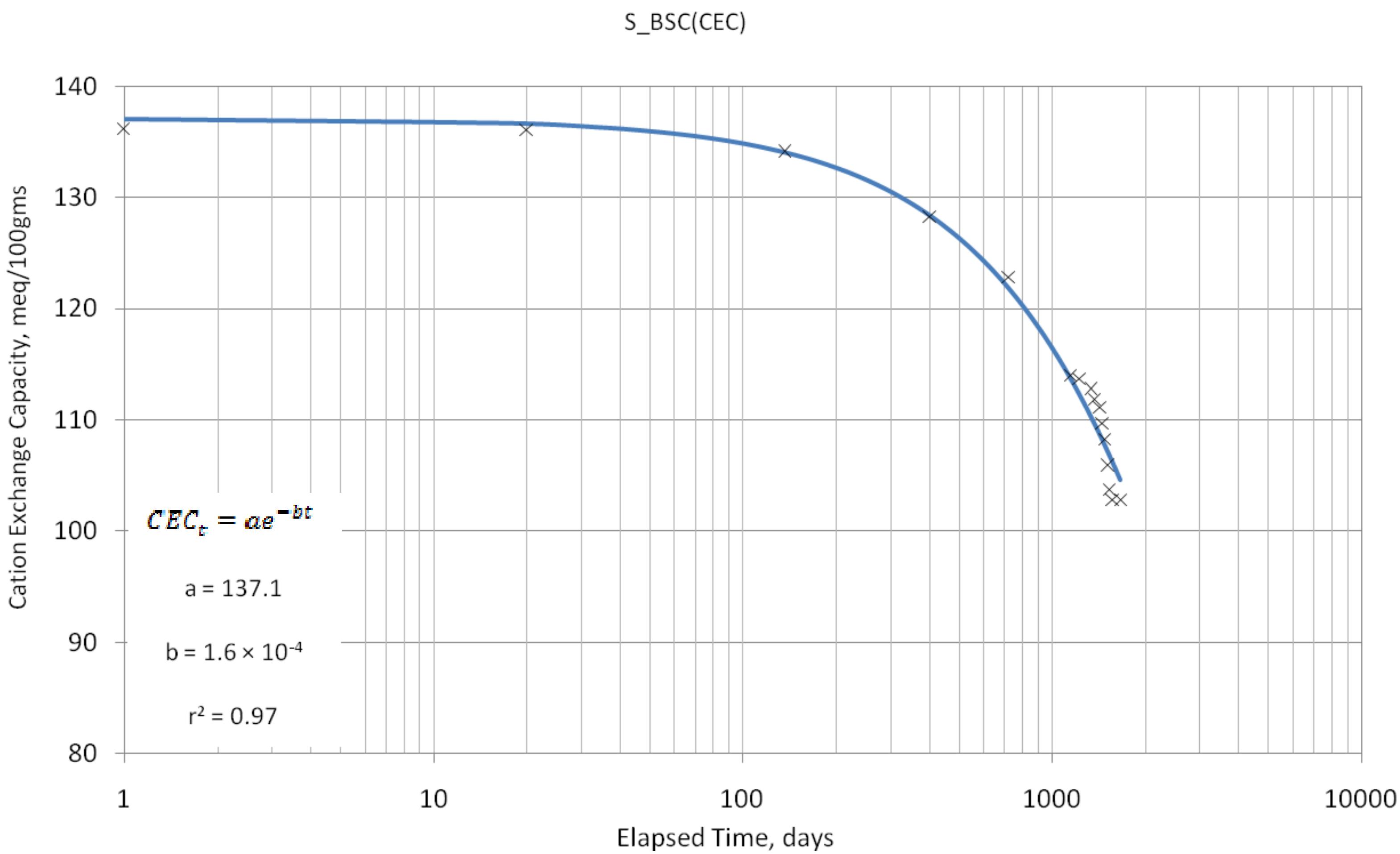


**Figure 6-22 Modeling of CEC results from S_BSC results**

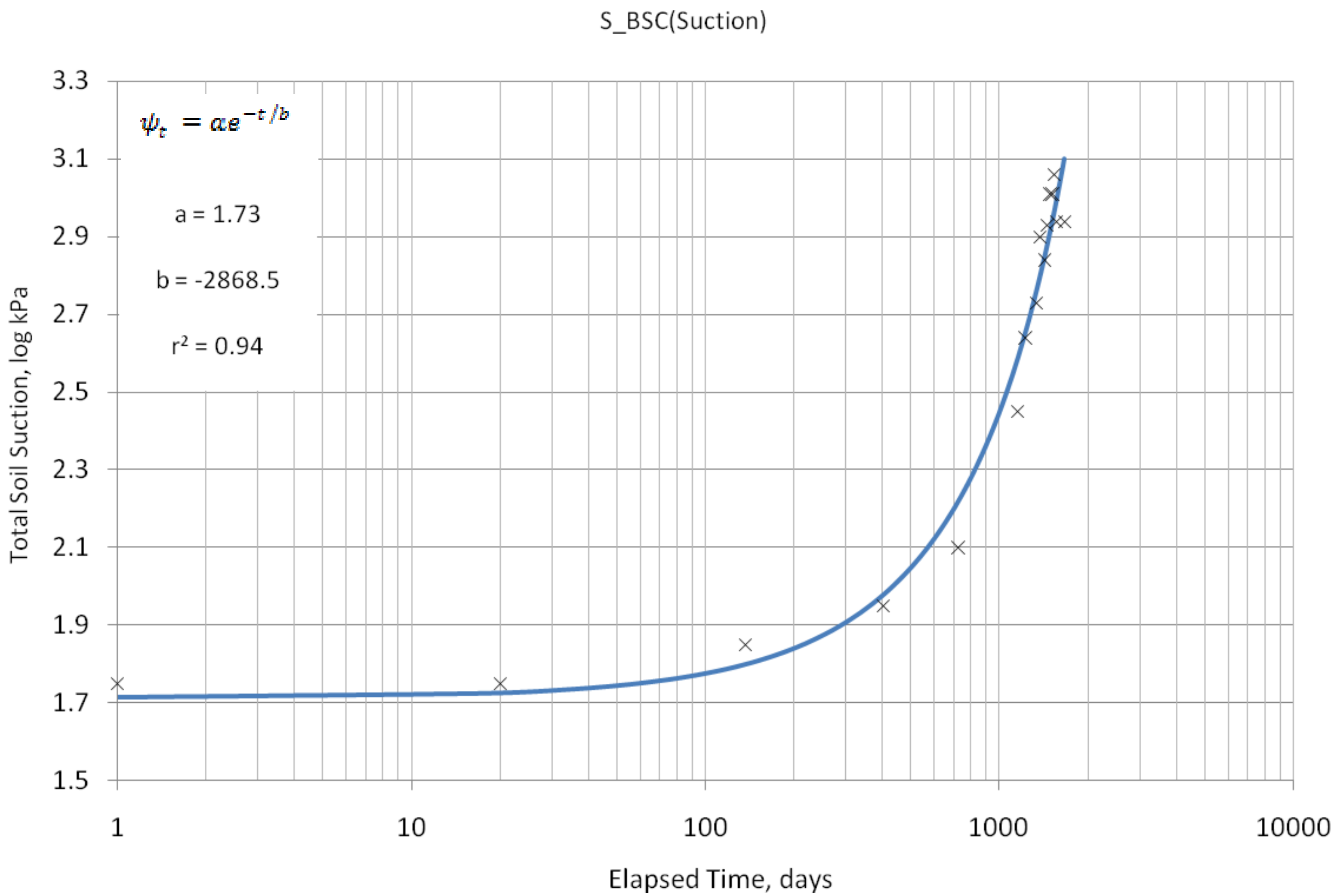


**Figure 6-23 Modeling of total soil suction from S_BSC suction**

Figures 6-20, 21, and 22 represent the laboratory values that were obtained from the Biosolids Compost treated sections at the Stephenville, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Biosolids Compost treated section. It can be observed that the coefficient of determination for the data fit into the exponential decay model was 0.98, 0.97, and 0.94 for the organic content, cation exchange capacity and total soil suction respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 15.43\ e^{-4.8\times10^{-4}t} \tag{6.2}$$

$$CEC_t = 137.1\ e^{-1.6\times10^{-4}t} \tag{6.3}$$

$$\psi_t = 1.73\ e^{t/2868.5} \tag{6.4}$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. For example in the Stephenville section the organic content of the control section was found to be 4.5 %. The biosolids compost treated section had an organic content of 16 % at the time of field implementation. Hence 7-10% of the difference between these two values was added to the control section value and the minimum allowable organic content value of 5.5 % was calculated. Thus once the organic content of the treated sections reached this value, the elapsed time was considered to be the service life of that particular compost treatment. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were determined.

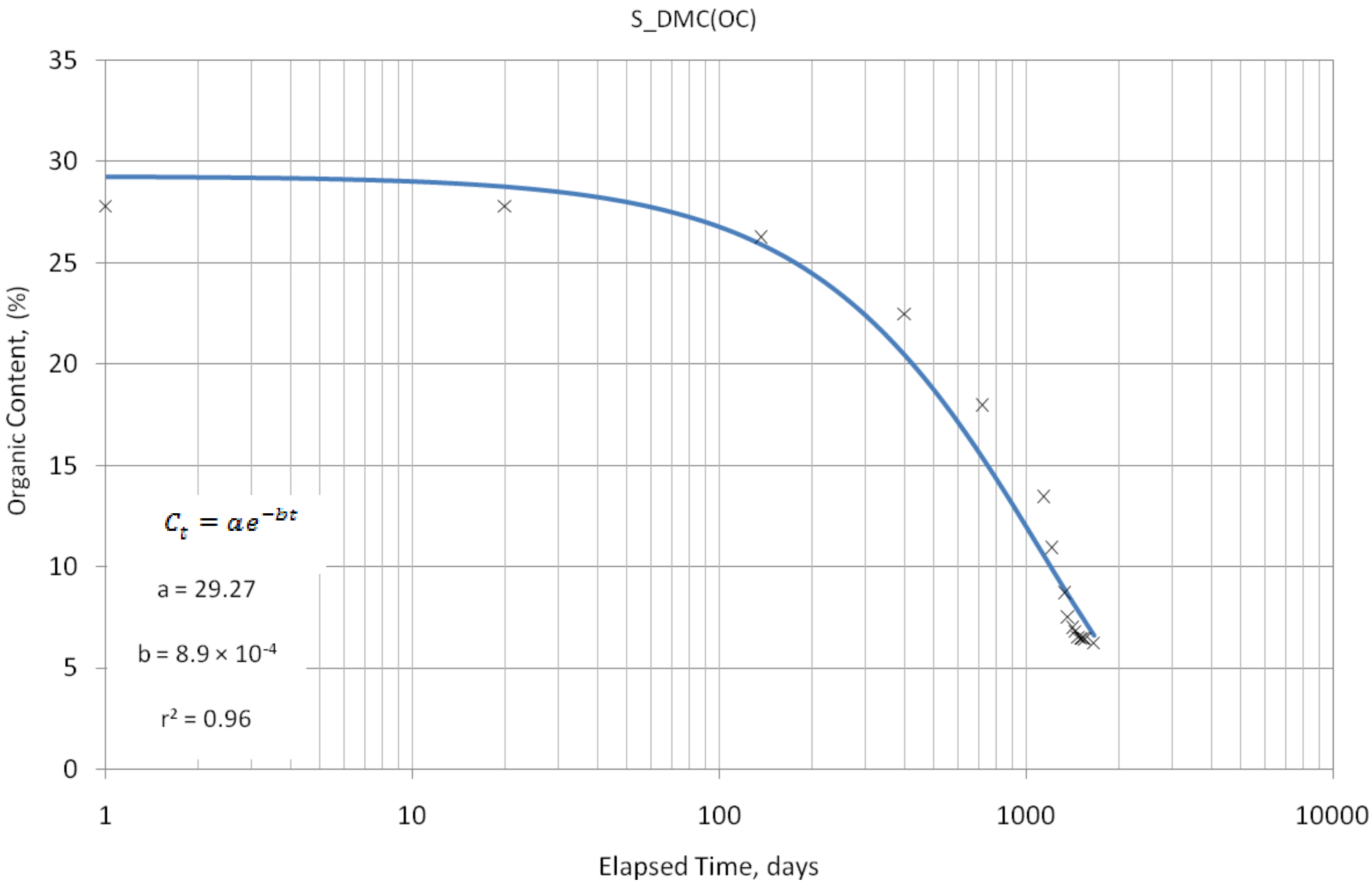


**Figure 6-24 Modeling of O.C. results from S_DMC section**

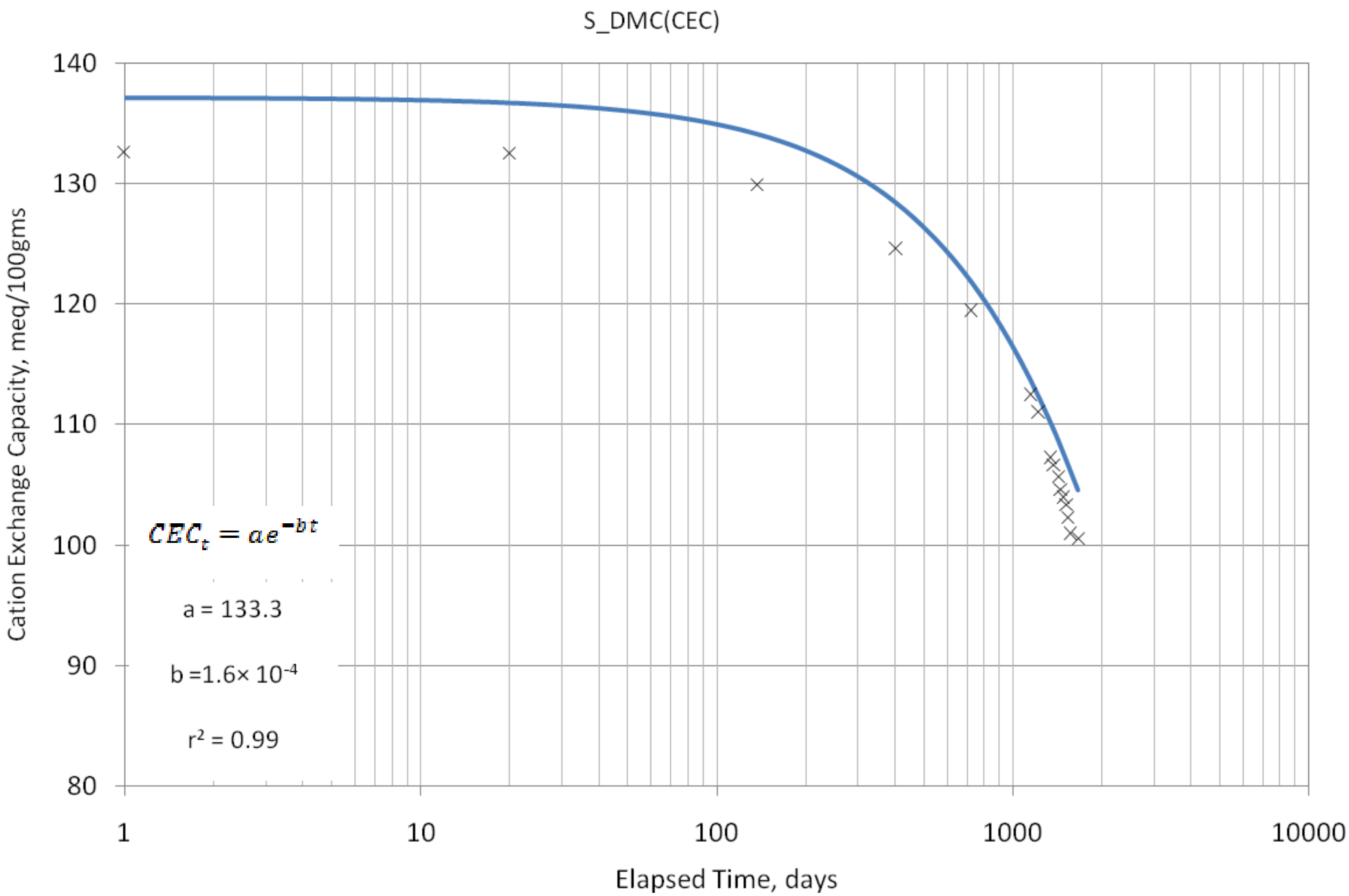


**Figure 6-25 Modeling of CEC results from S_DMC section**

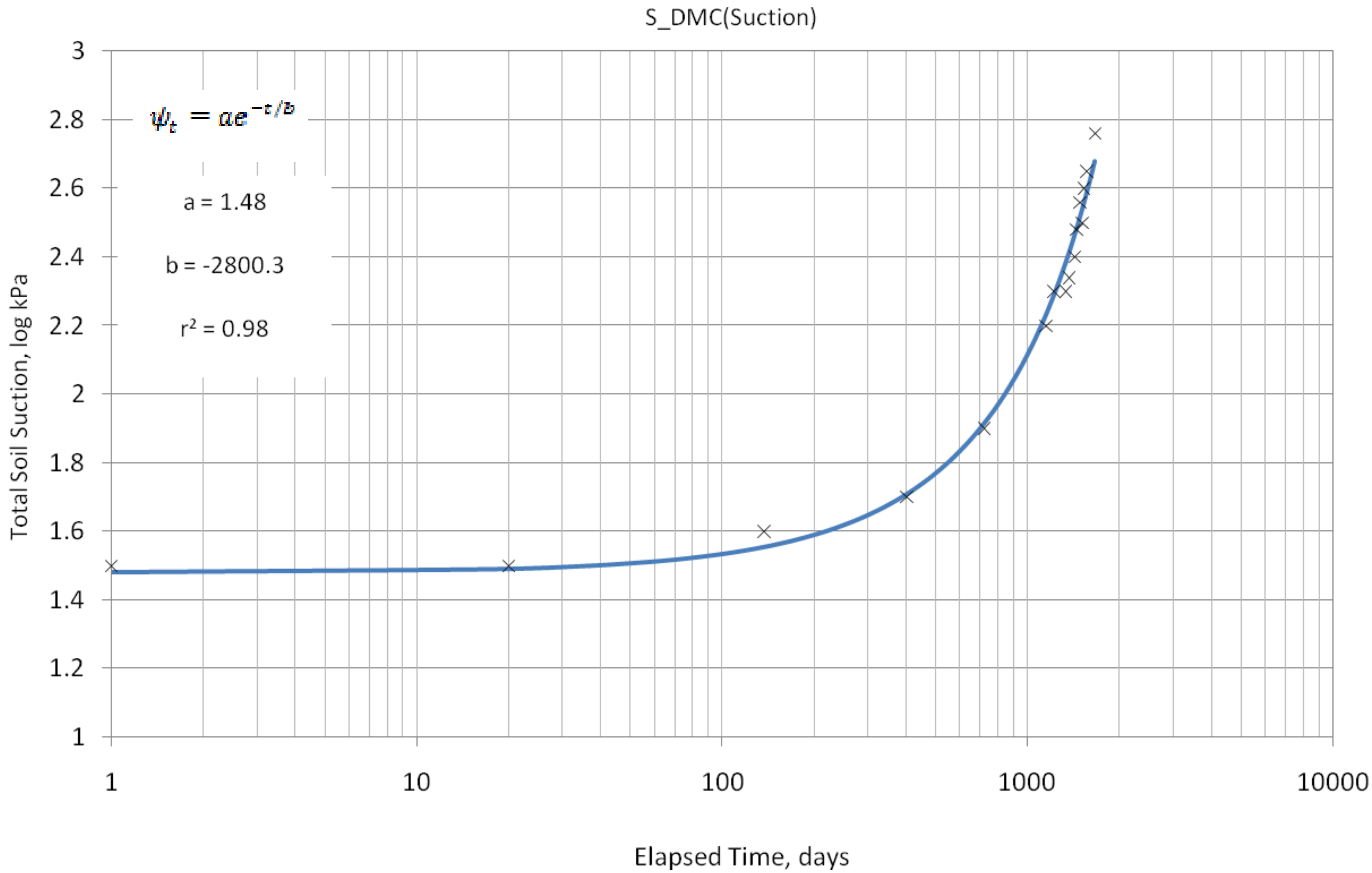


**Figure 6-26 Modeling of total soil suction results from S_DMC results**

Figures 6-23, 24, and 25 represent the laboratory values that were obtained from the Dairy Manure Compost treated sections at the Stephenville, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Dairy Manure Compost treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.96, 0.99, and 0.98 for the organic content, cation exchange capacity and total soil suction respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 29.3\, e^{-8.9\times10^{-4}t} \qquad 6.5$$

$$CEC_t = 133.3\, e^{-1.6\times10^{-4}t} \qquad 6.6$$

$$\psi_t = 1.48\, e^{t/2800.3} \qquad 6.7$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values was estimated.

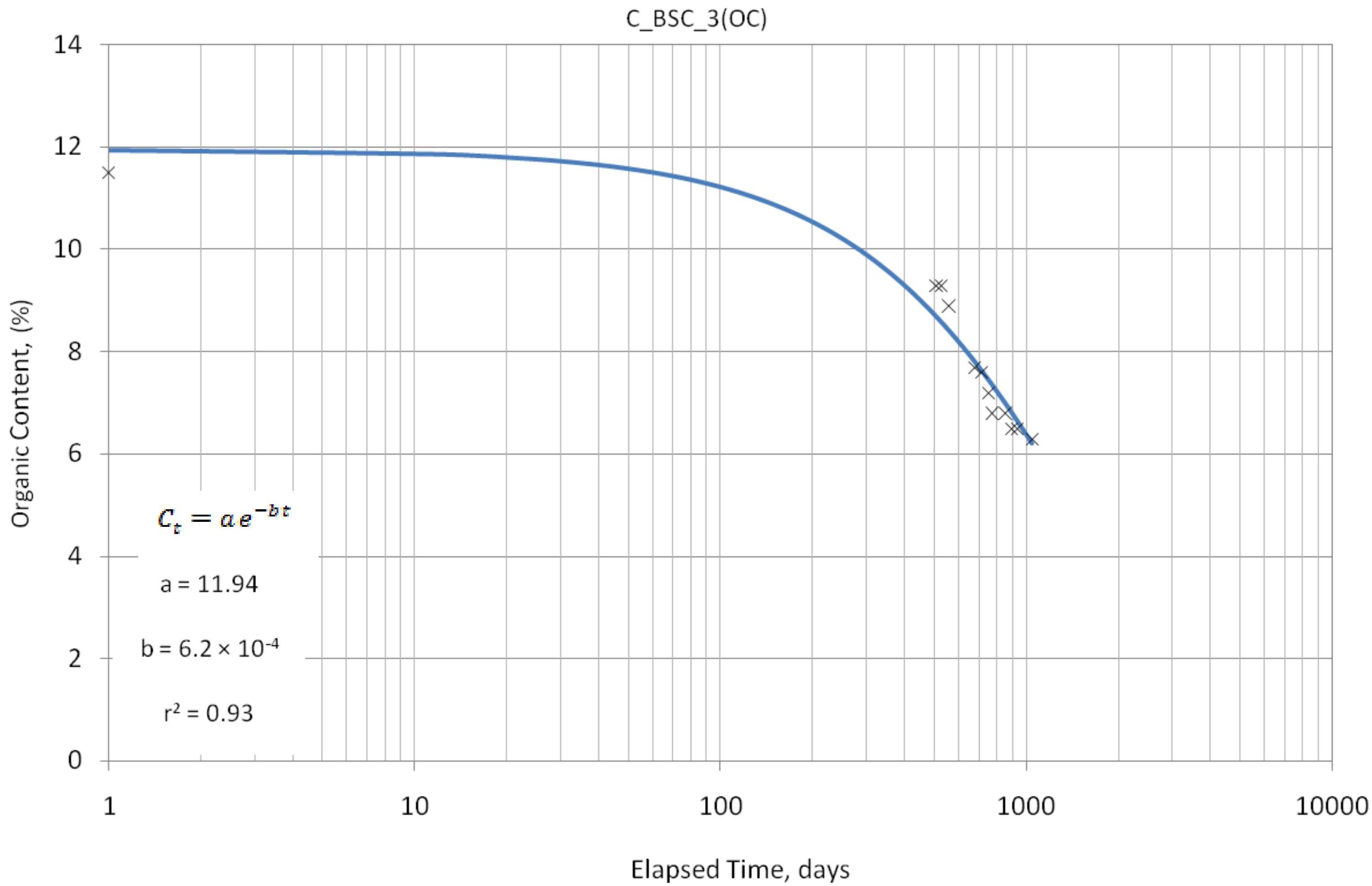


**Figure 6-27 Modeling of O.C. results from C_BSC_3 section**

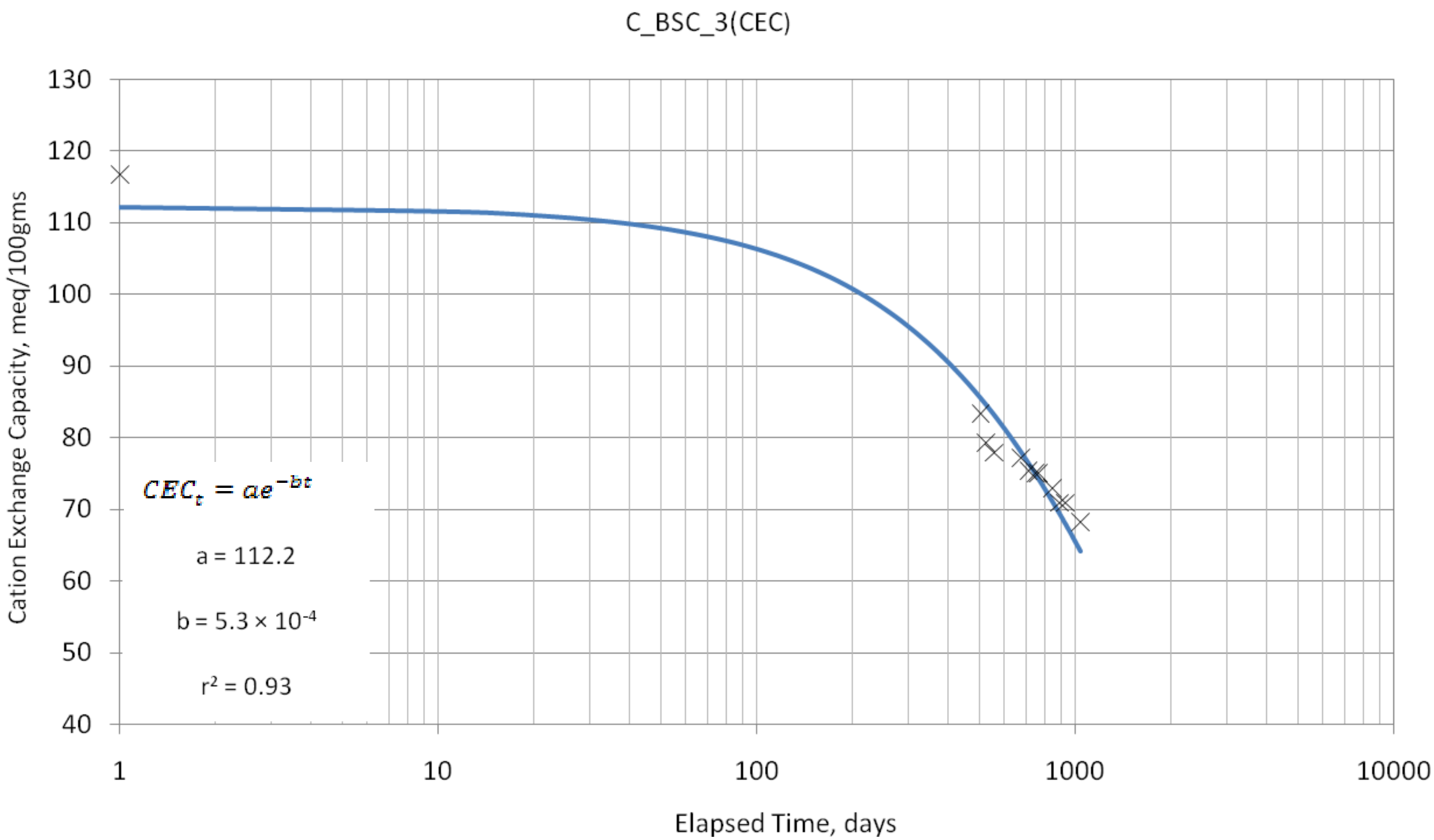


**Figure 6-28 Modeling of CEC results from C_BSC_3 section**

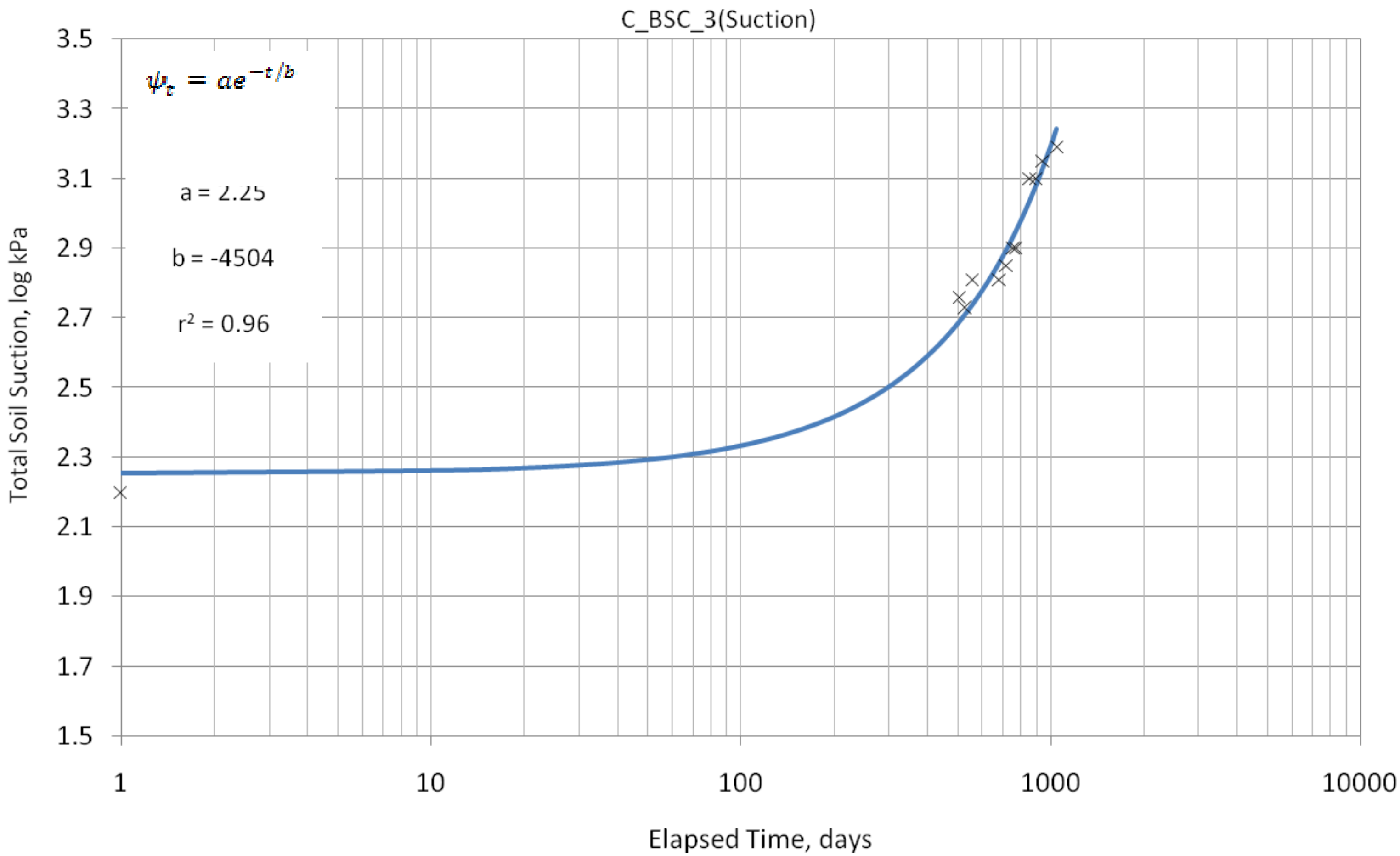


**Figure 6-29 Modeling of total soil suction from C_BSC_3 section**

Figures 6-26, 27, and 28 represent the laboratory values that were obtained from the Biosolids Compost treated sections at the Corpus Christi, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Biosolids Compost treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.93, 0.93, and 0.96 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 11.9\, e^{-6.2\times10^{-4}t} \qquad 6.8$$

$$CEC_t = 112.2\, e^{-5.3\times10^{-4}t} \qquad 6.9$$

$$\psi_t = 2.25\, e^{t/2869} \qquad 6.10$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values was estimated.

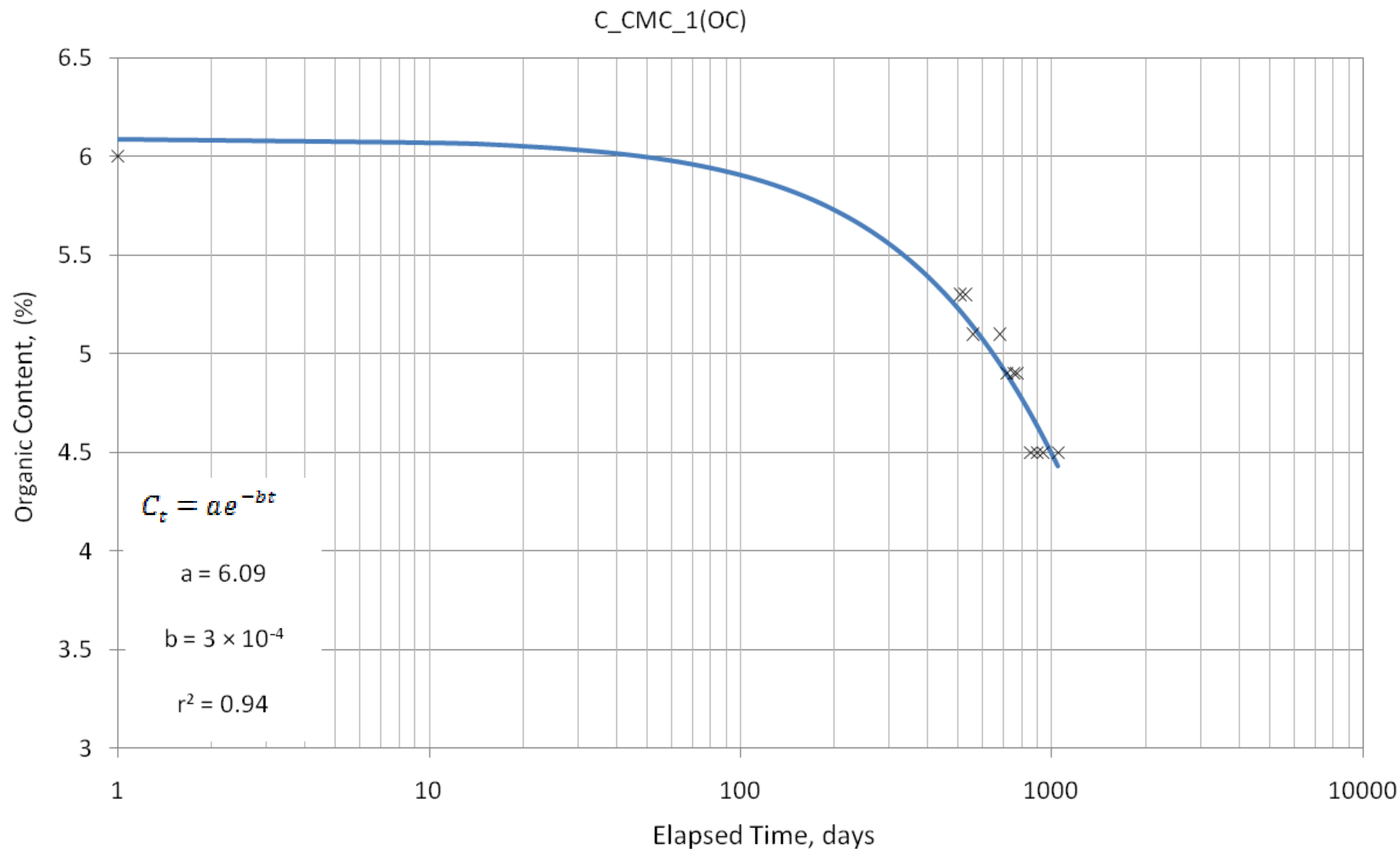


**Figure 6-30 Modeling of O.C. results from C_CMC_1 results**

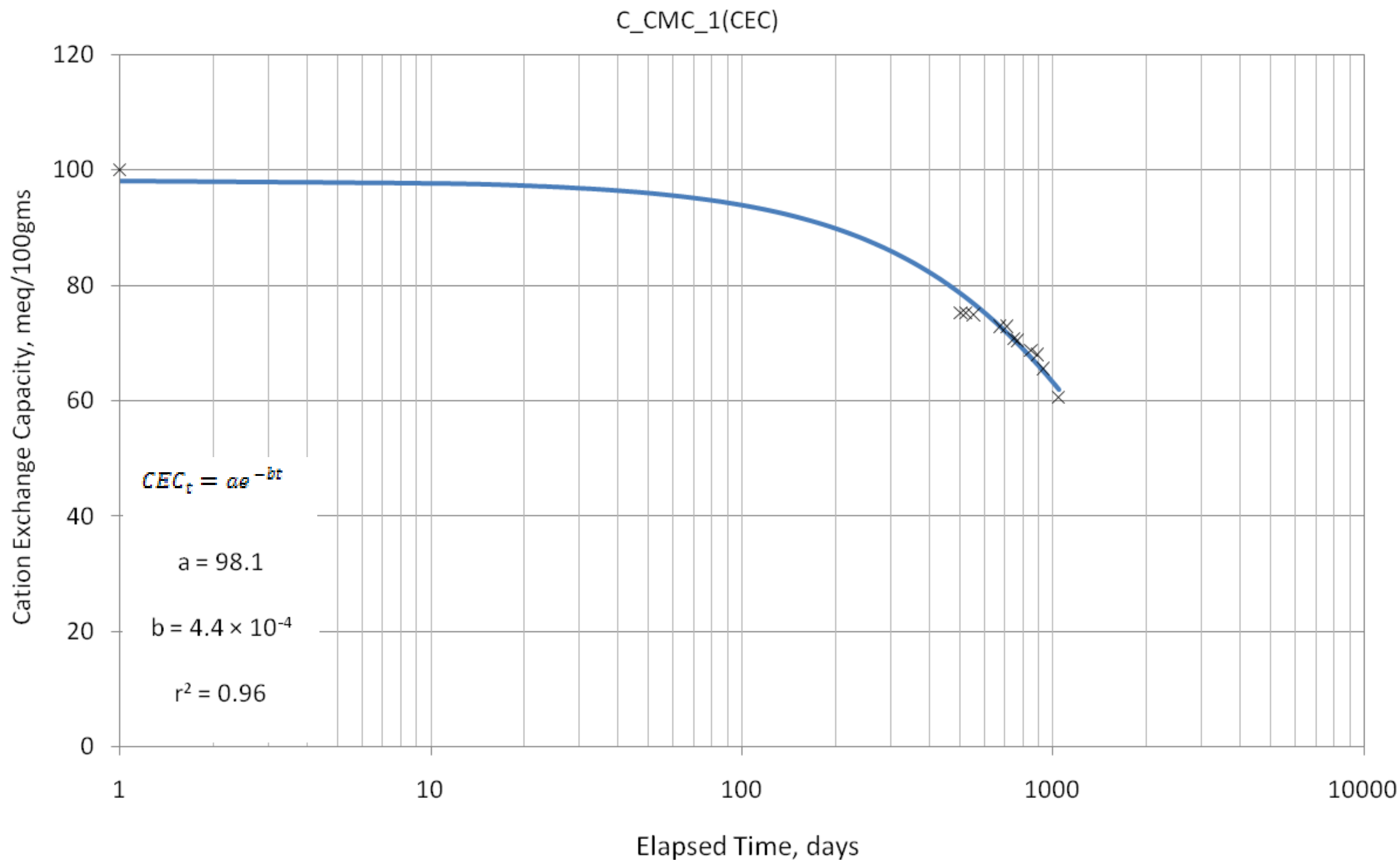


**Figure 6-31 Modeling of CEC results from C_CMC_1 section**

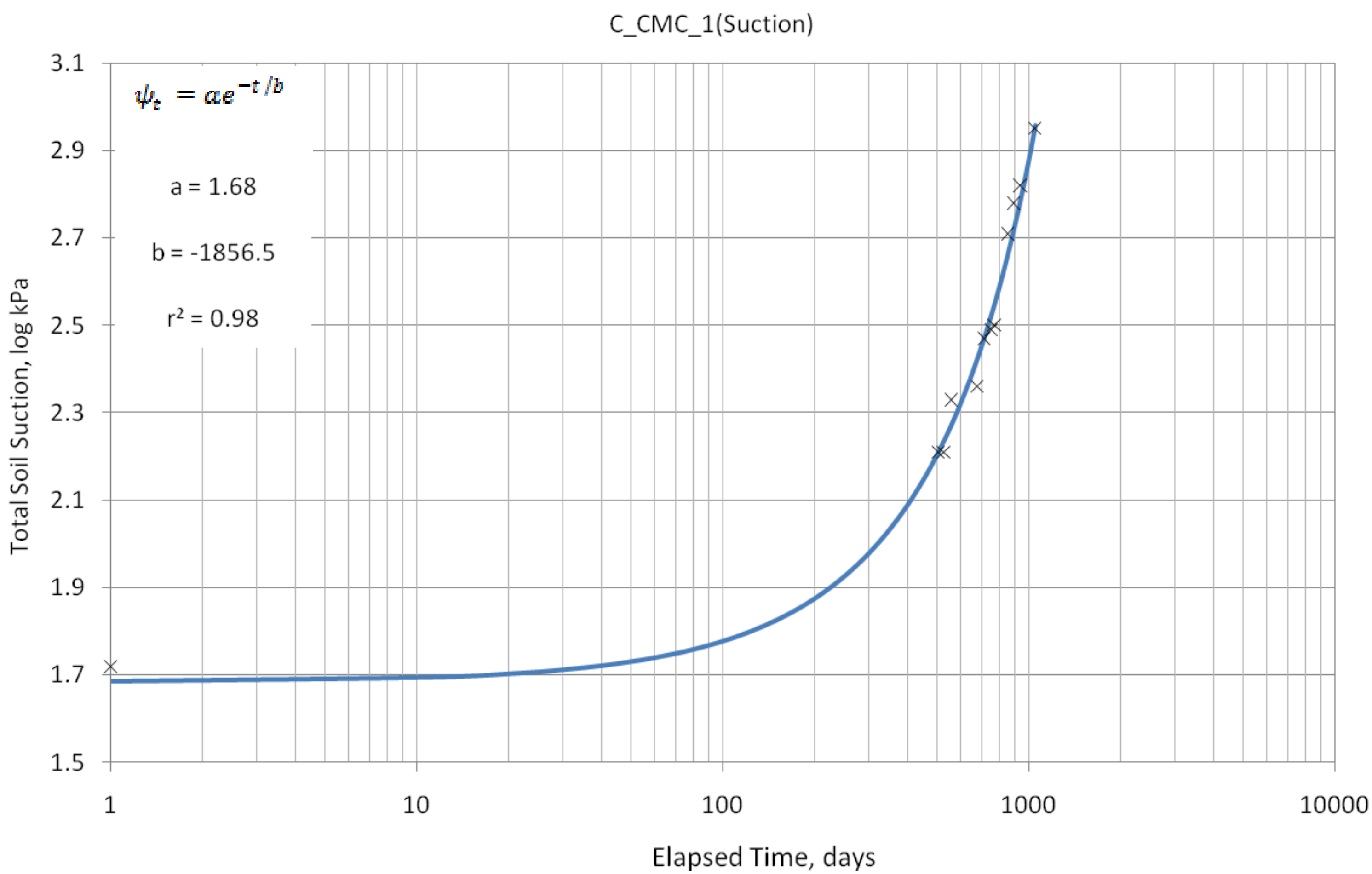


**Figure 6-32 Modeling of total soil suction from C_CMC_1 results**

Figures 6-29, 30, and 31 represent the laboratory values that were obtained from the Cow-Manure Compost treated sections at the Corpus Christi, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Cow-Manure Compost treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.94, 0.96, and 0.98 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 6.09\, e^{-3\times10^{-4}t} \tag{6.11}$$

$$CEC_t = 98.1\, e^{-4.4\times10^{-4}t} \tag{6.12}$$

$$\psi_t = 2.25\, e^{t/1856.5} \tag{6.13}$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were estimated.

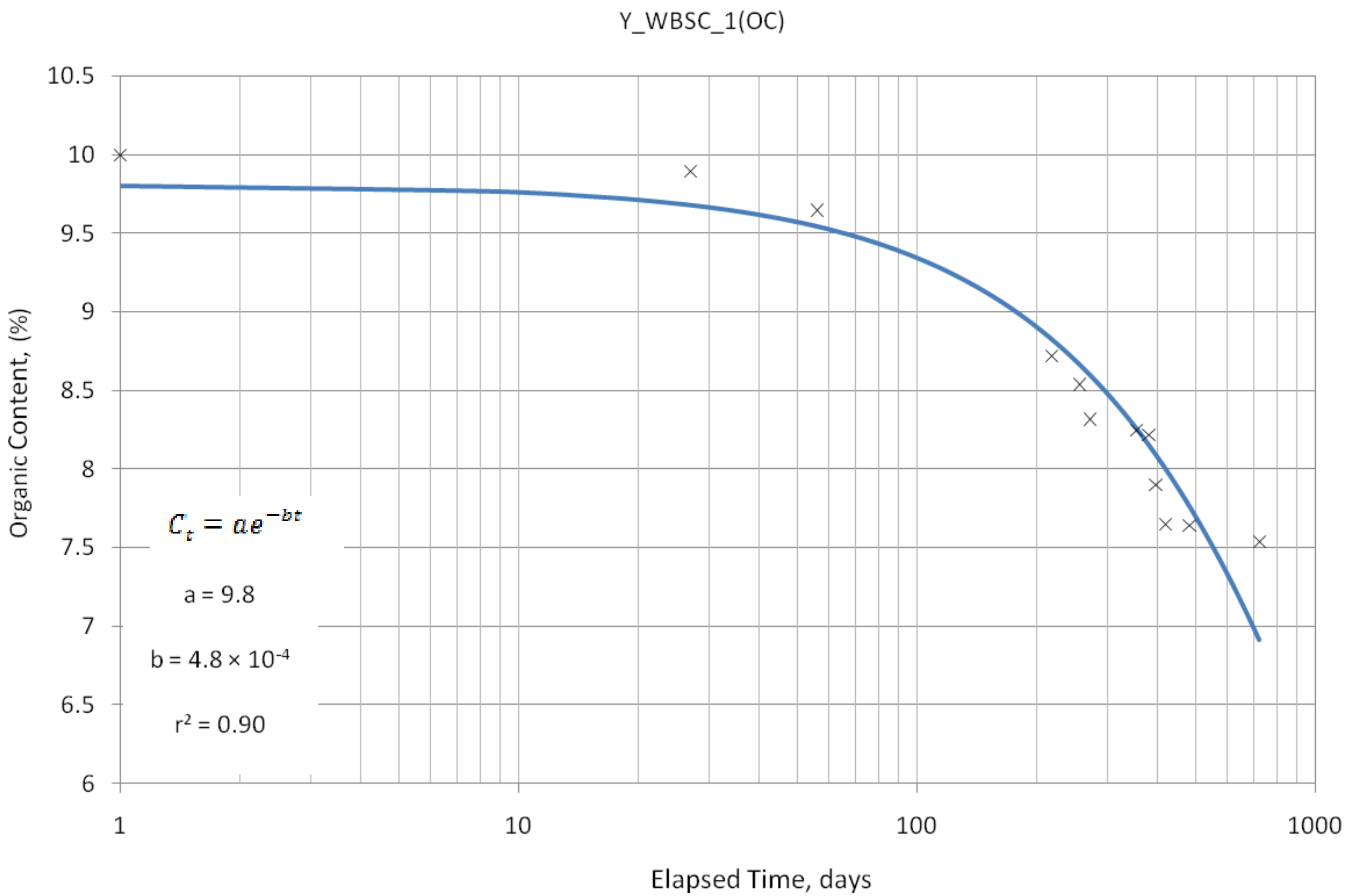


**Figure 6-33 Modeling of O.C. results from Y_WBSC_1 section**

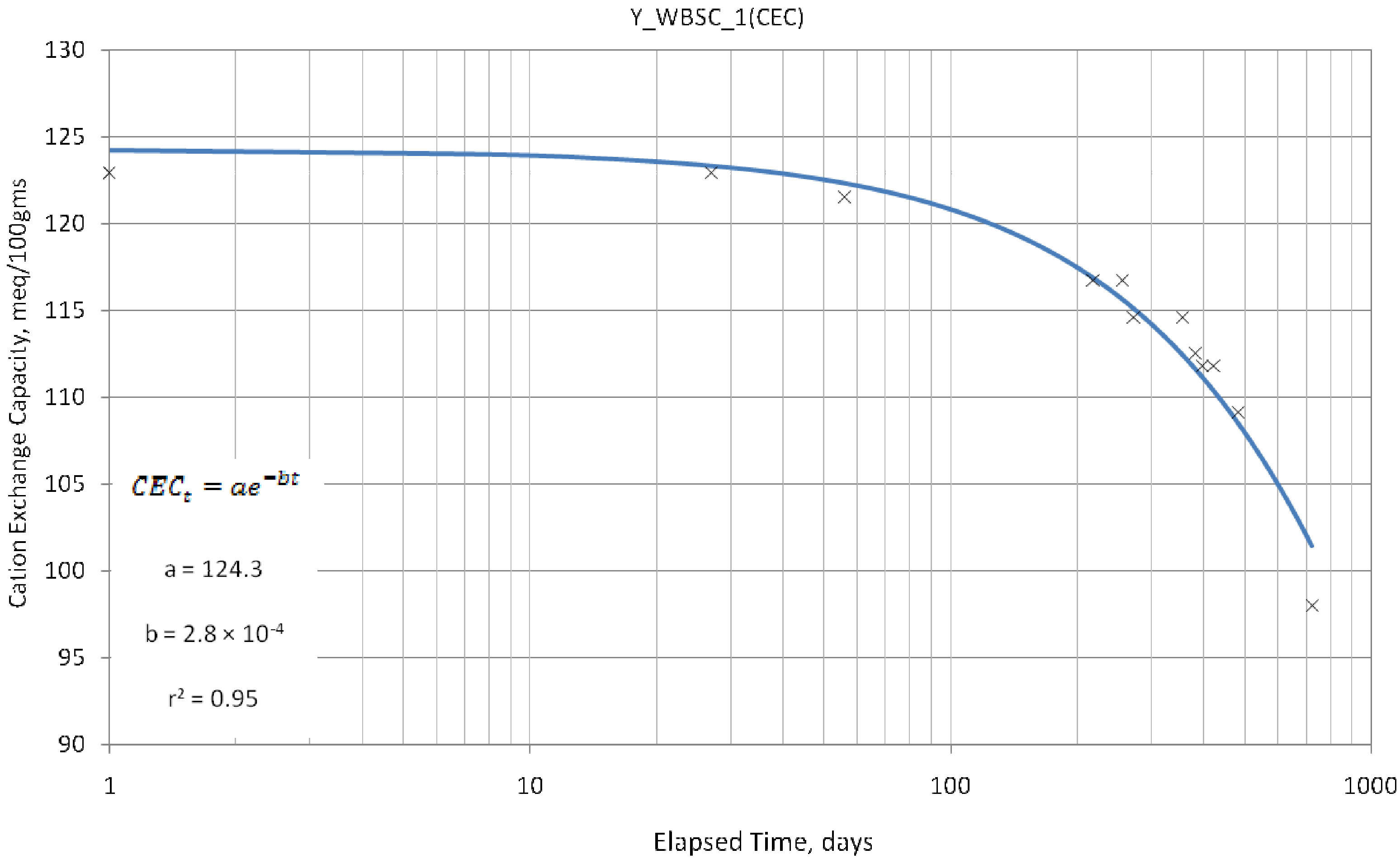


**Figure 6-34 Modeling of CEC results from Y_WBSC_1 section**

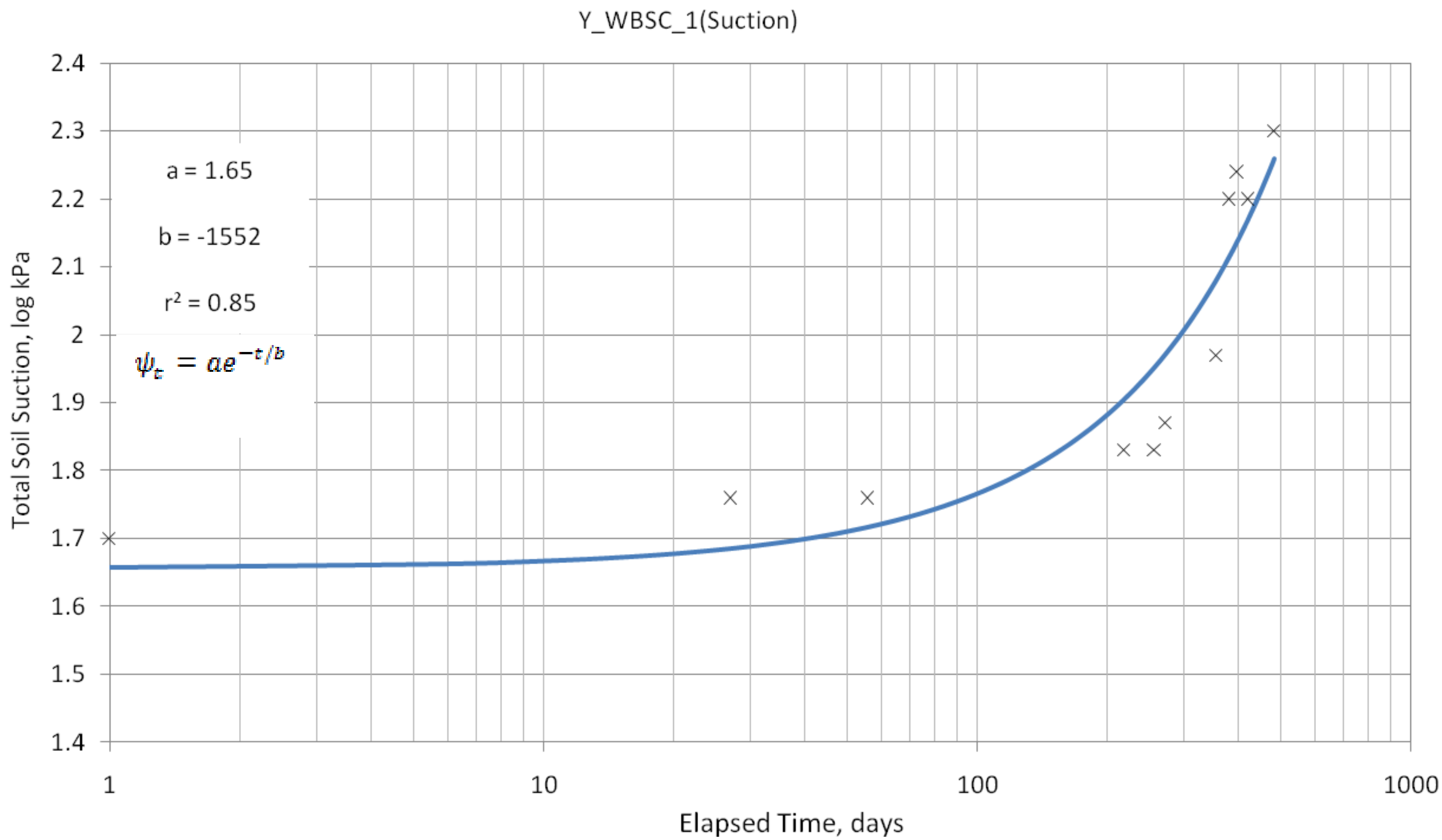


**Figure 6-35 Modeling of total soil suction results from Y_WBSC_1 section**

Figures 6-32, 33, and 34 represent the laboratory values that were obtained from the Y_WBSC_1 compost treated sections at the Yoakum, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Y-WBSC_1 compost treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.90, 0.95, and 0.85 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 9.8\ e^{-4.8\times10^{-4}t} \quad 6.14$$

$$CEC_t = 124.3\ e^{-2.8\times10^{-4}t} \quad 6.15$$

$$\psi_t = 1.65\ e^{t/1552} \quad 6.16$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were estimated.

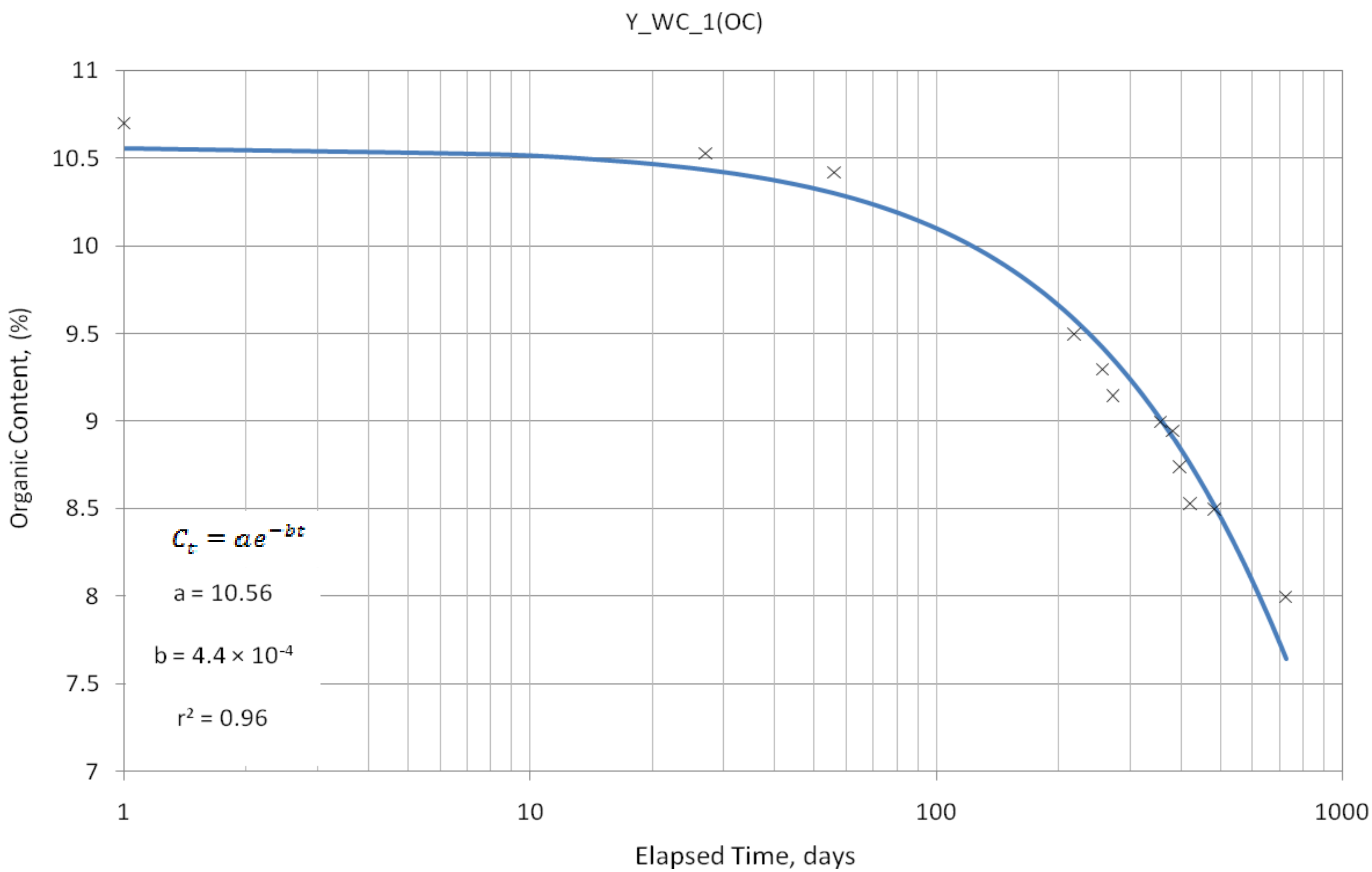


**Figure 6-36 Modeling of O.C. results from Y_WC_1 section**

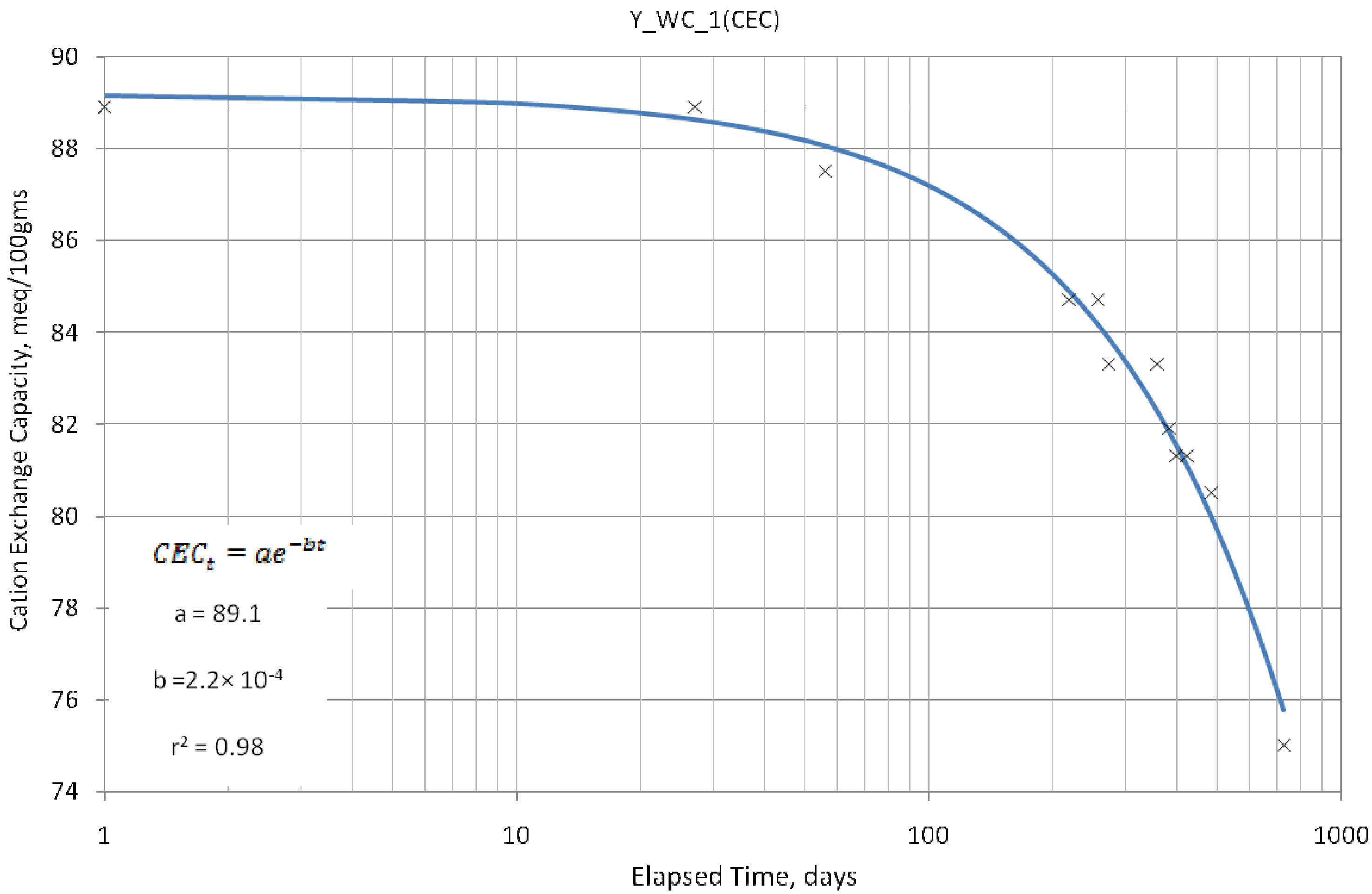


**Figure 6-37 Modeling of CEC results from Y_WC_1 section**

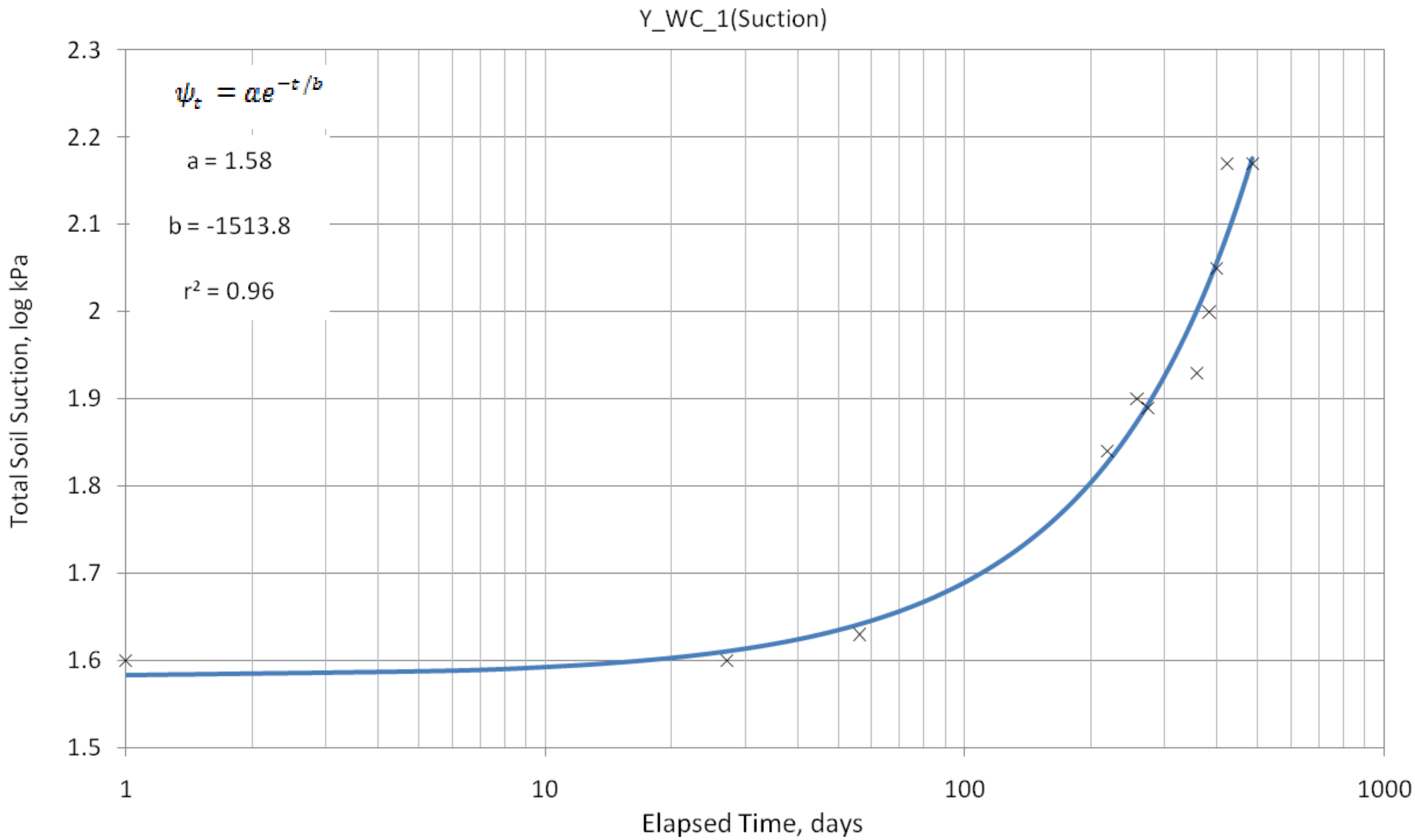


**Figure 6-38 Modeling of total soil suction results from Y_WC_1 section**

Figures 6-35, 36, and 37 represent the laboratory values that were obtained from the Wood Compost treated section at the Yoakum, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the Wood Compost treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.96, 0.98, and 0.96 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 10.56\, e^{-4.4\times10^{-4}t} \tag{6.17}$$

$$CEC_t = 89.1\, e^{-2.2\times10^{-4}t} \tag{6.18}$$

$$\psi_t = 1.58\, e^{t/1513.8} \tag{6.19}$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were estimated.

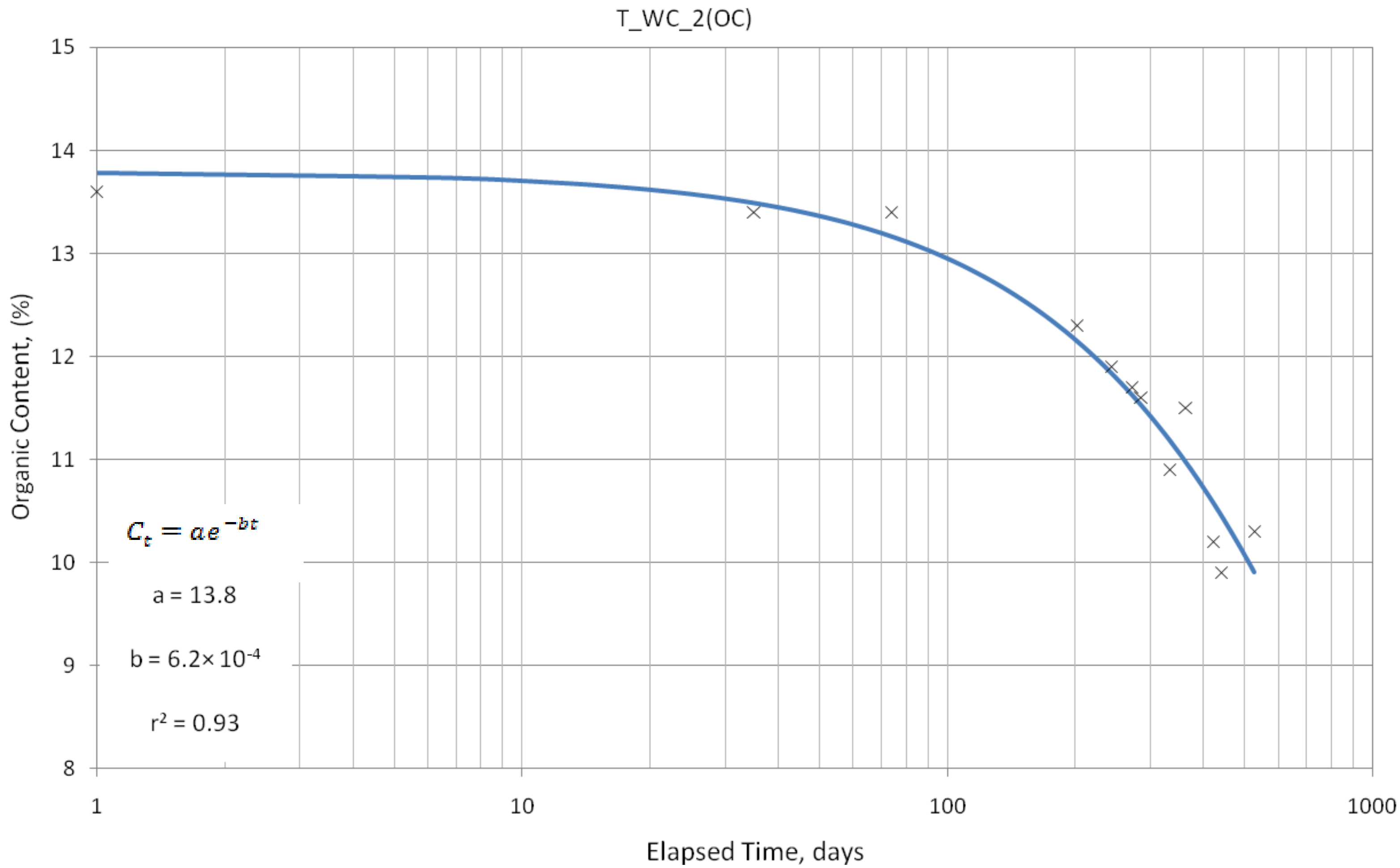


**Figure 6-39 Modeling of O.C. results from T_WC_2 section**

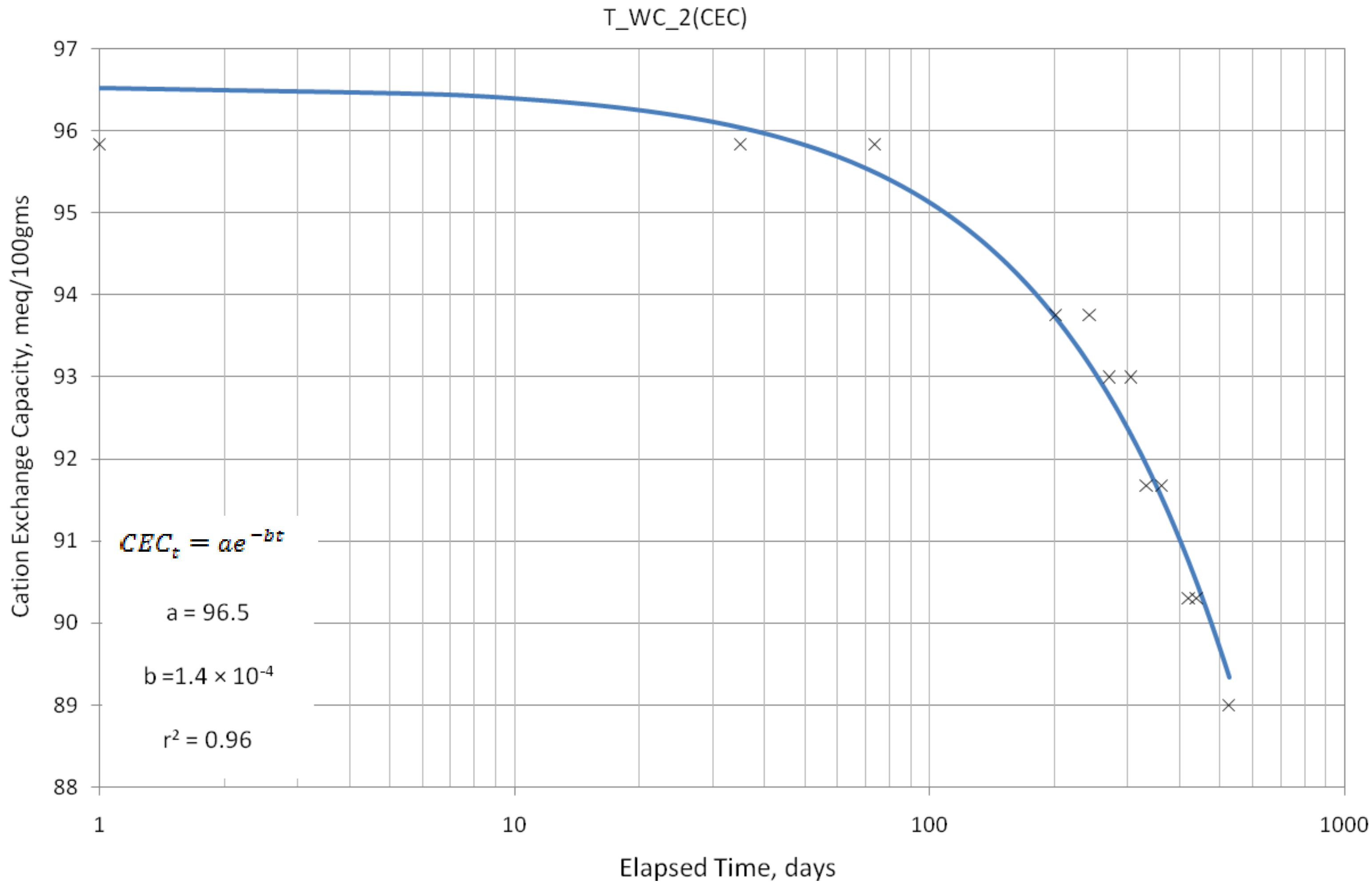


**Figure 6-40 Modeling of CEC results from T_WC_2 section**

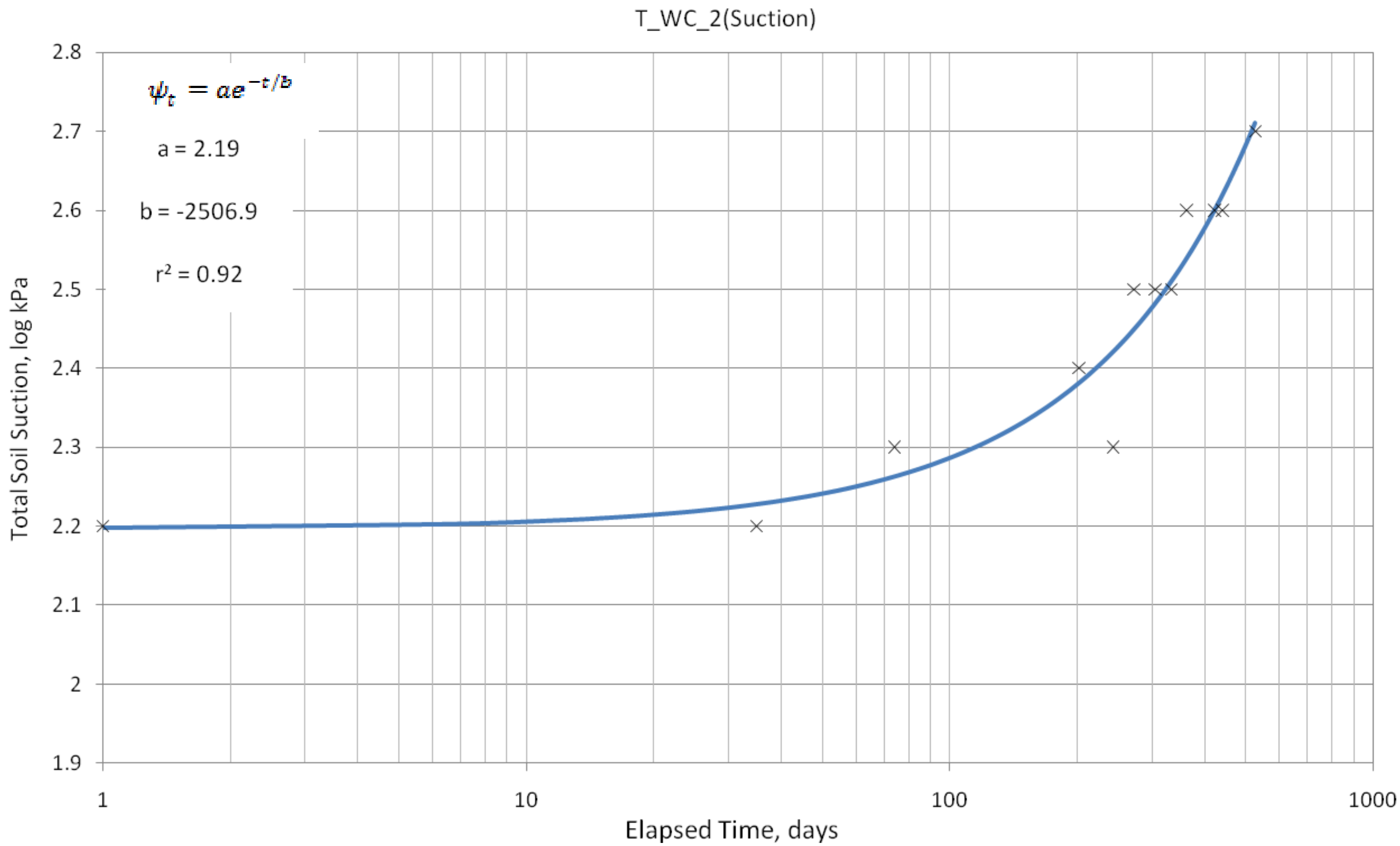


**Figure 6-41 Modeling of total soil suction results from T_WC_2 section**

Figures 6-38, 39, and 40 represent the laboratory values that were obtained from the WC_1 Wood Compost treated section at the Yoakum, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the WC_1 treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.93, 0.96, and 0.92 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 13.8\, e^{-6.2\times 10^{-4} t} \qquad 6.17$$

$$CEC_t = 96.5\, e^{-1.4\times 10^{-4} t} \qquad 6.18$$

$$\psi_t = 2.19\, e^{t/2506.9} \qquad 6.19$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were estimated.

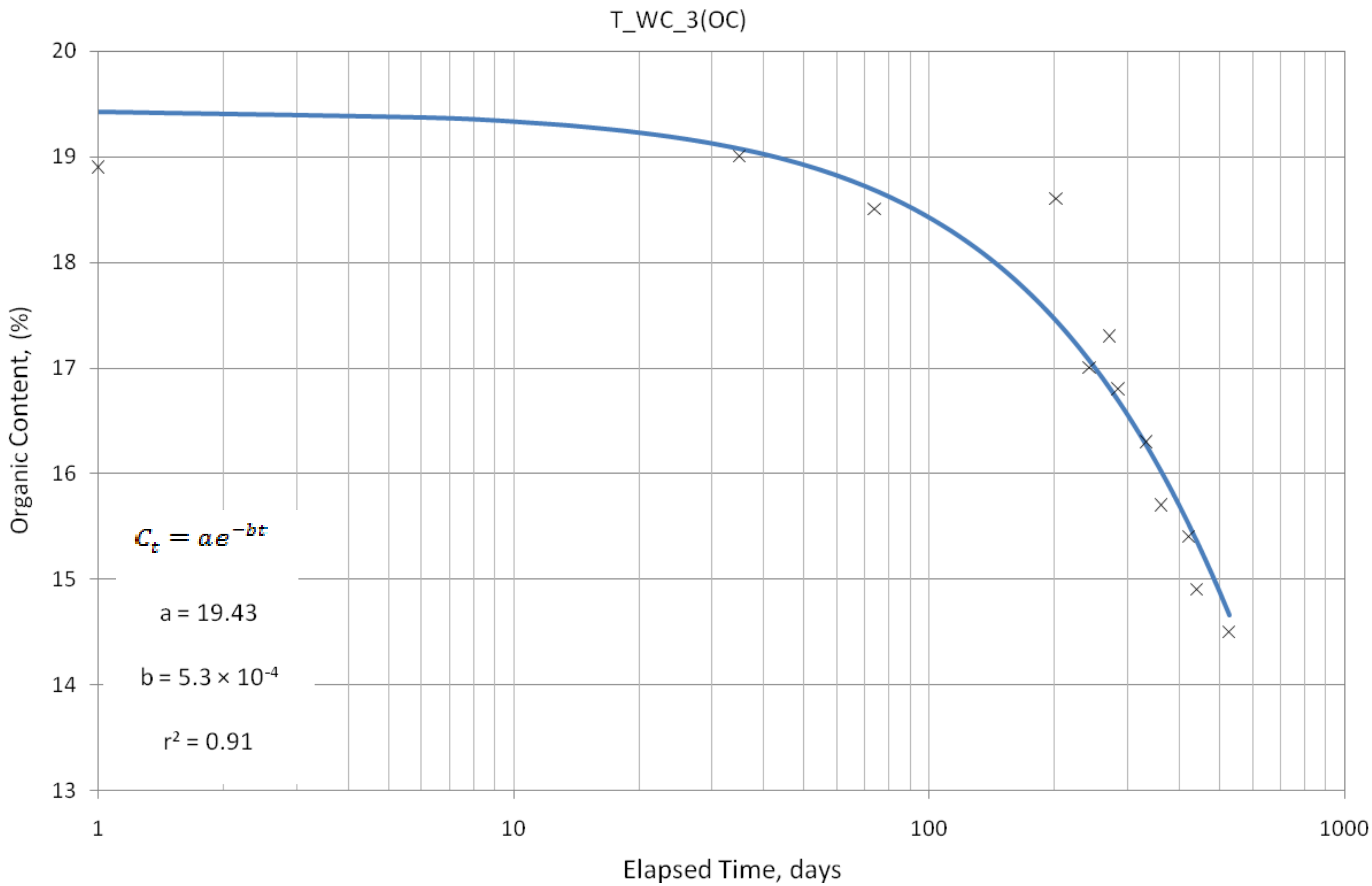


**Figure 6-42 Modeling of O.C. results from T_WC_3 section**

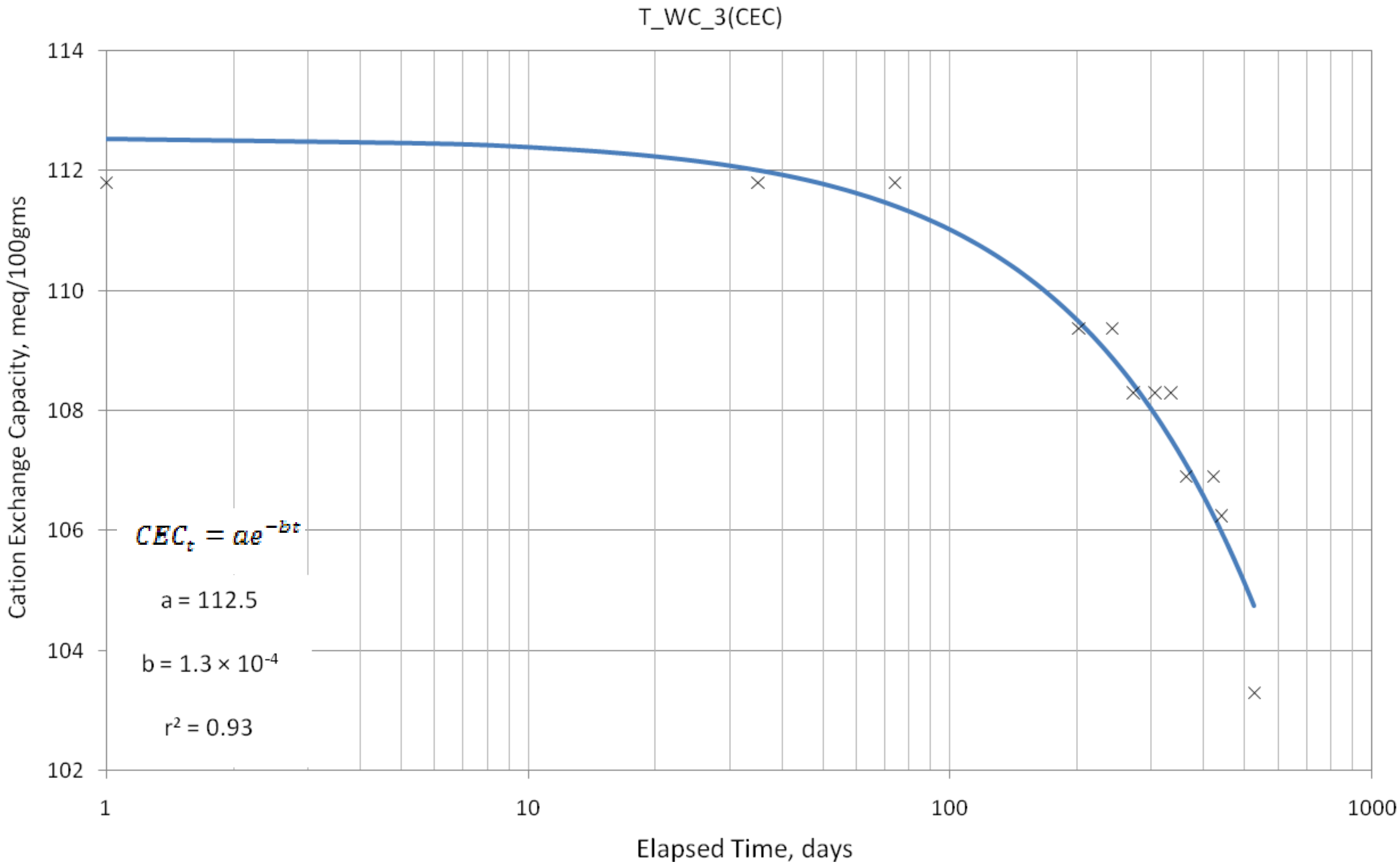


**Figure 6-43 Modeling of CEC results from T_WC_3 section**

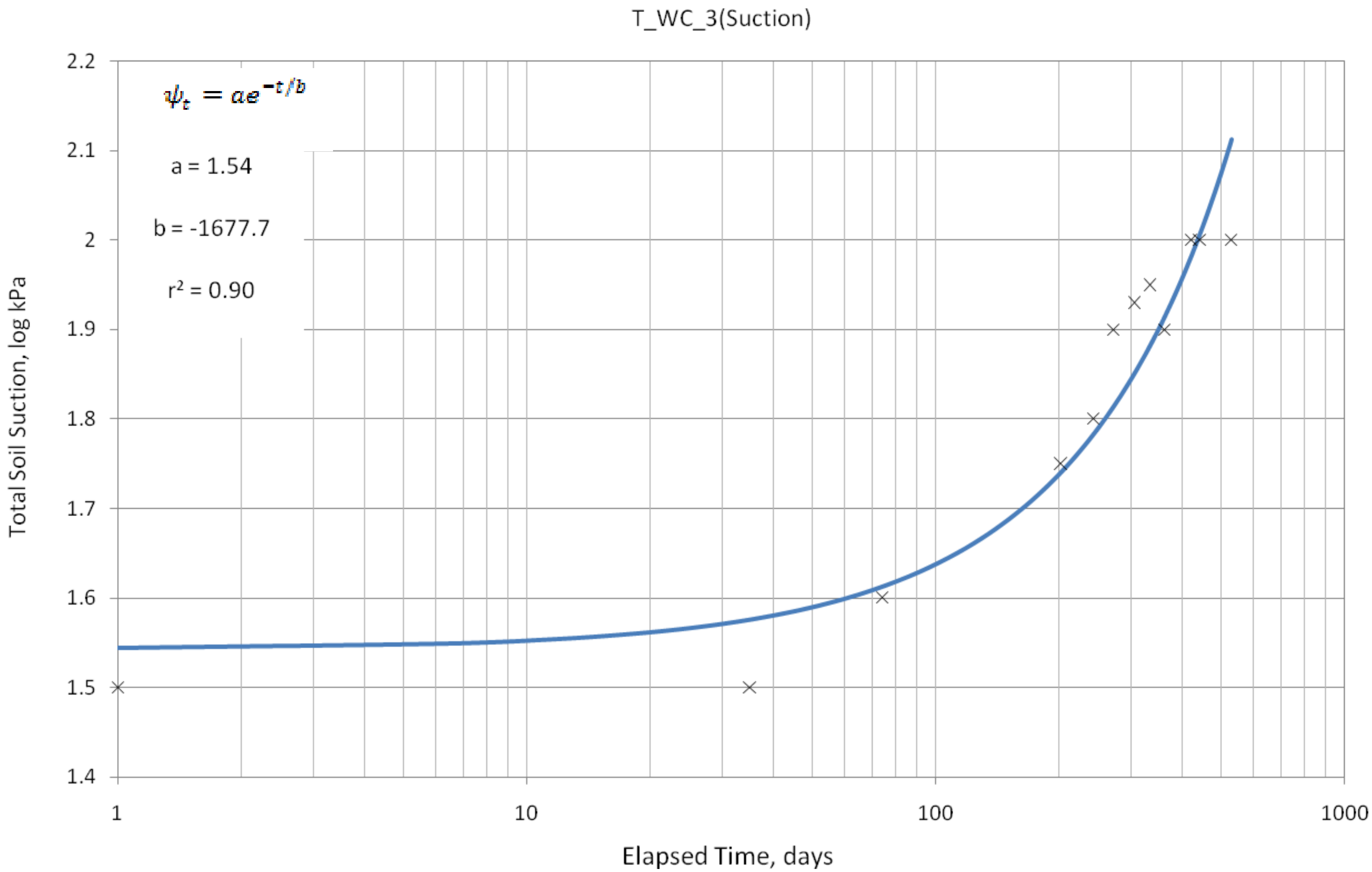


**Figure 6-44 Modeling of total soil suction results from T_WC_3 section**

Figures 6-41, 42, and 43 represent the laboratory values that were obtained from the WC_1 Wood Compost treated section at the Yoakum, TX test site. The exponential decay model was fitted with the organic content, cation exchange capacity, and the total soil suction that was obtained from the WC_1 treated section. It can be observed that the coefficient of determination of the data fit into the exponential decay model was 0.91, 0.93, and 0.90 for the organic content, cation exchange capacity and total soil suction data respectively. The following equations were derived by fitting the laboratory results into the model.

$$O.C_t = 19.4\, e^{-5.3\times10^{-4}t} \qquad 6.17$$

$$CEC_t = 112.5\, e^{-1.3\times10^{-4}t} \qquad 6.18$$

$$\psi_t = 1.54\, e^{t/1677.7} \qquad 6.19$$

The value t represents the elapsed time at which the parameters are measured. The service life of the compost treated sections was considered to be completed when the measured values of the different parameters with time reached the respective control section values. A suitable factor of safety of 7 – 10 % was applied to the organic content, CEC and total suction values of the control section and these were fixed as the allowable values up till which the respective treated section values could decrease. The minimum allowable organic content and cation exchange capacity values were calculated as explained in the previous section. In case of the total suction values the control section value was increased by the factor of safety and the maximum allowable total suction values were estimated.

A typical calculation of service life based on organic content for the Stephenville site for the biosolids compost treated section is shown below.

Organic Content at time of field Implementation ($O.C_o$) = 15.1 %

Organic Content of control soil ($O.C_{cs}$) = 3.9 %

Factor of Safety = 10%

$O.C_{Service\ Life} = [\ (O.C_o - O.C_{cs}\ ) \times F.S/100] + O.C_{cs}$ = 5.02 %

$5.02 = 15.43\ e^{-0.00048\ t}$

$-\ln(5.02/15.43) = -0.00048\ t$

$t = -1.1228/-0.00048$

t = 6.4 years

**Table 6-2 Life cycle assessment of the compost treatments**

| Test Section | Life Cycle of Compost Treatment (years) based on | | | |
|---|---|---|---|---|
| | **O.C** | **CEC** | **Suction** | **Average** |
| **S_BSC** | 6.4 | 6.16 | 5.06 | **5.9** |
| **S_DMC** | 4.55 | 5.02 | 5.01 | **4.86** |
| **C_BSC_3** | 5.41 | 4.15 | 4.4 | **4.65** |
| **C_CMC_1** | 4.75 | 4.4 | 4.26 | **4.47** |
| **Y_WBSC_1** | 4.85 | 8.12 | 3.83 | **5.6** |
| **Y_WC_1** | 5.83 | 7.03 | 3.4 | **5.42** |
| **T_WC_2** | 4.71 | 8.79 | 3.54 | **5.68** |
| **T_WC_3** | 6.51 | 13.66 | 3.93 | **8.03** |

The life cycle period of the different test section treated with compost for the mitigation of the shoulder pavement cracking is presented in Table 6-2. The life cycle period was calculated by selecting specific end points of the organic content, CEC, and suction at which the service life of the treatment was considered to be over. These end points were determined by calculating the difference between the initial values of each parameter at the time of field implementation and the value of the control section. About 7-10 % of this value was calculated and added to that of the control section parameter values. These values were considered to be the indicators for the end of the service life of the particular compost treatments. This end of service life indicator values were entered into the equation that was developed by the respective model and then the life cycle time was calculated. The service life was calculated based on three different parameters which were organic content, CEC and suction. The average of these three values would be considered as the service life of the compost treatment. It can be seen that the service life of the section T_WC_3 determined based on the CEC value is approximately 13 years. This unusually high value is because of the age of the test site. Since the Tyler test section is a relatively new test site, it requires some more monitoring period in order to predict the life time of the compost treatment with desirable accuracy.

## 6.6 Influence of Compost Characteristics on Service Life

An attempt was made to investigate the relationship between the compost characteristic and the degradation rate constants obtained from the degradation models. The plasticity index of different compost amended soils was taken as the parameter that would best describe the compost characteristic. This was compared with the model constants related to reaction degradation rates that were obtained for the respective compost treatments from organic degradation models as shown in Figure 6-45.

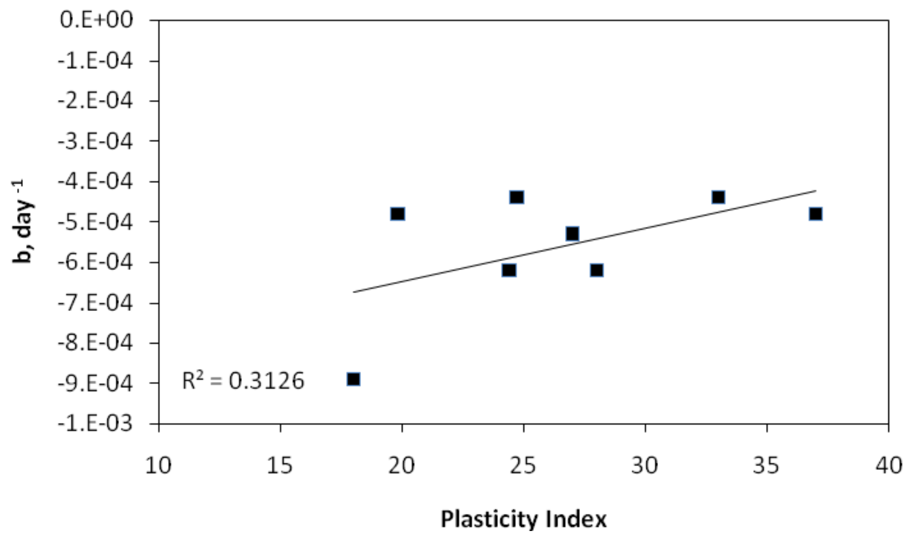


**Figure 6-45 Influence of plasticity index on reaction rate based on O.C. degradation data**

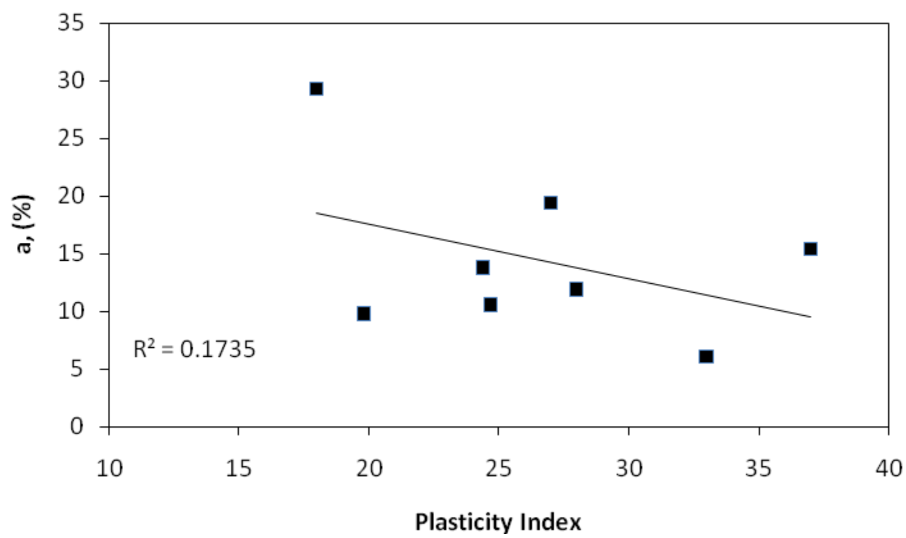


**Figure 6-46 Influence of plasticity index on degradation of compost based on OC data**

It can be observed from Figure 6-45 that there is no definite trend that exists between the plasticity index and the reaction rate coefficients. The lack of correlation could be due to the variations in the characteristics of the different compost materials, since the compost has different source materials and different conditions during composting. Hence it was not possible to develop a relationship between the compost characteristics and the degradation rate related parameters.

## 6.7 Cost Analysis

The Cost Analysis (CA) could be defined as a tool that deals with the engineering economics of a particular project. The CA could be performed in order to determine the cost effectiveness in the construction of a new project, or to determine the effectiveness of various maintenance methods to preserve existing structures (FHA, 2008). Typically a CA analysis is done in order to allocate the money that would be required for the construction and maintenance of the project. The CA analysis is popular in all the various braches of engineering, science and business applications. The input parameters that are required for the CA analysis are as listed below

- Material cost
- Construction labor cost
- Construction duration
- Maintenance options
- Maintenance frequency for the different options
- Maintenance cost and labor
- Rehabilitation work required if any

- Cost of traffic diversions
- Rehabilitation cost

*6.7.1 Maintenance Methods*

In this research three types of alternative maintenance methods were compared with the compost treatment for the prevention of shoulder cracking. It has to be noted that the compost treatment is a preventive measure against the pavement cracking while the other maintenance methods are to treat the pavement cracking after occurrence. The maintenance methods that were considered are as follows

- Crack Sealing
- Asphalt Hot Mix Resurfacing
- Seal Coating

6.7.1.1 Crack Sealing

Crack sealing could be considered as the easiest of the three alternative maintenance methods chosen. Before the crack sealing is done the cracks are cleaned by using compressed air. Then the required amount of asphalt concrete mixture is applied at the beginning of the crack by suing a special kind of hose attached the asphalt holding truck. After the asphalt is applied on the pavement it is spread over the length of the crack so that the asphalt penetrates at least a quarter of an inch into the crack. The asphalt is applied in such a way that it extends for a little bit onto the uncracked pavement on both ends of the cracks to provide good sealing property. There are two units in which the cost of the crack sealing is calculated which are as follows Linear Feet (LF) and Lane Mile (LMI). The labor charge for the application of the crack sealant is also included in this price by the contractors. If the cost is calculated per linear foot of crack sealing, then the designated state official would have to physically keep track of the length of crack which is present. This is done in order to prevent the contractor from unlawfully charging the state by using unnecessary excess asphalt on the pavement. If the cost is calculated in Lane Miles then the contractor would have to seal the crack in one mile of pavement irrespective of the number of cracks that are present. In this case the government official would have to make sure that all the cracks on the pavement are sealed properly by the contractor without trying to save the amount of material used. The typical cost incurred for the crack sealing maintenance method was obtained from the average low bid unit price provided by TxDOT. The typical crack sealing process is shown in Figure 6-44.

**Figure 6-47 Typical crack sealing process (fhwa.dot.gov)**

6.7.1.2 Seal Coat

Seal coating is a process that is similar to that of the hot mix application. In seal coating after the pavement is cleared of debris the asphalt is sprayed onto the pavement surface. The aggregate is then dropped onto to the sprayed asphalt layer so that it would stick onto the pavement surface. Then the aggregate over the asphalt is pressed together by using a smooth drum roller. Typically the life of a seal coat would be anywhere from 5 to 7 years. By doing a seal coat there is no need of crack sealant in between the seal coating process every 5 to 7 years. The cost for the seal coat is calculated by the amount of material that was used in the resurfacing process. The amount of asphalt used is measured in gallons and the amount of aggregate is used is measured in tons. The cost for the seal coating operation was obtained from the average low bid unit price provided by TxDOT. Here the cost of the asphalt and aggregate is separate unlike the hot mix application. A typical seal coating operation is shown in Figure 6-46.

**Figure 6-48 Typical application of seal coat (TTI, TAMU)**

**Table 6-3 Unit cost of the different maintenance methods**

| | | |
|---|---|---|
| Length of Roadway | 1760 | yd |
| Width of Roadway | 13.33 | yd |
| Width of compost treatment | 3.33 | 3.33 |
| PLANE ASPH CONC PAV (8" TO 16") | 7.25 | $/ sq.yd |
| Seal coat Asphalt ASPH (AC-20XP) | 2.6 | $/gallon |
| Seal Coat Aggregate Type-B Grade 4 | 41.8 | $/cu.yd |
| Seal Coat Asphalt Application Rate | 0.3 | gallons/sq.yd |
| Seal Coat aggregate Application Rate | 0.00909 | cu.yd/ sq.yd |
| Hot Mix D-GR HMA(QCQA) TY-C SAC-B PG 70 - 22 | 66.99 | $/ton |
| Hot Mix Application Rate | 230 | lb.mix/sq.yd-2in |
| JT/Crack Seal (Rubber - Asphalt) | 725.84 | LMI |
| Compost Manufactured Topsoil (BOS) 4" | 0.82 | $/sq.yd |

**Table 6-4 Summary of Cost Analysis for a 1 mile roadway section for 35 years**

| | Compost Treatment of Shoulder Soil | Crack Sealant | Seal Coat |
|---|---|---|---|
| Pavement | Asphalt Concrete (8" - 16") | Asphalt Concrete (8" - 16") | Asphalt Concrete (8" - 16") |
| Pavement Construction Cost | 170091 | 170091 | 170091 |
| Construction Cost Treatment | Compost @ 5 yr | n/a | n/a |
| Maintenance Cost | n/a | Crack Sealing @ 2 yr Intervals | Seal Coating @ 5 yr Intervals |
| Traffic (Lump) | n/a | n/a | 2000 |
| | | | |
| Maintenance Cost ($) | (0.82×1760×3.33×7) = 33641.0[a] | (725×2×17.5) 25404.4 | {(2.6×0.3×1760×13.33)+ (41.8×0.00909×1760×13.3)} × 7 = 190066.7 |
| Total Cost | 203731.8 | 195495 | 362157.7 |

Note: a – Maintenance cost calculated for 1 mile roadway section for a period of 35 years
The unit cost of the materials used in this calculation are shown in Table 6-3

The cost analysis was conducted for a period of 35 years. It can be observed from the above calculation that the total cost of the crack sealing ($ 176,529) is the lowest when compared to the other two methods. The cost involving the compost treatment ($178,616) of the shoulder soil costs slightly more than the costs of crack sealing. Cost of the seal coating ($218,872) is much more expensive than the crack sealing and the compost treatment. There are some disadvantages of crack sealing such as, it is a maintenance method for a failure that has already occurred on the pavement. The compost treatment can be considered to be a preventive method, where the formations of cracks are prevented from occurring in the first place.

Even though the crack sealing cost is less, the government official who is supervising the operations has to spend considerable amount of his time in the field for assessing the lengths of the cracks. If the cost of the crack sealing is paid in terms of linear feet, then the official would have to physically know the length of cracks that is present in the pavement. This is done by randomly selecting sections of pavement and measuring the linear length of cracking on them. If the crack sealing is paid for in 'lane miles' then the official would have to make sure that all the cracks are sealed effectively and also that the newly forming hairline cracks are not left unsealed. Hence a huge effort has to be placed in the quality control and quality assessment of the crack sealing operation by the concerned officials at every two year interval.

The appearance of the pavement after crack sealing is also not desirable since it results in a number of wavy patches of asphalt which could distract the driver of a vehicle. On the other hand the compost treatment only requires proper quality control at the time if field implementation. The proper compost dosage has to be maintained and the prepared compost manufactured top soil seeded and compacted effectively. This process would have to be done only once in 5 years. Based on the advantages and disadvantages of the crack sealant and the compost treatment it is recommended that the compost treatment of the shoulder soil be selected for further pavement cracking problems.

## 6.8 Summary

The samples that were collected from the field were subjected to various laboratory tests such as organic content, cation exchange capacity, and total soil suction. The measured laboratory results were fit into the exponential decay model and the degradation rate constants estimated. From these equations the service life of the compost treatments were calculated by applying a suitable factor of safety to the control section values. Once the values from the treated sections reached these minimum (O.C., CEC) and maximum (Total soil suction) allowable values the elapsed time was considered to be the service life of the compost treatments. It was observed that each composted soil showed varying rates of degradation constant. This was considered to be normal since biological degradation involves highly complex biological and physiological process that would evidently vary between each test sections. It was observed from the modeling results that the biosolids compost and the wood based compost had a service life of 5 to 6 years, whereas the manure based composed had an effective life span of 4 to 5 years. Hence it can be safely assumed that the service life of the compost treatments in general were approximately 5 years

The life cycle cost analysis was conducted based on the average service life determined from the modeling results. The cost of the compost treatment and crack sealant were approximately similar when compared to he seal coating and the hot mix asphalt layering. Based on the advantages and disadvantages of the compost treatment and crack sealant respectively discussed in section 6.6, it is recommended that compost treatments be selected to treat pavement cracking issues.

# CHAPTER 7

# SUMMARY AND CONCLUSIONS

## 7.1 Introduction

The effectiveness and the service life of the compost treatment for the mitigation of pavement cracking were analyzed in this research. Four test locations situated in Stephenville, Corpus Christi, Yoakum and Tyler were employed to develop the service life models for the compost treatment. Different composts were used in each test section in each site location respectively. The mean moisture variation, temperature variation, elevation surveys, and pavement cracking analysis were used in order to determine the long term effectiveness of the compost treatment. The student's t-test was used in order to determine any significant difference between the treated and the untreated sections.

The service life models were developed from the laboratory results obtained from the soil samples collected periodically from the different test sections. The laboratory tests that were conducted were organic content, cation exchange capacity, and total soil suction. The life cycle cost analysis was conducted based on the service life of the compost treatment predicted by the developed models. The conclusions that were obtained from the analysis of the laboratory and field results are presented in section 7.2.

## 7.2 Summary

This section includes the conclusions that were based on the analysis of the results presented in chapter 5 and 6.

- The bio solids compost used in the Stephenville and Corpus Christi TX site was found to be effective in the long term in the prevention of crack formation on the pavement shoulder. This could be due to the material characteristics of the compost and the presence of wood chips that was added as a bulking agent to the feedstock material during the composting process. The wood chips help in providing more void space in the coil compost structure which further helps in increasing its water holding capacity.
- The manure based compost dosage of 100 % that was applied in the Stephenville, TX test site proved to be not effective in the prevention of pavement cracking. The t-test analysis done on the moisture variation and temperature variation showed that there was no significant difference between the 100 % manure compost treated section and the compost section. The pavement cracking analysis showed that the 100% dairy manure compost showed half of the cracks formed on the control section.
- The application of compost in its pure form is not effective in addressing the pavement cracking problem. This is due to the absence of fibrous material in the pure form of the manure compost.
- The wood based compost that was applied on the Yoakum test site and both the test sections in the Tyler, TX test site proved to be effective in the prevention of

pavement cracking. The moisture variation, temperature variation and the pavement cracking analysis were used to determine the effectiveness of the wood compost treatment. Even though the temperature variation was found not to be significantly lesser than the control section values, the analysis of the pavement cracking confirmed that the wood compost was effective in preventing pavement cracks. Wood based composts with low percentages of biosolids used in the Yoakum, TX site also proved to be effective in the prevention of pavement cracking.

- It was observed that the cation exchange capacity of the soil was directly proportional to that of the organic content of the soil. This explains the effectiveness of compost in preventing the pavement cracking. As the cation exchange capacity of the compost treated soil is higher the water holding capacity of treated soil also increases, thus reducing the moisture fluctuations which lead to prevention of pavement cracking.
- The total soil suction is inversely proportional to the organic content of the soil. The void ratio of the soil increases due to the addition of compost material (high void ratio material). Hence as the compost degrades the soil compost mixture forms a closer matrix resulting in lower void ratio and higher soil suction. As the compost degrades the water holding capacity of the amended soil decreases resulting in lower water content and higher suction
- All the laboratory results that were obtained from the soil samples collected during periodic field visits were fitted into the exponential rate of degradation

model. It was found by analyzing the coefficients of determination that the data had a good fit with the exponential models.

- Compost amended shoulder soil also provides good protection against soil erosion since it promotes vegetative growth on the shoulder. The roots spread into the soil and hold it together preventing the soil erosion.
- The service life of the biosolids compost used in the Stephenville and Corpus Christi was found to be approximately 5 to 6 years. The manure compost used in the Stephenville, and Corpus Christi, TX test sites was found to be approximately 4 to 5 years. The service life of the wood based compost used in the Yoakum and Tyler, TX test sites was found to be approximately from 5 to 6 years.
- It was found that the manure compost has a service life lesser than that of the biosolids compost and the wood based compost. Since the age of the newly constructed compost treatment sections is less, further monitoring of the Yoakum and Tyler, TX sites are required to predict the service life with greater accuracy.
- It was found that all the different compost treated sections had different rates of degradation. Hence the models developed for a particular type of compost on a particular soil cannot be applied to another system to predict the service life. This might have been due to the variations in the characteristics of the compost and the different feed stock sources and the conditions during composting.
- The service life of the compost treatment depends upon the initial organic content of the soil compost mixture. Even though the organic material in the

compost might degrade rapidly it would be conservative to apply compost that is rich in organic content.

- The compost treatment is recommended when compared to the seal coat and crack sealing based on cost effectiveness, quality control issues and the benefits of CMTs encouraging environmental recycling efforts and providing newer compost markets.

## 7.3 Future Recommendations

- Compost materials with different feed stock sources could be applied at various locations where pavement cracking occurs and their effectiveness analyzed.
- The application of animal manure compost mixed with fibrous materials such as wood chips could be applied to the soil and their effectiveness in preventing pavement cracking could be analyzed.
- Laboratory scale test sections could be constructed with control soil from a particular test site and the biological degradation of the organic material in the compost without the environmental effects studied. The trend of organic degradation in the lab scale test section and the field test section could be compared to understand the effect and influence of the environmental factors.

**Table 7-1 Summary of statistical analysis done to determine effectiveness of compost**

| Compost Feed stock Source | Test Section | Moisture Variation | | | | Temperature Variation | | | | Pavement Cracking (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Control Plot Value | Treated Section Value | p-value | Effectiveness | Control Plot Value | Treated Plot Value | p-value | Effectiveness | Control Plot Value | Treated Section Value |
| Biosolids Compost | S_BSC_1 | 12.75 | 9.76 | 0.00 | Effective | 12.21 | 11.31 | 0.36 | Not Effective | 0.73 | 0.36 |
| | S_BSC_2 | 12.75 | 8.31 | 0.00 | Effective | 12.21 | 10.23 | 0.14 | Not Effective | 0.73 | 0 |
| | C_BSC_3 | 15.56 | 10.06 | 0.01 | Effective | 10.54 | 8.29 | 0.13 | Not Effective | 0.12 | 0.04 |
| Animal Manure Compost | S_DMC_1 | 12.75 | 11.58 | 0.16 | Not Effective | 12.21 | 12.98 | 0.25 | Not Effective | 0.73 | 0 |
| | S_DMC_2 | 12.75 | 10.35 | 0.00 | Effective | 12.21 | 16.56 | 0.00 | Not Effective | 0.73 | 0.08 |
| | C_CMC_1 | 15.56 | 17.6 | 0.23 | Not Effective | 10.54 | 9.01 | 0.21 | Not Effective | 0.12 | 0.13 |
| Wood Test | Y_WC_1 | 27.65 | 20.4 | 0.00 | Effective | 12.78 | 21.1 | 0.00 | Not Effective | 0.41 | 0.11 |
| | T_WC_2 | 11.38 | 8.84 | 0.04 | Effective | 15.39 | 21.6 | 0.00 | Not Effective | 0.23 | 0 |
| | T_WC_3 | 11.38 | 10.6 | 0.36 | Not Effective | 15.39 | 17.1 | 0.24 | Not Effective | 0.23 | 0 |
| Wood + Biosolids | Y_WBSC_1 | 27.65 | 20.4 | 0.03 | Effective | 12.78 | 15.6 | 0.03 | Not Effective | 0.41 | 0.18 |

**Table 7-2 Summary of the service life model on the different compost treated sections**

| Compost Feed Stock Source | Test Section | Service Life Based on | Equation developed | Service Life (Years) | Average Service Life (Years) |
|---|---|---|---|---|---|
| Biosolids Compost | S_BSC | O.C. | $O.C_t = 15.43\,e^{-4.8\times10^{-4}t}$ | 6.4 | 5.9 |
| | | CEC | $CEC_t = 137.1\,e^{-1.6\times10^{-4}t}$ | 6.2 | |
| | | Total Soil Suction | $\psi_t = 1.73\,e^{t/2868.5}$ | 5.1 | |
| | C_BSC_3 | O.C. | $O.C_t = 11.9\,e^{-6.2\times10^{-4}t}$ | 5.4 | 4.65 |
| | | CEC | $CEC_t = 112.2\,e^{-5.3\times10^{-4}t}$ | 4.1 | |
| | | Total Soil Suction | $\psi_t = 2.25\,e^{t/2869}$ | 4.4 | |
| Animal Manure Compost | S_DMC | O.C. | $O.C_t = 29.3\,e^{-8.9\times10^{-4}t}$ | 4.5 | 4.86 |
| | | CEC | $CEC_t = 133.3\,e^{-1.6\times10^{-4}t}$ | 5.0 | |
| | | Total Soil Suction | $\psi_t = 1.48\,e^{t/2800.3}$ | 5.0 | |
| | C_CMC_1 | O.C. | $O.C_t = 6.09\,e^{-3\times10^{-4}t}$ | 4.7 | 4.47 |
| | | CEC | $CEC_t = 98.1\,e^{-4.4\times10^{-4}t}$ | 4.4 | |
| | | Total Soil Suction | $\psi_t = 2.25\,e^{t/1856.5}$ | 4.3 | |
| Wood Compost | Y_WC_1 | O.C. | $O.C_t = 10.56\,e^{-4.4\times10^{-4}t}$ | 5.8 | 5.42 |
| | | CEC | $CEC_t = 89.1\,e^{-2.2\times10^{-4}t}$ | 7.0 | |
| | | Total Soil Suction | $\psi_t = 1.58\,e^{t/1513.8}$ | 3.4 | |
| | T_WC_2 | O.C. | $O.C_t = 13.8\,e^{-6.2\times10^{-4}t}$ | 4.7 | 5.68 |
| | | CEC | $CEC_t = 96.5\,e^{-1.4\times10^{-4}t}$ | 8.8 | |
| | | Total Soil Suction | $\psi_t = 2.19\,e^{t/2506.9}$ | 3.5 | |
| | T_WC_3 | O.C. | $O.C_t = 19.4\,e^{-5.3\times10^{-4}t}$ | 6.5 | 8.03 |
| | | CEC | $CEC_t = 112.5\,e^{-1.3\times10^{-4}t}$ | 13.6 | |
| | | Total Soil Suction | $\psi_t = 1.54\,e^{t/1677.7}$ | 3.9 | |
| Wood Compost + Biosolids | Y_WBSC_1 | O.C. | $O.C_t = 9.8\,e^{-4.8\times10^{-4}t}$ | 4.8 | 5.6 |
| | | CEC | $CEC_t = 124.3\,e^{-2.8\times10^{-4}t}$ | 8.1 | |
| | | Total Soil Suction | $\psi_t = 1.65\,e^{t/1552}$ | 3.8 | |

# APPENDIX A

# DIGITAL IMAGING DATA


**Figure A-1 DMC_1 section at Stephenville, TX on August 2006 (Part 1)**


**Figure A-2 DMC_1 section at Stephenville, TX on August 2006 (Part 2)**


**Figure A-3 Control Section at Stephenville, TX on August 2006 (Part 1)**


**Figure A-4 Control Section at Stephenville, TX on August 2006 (Part 2)**


**Figure A-5 DMC_1 section at Stephenville, TX on December 2006 (Part 1)**


**Figure A-6 DMC_1 section at Stephenville, TX on December 2006 (Part 2)**


**Figure A-7 Control Section at Stephenville, TX on December 2006 (Part 1)**


**Figure A-8 Control Section at Stephenville, TX on December 2006 (Part 2)**


**Figure A-9 DMC_1 section at Stephenville, TX on February 2007 (Part 1)**


**Figure A-10 DMC_1 section at Stephenville, TX on February 2007 (Part 2)**


**Figure A-11 Control Section at Stephenville, TX on February 2007 (part 1)**


**Figure A-12 Control Section at Stephenville, TX on February 2007 (part 2)**

**Figure A-13 DMC_1 section at Stephenville, TX on December 2007 (Part 1)**

**Figure A-14 DMC_1 section at Stephenville, TX on December 2007 (Part 2)**

**Figure A-15 Control Section at Stephenville, TX on December 2007 (part 1)**

**Figure A-16 Control Section at Stephenville, TX on December 2007 (part 2)**


**Figure A-17 CMC_1 section at Corpus Christi, TX August 2006 (Part 1)**


**Figure A-18 CMC_1 section at Corpus Christi, TX on August 2006 (Part 2)**


**Figure A-19 Control section at Corpus Christi, TX August 2006 (Part 1)**


**Figure A-20 Control section at Corpus Christi, TX August 2006 (Part 2)**

**Figure A-21 CMC_1 section at Corpus Christi, TX May 2007 (Part 1)**

**Figure A-22 CMC_1 section at Corpus Christi, TX May 2007 (Part 2)**

**Figure A-23 Control section at Corpus Christi, TX May 2007 (Part 1)**

**Figure A-24 Control section at Corpus Christi, TX May 2007 (Part 2)**

**Figure A-25 CMC_1 section at Corpus Christi, TX October 2007 (Part 1)**

**Figure A-26 CMC_1 section at Corpus Christi, TX October 2007 (Part 2)**

**Figure A-27 Control section at Corpus Christi, TX October 2007 (Part 1)**

**Figure A-28 Control section at Corpus Christi, TX October 2007 (Part 2)**


**Figure A-29 WBSC_1 section at Yoakum, TX on August 2006 (Part 1)**


**Figure A-30 WBSC_1 section at Yoakum, TX on 2006 (Part 2)**


**Figure A-31 WBSC_1 section at Yoakum, TX on August 2006 (Part 3)**


**Figure A-32 WBSC_1 section at Yoakum, TX on August 2006 (Part 4)**


**Figure A-33 WC_1 section at Yoakum, TX on August 2006 (Part 1)**


**Figure A-34 WC_1 section at Yoakum, TX on August 2006 (Part 2)**


**Figure A-35 WC_1 section at Yoakum, TX on August 2006 (Part 3)**


**Figure A-36 WC_1 section at Yoakum, TX on August 2006 (Part 4)**


**Figure A-37 Control section at Yoakum, TX on August 2006 (Part 1)**


**Figure A-38 Control section at Yoakum, TX on August 2006 (Part 2)**


**Figure A-39 Control section at Yoakum, TX on August 2006 (Part 3)**


**Figure A-40 Control section at Yoakum, TX on August 2006 (Part 4)**

**Figure A-41 WBSC_1 section at Yoakum, TX on April 2007 (Part 1)**

**Figure A-42 WBSC_1 section at Yoakum, TX on April 2007 (Part 2)**

**Figure A-43 WBSC_1 section at Yoakum, TX on April 2007 (Part 3)**

**Figure A-44 WBSC_1 section at Yoakum, TX on April 2007 (Part 4)**

**Figure A-45 WC_1 section at Yoakum, TX on April 2007 (Part 1)**

**Figure A-46 WC_1 section at Yoakum, TX on April 2007 (Part 2)**

**Figure A-47 WC_1 section at Yoakum, TX on April 2007 (Part 3)**

**Figure A-48 WC_1 section at Yoakum, TX on April 2007 (Part 4)**

**Figure A-49 Control section at Yoakum, TX on April 2007 (Part 1)**

**Figure A-50 Control section at Yoakum, TX on April 2007 (Part 2)**

**Figure A-51 Control section at Yoakum, TX on April 2007 (Part 3)**

**Figure A-52 Control section at Yoakum, TX on April 2007 (Part 4)**

**Figure A-53 WBSC_1 section at Yoakum, TX on October 2007 (Part 1)**

**Figure A-54 WBSC_1 section at Yoakum, TX on October 2007 (Part 2)**


**Figure A-55 WBSC_1 section at Yoakum, TX on October 2007 (Part 3)**


**Figure A-56 WBSC_1 section at Yoakum, TX on October 2007 (Part 4)**

**Figure A-57 WC_1 section at Yoakum, TX on October 2007 (Part 1)**

**Figure A-58 WC_1 section at Yoakum, TX on October 2007 (Part 2)**

**Figure A-59 WC_1 section at Yoakum, TX on October 2007 (Part 3)**

**Figure A-60 WC_1 section at Yoakum, TX on October 2007 (Part 4)**

**Figure A-61 Control section at Yoakum, TX on October 2007 (Part 1)**

**Figure A-62 Control section at Yoakum, TX on October 2007 (Part 2)**

**Figure A-63 Control section at Yoakum, TX on October 2007 (Part 3)**

**Figure A-64 Control section at Yoakum, TX on October 2007 (Part 4)**

**Figure A-65 WC_2 compost treated section at Tyler, TX on December 2006**


**Figure A-66 WC_3 compost treated section at Tyler, TX on December 2006**


**Figure A-67 Control section at Tyler, TX on December 2006 (Part 1)**


**Figure 7-68 Control section at Tyler, TX on December 2006 (Part 2)**


**Figure A-69 Control section at Tyler, TX on December 2006 (Part 3)**


**Figure A-70 Control section at Tyler, TX on December 2006 (Part 4)**


**Figure A-71 Control section at Tyler, TX on December 2006 (Part 5)**


**Figure A-72 WC_2 compost treated section at Tyler, TX on August 2006**


**Figure A-73 WC_3 compost treated section at Tyler, TX on August 2006**


**Figure A-74 Control section at Tyler, TX on August 2006 (Part 1)**


**Figure A-75 Control section at Tyler, TX on August 2006 (Part 2)**


**Figure A-76 Control section at Tyler, TX on August 2006 (Part 3)**


**Figure A-77 Control section at Tyler, TX on August 2006 (Part 4)**


**Figure A-78 Control section at Tyler, TX on August 2006 (Part 5)**

**Figure A-79 Control section at Tyler, TX on August 2006 (Part 6)**

**Figure A-80 WC_2 compost treated section at Tyler, TX on March 2007**

**Figure A-81 WC_3 compost treated section at Tyler, TX on March 2007**

**Figure A-82 Control section at Tyler, TX on March 2007 (Part 1)**


**Figure A-83 Control section at Tyler, TX on March 2007 (Part 2)**


**Figure A-84 Control section at Tyler, TX on March 2007 (Part 3)**


**Figure A-85 Control section at Tyler, TX on March 2007 (Part 4)**


**Figure A-86 Control section at Tyler, TX on March 2007 (Part 5)**


**Figure A-87 Control section at Tyler, TX on March 2007 (Part 6)**

**Figure A-88 WC_2 compost treated section at Tyler, TX on April 2007**

**Figure A-89 WC_3 compost treated section at Tyler, TX on April 2007**

**Figure A-90 Control section at Tyler, TX on April 2007 (Part 1)**

**Figure A-91 Control section at Tyler, TX on April 2007 (Part 2)**

**Figure A-92 Control section at Tyler, TX on April 2007 (Part 3)**

**Figure A-93 Control section at Tyler, TX on April 2007 (Part 4)**

**Figure A-94 Control section at Tyler, TX on April 2007 (Part 5)**

**Figure A-95 Control section at Tyler, TX on April 2007 (Part 6)**

**Figure A-96 WC_2 compost treated section at Tyler, TX on May 2007**


**Figure A-97 WC_3 compost treated section at Tyler, TX on May 2007**


**Figure A-98 Control section at Tyler, TX on May 2007 (Part 1)**

**Figure A-99 Control section at Tyler, TX on May 2007 (Part 2)**

**Figure A-100 Control section at Tyler, TX on May 2007 (Part 3)**

**Figure A-101 Control section at Tyler, TX on May 2007 (Part 4)**

**Figure A-102 Control section at Tyler, TX on May 2007 (Part 5)**

**Figure A-103 Control section at Tyler, TX on May 2007 (Part 6)**

**Figure A-104 WC_2 compost treated section at Tyler, TX on August 2007**

**Figure A-105 WC_3 compost treated section at Tyler, TX on August 2007**

**Figure A-106 Control section at Tyler, TX on August 2007 (Part 1)**

**Figure A-107 Control section at Tyler, TX on August 2007 (Part 2)**

**Figure A-108 Control section at Tyler, TX on August 2007 (Part 3)**

**Figure A-109 Control section at Tyler, TX on August 2007 (Part 4)**

**Figure A-110 Control section at Tyler, TX on August 2007 (Part 5)**

**Figure A-111 Control section at Tyler, TX on August 2007 (Part 6)**

**Figure A-112 WC_2 compost treated section at Tyler, TX on October 2007**

**Figure A-113 Control section at Tyler, TX on October 2007 (Part 1)**

**Figure A-114 Control section at Tyler, TX on October 2007 (Part 2)**


**Figure A-115 Control section at Tyler, TX on October 2007 (Part 3)**


**Figure A-116 Control section at Tyler, TX on October 2007 (Part 4)**

**Figure A-117 Control section at Tyler, TX on October 2007 (Part 5)**

**Figure A-118 Control section at Tyler, TX on October 2007 (Part 6)**

# APPENDIX B

# RAINFALL DATA

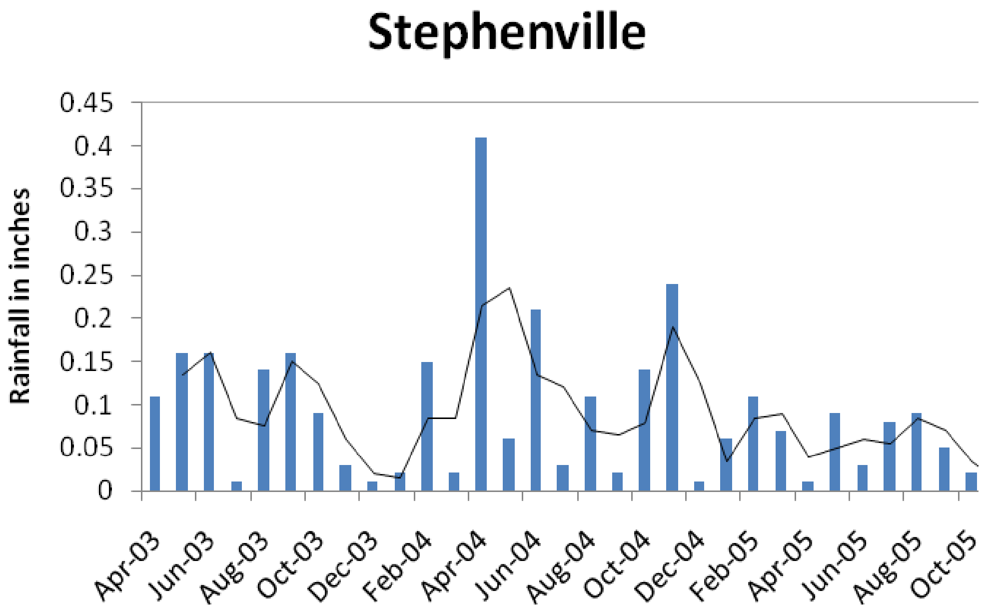


**Figure B-1 Rainfall data at Stephenville, TX test site (Part 1)**

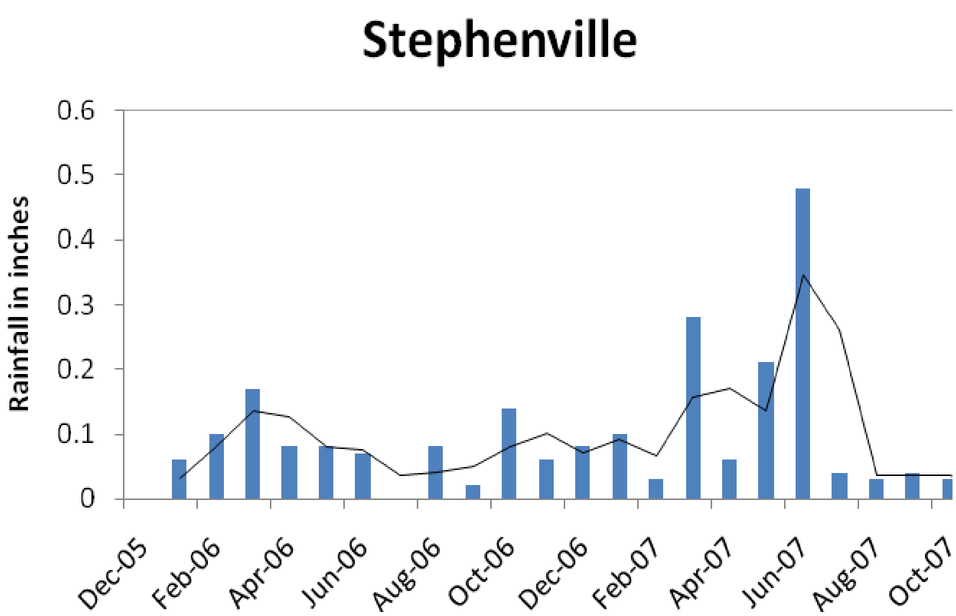


**Figure B-2 Rainfall data at Stephenville, TX test site (Part 2)**

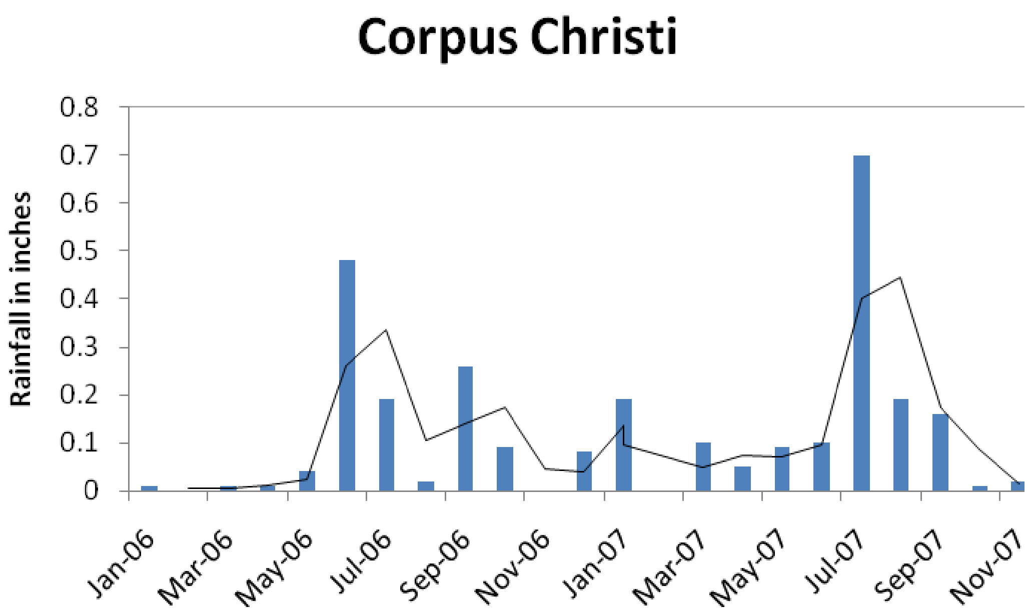


**Figure B-3 Rainfall data at Corpus Christi, TX test site**

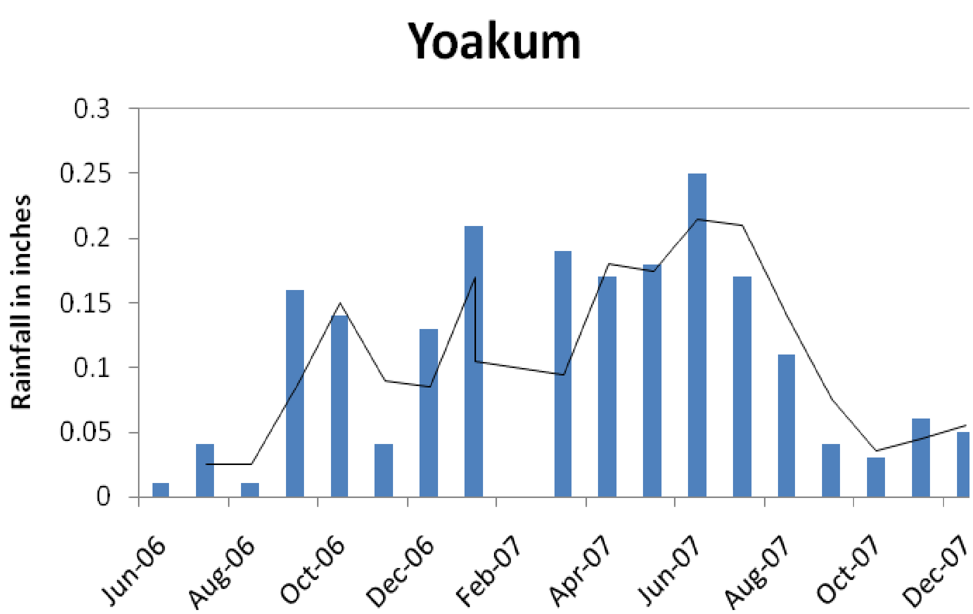


**Figure B-4 Rainfall data at Yoakum, TX test site**

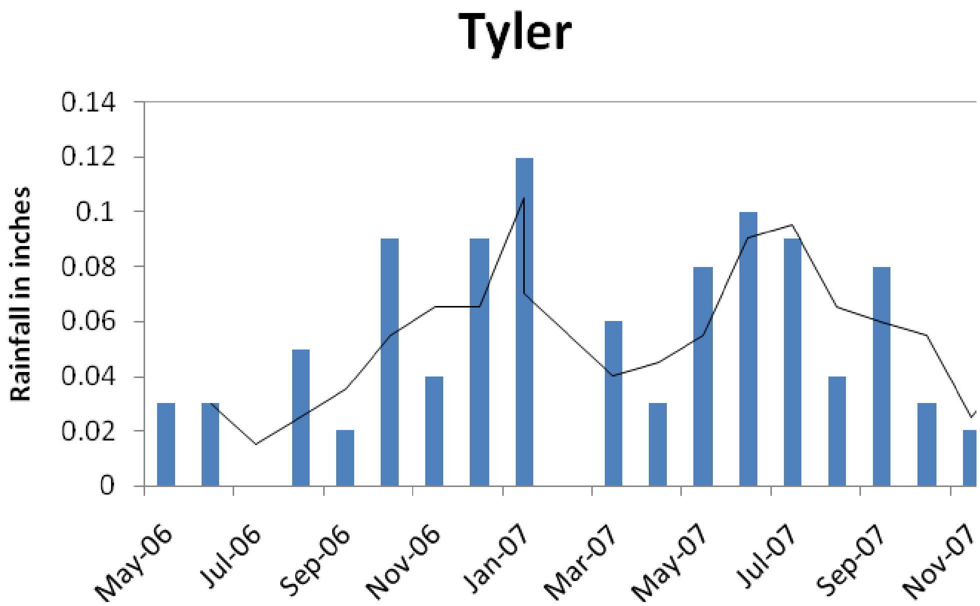


**Figure B-5 Rainfall data at Tyler, TX test site**

APPENDIX C

MOISTURE AND TEMPERATURE VARIATION DATA

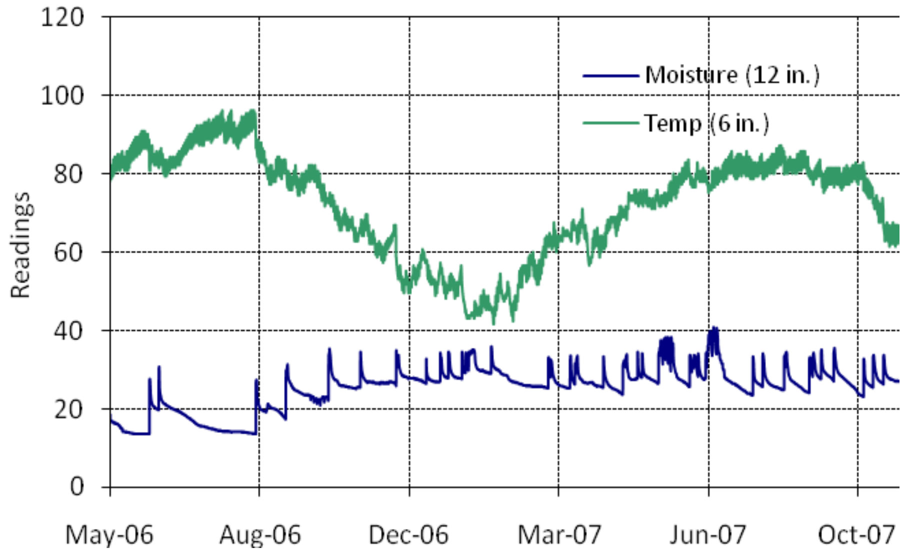


**Figure C-1 Temperature and Moisture variation at the Control section at Stephenville, TX test site**

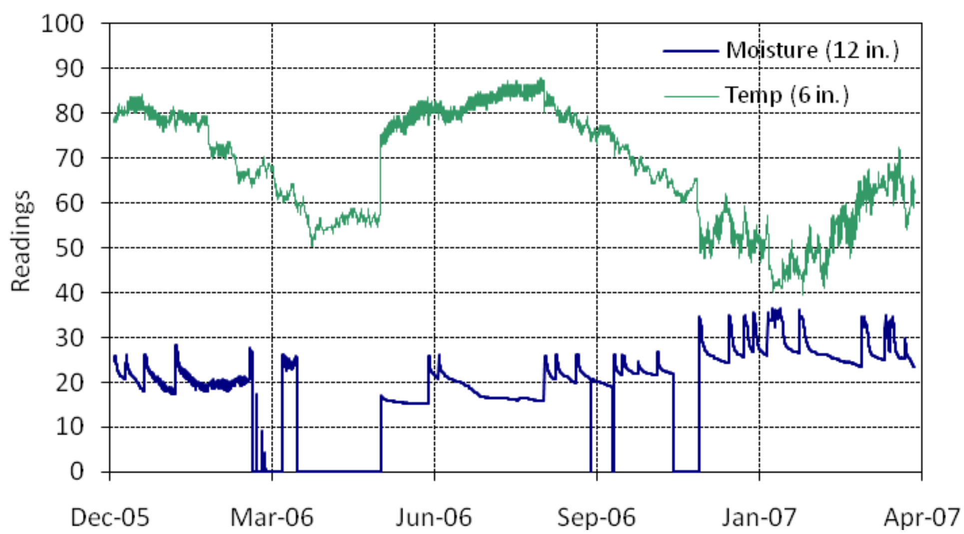


**Figure C-2 Temperature and Moisture variation at the DMC_1 at Stephenville, TX test site**

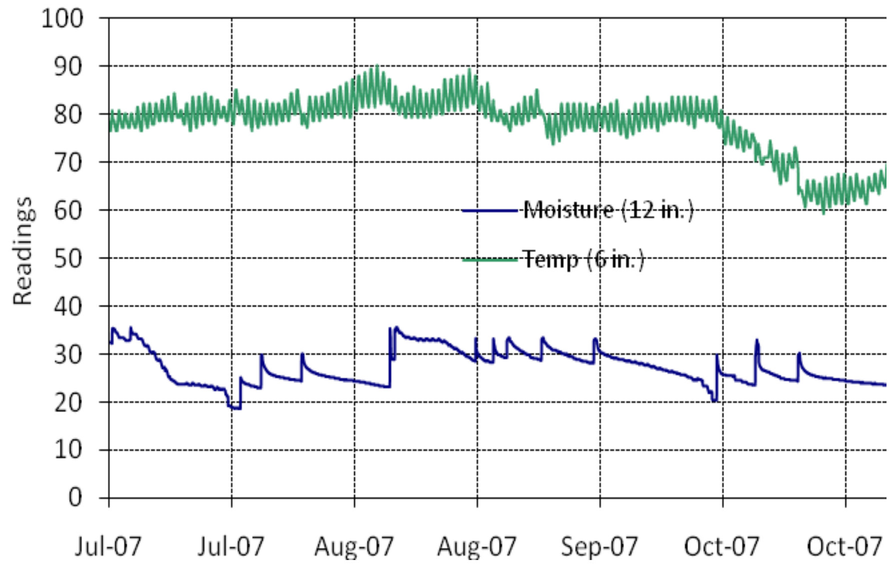


**Figure C-3 Temperature and Moisture variation at the DMC_1 section at Stephenville, TX test site**

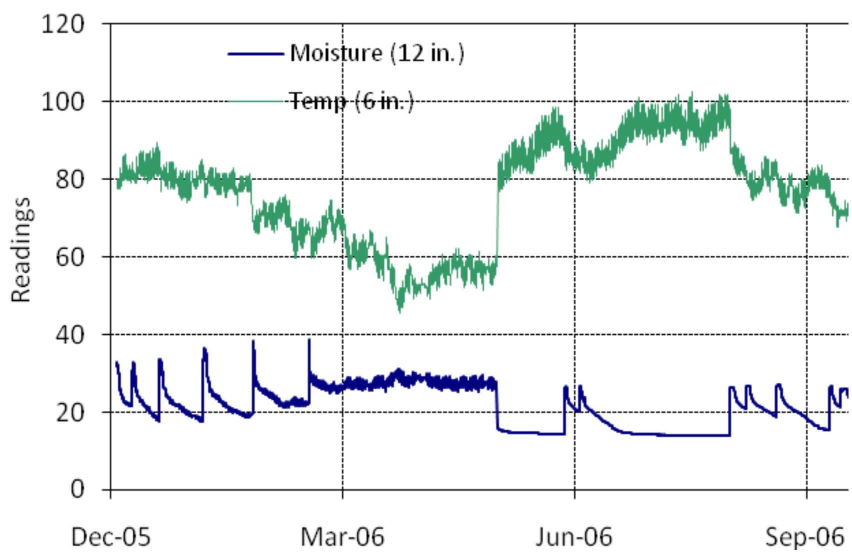


**Figure C-4 Temperature and Moisture variation at the DMC_2 section at Stephenville, TX test site**

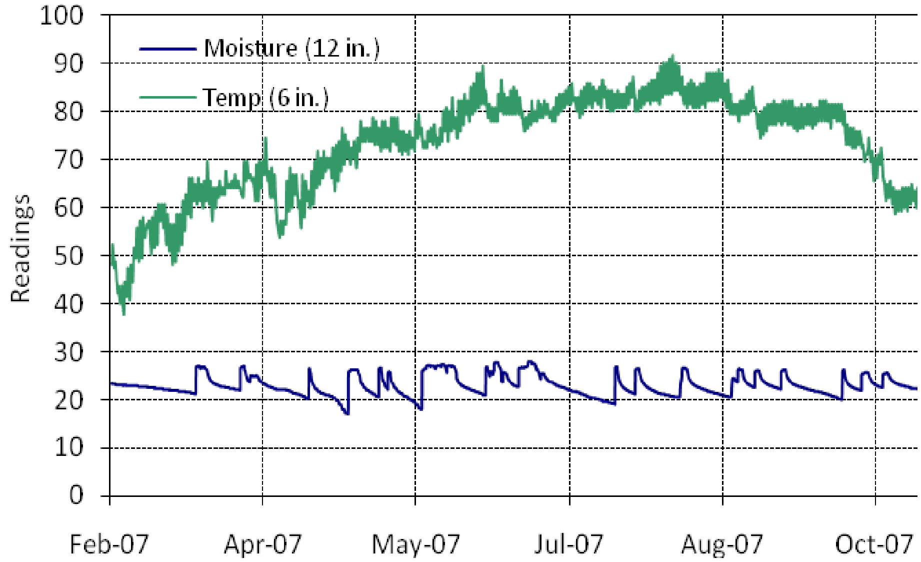


**Figure C-5 Temperature and Moisture variation at the DMC_2 section at Stephenville, TX test site**

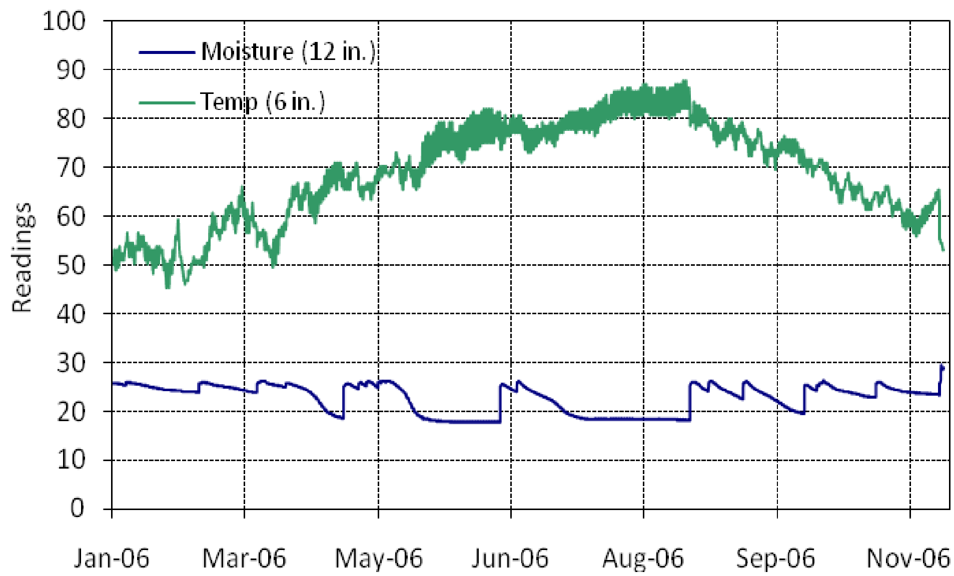


**Figure C-6 Temperature and Moisture variation at the BSC_1 section at Stephenville, TX test site**

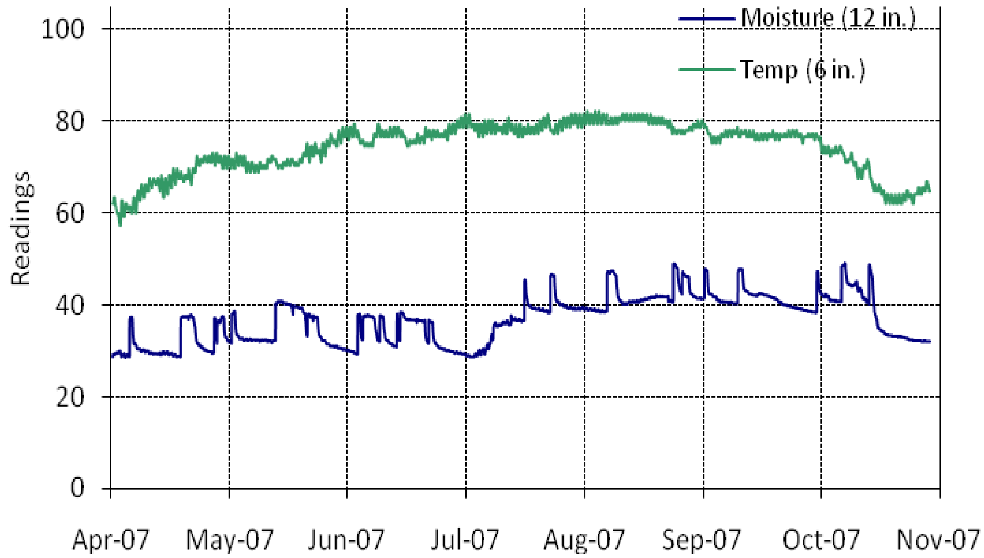


**Figure C-7 Temperature and Moisture variation at the BSC_1 section at Stephenville, TX test site**

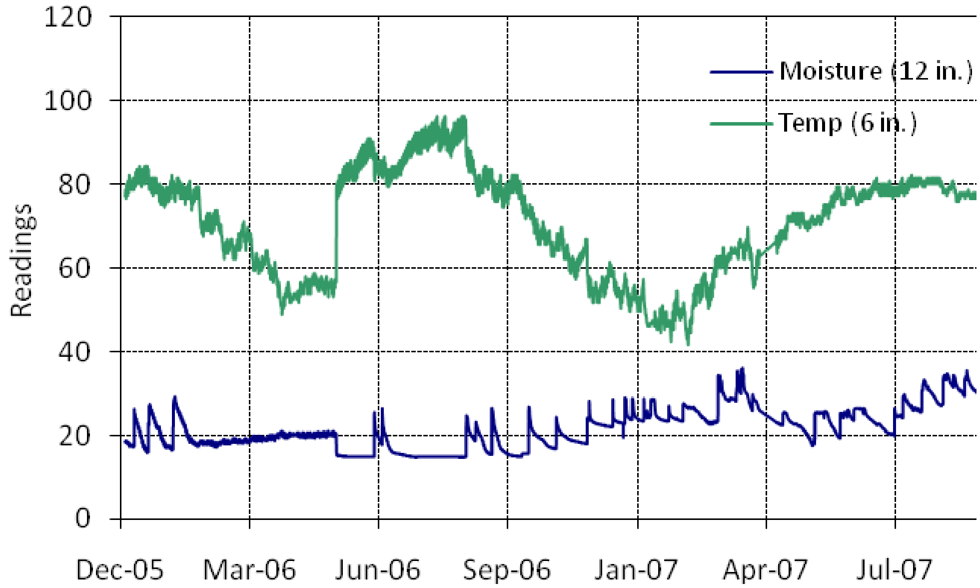


**Figure C-8 Temperature and Moisture variation at the BSC_2 section at Stephenville, TX test site**

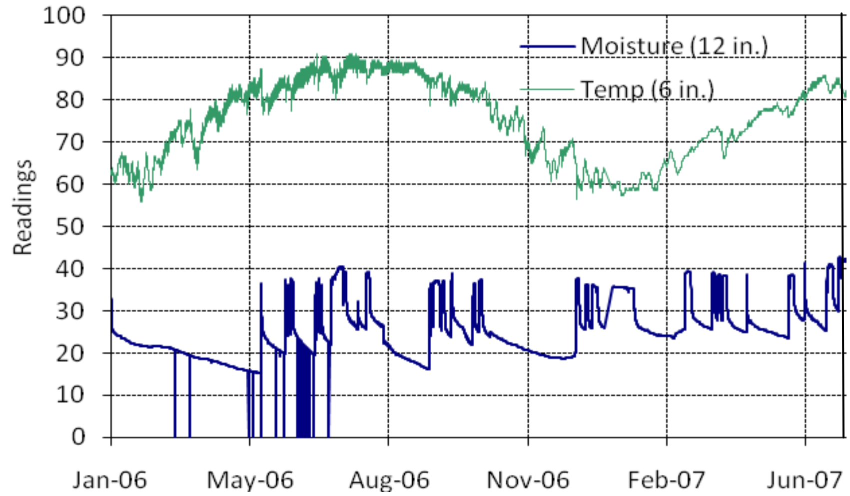


**Figure C-9 Temperature and Moisture variation at the Control section at Corpus Christi, TX test site**

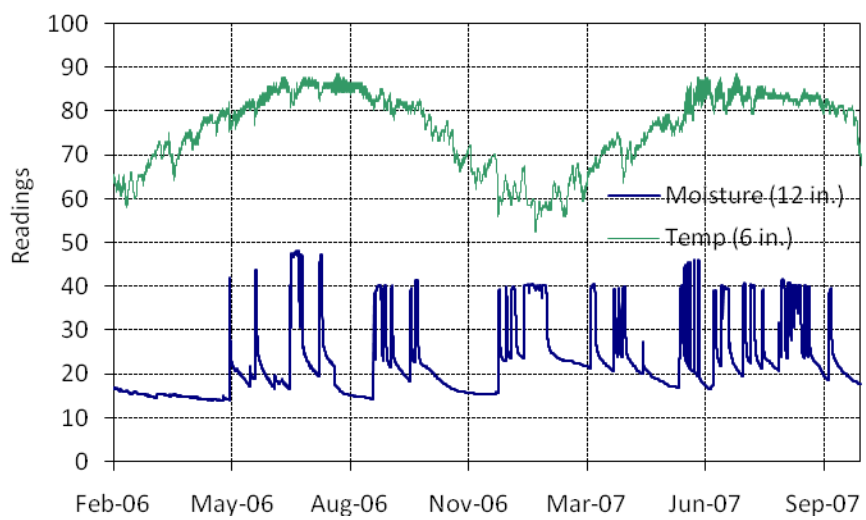


**Figure C-10 Temperature and Moisture variation at the BSC_3 section at Corpus Christi, TX test site**

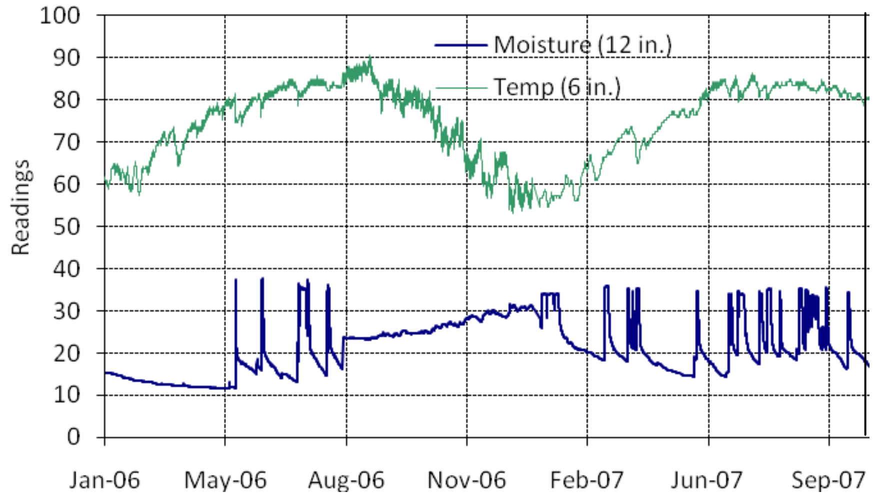


**Figure C-11 Temperature and Moisture variation at the CMC_1 section at Corpus Christi, TX test site**

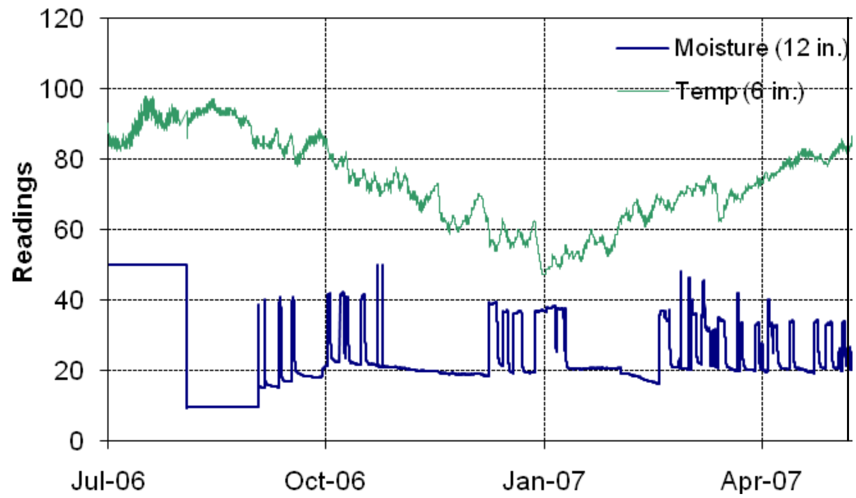


**Figure C-12 Temperature and Moisture variation at the Control section at Yoakum, TX test site**

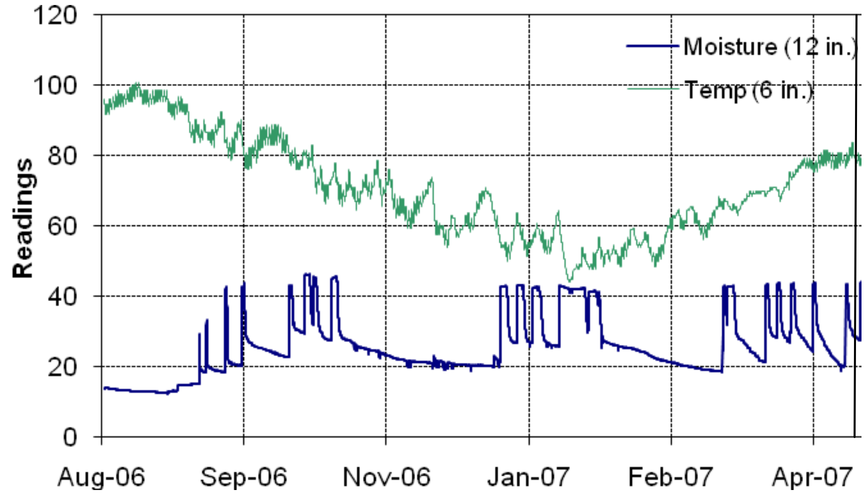


**Figure C-13 Temperature and Moisture variation at the WBSC_1 section at Yoakum, TX test site**

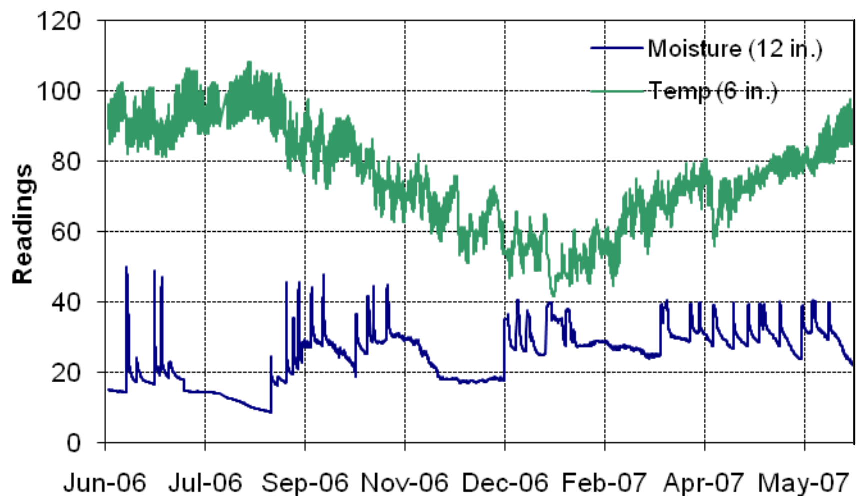


**Figure C-14 Temperature and Moisture variation at the WC_1 section at Yoakum, TX test site**

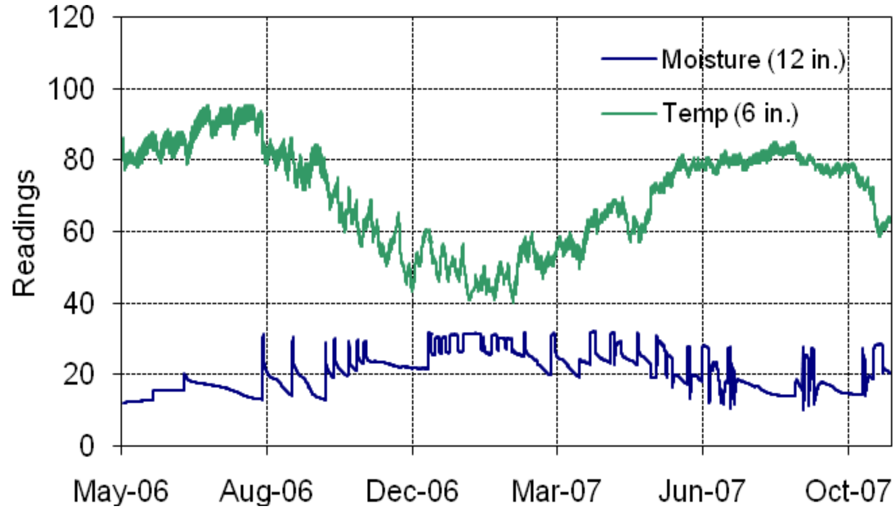


**Figure C-15 Temperature and Moisture variation at the Control section at Tyler, TX test site**

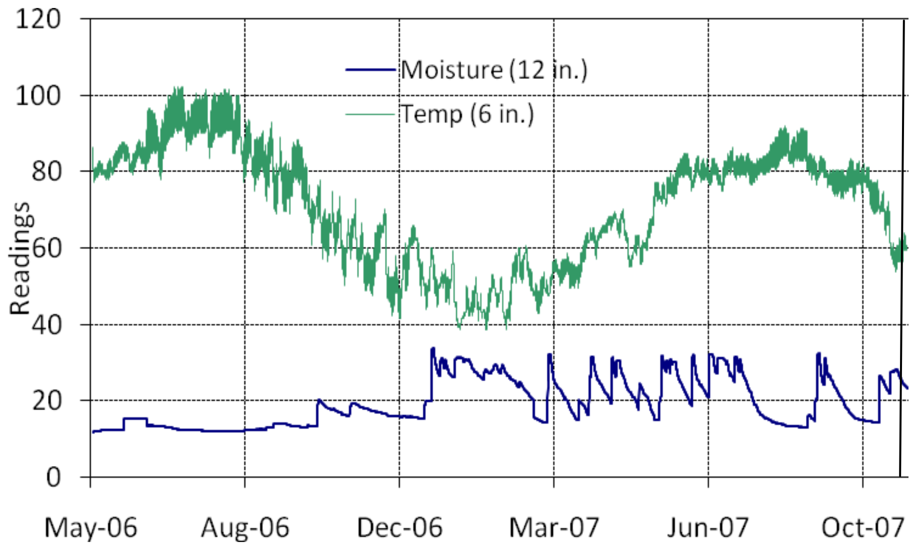


**Figure C-16 Temperature and Moisture variation at the WC_2 section at Tyler, TX test site**

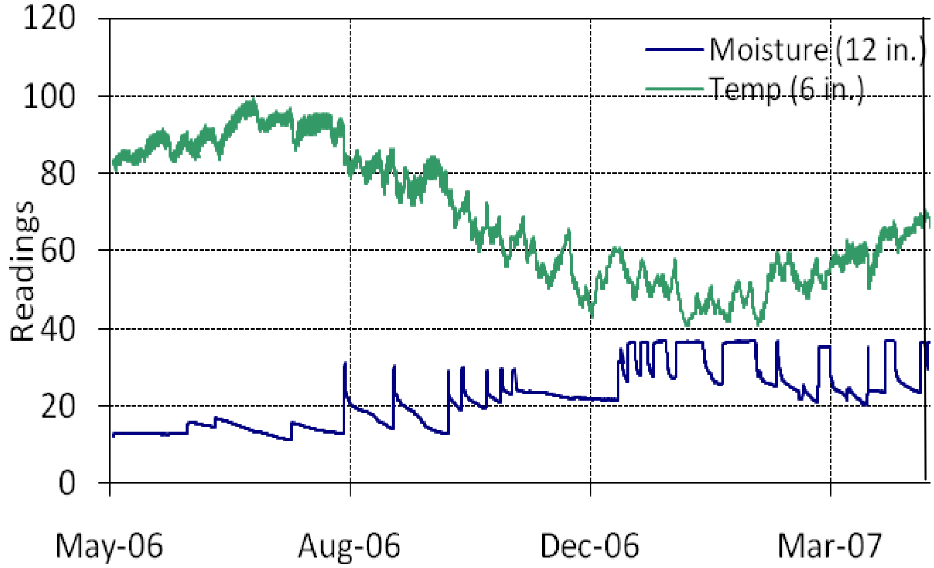


**Figure C-17 Temperature and Moisture variation at the WC_3 section at Tyler, TX test site**

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Ranjith Samuel Rosenberk was born on September 14th, 1980 at the city of Villupuram, India. He completed his bachelor's degree from Civil Engineering at the Madras University, Madras, India in 2001. After completing his bachelor's degree he decided to pursue his Masters Degree at the University of Texas at Arlington in 2001. He completed his Masters degree under the guidance of Dr. Melanie Sattler. He received his Masters degree from the University of Texas at Arlington on August 2004. During his graduate studies he was working as a Graduate research Assistant under Dr. Melanie Sattler on "Adsorption of Carbonyl Sulfide using Activated Carbon". In 2005 he decided to enter into the doctoral program majoring in Geotechnical Engineering under the guidance and supervision of Dr. Anand J. Puppala. During the Doctoral program he worked both as a Graduate research Assistant and Graduate Teaching Assistant. He was offered the Dean Doctoral Fellowship and STEM GRA Scholarship during his program. His project was sponsored by the Texas Department of Transportation. He received his Doctor of Philosophy degree from the University of Texas at Arlington on August 2008.