University of Ottawa

Experimental Characterization of the Thermal, Hydraulic and Mechanical (THM) Properties of Compost based Landfill Covers

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Abstract

Landfills are considered to be one of the major sources of anthropogenic methane (CH_4) emissions in the environment. A landfill biocover system optimizes environmental conditions for biotic CH_4 consumption that controls the fugitive and residual emissions from landfills. A compost material has more oxidation potential in comparison to any other material due to its high porosity, organic content, free flux for gases and water holding capacity. Thermal, hydraulic, bio – chemical and mechanical (THMCB) properties are important factors that can significantly affect the performance of biocover material with regards to CH_4 oxidation potential as well as structural stability. Technical data on the thermal, hydraulic and mechanical (THM) properties of compost based biocover materials are quite limited. Hence, a detailed experimental program has been carried out at the University of Ottawa to study the THM properties and behaviour of compost biocover material by conducting experimental tests on small compost samples as well as by performing column experiments.

The test results indicate that lower water content (dry of optimum for compaction curve) shows more free air space (FAS) in comparison to higher water content. The compost has almost the same shear strength for various initial water contents and dry unit weights; however, it settles and swells more at higher water content than lower water content per mechanical test results. The thermal and hydraulic properties of compost are a function of the compaction degree in addition to various other parameters. It is also found that the THM properties of compost are strongly coupled and the degree of saturation greatly affects the FAS.

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List of Symbols, Abbreviations and Nomenclature

THCMB	Thermal, hydraulic, chemical, mechanical and biological
GWP	Global warming potential
CH_4	Methane
CO_2	Carbon dioxide
C-N-P	Carbon nitrogen phosphorous
Tg	Tetra gram
USA	United States of America
LFG	Landfill gases
GHG	Greenhouse gases
G	Gram
kPa	Kilopascal
c	Cohesion
φ	Angle of internal friction
DM	Dry matter
WHC	Water holding capacity
Ppm	Parts per million
bp	Billion parts
%	Percentage
DNA	Deoxyribonucleic acid
mmoc	Methane monooxygenase
RNA	Ribonucleic acid

PCR	Polymerase chain reaction
uL	Micro litre
^{O}C	Degree centigrade
ICP	Inductively coupled plasma
W/m. ^{0}c	Watt per meter degree centigrade
K. m/W	Kelvin meter per watt
kJ $kg^{-1}K^{-1}$	Kilo joule kilogram per degree centigrade
mm^2/sec	millimetre sq per second
cm^2/sec	centimetre sq. per second
cm/sec	Centimetre per second
kN/m^3	Kilo newton per cu. meter
THCM	Thermo-hydro-chemical and mechanical
EC	Electrical conductivity
VWC	Volumetric water content
μS/cm	Micro seimens per centimetre

Chapter 1. INTRODUCTION

1.1 Background

Municipal solid waste landfill is one of the largest sources of anthropogenic methane (CH_4) emissions in the atmosphere which contributes 9 to 70 Tg/year of CH_4 to the environment (Yuan, 2006). The occurrence of the anaerobic degradation of municipal solid waste results in the production of two important gases, namely, carbon dioxide (CO_2) and CH_4. Table 1-1 shows the composition of landfill gases (LFG). CH_4 has 23 times more global warming potential (GWP) than CO_2 due to its stronger molar absorption coefficient, despite its smaller quantity in the atmosphere (IPCC 2007). CH_4 is second in order after CO_2 for atmospheric concentration (Pokhrel, 2006). According to Yuan (2006), landfills in the USA are contributing to about 30 – 35% of CH_4 into the atmosphere.

Table 1-1: Composition of landfill gases

Compound	**mL/L**
Methane (CH_4)	400 - 700
Carbon dioxide (CO_2)	300 - 600
Carbon monoxide	0 - 30
Nitrogen (N_2)	30 - 50
Hydrogen (H_2)	0 - 50

Oxygen	0 - 30
Hydrogen sulphide (H_2S)	0 - 20
Trace compounds	0 - 10

(Data source: Yuan, 2006)

Two main approaches can be used for the mitigation of LFG. Up to 40% to 90% of LFG can be used for commercial recovery by using a network of collection pipes. The remaining gas passes through an intermediate, final cover and in some cases, through lateral adjoining areas (Huber-Humer, 1998). However, commercial recovery is not economically feasible if the landfills are small or the biodegradation process is slow. In such scenarios, a layer of biocover is incorporated into the landfill cover system. The biocover is an integral part of the landfill system. The CH_4 gas that passes through a biocover transforms into CO_2. Methanotrophs are the bacteria that actively take part in the conversion of CH_4 into CO_2 under aerobic conditions through a microbial oxidation process (Ait-Benichou, 2009).

Different materials, such as soil, compost, mixtures of sand and compost, etc., can be used for the construction of landfill biocovers. According to Abichou et al. (2009), Humer-Humber et al. (2009), Scheutz et al. (2009), and Tanthachoon et al. (2007), compost material has more oxidation capability in comparison to other materials. The basic principle of a landfill biocover is to keep the landfill CH_4 emission at zero or a negligible amount for a specified thickness. This can be achieved by establishing a balance between the quantities of CH_4 gas generation and consumption. However, biocover design is quite complex due to the number of parameters involved, such as thermal (T; temperature, thermal properties), hydraulic (H; hydraulic conductivity, water content and degree of saturation, suction, diffusivity, etc.), biological (B; types of bacteria, bacterial activities, CH_4 oxidation capacity, etc.), chemical (C; pH, chemical composition, etc.) and mechanical (M; settlement, shear strength, etc.) factors that can affect its performance.

It is essential to take into consideration the effect of these THMBC parameters for the optimal design of a landfill biocover. Furthermore, these THMBC factors are coupled. This means that the variation in one parameter may influence another parameter, e.g., a change in the settlement behaviour of a cover would definitely affect the hydraulic conductivity (K_u). Figure 1-1 depicts the coupling mechanisms of THCMB for a landfill biocover. Hydraulic, thermal, bio-chemical and mechanical characteristics are key properties that define the performance of a cover material for CH_4 oxidation potential as well as stability. Most of the previous studies on landfill compost-biocover material focused on investigating the biological and chemical properties of compost biocover material and their impact on the CH_4 oxidation capacity of the cover (Abichou et al., 2009; Humer-Huber, 2009; Pokhrel, 2006). However, technical data on the THM properties of compost biocover material and the coupled THM behaviour of compost are quite limited. There is a need to better understand these properties and the coupled THM behaviour of compost, since this is crucial for an optimal design of a compost biocover.

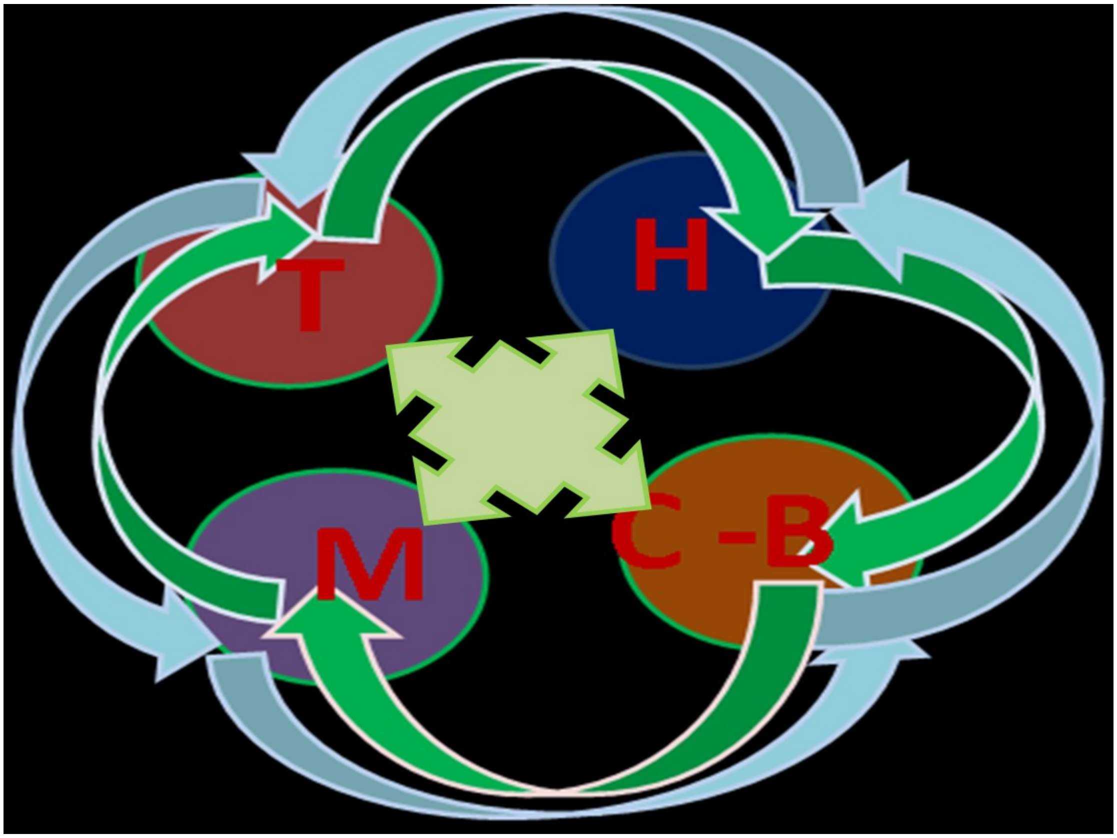


Figure 1-1: Coupling processes in a landfill biocover

1.2 Research Objectives

The main objective of this research is to evaluate the THM properties of the compost material used as a landfill biocover. The research also provides an understanding of the coupled THM properties of compost landfill biocover materials.

The specific objectives of the research are:

- to evaluate the THM properties of compost biocover material by conducting experimental studies on small samples;
- to develop a column experiment that can simulate the field conditions of a landfill biocover in the laboratory as well as allow the study of THMBC behavior of the compost-biocover; and
- to monitor and study coupled THM behavior of compost material in the column experiment.

1.3 Organization of thesis

The thesis is divided into six chapters. **Chapter 1** provides an introduction of the research work as well as the objectives of the research. **Chapter 2** gives a comprehensible literature review. **Chapter 3** explains the materials used and provides the physical (index properties), chemical and biological characteristics of the materials. **Chapter 4** presents the experimental program and the results of the investigation on the THM properties of small samples of compost biocover materials. **Chapter 5** provides the monitoring results for the evolution of coupled THM properties of compost in a column experiment. The conclusions and recommendations are presented in **Chapter 6**. The appendices are supplemented with figures and photographs in the last part.

Chapter 2. LITERATURE REVIEW

2.1 Landfills and importance of greenhouse gases (GHG)

The average temperature of the global climate is increasing day by day due to the increase in concentration of atmospheric gases, such as CO_2, CH_4, nitrous oxide, ozone, and some others due to changes in the living habits of human beings and especially after the Industrial Revolution (Pokhrel, 2006). These atmospheric gases are called greenhouse gases (GHG). Figure 2 - 1 shows the nomenclature of green house gases in the atmosphere.

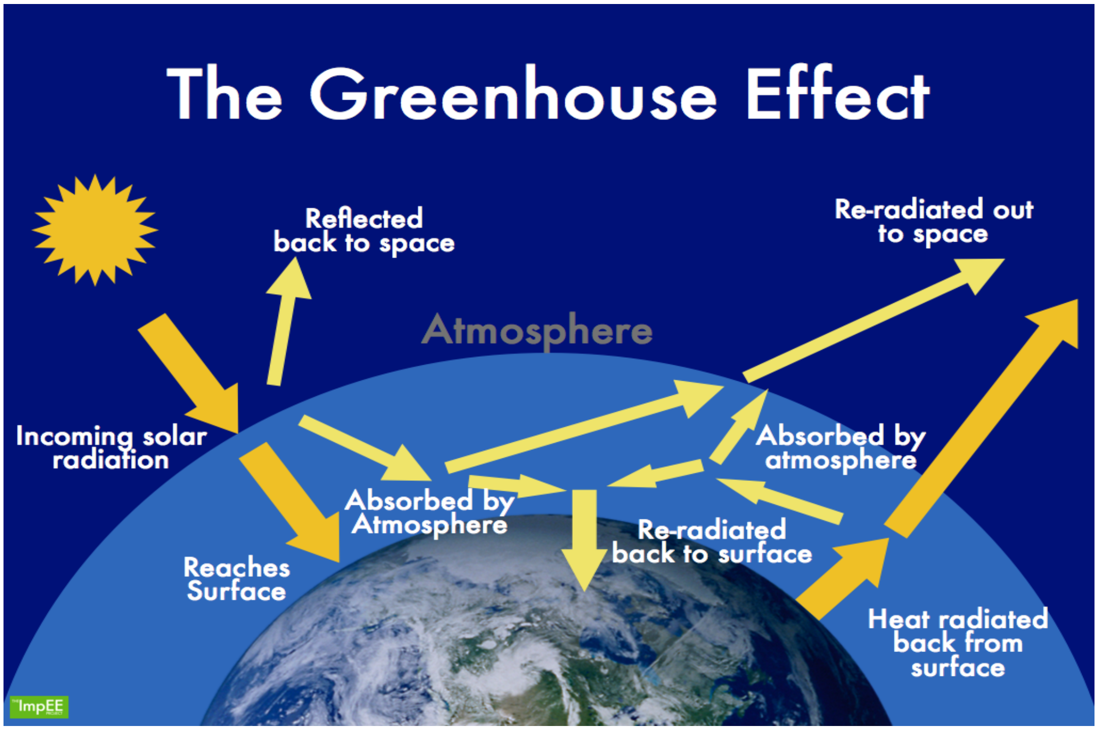


Figure 2-1: Nomenclature of GHG in the atmosphere

Source: Bing images.com

CH_4 is second in descending order after CO_2. However, CH_4 has more oxidation potential in comparison to CO_2. CH_4 has 21 to 23% more global warming potential than CO_2 (IPCC 2001; Karakurat et al., 2011). The concentration of CH_4 in the atmosphere has increased in the past several decades principally due to a great amount of increase in anthropogenic emissions (IPCC 2001). It is now estimated that as much as 30-35 % of the CH_4 anthropogenic emissions into the atmosphere can be attributed to landfills (IPCC 2001). Landfills are one of the most common disposal methods of municipal solid waste in many countries. According to Figure 2-2, landfills in the USA are contributing to 33% of the total CH_4 in the atmosphere.

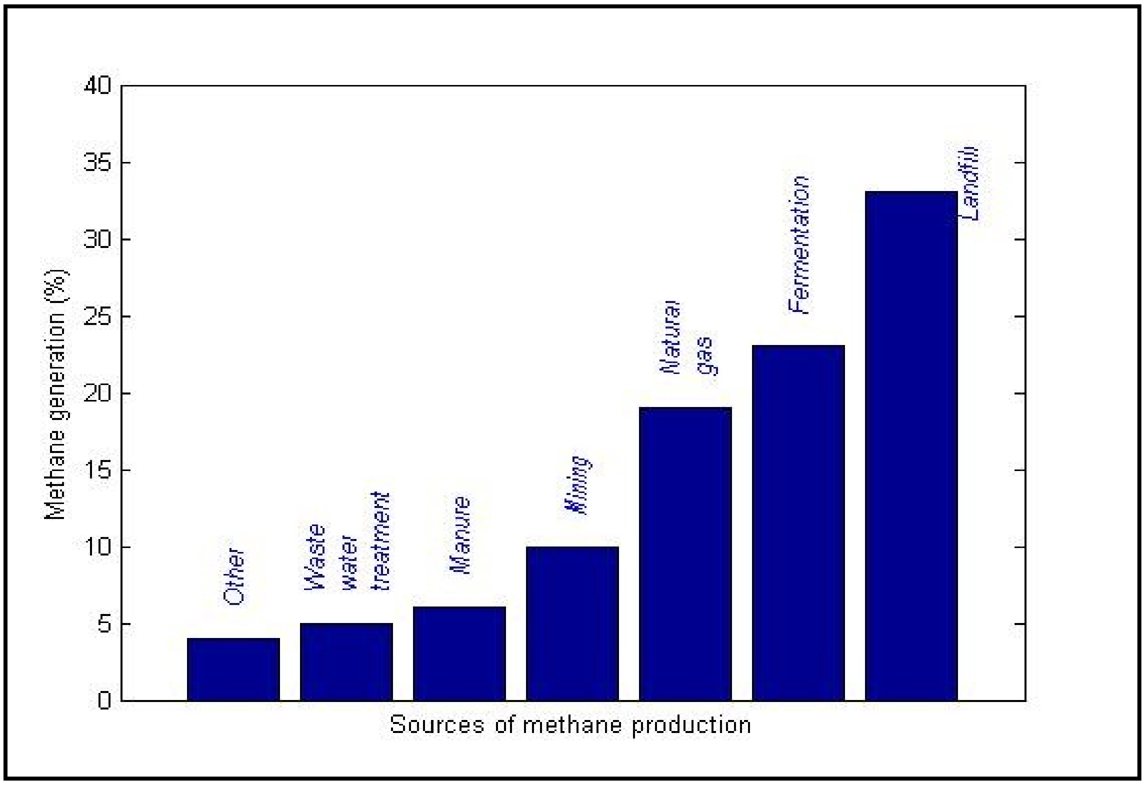


Figure 2-2: Sources for methane generation

(Source: Yuan , 2006)

A landfill cover is an integral part of a landfill that can be used to mitigate this CH_4 emission. The cover may be a conventional cover or a biocover. Figure 2-3 shows a schematic of a landfill biocover. The oxidation layer can be constructed from a variety of materials depending on their oxidation capability.

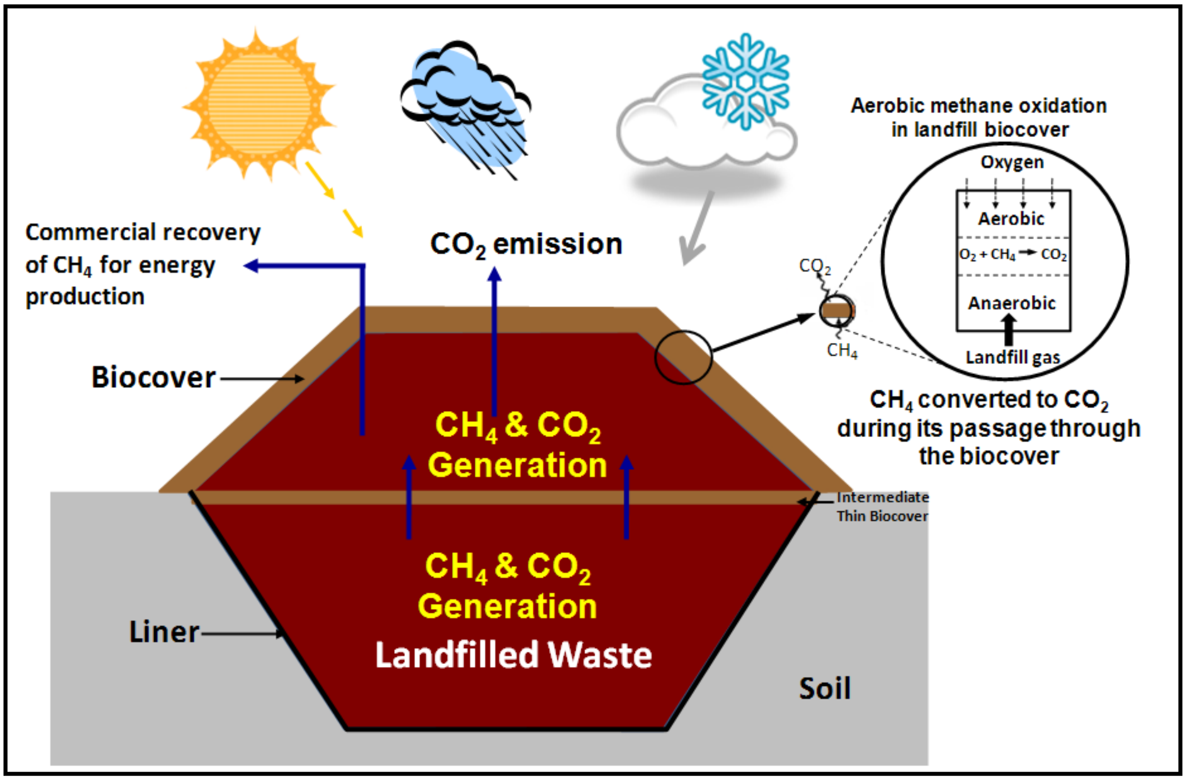


Figure 2-3: Schematic of a landfill biocover

(Source: Fall, 2010)

However, one of the most commonly used materials include composted waste; municipal source separated organics, such as food, kitchen, leaf and yard waste, and carbon-based bulking agents. Compost material is an excellent biocover material due to its long term nutrient supply, greater water holding capacity, and free air space (FAS, Abichou et al., 2009; Humer-Humber et al., 2009; Scheutz et al., 2009; and Tanthachoon et al., 2007).

2.2 Factors that affect the performance of landfill biocovers

A number of parameters, such as water content, temperature, organic and inorganic content, and settlement, may influence the performance of landfill biocovers with regards to CH_4 oxidation potential as well as structural stability. It seems quite cumbersome to provide favorable conditions for landfill biocovers due to a number of parameters that influence the cover design. The above mentioned parameters are associated with THMCB properties which define the behaviors of cover material.

2.2.1 Biological factors

2.2.1.1 Microbiological Oxidation of Methane

A number of diverse organisms are present in the biosphere, which play an important role in deciding the presence of atmospheric trace gases. Methanotrophs are among these organisms that can effectively take part for CH_4 oxidation purposes. According to Pokhrel (2006), methanotrophic bacteria were first discovered in the early 20th century in the gas leak spots of soil. These microorganisms take CH_4 as their food from the atmosphere. Equation 1 represents the oxidation equation in a simplified form.

$$[1] \qquad CH_4 + 2O_2 = CO_2 + 2H_2\text{o} \ (+\ 883\ \text{KJ})$$

Albana (2009) reported that two main groups of methanotrophs exist in nature, namely, Types 1 and II: i) Type I methanotrophs work on the monophosphate pathway (RuMP) to assimilate dehydrate, and ii) Type 2 methanotrophs follow the serine pathway to assimilate formaldehyde. Pokhrel (2006) reported a third form of methanotrophs that use both ways. These types of bacteria are classified based on substrate limitation. Type II methanotrophs are generally found in landfills and wetlands, and commonly known as methanotrophic bacteria.

Tanthachoon (2007) reported that CH_4 is the only carbon and energy source for specific soil microorganisms, methanotrophic bacteria or methanotrophs. These microorganisms entirely degrade CH_4 into CO_2 through their metabolism under aerobic conditions. This process is known as microbial CH_4 oxidation. The study further adds that CH_4 emission from landfills can be effectively controlled by CH_4 oxidation with methanotrophs. Pokhrel (2206) revealed that the methanotrophs in landfill covers play a vital role in the conversion of CH_4 into CO_2 in the presence of atmospheric oxygen (O_2). The CH_4 oxidation rate varies from location to location in the landfills, depending on the seasonal climate changes, physical heterogeneities in the cover medium as well as the concentration of CH_4 within the landfills.

Albana et al. (2007) explained that the CH_4 oxidation rate depends upon the microbial activity growth in the cover medium. It also depends on temperature, moisture content, nutrients and O_2 concentrations. Huber-Humer et al. (2009) confirmed that compost is the most promising cover material which provides suitable chemical and physical properties to methanotrophs under favorable conditions. According to Haug

(1980), the biological system needs a number of inorganic nutrients to maintain its cellular function. Furthermore, the percentage of organic matter in a cover material plays a very crucial role in defining the microbial oxidation process. A particular range of water content may provide the best conditions to methanotrophs, which primarily mitigate CH_4 generation from landfills. Water content may affect the performance of methanotrophic bacteria in different ways. The microbial organisms in the cover may die due to insufficient water content. On the other hand, an excess of water content may block the passage of atmospheric O_2 that is essential for the survival of methanotrophs.

Albana (2009) reported optimal water content between 20% and 35% in a landfill cover soil for maximum CH_4 oxidation whereas Pokhrel (2006) suggested a volumetric water content range from 25% to 75% for maximum CH_4 oxidation with respect to the microbial oxidation process.

Temperature is another parameter that not only influences the growth of methanotrophs, but also the rate of O_2 diffusion in the landfill system. According to Albana (2009), the favorable temperature in the landfill for CH_4 oxidation potential with respect to microbial activity varies from 25^0C to 36^0C. Pokhrel (2006) reported an optimal temperature between 20^0C and 40^0C for CH_4 oxidation purposes.

Albana et al. (2007) reported that the CH_4 oxidation rate is interlinked to microbial growth activity in the cover medium which depends on constituents such as nitrogen, phosphorous and potassium. The proper ratio of carbon, nitrogen, and phosphorus (C - N – P) needs to be established for the nutrient source to meet the demands of methanotrophs (aerobic bacteria). The study added that the addition of these nutrients to cover soil increases the oxidation rate from 38% to 81% at a water content of 30%. However, lower water content reduces the CH_4 oxidation rate despite the addition of nutrients. According to Pokhrel (2006), nitrogen (ammonia, nitrate, nitrite, etc.) is the most favorable nutrient for microbial growth.

A sufficient quantity of O_2 plays a vital role in describing CH_4 oxidation potential with respect to the microbial activities of methanotrophs. Albana (2009) reported that the maximum amount of O_2 exists in the top cover depth which ranges from 0.1- 0.2 m corresponds to maximum oxidation. The study further added that a sufficient quantity of O_2 is necessary to carry out microbiological activities for oxidation purposes. Pokhrel (2006) reported that maximum oxidation takes place at a 3% O_2 concentration. A higher O_2 concentration affects the nitrogen source which limits the growth of methanotrophs for CH_4 oxidation.

2.2.2 Physical and chemical factors

Medium properties, such as texture, particle size and soil gas concentration, affect CH_4 oxidation potential. Pokhrel (2006) reported that a higher probability of CH_4 oxidation takes place in coarse sand. Finer particles prevent O_2 penetration due to decreased gas permeability. Soil texture affects gas transport and controls CH_4 emission and oxidation rates. The study further explained that soil with a particle size of 0.5 to 2 mm results in high oxidation rate. Iscoriaza (2005) explained that porosity affects the performance of methanotrophic bacteria which provide channels for O_2 penetration and contact surface area. Soil gas transport properties, such as permeability and diffusion, are essentially important factors that affect the CH_4 oxidation potential in soil. According to Pokhrel (2006), the soil type may affect the gas transport properties to a great extent, and consequently, influences the CH_4 oxidation rate as CH_4 oxidation potential is more dependent on the interconnected pores despite the surface property of the media. Barometric pressure is another parameter that may influence CH_4 oxidation potential. A reduction in atmospheric pressure may suck the gas out from the cover and vice versa. Iscoriaza (2005) revealed a strong negative correlation between CH_4 oxidation potential and air pressure.

Electrical conductivity (EC) is an important property that defines the salinity status of a soil. EC may play an important role in the transport of nutrients as it predicts the soluble salts in the medium. EC depends on the bulk density, texture, and water holding capacity of the medium (Agnew and Leonard 2003). Soils with an EC more than 4 µS/cm are considered saline. A higher quantity of soluble salt can harm the microbial activities that may affect the CH_4 oxidation potential. The desired EC range of a composting material is less than 4 µS/cm (Huber-Humer, 2009) for covers. The study further discussed that conductivity does not provide sufficient information about the suitability of a substrate for CH_4 oxidation.

The performance of methanotrophs depends upon the maturity and quantity of organic matter in the cover material. Huber-Humer et al. (2009) stated that the organic matter in compost must be stable and mature for CH_4 oxidation purposes. Pupalla et al. (1995) described that a material with less than 75% organic content or more than 25% ash content is classified as an organic soil, whereas a material with an organic content higher than 75% or ash content less than 25% is a peat. Yuan (2006) reported that compost covers enriched with organic matter are able to oxidize all CH_4 emitted from a landfill. Organic matter provides nutrients for methanotrophic bacteria and has high porosity which allows more O_2 penetration sufficient for microbial organisms. These facts really show that the organic content is a useful consideration in the landfill cover design. Huber-Humer et al. (2009) reported that a material with 15% organic content is considered good for landfill cover designs. Mature compost has more potential for CH_4 oxidation in comparison to humus poor soils and cohesive mineral clay soils that are used as cover material. It is added that fresh and not fully matured compost may generate CH_4 rather than oxidize it under unfavorable water-saturated, anaerobic conditions. Mature compost is considered more efficient in that it prevents interference by heterotrophs which compete for O_2 supplies.

The pH of composting material may also play an important role in defining the behavior of the compost material to be used as cover material. Haug (1980) reported that the effect of low and high pH may generate changes in the ionization state of various protein components, such as amine and carboxyl groups, which consequently disturb the enzymatic activity of methanotrophs in the cover material. The study described that a pH ≥ 11.5 significantly reduces the total aerobic count in the composting material. On the other hand, the bacteria cannot survive in pH less than 3. Huber-Humer et al. (2009) reported that various forms of nitrogen, such as ammonia, nitrate, nitrite and Kjehldahl nitrogen (N_{total}), may affect the performance of methanogenic bacteria. On the other hand, an increase in N_{total} or organic matter as well the respiratory activity shows the indication of methanotrophic activities in the cover medium. Higher sulfate contents are also favorable to CH_4 oxidation. Similarly, nitrite is a strong inhibitor of CH_4 oxidation, whereas P is an essential nutrient for methanogenic bacteria. Table 2-1 reports the ranges of chemical parameters favorable for CH_4 oxidation as reported by Huber-Humer et al. (2009).

2.2.3 Hydraulic factors

Various research studies, namely, Albana (2009); Huber-Humer et al. (2009); Visvanathan et al. (2009); Yuan, (2006) and Pokhrel, (2006) have reported the strong impact of water content variation on the performance of covers for CH_4 oxidation. These studies stressed the need to define a proper range of water content for the microbial oxidation process in a cover medium. The degree of saturation may affect the landfill cover in different aspects, such as: i) the degradation phenomenon, ii) the gas flow through a medium, and iii) geotechnical stability of the cover. Huber-Humer et al. (2009) reported that water content is more critical in comparison to temperature for a landfill cover material, and performs three important roles for CH_4 oxidation in landfill covers: i) provides an optimum environment for methanotrophs, ii) may have an effect on the diffusion of O_2 into the cover medium, influencing CH_4 oxidation, and iii) influences gas fluxes through the cover medium. As the water content is increased in the cover medium, it decreases the gas flow due to the filling of the medium (soil/compost) pores with water. The water content that corresponds to the maximum oxidation rate is referred to as optimum water content. Yuan (2006) explained that the oxidation rate increases with an increase in water content up to the optimal water content for a particular cover material. Beyond the optimal water content, CH_4 oxidation rate drops due to the filling of pores with water. Figure 2-4 shows the relationship between oxidation rate and water content variation in a landfill cover.

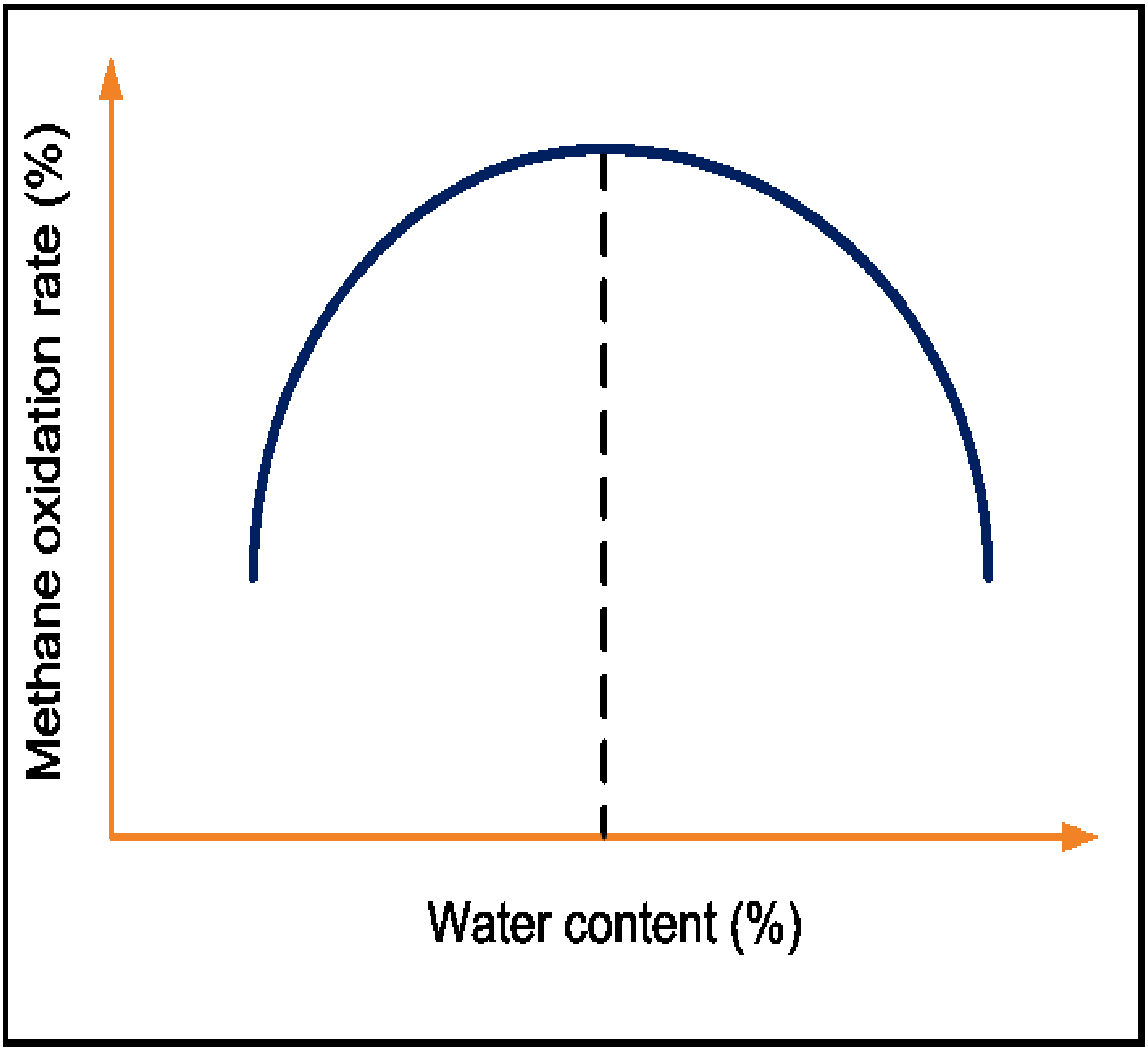


Figure 2-4: Relationship between water content and methane oxidation rate (Source: Yuan, 2006)

Figure 2-4 schematically depicts an optimal range for the maximum CH_4 oxidation rate for specified water contents in a soil cover. At optimal water content, a rapid gas phase molecular diffusion takes place which results in a higher CH_4 oxidation rate due to sufficient microbial activity. As the water content falls below a certain limit, the CH_4 oxidation capability of the cover medium reduces due to the insufficient microbial activity that takes place in the cover medium. On the other hand, higher water content results in the transformation of gas phase molecular diffusion to aqueous phase molecular diffusion which results in the reduction of the CH_4 oxidation rate. Yuan (2006) reported that aqueous diffusion is 104 times slower than gaseous phase diffusion. The optimal oxidation water content depends on the type of cover medium (soil, compost, or a combination, etc.) and varies from location to location depending on the environmental constraints.

The water content which corresponds to the maximum CH_4 oxidation rate is greatly interlinked to some other parameters, such as temperature, organic content, etc. Huber-Humer et al. (2009) stated that compost has more favorable properties, including gas permeability, water retention capacity, and texture for CH_4 oxidation if a water content range from 30% to 50% is maintained in the cover material. The study further added that methanotrophic microorganisms tend to become inactive enzymes as the water content falls below 13% of the maximum water capacity.

Oxidation tends to be zero at a water content less than 6%, and decreases up to 56% under saturation conditions. In addition to water content, gas transport properties considerably affect the CH_4 oxidation rate. Advection and dispersion are two important gas transport mechanisms that control the transport process of CH_4 (outflow) and O_2 (inflow) for CH_4 oxidation in the cover medium. Pokhrel (2006) stated that both of these properties have no connection to each other, and behave in an independent manner. The advective and diffusive fluxes are greatly dependent on the magnitude of partial and total pressure gradients, molar composition of the gas, molecular weight and viscosity of various gas components. The differential pressure between the waste mass and the atmosphere controls the availability of O_2, and the air-filled porosity. The availability of O_2 is absolutely important for CH_4 oxidation purposes.

The hydraulic conductivity (K_u) is an important parameter for consideration in a cover medium for CH_4 oxidation. It defines the movement of water molecules in a cover. It greatly depends on the viscosity, density and porous media properties (Pokhrel, 2006). The soil pores are filled with water for saturated conditions and Darcy's law is followed to determine the K_u. For a particular condition, the saturated K_u is constant in a soil.

Unsaturated K_u is not a constant value and depends on the soil water content. Unsaturated K_u is a function of water content or suction head. According to Pokhrel (2006), the climate and soil factors affect unsaturated $K_{u.}$ The climatic factors are associated with temperature, relative humidity, radiation, etc., whereas the soil factors include soil water potential and water content relationship. The texture and specific area of the soil particles define the retention capacity of the soil. A soil water characteristic curve (SWCC) provides the behaviour of unsaturated soil which defines the relationship between degree of saturation and suction. It also represents the water holding capacity of a soil or any other medium. Figure 2 -5 shows the features of a typical soil SWCC.

The K_u follows a steep fall in transition from saturated to unsaturated conditions and tends to become zero at a particular water contents in which the pore water takes the form of disconnected menisci among soil grains. The suction value increases with a loss in water content.

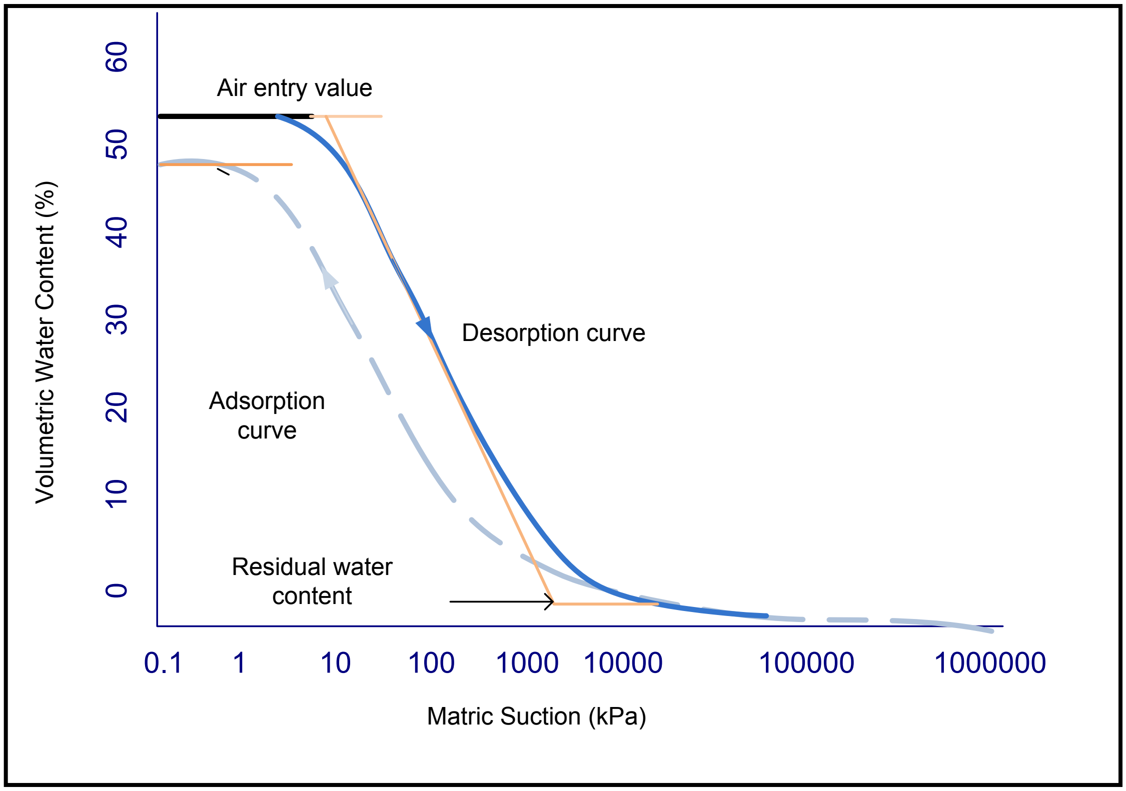


Figure 2-5: Typical soil water characteristic curve
Fredlund and Xing (1994)

Abramson (2001) reported that CH_4 oxidation capability depends on a number of parameters that include climatic conditions and the storage characteristics of the medium. According to Paradelo and Barral (2009), microbial activity takes place at a certain suction pressure of 0.1 MPa in a soil.

The biological activity in soil reduces to a great extent with a suction pressure below and above 0.1 MPa. This shows that the CH_4 oxidation rate is strongly correlated with suction pressure. Daniel (1993) and Kamon (2002) recommended the use of a soil cover K_u that is less than $1x10^{-7}$ cm/sec. Benson (1993) proposed the use of a K_u that is less than $1 x10^{-9}$ cm/sec in a landfill cover. Few studies propose a K_u for the landfill cover in a range between $1x10^{-7}$ and $1x 10^{-10}$ cm /sec (Caldwell 1993).

2.2.4 Thermal factors

Temperature is a critical parameter with a direct impact on microbial activity. It needs to be carefully considered in the evaluation of landfill cover medium to enhance CH_4 oxidation capability. Diaz et al. (2004) reported that the temperature of compost cover material should not increase beyond 50 - 60^0C. The effect of temperature needs to be considered for a landfill biocover in light of its variability with respect to water content, organic matter, chemical inhibitors, and index properties. According to Haug (1980), the chemical reaction and biological activity in compost material take place within a certain temperature range. Temperature outside this range produces inactive enzymes, which is not sufficient to generate the desired reaction for microbes.

Yuan (2009) revealed that CH_4 oxidation in a landfill cover medium is strongly correlated with temperature. Cabral et al. (2010) reported that the optimum temperature for CH_4 oxidation is 25^0C in landfill cover material. According to Pokhral (2006), the CH_4 oxidation of various media is different at different temperatures. The optimal temperature for CH_4 oxidation varies from 20^0C to 35°C. The thermal conductivity (K), thermal resistivity (ρ), thermal diffusivity (α) and volumetric heat capacity are the most important parameters associated with temperature. The growth rates of microbial species are highly related to water variations in relationship to thermal properties along with some other parameters, such as porosity, permeability, etc. Chandrakanthi (2005) added that K is a function of volume fraction and the K of compost depends on the water content, porosity, dry density and temperature. Tan (2009) reported that K depends on the mineral composition of the medium, texture, structure, organic matter, and water and air content. Abu - Hamdeh (2003) reported that K depends on the contact surface area. Chandrakanthi (2005) stated that α and heat capacity (C_p) are also important thermal properties in addition to the K of compost. Abu - Hamdeh (2003) explained that α depends on the air-dry wetness. Pokhral (2006) stated that α is a function of the texture of a medium, organic matter, degree of saturation, and density.

Agnew and Leonard (2003) explained that the specific heat of composting material should not be ignored while defining the thermal behavior of composting material. It was added that specific heat is a function of time and may vary from 200% to 300% for the composting period. The proportion of organic matter plays an important role in defining the percentage increase in the specific heat of compost material. Thermal properties are used to model the transport of heat in any medium, and these properties have to be considered for landfill biocovers as the performance of methanotrophs is greatly dependent on them.

2.2.5 Mechanical factors

Mechanical properties are very important for consideration in a landfill cover design. Settlement plays a very crucial role in determining the performance of landfill cover material as the CH_4 oxidation potential is directly related to FAS. Microbial organisms need a sufficient quantity of O_2 to work in an active and efficient manner. Tim (1993) added that FAS values of 20% to 35% in compost establish the maximum O_2 consumption rate i.e., 95%. According to Diaz (2004), O_2 is the primary element that maintains the respiratory and metabolic activities of microbes. This criterion makes the settlement consideration of landfill cover material more important to be undertaken in the design phase. On the other hand, the landfill cover should have sufficient strength to resist against sliding, rotation and movement of the slope as the slope is considered to be the most critical component of a landfill cover system.

The physical structure of the CH_4 oxidation layer is particularly crucial as it determines gas permeability and subsequently CH_4 load. Moo-Young et al. (1996) reported that the normal stresses across landfill covers may fluctuate between 40 kPa and 60 kPa, and these may reach up to 80 kPa in some circumstances. Benson and Othman (1993) commented that the normal stresses in a landfill cover vary from 14 to 61 kPa. According to Rajesh and Viawanadhem (2009), a landfill barrier is subjected to an overburden pressure of 25 kN/m^2 that includes the self-weight of the drainage layer and cover material. Cabrel et al. (2002) revealed that the normal stresses in a landfill cover vary between 10 -20 kPa. The mechanical characteristics and settlement behavior define the physical structural arrangement of the cover material.

Therefore, cover material may be characterized by these stresses to simulate field conditions. The water content variation in a landfill cover is a critical in that it influences the structural stability as well as oxidation potential of the cover material to a great extent. It is absolutely important to examine the shear strength parameters (c and Φ) and settlement behavior of the cover for different water contents and dry unit weights to figure out the appropriate water content with respect to structural stability and CH_4 oxidation potential.

2.3 Coupled effects and interactions between different factors

CH_4 oxidation potential depends on a number of parameters as discussed above. These parameters may individually affect the CH_4 oxidation rate as well as their interaction with each other. For example, CH_4 oxidation rate is a function of both FAS and gas transport properties. If the settlement in a biocover takes place after some time due to environmental changes, it affects the FAS which ultimately results in an increase or decrease in the diffusivity potential of the cover medium. According to Pokhrel (2006), gas transport properties are associated with soil texture and water content. The CH_4 oxidation rate is greatly related to the diffusivity potential of the cover medium with respect to microbial activity.

Pokhrel (2006) reported a complex relationship between water content and temperature for the CH_4 oxidation rate. A high amount of water content in the cover medium may reduce the CH_4 oxidation potential with respect to low O_2 diffusion and high ammonia concentration. Visvanathan et al. (1999) indicated that the CH_4 oxidation rate in a soil cover is strongly dependent on the interaction between temperature and water content. According to Albana and Fernandes (2009), the interaction between water content, temperature and nutrients affects the CH_4 oxidation rate. Chanderkanthi et al.

(2005) explained that microbial respiration activity in relation to temperature has a strong impact on the CH_4 oxidation capability of the cover medium. Yuan (2006) confirmed that the CH_4 oxidation rate depends on the air-filled porosity of the medium in addition to its water content.

2.4 Essential features of landfill biocover

The main physical and chemical properties of landfill biocover material are summarized in Table 2-1

Table 2-1: Essential features of landfill biocovers

Parameters	**Proposed value**	**Unit**	**Remarks**
Water content	30 - 50	%w/w	Recommended value = 50%
Water holding capacity	50 - 130	%DM	For arid regions, higher WHC is recommended
Air filled pore volume	>25	%v/v	Minimum value = 25%, more suitable >30% at average water content
Particle size distribution	0.063 -2mm: 20 -30; 2 – 6.3 mm,		Approximate target values for well balanced compost structure

conductivity	<4	mS/cm	Methanotrophs are rather tolerant to higher conductivity
pH - value	6.5 – 8.5	-	Methanotrophs are rather tolerant to higher conductivity
SO_4^{-2}	>500	ppm DM	Higher sulfate contents may be favorable for CH_4 oxidation under micro-aerophilic / anaerobic conditions
NH^+ - N	<400	ppm DM	At higher ammonium concentrations CH_4 oxidation may be inhibited
NO^-_2 – N	<0.1 (below detection value)	ppm DM	Nitrite is a strong inhibiter for CH_4 oxidation
NO^-_3	No limit value	ppm DM	Most methanotrophs can use nitrate as N-source
P_{total}	>0.3	%DM	P is an essential nutrient for methanotrophs
Organic content (loss on ignition at 550 ^{0}C	>15	%DM	Higher organic contents are favorable – organic matter must be stable and mature
TOC	>7	%DM	As a substitute factor for the organic content
N_{total} (Kjeldalh)	>0.5 (composts	%DM	Higher N values are favorable

	often >1.0		

(Source: Huber-Humer et al. 2009)

2.5 Summary and conclusions

Compost generally contains two types of bacteria, namely, methanotrophs and methanogenes, and the proportion of these microbial organisms depends on the characteristics of the cover medium. Methanotrophs oxidize CH_4 under aerobic conditions whereas methanogenes generate CH_4 under anaerobic conditions. The performance properties of the bacteria depend on various parameters, such as temperature, organic content, water content, etc., of compost materials. It is absolutely important to define a specific range for all of these parameters for the efficient performance of methanotrophs. For example, the compost should be mature and contain sufficient organic matter. Water content is another key parameter that affects the performance of microbial organisms, and the bacteria may only survive at particular ranges of water content. In addition to water content, knowledge of suction and K_u is also crucial for compost based landfill covers. Physical properties, such as medium texture, atmospheric pressure, interconnected pores and size affect the performance of microbial organisms. Temperature is also a key component that influences the performance of methanotrophic bacteria within a compost biocover. Settlement is another issue for compost based covers as the inclusion of O_2 depends on the amount of FAS and FAS is a function of settlement. It can be concluded from the discussion that a number of parameters that define the THM properties need to be taken into consideration in the design of compost based landfill covers. Technical data is quite limited for the parameters of these properties. In addition to this, the coupled THM behaviour of compost is also not well understood in the literature so far. This stresses the need to individually characterize compost for THM properties and behaviour with small sample laboratory tests and column experiments, respectively. This research program therefore presents detailed small sample laboratory tests in order to characterize the compost material. The coupled THM behaviour of compost based landfill covers is also evaluated with column experiments. The study also presents a useful conclusion as a result of this experimental program.

Chapter 3. MATERIAL USE AND CHARACTERIZATION

3.1 Introduction

To achieve the objectives outlined in Chapter One, it is necessary to describe the compost material used in this study as well as determine its physical, chemical and biological characteristics. The objectives of the present chapter are:

- to provide a description of the compost material used and the composting process,
- to determine the geotechnical index properties of the compost material,
- to determine the biological characteristics of the compost, and
- to determine the chemical characteristics of the compost.

3.2 Compost biocover material used

Compost is a stabilized and sanitized product of composting. Research shows that compost not only works well as a soil conditioner, which is beneficial to plant growth, but also a good CH_4 oxidation agent. Diaz et al. (2006) defined composting as follows: "composting is the biodegradation of the organic content of municipal solid waste taking place due to the biological decomposition under favorable conditions". The organisms that actively take part in the composting process are classified into six groups, which include: i) bacteria, ii) actinomycetes, iii) fungi, iv) protozoa, v) worms, and vi) some types of larvae. Composting is associated with aerobic and anaerobic processes.

However, the aerobic process is more favored as it supports CH_4 oxidization capability. Composting is categorized into mesophylic and thermophylic bacteria for certain temperature ranges. For mesosphylic bacteria, the temperature varies between 5°C and 45°C whereas for thermophylic bacteria, the temperature range is from 45°C to 75°C. It has high water retention capacity as compared to other materials, which plays an important role in increasing the microbial population for CH_4 oxidation purposes. Albanna et al. (2007) revealed that the CH_4 oxidation rate increases as the microbial activity grows more in the composting material.

The compost material used in this study is sampled from a landfill site at Lafleche Inc. in Canada. It consists of municipal source separated organics, such as food, kitchen, leaf and yard wastes, and carbon. This biodegradable feed stock is separated from multiple municipal, commercial and institutional sources at the Lafleche facility. The above mentioned organic materials are mixed in an industrial-grade mixer in order to achieve a homogeneous blend with proper carbon to nitrogen ratio and moisture content. The compost feedstock and bulking agents are subjected to an active composting phase for a minimum of 25 days. The material was stored outdoors on a curing pad for 6 months at the Lafleche facility before being sampled for the purpose of the present research. Figure 3-1 shows the compost material used in this study. In the first stage, a bulk quantity of compost (1 m^3) was obtained from the Lafleche site to perform the different laboratory tests and analysis. The compost sample was stored in a cold room (3^0C) at the University of Ottawa to preserve the compost properties for a longer period of time. A small quantity of compost in buckets was transferred to the geotechnical laboratory for each analysis and/or test.

Figure 3-1: Composting materials used for experimental characterization

3.3 Compost material characterization

3.3.1 Geotechnical index and physical property tests

The water content was gravimetrically determined in accordance with the American Society for Testing and Materials (ASTM) procedure D 4959-07. The specific gravity of the compost was measured by following the ASTM standard D 854–06. The bulk density, void ratio (e) and porosity were determined in accordance with conventional soil mechanical methods (McCarthy, 2007). The Atterberg limits of the compost were determined by following the ASTM D4318 -10 procedures for liquid limit, plastic limit, and plasticity index of soils. The plastic limit could not be determined due to the brittleness of the material. The specimens were split into pieces at low water content, but stuck to a glass plate in the form of small clods at higher water content, and rolled onto the glass plate. Table 3 -1 shows the geotechnical index properties of the compost material.

Table 3-1: Geotechnical index properties

Parameters	**Values**	**Parameters**	**Values**
Water content (%)	68	Degree of saturation (%)	26
Bulk density (kg/m³)	520	Liquid limit (%)	88
Specific gravity (Gs)	1.68	Plastic limit	0
Void ratio	3.93	Plasticity index	88
Porosity (%)	80	Liquidity index	0.772

On the other hand, there was an issue in determining the liquid limit of the compost. Specimens prepared at low water content demonstrated the development of cracks with 7 – 10 blows, whereas the specimen with higher water content came into complete contact at once with 5 – 7 blows. However, after a number of trials, a liquid limit of 88% was determined for the compost. A liquidity index for the specimen was also determined and found to be 0.772. Benson and Othman (1993) reported an attempt to determine the plastic limit of compost, but no results were attained. Figure 3-2 shows the determination of the Atterberg limits.

Figure 3-2: Determination of liquid limit for compost

The range and number of different sized particles in the compost sample determine the shape of the grain size distribution curve. The uniformity coefficient (Cu) and coefficient of curvature (Cc) determine the range of particle size and type of soil (McCarthy, 2007). A grain size distribution analysis of the compost was carried out by following ASTM standard D 6913 - 04. Figure 3-3 shows the grain size distribution curve of the compost material used.

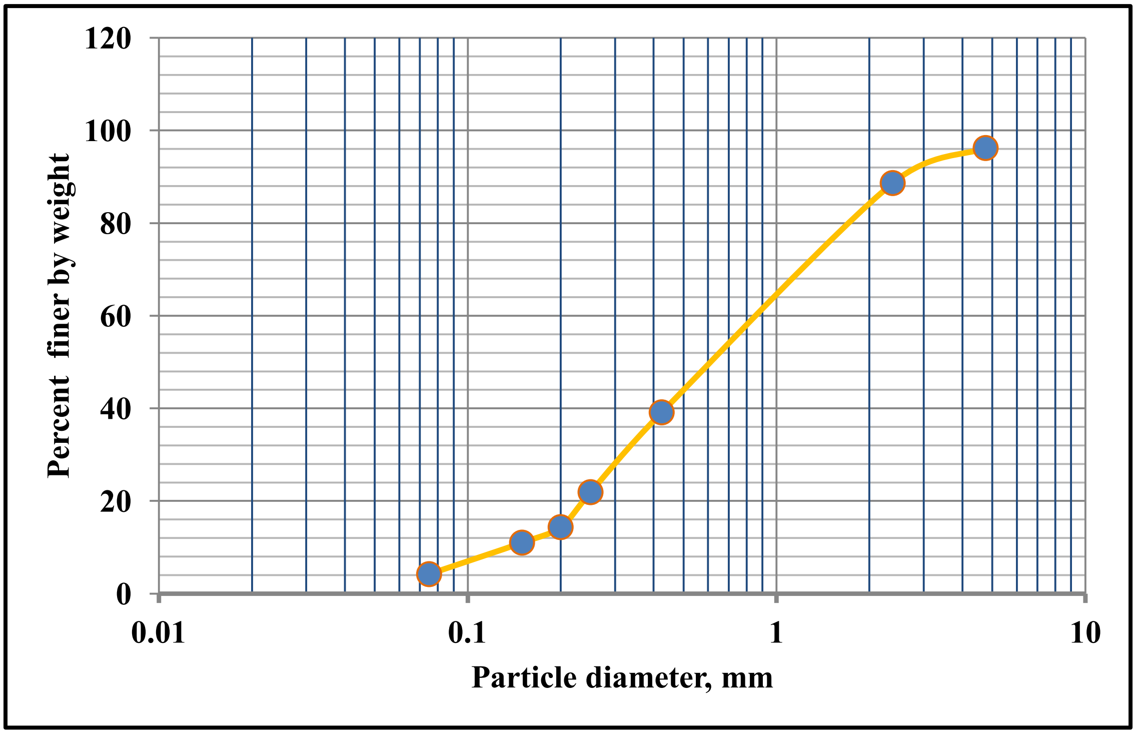


Figure 3-3: Grain size distribution curve of compost

It is clear from Figure 3-3 that only 3% of the sample is retained on sieve #4, and 90% is observed to fall in the range between 2.38 mm and 0.15 mm. Moreover, the C_u and C_c of the sample were also determined and found to be 6.0 and 0.70, respectively.

Based on these results, the compost was classified as well graded organic silty sand, which can be represented as SW-SM according to the Unified Soil Classification System.

3.3.2 Water content, ash content, organic and inorganic matter tests

The gravimetric water content, organic and inorganic matter, and ash content of the compost were examined at different water contents by following the procedures as described in the ASTM standard. ASTM standard D 2974 - 07a (B) is used to estimate these parameters in the present study. This method involves two steps to determine the water content contrary to the routine water content determination. In the first step, the sample is de aired at room temperature, i.e., the evaporation of moisture takes place in the presence of air.

The subsequent air dried sample was oven dried at 105^{o}C. This test is preferable in the situation where the samples are to be used for further analysis, such as the determination of nitrogen, pH, cation exchange, etc. The present research includes the determination of these parameters, so this method is followed to determine the water content. First of all, three samples with different degrees of saturation were selected for the analysis. The samples were oven dried at 105^{0}C to determine the water content. After the determination of the water content, the same samples were ignited at 440^{0}C to classify the organic and inorganic contents. A muffle furnace was used for ignition purposes. After igniting the sample, the residue was ash. The ash content i.e., the inorganic content of the sample is expressed as a percentage of the mass of the oven dried sample. After that, the organic matter was estimated by subtracting the percent ash content from one hundred. Figure 3-4 represents the compost samples used for the organic and inorganic matter tests.

Figure 3-4: Water content, ash, and organic content determination

3.3.3 Organic and inorganic content test results

Figure 3-5 shows the relationship between time and percentage for loss of water potential in the compost samples. It is clear from the figure that all of the samples lose their maximum water potential in the first five hours, and after that, there is no more water loss from the samples during the oven drying. The curves in Figure 3-5 verify this statement. Figure 3-6 shows the testing results of organic matter and inorganic contents of the compost sample expressed per percentage of dry matter (DM).

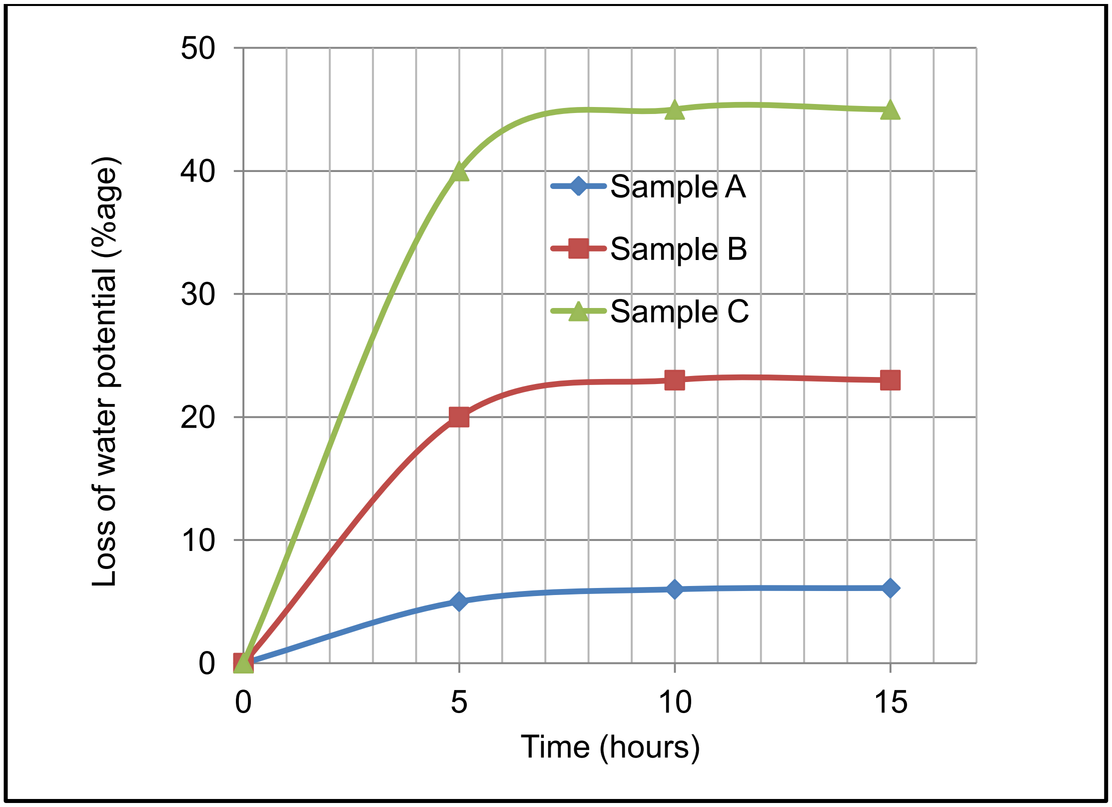


Figure 3-5: Drying of compost samples with time

Three samples are analyzed for this purpose, and the same percentages of organic and inorganic components were determined from all the samples. The values of the organic content obtained are between 39 and 41%. An average organic content of 40% for the DM was obtained which corresponds to an excellent DM with regards to CH_4 oxidation by the biocover (Huber-Humer, 2009; Yuan, 2006). Huber-Humer et al. (2009) suggested that a landfill biocover material should have at least 15% DM from the organic content. Higher organic content values indicate more favorable conditions for CH_4 oxidation purposes.

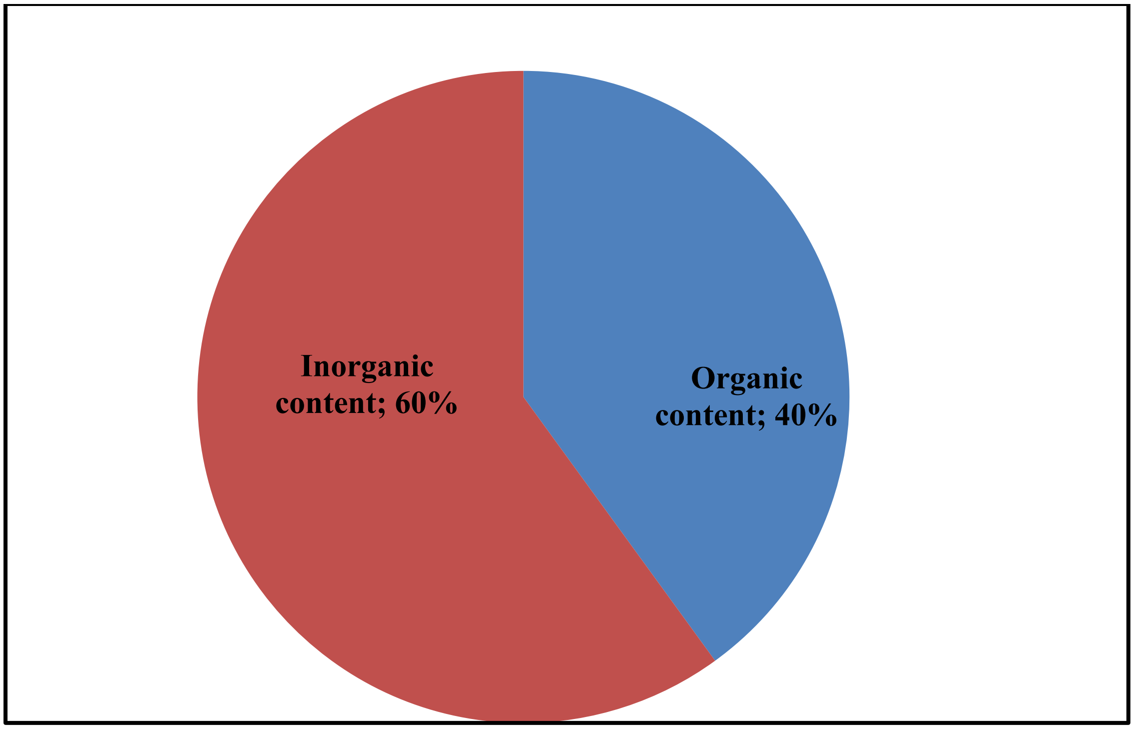


Figure 3-6: Organic and inorganic concentrations of the compost material

3.4 **Biological characterization of compost**

3.4.1 Methanotrophs and methanogenes

Figure 3-7 shows a schematic diagram of agarose gel electrophoresis used for the biological analysis of compost. First, four compost samples with different water contents, such as 30%, 46%, 59% and 72%, were transferred into test tubes. The samples were carefully placed into the tubes to prevent contaminating the bacteria present in the sample. A polymerase chain reaction (PCR) was carried out on all samples to quantify the deoxyribonucleic acid (DNA) and ensure the presence of methanotrophs and methanogenes in the samples.

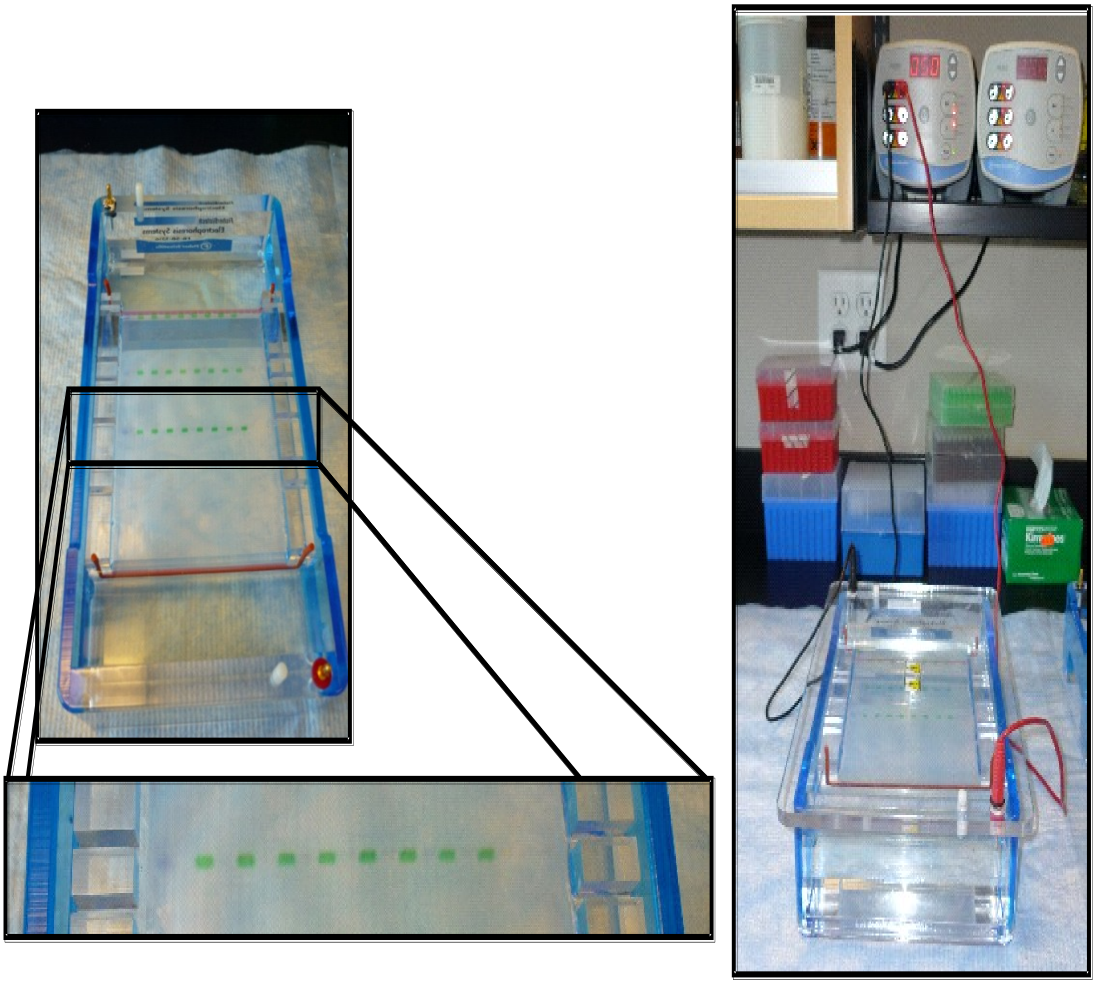


Figure 3-7: Schematic drawing of agarose gel electrophoresis

A sequence analysis of the 16Sr RNA sequences was carried out with the help of several primers, called "universal primers”. Gel (1.5%) was used to amplify the DNA in a total load of 5 uL for each sample to quantify the microbial organisms in the composting material. However, the loading volume corresponds to the volume of RNA reaction that is being loaded onto the gel; this does not affect the outcome of the PCR reactions.

3.4.2 Biological tests results

Figures 3-8 and 3-9 illustrate the presence of methanogenes and methanotrophs in the compost material, respectively.

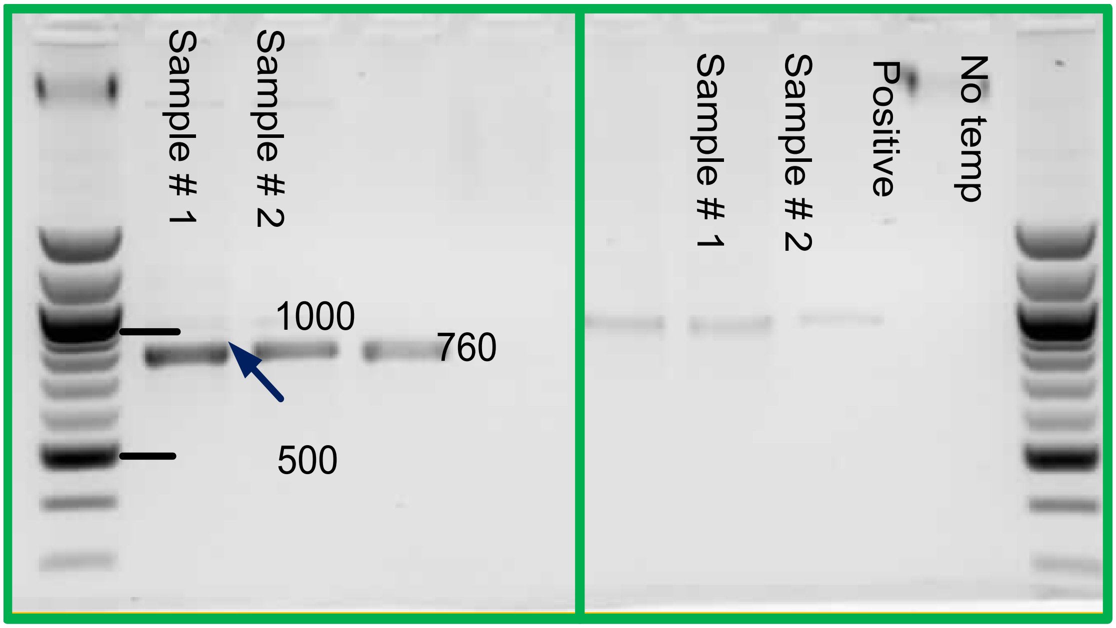


Figure 3-8: Methanogenes in the compost material

Figure 3-8 shows that a band of 760 bp is observed in all the samples for methanogenes. In the laboratory, the presence of these bacteria was also verified with archaeal methanogenes. The archaeal methanogenes were run in the specimens that showed positive controls with the sample for methanogenes. After that, the 16 S rRNA that was amplified on the specimens confirmed the presence of both bacteria and archaea in the samples. The size of the band length determines the presence of methanotrophic bacteria in the specimens. A band length of 500 bp assures the presence of a large amount of methanotrophs in the samples. Figure 3-9 shows that a band of 250 bp is observed in all of the samples for methanotrophs. This means that the molecular microbiological kit could not detect bands of appropriate lengths that ensured the presence of methanotrophic bacteria in the samples.

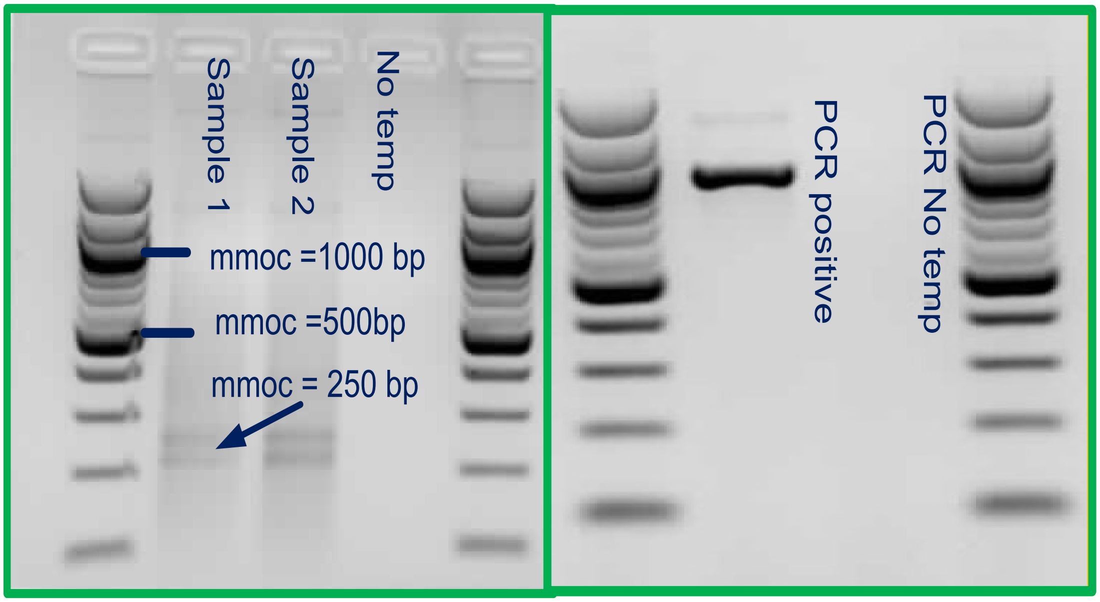


Figure 3-9: Methanotrophs in the compost material

This does not mean that the compost does not have any methanotrophs. Methanotrophs may be present in the compost in a larger band length, yet the testing method and molecular kit are unable to recognize the bacteria, as the method needs optimization to more precisely detect the methanotrophic bacteria in the compost material.

3.5 Chemical characterization of compost

3.5.1 Inductively coupled plasma spectrometer tests

An elementary analysis of the compost materials was carried out with an inductively coupled plasma (ICP) spectrometer (atomic emission spectrometry) as shown in Figure 3-10. Three samples were used for the analysis with various degrees of saturation.

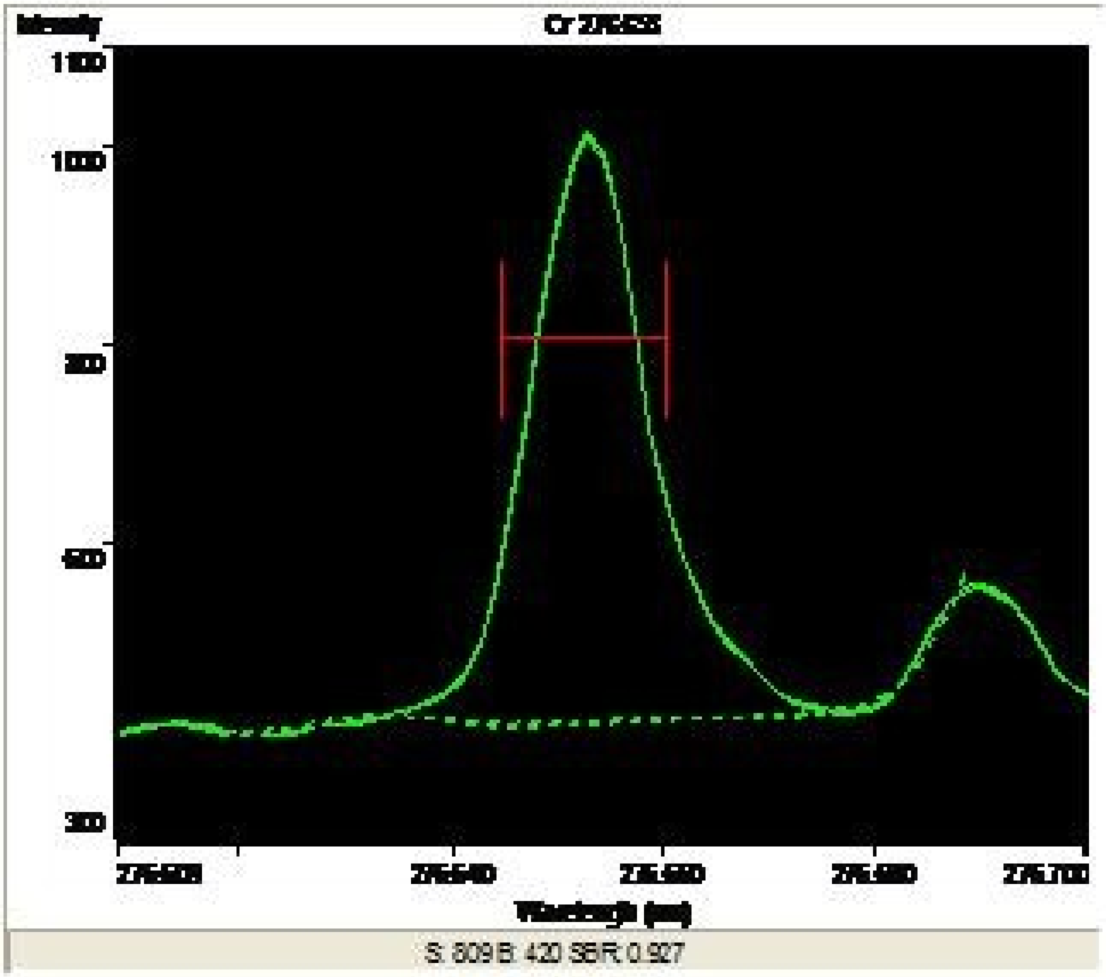
Figure 3-10: Inductively coupled plasma spectrometer

ICP spectroscopy techniques have a vast number of applications in geo-environmental engineering. ICP spectroscopy uses the features of atomic emission spectrometry for the elementary analysis of media.

All media, such as ground water, industrial waste, aqueous samples, soils, sludge, EP extracts, sediments, other solid waste, etc., need digestion for elementary analysis. The samples are used in the liquid form for analysis, so the ICP technique is also called a wet sampling technique. The working principle of plasma optical emission spectroscopy (OES) is simple and incorporates the dissolved sample into the core of inductively coupled argon plasma. ICP is facilitated with features that generate a temperature of about 8000^0C. This high temperature thermally excites all elements present in the sample.

The excited elements emanate light with appropriate wavelengths. A spectrometer collects this light and divides the rays of light into a continuum of its component wavelengths with a diffraction grating process inside the spectrometer. The intensity measurement of these wavelengths takes place by the amplification of diffracted light within the spectrometer. The spectrometer then transfers the intensity measurement to an elemental concentration in order to compare these values with calibration standards. The spectrometer has the potential to analyze up to 70 elements in a single analysis. The test was performed to categorize the concentration of metals, non-metals, and trace elements of inorganic components in the compost.

Figure 3-11 shows the wavelength for chromium in the compost sample during testing.



S: 809 B: 420 SBR 0.927

Figure 3-11: Wave length of chromium for ICP (AES) test

3.5.2 Inductively coupled plasma spectrometry test results

Figures 3-12 and 3-13 show the test results of the elementary analysis for contaminants in the compost materials.

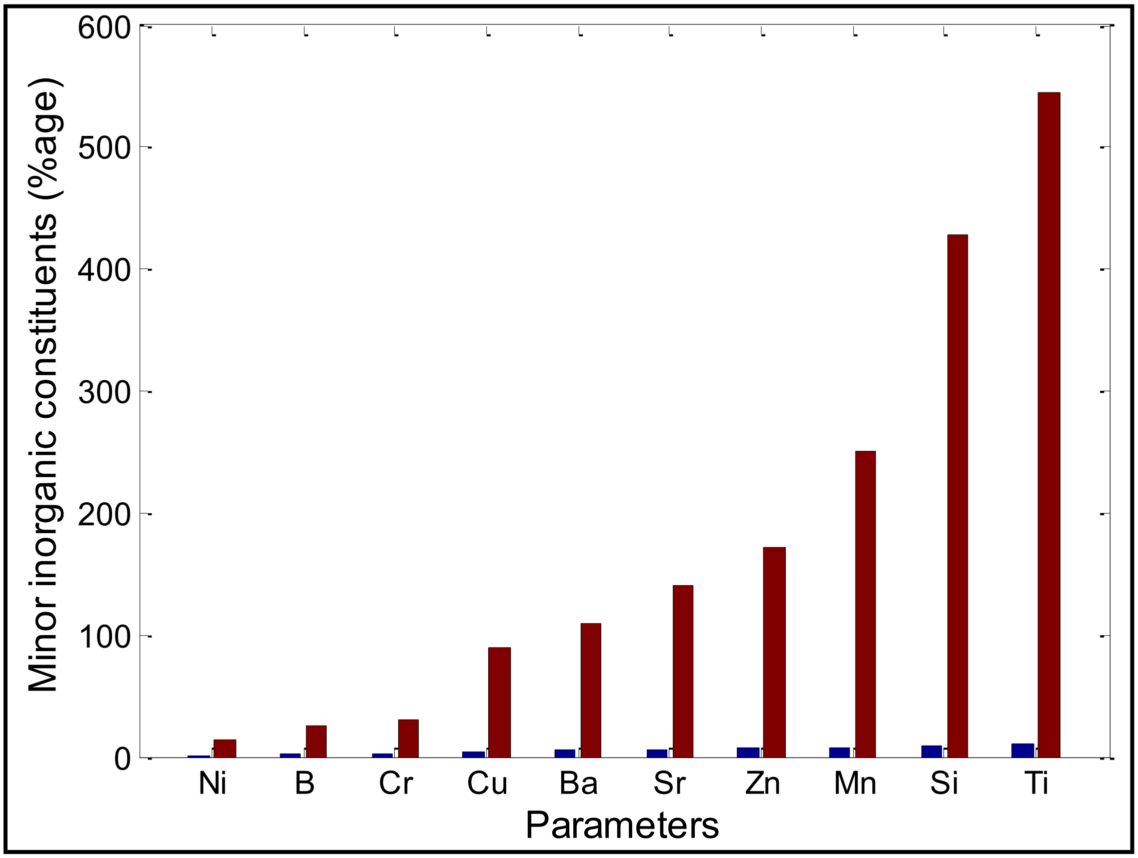


Figure 3-12: Major inorganic constituents in the compost (%age)

The constituents were classified in two groups, with i) the major constituents being measured in percentage as shown in Figure 3-12, and ii) the minor constituents being measured in parts per billion (ppb) as indicated in Figure 3-13. Silica (SiO_2) was found to be quite high in concentration for all the samples which is about 39% out of a total of 60% inorganic ingredients. SiO_2 is also recognized as silicon oxide, which is well-known for its hardness. SiO_2 is most commonly found in sand or quartz. The present study also indicates that calcium (Ca) is the other major element present in the compost, which is found to be 4.28% of the inorganic materials. Nitrite is a strong inhibitor for CH_4 oxidation. Most methanotrophs can use nitrate as the N-source. P is an essential nutrient for methanotrophs.

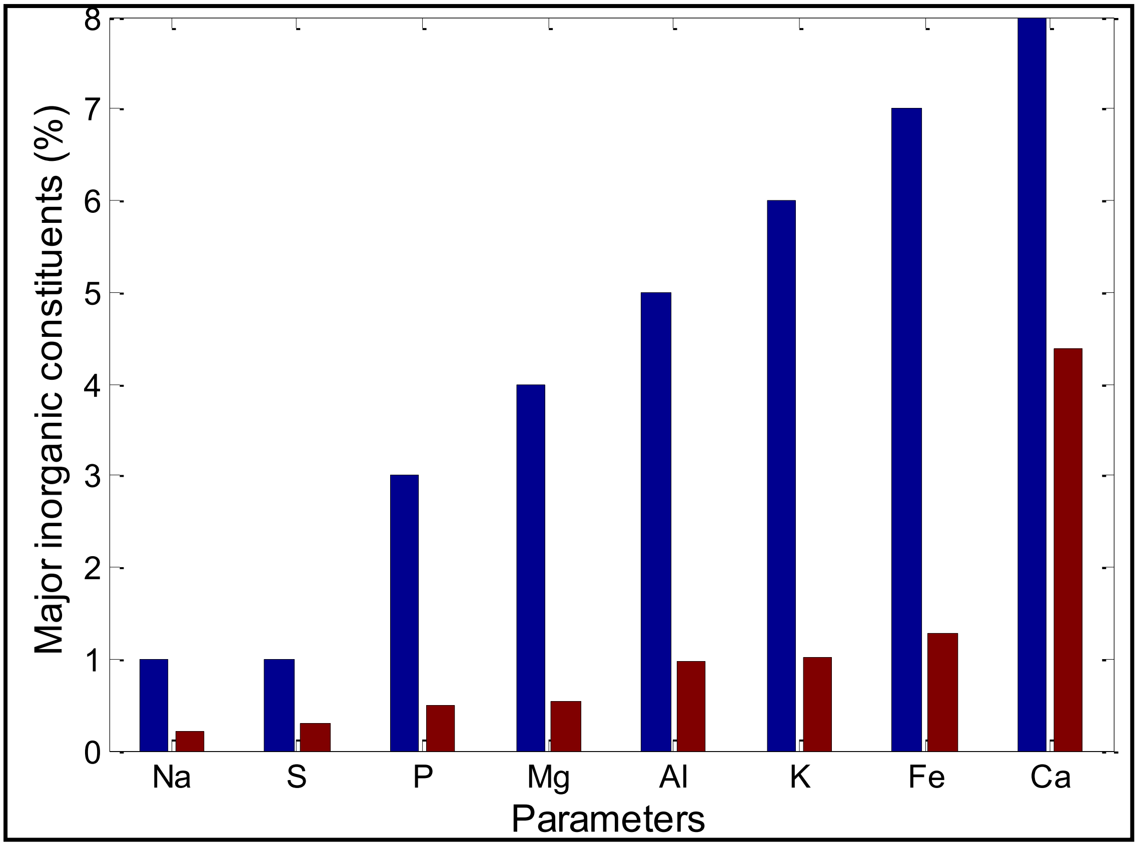


Figure 3-13: Minor inorganic constituents in the compost (ppb)

The pH was also determined by using a pH meter for all of the samples. The samples were uniformly dissolved in water prior to determining the pH value. Huber-

Humer et al. (2009) reported that an efficient cover material should have a pH value between 6.5 and 8.5. In this study, the pH is found to be 8.15 in the selected compost for all of the samples.

3.6 Summary and conclusions

- Compost materials have a liquid limit of 88%. However, it is difficult to determine the plastic limit of compost material, which categorizes compost as a brittle material and well graded silty sand.

- The compost materials are also classified as organic material that contains 40% organic content and 60% inorganic content.

- Compost materials may contain both methanogenes and methanotrophs depending on their characteristics and age, and the maturity of the medium, which determine the proportions of these microbial organisms.

- As per chemical testing, SiO_2 is found in 39% of the 60% inorganic components in the compost materials. Ca is second in descending order after SiO_2 at 4.2%. Compost is neither acidic nor has basic materials.

The next section (Chapter 4) of the research study examines the hydraulic, thermal and mechanical properties of compost materials with small sample laboratory tests.

Chapter 4. HYDRAULIC, THERMAL AND MECHANICAL CHARACTERIZATION OF COMPOST BASED LANDFILL COVER MATERIAL

4.1 Introduction

It is necessary to assess the hydraulic, thermal and mechanical properties of compost materials in order to better understand their influence on the performance of biocovers. Hydraulic, thermal, and mechanical properties may affect the performance of compost material. However, technical data on the properties of compost materials for various water contents and dry unit weights are quite limited. Most of the previous studies on compost biocover focus on their CH_4 oxidation capacity (Pokhrel, 2006; Kettunen et al., 2006). Very few studies (Huber-Humer et al., 2009; Chandrakanthi et al., 2006; Benson and Othman, 1994**)** have addressed the THM properties of compost. Furthermore, these studies were limited to investigate the aforementioned properties of organic waste materials for a specified range of initial water contents or compaction degrees. Thus, there is a paucity of information on the THM properties of compost for a large range of initial water contents or compaction degrees of composting materials.

Thermal conductivity, thermal diffusivity and specific heat capacity are important thermal properties that define the heat transfer in a medium. These properties depend on the temperature. According to Ahn et al. (2009), the temperature variations in compost takes place due to the thermal balance between heat generated by microorganisms and heat loss through convection, radiation and evaporation.

Furthermore, the values of thermal properties vary, depending on the ingredients of the compost materials. Most of the previous studies on the thermal properties of compost dealt only with the thermal conductivity. Studies on the thermal diffusivity and specific heat capacity are quite neglected. Van Ginkle et al. (2002) explained that thermal conductivity is a complex property of compost and not only depends on the components, but also the water content, organic content, composition, density, porosity, and temperature. Ahn et al. (2009) indicated that the thermal conductivity of compost which contains dairy cow manure and saw dust mixture is 0.051 w/. m.^{o}C at a water content of 75%. The thermal conductivity of dairy cow manure and saw dust as a mixed compost is 0.05-0.202 w/m.^{o}C at a volumetric water content of 0 – 44.2%. The specific heat depends on the mineral ingredients and water content of the compost material. A thorough understanding of all the thermal properties of compost is important to develop and model heat and mass transfer (Ahn et al. 2009) and understand the performance of biocovers in various climatic and thermal loading conditions.

The hydraulic conductivity determines the movement of water molecules through a material. The hydraulic conductivity is a key property that defines the behavior of covers with respect to their fluid transport abilities, stability and CH_4 oxidation potential. It is really important to use the proper values of hydraulic conductivity for a cover structure. Proper selection of hydraulic conductivity values paves the path for good designing of any cover design. Low hydraulic conductivity of cover materials may reduce the percolation of water movement through it. Furthermore, gas transport is important in biocovers, as it controls the supply of O_2 and CH_4 to the CH_4 oxidation zone. CH_4 is mainly controlled by advective flux and O_2 by diffusion. This gas transport is strongly affected by the hydraulic conductivity. However, our knowledge about the hydraulic properties of compost biocover material is limited.

Not only must a biocover have suitable hydraulic conductivity, but it also must be physically stable. This means that a biocover must have sufficient shear strength parameters and appropriate settlement behaviour. Settlement plays a very crucial role in determining the performance of landfill cover material as CH_4 oxidation potential is directly related to FAS. Tim (1993) had stated that FAS values of 20% to 35% in compost establish the maximum O_2 consumption rate i.e., 95%. This criterion means that it is even more important to take into consideration the settlement of landfill cover material in the design phase. High and/or differential settlement could result in a significant reduction of the FAS or development of cracks in the biocover. Furthermore, the landfill cover should have sufficient strength to resist slope sliding, rotation and movement as the slope is considered to be the most critical component of a landfill cover system. It was found that information about the shear strength parameters and settlement behaviour of compost biocover is quite limited.

The objectives of this chapter are:

- to study the thermal properties of compost biocover materials of various initial compaction degrees or initial water contents and dry densities;
- to study the saturated hydraulic conductivity of compost biocover materials of various initial compaction degrees or initial water contents and dry densities;

- to investigate the shear strength parameters and consolidation behavior of compost biocover materials of various initial compaction degrees or initial water contents and dry densities; and
- to gain a good understanding of the THM properties of compost biocover material.

4.2 **Laboratory testing program**

4.2.1 Compaction tests

Standard Proctor tests were performed at different water contents to obtain the compaction curve of the compost by following the ASTM D 698 - 07 procedures. First of all, a desired quantity of compost was passed through sieve #4, and placed back into a covered pail to preserve the existing water content. Each sample was uniformly mixed in a large mixing pan with the specified water content prior to performing the testing. Figure 4-1 shows the behavior of the compost with a high degree of saturation during the compaction testing. In the beginning, each addition of water resulted in the formation of different sized clods. However, each test was performed after assuring a uniform mixing of the sample with water. The compaction tests were carried out for a wide range of water contents on both the wet and dry sides of optimum water content. Furthermore, the compaction tests were carried out two times at specific water contents for optimal, wet of optimum, and dry of optimum segments of the compaction curve. Finally, the average of the two values was considered as the final resulting value. A compaction effort of 600 kN.m / m^3 was used for all the tests. Several specimens of compost were prepared and tested at water contents that ranged from 4% to 32% with a gradual increment of water (2%) for every following sample.

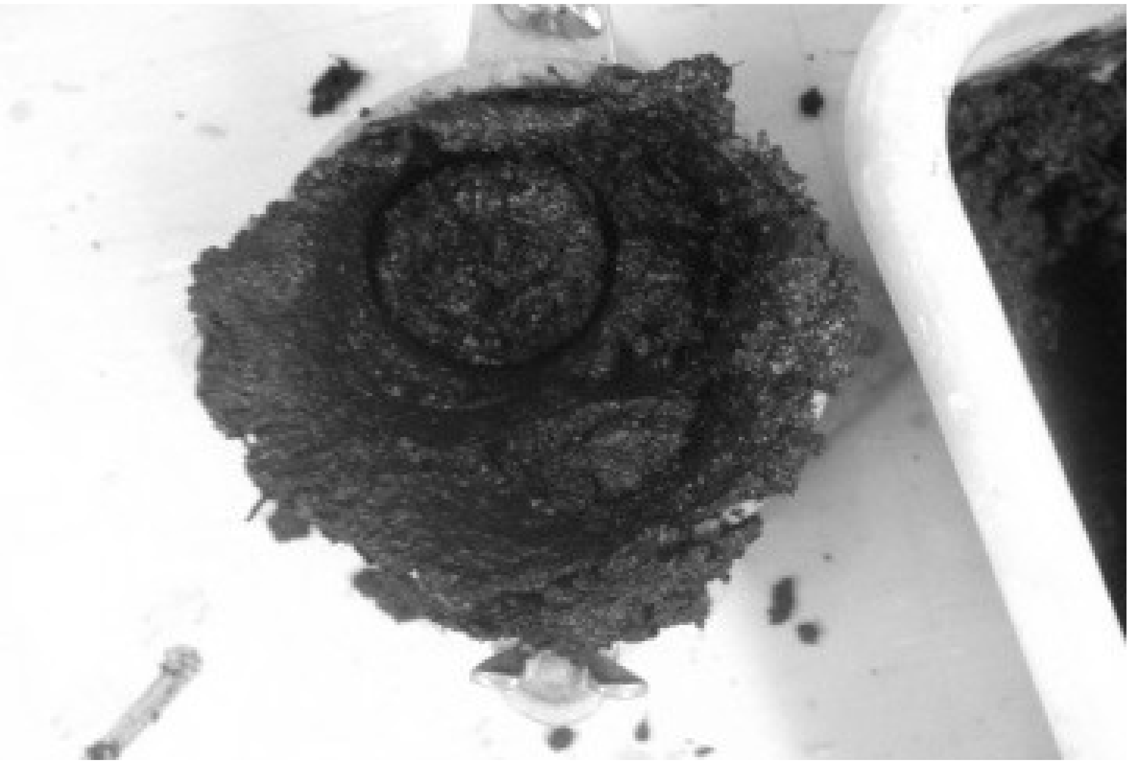


Figure 4-1: Behaviour of compost for wet of optimum

Each sample was used once and discarded after testing. The compost material showed a unique behavior for higher and lower degrees of saturation during compaction. For wet of optimum, the specimen started to jump out from the compaction mould with each blow of the hammer. This situation occurred for samples with a water content more than 100%. On the other hand, the finer particles of the sample were also observed to jump out from the mould during compaction on the dry of optimum. However, such a problem was not observed for those with a water content that ranged from 55% to 100%.

4.2.2 Hydraulic conductivity tests

Hydraulic conductivity (K_u) tests were performed by following the procedure as described in ASTM D 5084-03. Flexible wall constant head permeability tests were used to determine the permeability of the compost. It is important to mention here that for compost landfill biocovers, the consideration of free flux and K_u is extremely important. For a landfill biocover design, it is not realistic to only focus on K_u as is the case for a traditional landfill cover. The working scheme of a landfill biocover is different from a traditional cover. Due to the above fact, K_u tests were carried out for a wide range of water content, including optimal, wet of optimal, and dry of optimal conditions for the compaction curve of the compost. First of all, a compost sample was thoroughly mixed in a mixing pan with a specified quantity of water in accordance with the compaction curve. After that, the sample was transferred to a small metallic compaction mould that had a diameter of 50 mm and depth of 115 mm. A small metallic tamper was used to compact the specimen. The specimen was compacted in three equal layers with 30 blows on each layer.

The number of blows was determined by trial and error prior to starting the testing with the original samples. The compaction was done to reach the same dry density and water content as determined in standard compaction efforts (ASTM D 698-07). K_u tests were conducted at room temperature, and the compacted compost samples were prepared at various initial water contents. The sample was fragile so extreme care was undertaken in extruding the sample from the mould and placing it into the triaxial permeameter. The prepared sample was trimmed with a sharp knife to remove the anomalies and fit the specifications. This was also done to eliminate the blockage of pores, which occurred due to the blows from the tamper onto the top surface. Sometimes, the sample was broken into pieces, especially at low water content, and the test had to be repeated. The prepared sample was carefully transferred into a triaxial cell without damaging its edges. The sample was fixed in the test cell with extreme care to eliminate any chances of air inside the cell. The cell was filled with water and connected to a triplex device through the lateral, upper and lower ports.

Saturation was achieved by bridging the influent and effluent lines and applying backpressure. Saturation was considered complete by verifying influent intake against effluent water volume supply until they became equal. Furthermore, post-test determination of the degree of saturation for some samples was undertaken to confirm the full saturation of the samples tested. Benson and Othman (1993) reported that seepage force produces an effective stress of 15 - 20 kPa in a landfill cover. Moreover, this study suggested the use of a hydraulic gradient of 10 or a little higher to evaluate the hydraulic behaviour of landfill cover material. Thus, a hydraulic gradient of 20 is used for this study. The head difference was generated in a specimen by adjusting the upper and lower burettes of the channels. After saturation was completed, the upper and lower burettes were bridged to the same pressure for a few minutes in order to equalize the pressure inside the specimen.

A hydraulic gradient was applied to the sample placed in a triaxial cell to determine its permeability. The water level in the upper and lower burettes was recorded with increased time intervals. Finally, an average was taken to obtain accurate results. The same process was repeated for all the tests at different water contents and dry unit weights to determine the K_u of the compost material. Then, a constant head formula (per ASTM standard 5084-10) was used to determine the K_u for all of these samples. Equation 2 is the mathematical representation of K_u.

[2] $k = V(t_1, t_2)L/P_B A_t$

where $V(t_{1,} t_2)$ = Volume of flow from t_1 to t_2

L = Length of sample (cm)

P_B = Bias pressure psi x 70.37 cm/psi (cm of H_2O)

A = Area of sample (cm^2)

t = time from t_1 to t_2

It had been difficult to perform K_u testing on larger water content as well as lower water content. For higher water content, the particles of the compost samples started to dissolve in the water and came apart from the sample. For low water content, the samples collapsed into small pieces. Figure 4-2 shows the behaviour of compost samples for low water content on the dry of optimum in the K_u tests.

Figure 4-2: Behavior of compost for low water content on the dry of optimum from the compaction curve

However, lower water content has more issues as compared to high water content while K_u testing was performed on the compost samples. Due to the arrangement of the testing procedures and especially fragile nature of the specimens, the tests proved to be time consuming. Figure 4-3 shows the samples that were tested for K_u. It should be emphasized that each K_u test was performed at least twice to ensure the repeatability of the results. Finally an average was taken for all the test results evaluated for a particular water content.

Figure 4-3: Hydraulic conductivity test samples

4.2.3 Thermal property tests

First, the required quantities of compost and water were determined by following the criteria set in the compaction tests for different water contents and dry densities. A specified quantity of compost was mixed well with a certain amount of water in a container. Uniformity was ensured for the entire sample. After that, the sample was put into a compaction mould with a diameter of 5 cm and height of 11.5 cm in three different layers. Each layer was subjected to a constant degree of compaction with a square metal rod to attain the required dry density at the specified water content as set in the compaction test. An equal number of blows for each layer were determined by trial and error prior to starting the compaction. A uniform compaction was assured for each layer on a mass – volume basis. After that, the sample was taken out from the compaction mould, wrapped in sealed plastic bags, and put it in a container for more than two hours before testing to attain thermal equilibrium. Figure 4 - 4 shows the samples placed in sealed plastic bags to attain isothermal equilibrium in the thermal tests.

Figure 4-4: Isothermal equilibrium of compost samples for thermal tests:

A KD2 Pro device was used to determine the thermal conductivity and thermal resistivity of the prepared samples under isothermal conditions. The KD2 calculates values for K and resistivity by monitoring the dissipation of heat from a line heat source given a known voltage (Decagon Devices, Inc. 2006). Figure 4-5 shows the KD2 analyzer for the thermal conductivity tests.

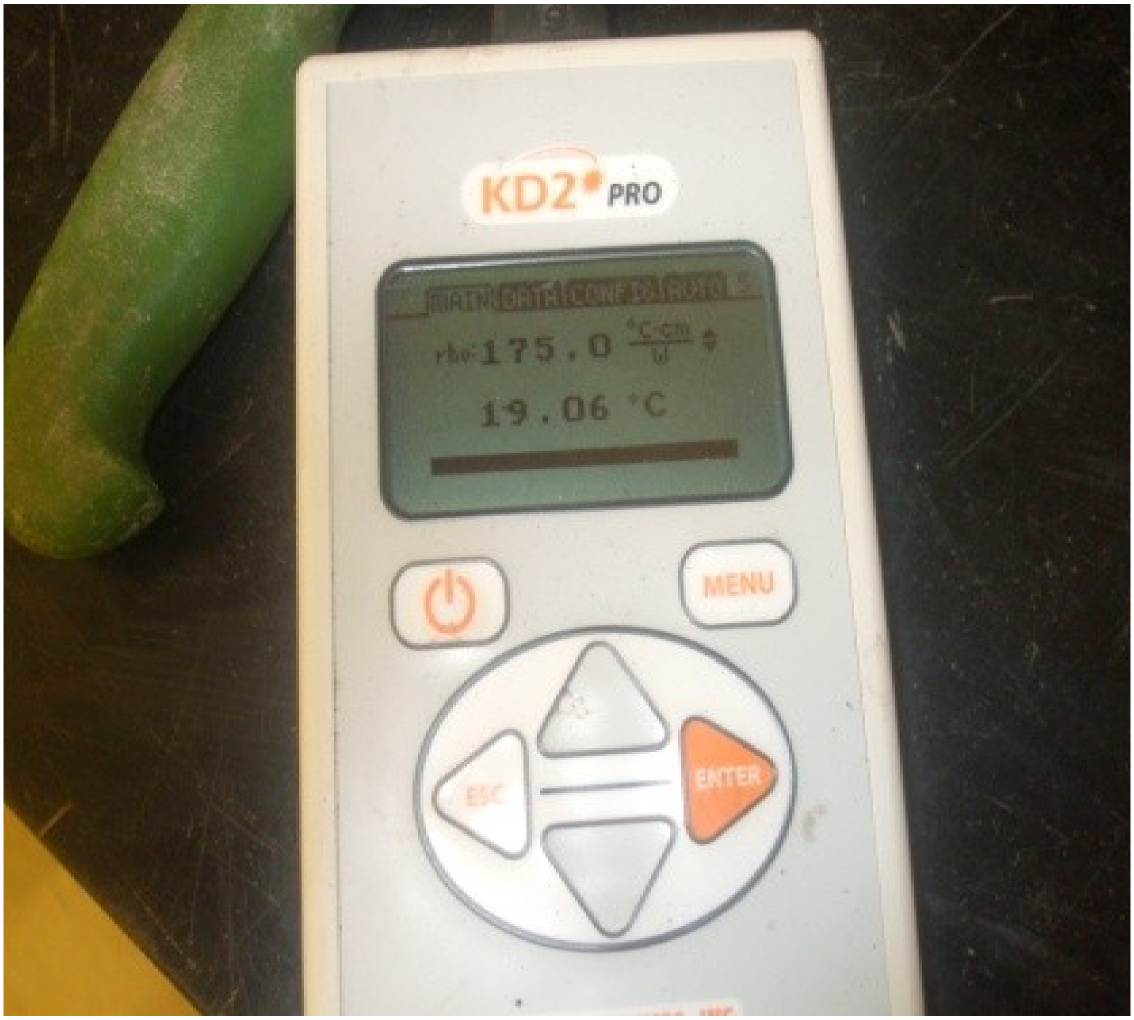


Figure 4-5: KD2 Pro device for thermal tests

The principle is based on transient line heat conduction in a homogeneous, isotropic medium. The thermal conductivity was measured with a relative error of 5%. The KD2 analyzer allows a quick determination of the thermal conductivity to be quickly determined in contrast to the differential scanning calorimeter (DSC) which requires a relatively long equilibrium time (Celestin and Fall 2009).

The KD2 Pro device consists of a TR1 sensor, which contains a large single needle that is 2.4 mm in diameter and 100 mm in length. The sensor needle was slowly and steadily inserted into the compacted compost sample to avoid any bending of the needle and to reduce the chances of any gaps between the needle and granular particles of the compost. It was taken into account that the amount of sample that surrounds the needle should be 1.5 cm from all sides for accurate results as recommended in the user manual for the KD2 Pro.

The default reading time for a TR1 sensor is 5 minutes. As a longer reading time provides more accurate and reliable results, hence, the reading time was adjusted and 10 minutes was used for all of the readings. A lengthy reading time minimizes the chances of errors that take place due to the effects of the large diameter needle and contact resistance between the sensor and the solid materials in the compost. The samples for different water contents and dry densities were prepared by following the same procedure as outlined above and the KD2 Pro was used to determine the thermal conductivity and thermal resistivity of all of these samples under isothermal conditions. Each thermal conductivity test was repeated twice and the average value was considered as the thermal conductivity of the material tested. Finally, the thermal diffusivity and specific heat of compost were estimated by using mathematical relationships described below.

Agnew and Leonard (2003) used Equation [3] to determine the specific heat of any organic media:

[3] $$\mathrm{C_p} = 1.48 - 0.64\,(\mathrm{ASH}) + 4.18(\mathrm{M.C_{d.b}})$$

In the above equation, $\mathrm{C_p}$ = specific heat of compost and its units are $\mathrm{kJ/kG.K}$, $\mathrm{M.C_{d.b}}$= water content of the composting material per dry basis, and ash is the mineral content or ash of the material. First, the organic and ash contents of the specified compost were determined by following ASTM standards. Detailed results of the organic and ash contents with respect to different degrees of saturation along with the detailed procedures have already been discussed in Section 3.3.3. Chandrakanthi et al. (2005) established a relationship to determine the thermal diffusivity of an organic medium. Equation [4] gives the mathematical representation of thermal diffusivity in relation to specific heat and thermal conductivity.

[4] $$\alpha = \mathrm{k}/\rho \mathrm{C_P}$$

In the above equation, ρ is the bulk density, $\mathrm{C_p}$ is the specific heat of the material and k is the thermal conductivity. Van Ginkel et al. (2002) suggested the relationship below for the estimation of α in relation to volumetric heat capacity.

[5] $\rho C / \lambda d_T$

In the above equation, λ = thermal conductivity coefficient, d_T = thermal diffusivity, C = volumetric heat capacity, and ρ = bulk density. Equation [5] can be used to estimate the value of α, but the accuracy of d_T is low (Van Ginkel et al., 2002). Equation [4] is used to determine the α for the composting material in the present study.

4.2.4 Direct shear tests

A direct shear testing program was carried out to evaluate the shear strength parameters (cohesion and the angle of internal friction) and shear behaviour of the compost. For this purpose, consolidated drained (CD) direct shear testing was performed by following the ASTM procedure D 3080-04. First, a compost sample was thoroughly mixed at a specified water content and a specified dry density in accordance with an ASTM standard effort compaction test (ASTM D 698-07). After that, the sample was carefully transferred to a dissembled direct shear machine mold. The size of the direct shear machine mold was selected as 60x60x20 mm^3. The specimen was compacted in three equal layers with a small square tamper to achieve the desired level of compaction for the specified water content and dry unit weight. An equal number of blows to achieve the specified density were selected by trial and error. Figure 4-6 shows the samples after direct shear testing.

The mold which included the compacted sample was again assembled with the direct shear machine.

Figure 4-6: Direct shear test samples of compost

The shear box was filled with water, and the sample was left untested for two hours to attain equilibrium. CD tests were carried out for wet of optimum, dry of optimum and optimal water contents for the compost samples. However, more tests were carried out for dry of optimum as this condition is more prevalent in landfill covers. The samples were first consolidated and then sheared. A very slow rate of shearing, i.e., 0.0277, was selected to shear the specimen. The shear rate was calculated by following the two methods: i) the settlement method, and ii) the method prescribed in ASTM

D3080 -04. It was ensured that an excess of pore water pressure would not develop during testing. Equation 6 is used to determine the shearing rate of the compost (ASTM 3080):

$$[6] \qquad d_r = d_f / t_f$$

where d_r = displacement rate (mm/min), d_f = estimated horizontal displacement at failure (mm), and t_f = total estimated elapse time to failure (min).

However, the compost was observed to be a fragile natural material, so the tests were carried out for each specified density and water content two to three times in order to the verify the repeatability and accuracy of the results.

4.2.5 Oedometer (consolidation) tests

A series of consolidation tests were performed to evaluate the consolidation behavior of the compost for different initial water contents and dry unit weights under field prevalent loading conditions. The consolidation test (oedometer test) was carried out by following the method described in ASTM D 2435 – 04. First, the compost sample was thoroughly mixed at a specified water content as indicated in the standard effort compaction test. The sample was transferred into the consolidometer mold with a diameter of 62 mm. A circular base tamper was used to compact the specimen into the mold. The specimen was compacted in three equal layers in order to achieve the specified dry density and water content. The number of blows was determined by trial and error.

The compacted sample was trimmed with a sharp knife to give it a proper shape and accurate dimensions. After that, the sample was carefully pushed into the consolidometer ring with a piston. The same procedure was applied to all of the tested samples. Figure 4-7 shows the consolidation test samples.

Figure 4-7: Consolidation tested samples of compost

Due to the fragility of the compost, some samples had broken into pieces during insertion into the ring and the test had to be repeated. This scenario was more prevalent in lower water content samples. Each sample was kept soaked in an oedometer cell throughout the testing. Consolidation pressure was applied in a conventional manner with gradual increases from 2.5 kPa to 80 kPa at a load incremental ratio (LIR) of 2.5, i.e., 2.5, 5, 10, 20, 40 and 80 kPa. The sample was left under each loading for 24 hrs to reach its maximum consolidation capacity. However, most of the samples reached 50% consolidation in just 8 to 10 minutes. At the end of each test, the wet and dry weights of the sample were determined for further analysis. The compression and swelling indexes and coefficient of compressibility of the tested samples were also estimated.

Equation 7 shows the mathematical representation to determine the coefficient of compressibility by using the logarithm of time method.

$$[7] \qquad C_v = 0.197H^2d_r/t_{50}$$

where C_v = coefficient of consolidation/ compressibility;

H_{dr} = average longest drainage path during consolidation. It should be emphasized that long-term compressibility testing to assess secondary compression and biodegradation was beyond the scope of this study.

4.3 Laboratory test results

4.3.1 Compaction tests results

Figure 4-8 shows the compaction curve of the compost material.

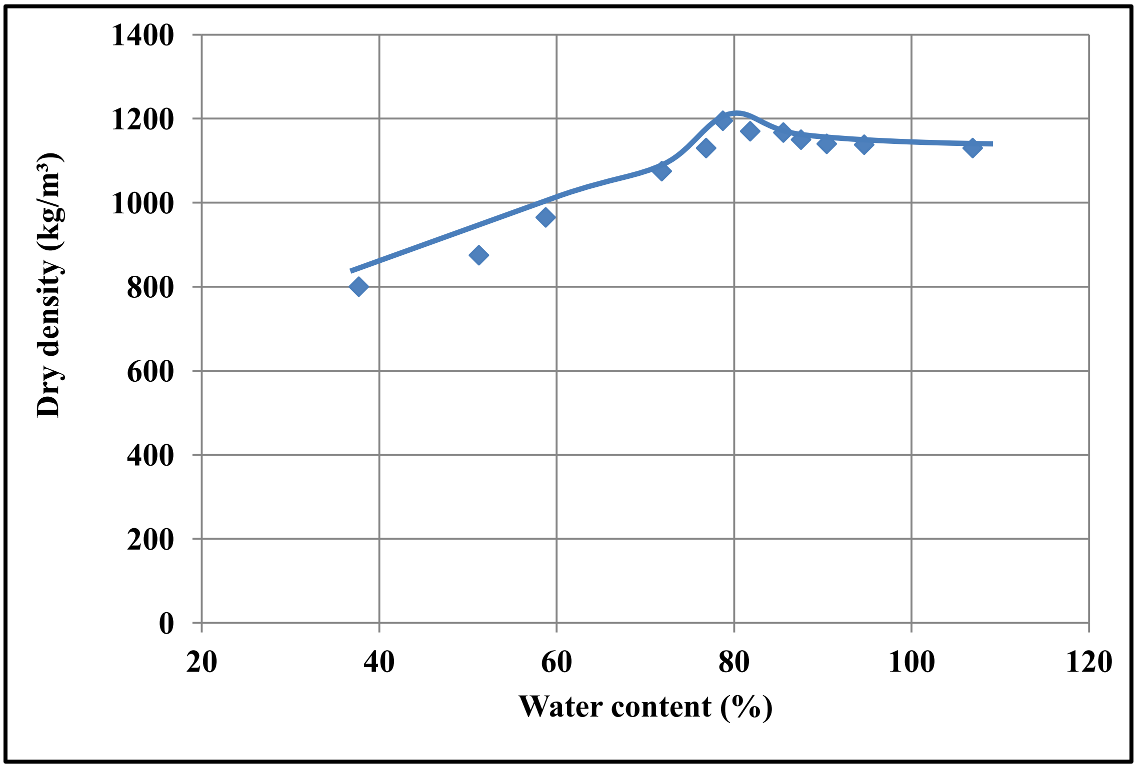


Figure 4-8: Standard compaction effort for compost

As expected, it can be seen that the dry density increases as the water content increases until it attains a maximum value of 1200 kg/m^3 at an optimal water content of 79%. After that, the dry density starts to decrease with an increase in water content, and this behaviour continues for the wet of optimum segment. For wet of optimum, the water starts to fill the pores between the compost particles; this compels the compost particles far apart resulting in the reduction of mass to volume ratio. Furthermore, the decrease in dry density takes place due to swelling of compost particles. The swelling behaviour of compost will be discussed in the experimental test results section 4.3.5. for various initial water contents. However, the Proctor curve on the dry of optimum side represents a gradual rise up to the optimal water content. Furthermore, the pattern of the compaction curve shows a wide range of change in water content on the dry of optimum segment in comparison to the wet of optimum segment. This may be due to the fact that for the wet of optimum, the water added only fills the pores rather than also being absorbed by the compost particles. The dry density fluctuates between 800 kg/m^3 and 1200 kg/m^3 with water content variations from 38% to 110%.

Scheutz et al. (2009) stated that the CH_4 oxidation process is dependent on the O_2 penetration capability of landfill cover soil. The soil composition, particle size, and porosity are considered to have significant influences on O_2 transport and thus on the CH_4 oxidizing capacity of the biocover material. It is well understood that a low permeability cover reduces rainfall infiltration, which results in the saturation of cover material during the rainy season. The cover may also face a desiccation problem during the dry season (Othman and Benson, 1993). In light of the above arguments, index properties such as porosity (n), degree of saturation (S), void ratio (e) and FAS of compost may have significant effects on the performance properties of landfill biocover material in association with CH_4 oxidation potential. The consideration of these parameters is essential in the design of any or compost based cover system. Considering the importance of these parameters for any cover design, the variation of the aforementioned factors with the compaction degree of compost has been studied.

Figure 4-9 illustrates the relationship between water content and degree of saturation of the compaction curve, and Figure 4-10 represents the relationship between water content and FAS of compost materials.It can be seen from Figure 4-9 that as expected, S increases with an increase in water content up to the optimal water content. The S increases in a gradual manner for the dry of optimum segment until reaching the Proctor optimum. After the optimum, the saturation curve remains almost constant and follows a straight horizontal line for the wet of optimum segment.

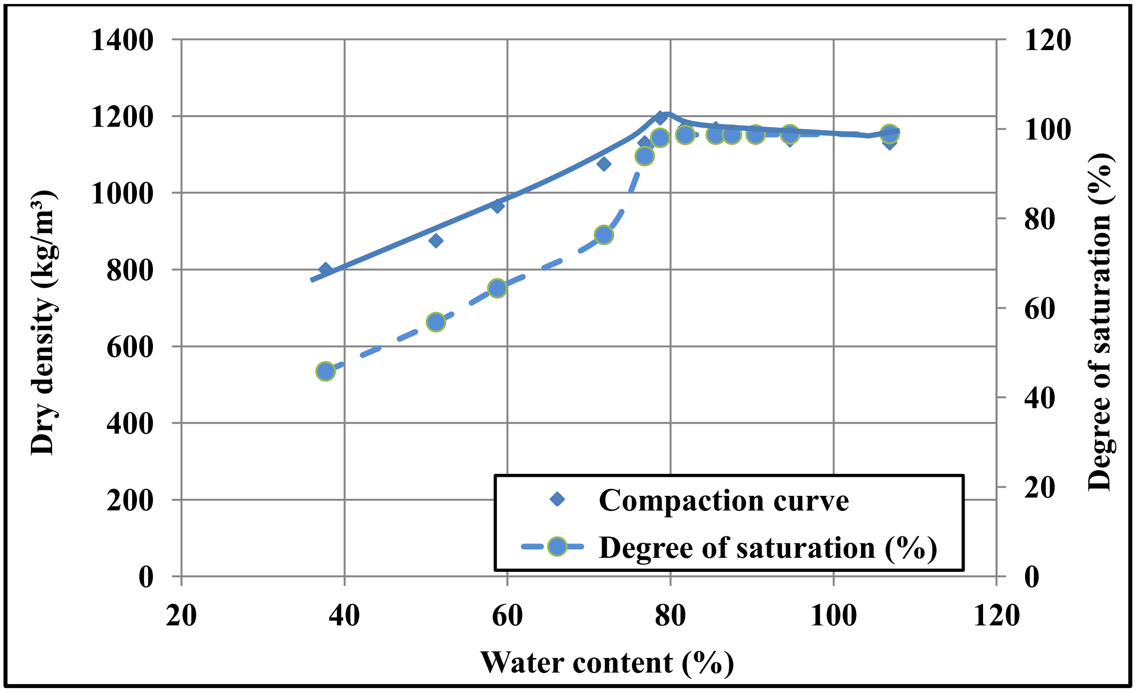


Figure 4-9: Relationship between water content and degree of saturation and water content for compaction curve.

This suggests that most of the voids are filled with water. Studies have shown that when the degree of saturation reaches approximately 85%, gas diffusion should be completed in the liquid phase which is much slower than that in the gas phase (Cabral et al. 2004; Scheutz, 2009). This can radically decrease CH_4 oxidation due to the lack of both O_2 and CH_4 in the biocover (Scheutz et al., 2009). Thus, from an analysis of Figure 4-9, it can be concluded that the compacted compost materials with an initial water content higher than 73% (corresponds to the point with a degree of saturation of 85%) will show low CH_4 oxidation capacity, and are thereby unsuitable for landfill biocovers.

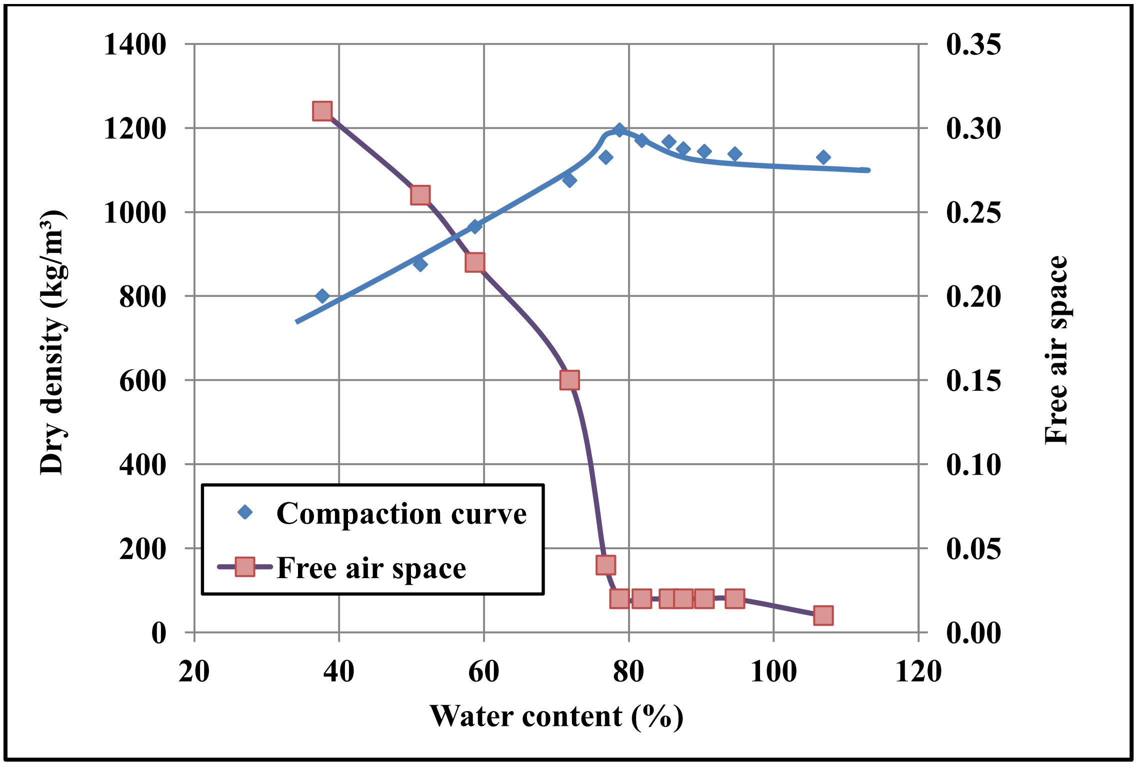


Figure 4-10: Relationship between free air space and water content for compaction curve

From Figure 4-10, it can be observed that as the water content increases up to the optimal water content, the FAS curve sharply decreases, which shows the reduction of voids in the compost materials. Then, the FAS continues to slowly decrease with an increase in water content, until it attains a value close to zero. This means that most of the voids are filled with water and the compost does not allow sufficient gas flux to pass through the sample at a particular water content which may certainly affect the microbial oxidation phenomenon due to an insufficient supply of O_2. Indeed, with reference to Tim (1993) who stated that FAS values of 20% to 35% in compost establish the maximum O_2 consumption rate i.e., 95%, this means that from the analysis of the results presented in Figure 4-9, it can be concluded that the studied compost material with a water content of 42% to 65% will show the highest consumption rate and thereby highest CH_4 oxidation potential.

The porosity of the compost was also estimated and observed to vary in a narrow range of 57 to 65% for water contents from 40% to 106%. Table 4 - 1 represents the values of porosity of different porous materials for comparison.

Table 4-1: Porosity values for various materials

Material	**Porosity**
Ground food	81.3 – 72.9
Two manure compost	64.6
Toplar bark and urban sewage sludge compost	72.99

Red tuff derived from volcanic ash	58.7
Ground food (garbage compost)	81.3 – 72.9
Compost (present study)	59 - 62

References: Agnew and Leonard, 2003

4.3.2 Hydraulic conductivity test results

Figure 4-11 shows the variation of the hydraulic conductivity with the compaction curve of the compost. It can be noted from Figure 4-11 that the hydraulic conductivity curve of the compost shows a gradual decrease in value, until it attains a value of around 1.0 E-09 cm/sec at a water content of 82%. The compost material has a dry density of 1195 kg/m^3 for this particular water content. Then, the hydraulic conductivity curve starts to sharply increase which continues up to 107% of the water content value. The highest hydraulic conductivity value obtained is 1.0×10^{-5} cm/sec and corresponds to that of a sample located on the dry of optimum segment of the compaction curve, whereas the lowest hydraulic value reached is equal to 1.0×10^{-9} cm/sec at a water content of 82%. These values are in accordance with the values reported by Daniel (1993), Kamon (2002), and Caldwell (1993) for soil covers.

The explanation for this observed decrease in hydraulic conductivity as the dry density increases on the dry side of the compaction curve, and increase in hydraulic conductivity as the dry density decreases on the wet side of the compaction curve can entail the following reasons. Sharma and Derry (2004) reported that hydraulic conductivity depends on the density and viscosity of water as well as the soil specific surface, porosity and tortuosity, and degree of saturation.

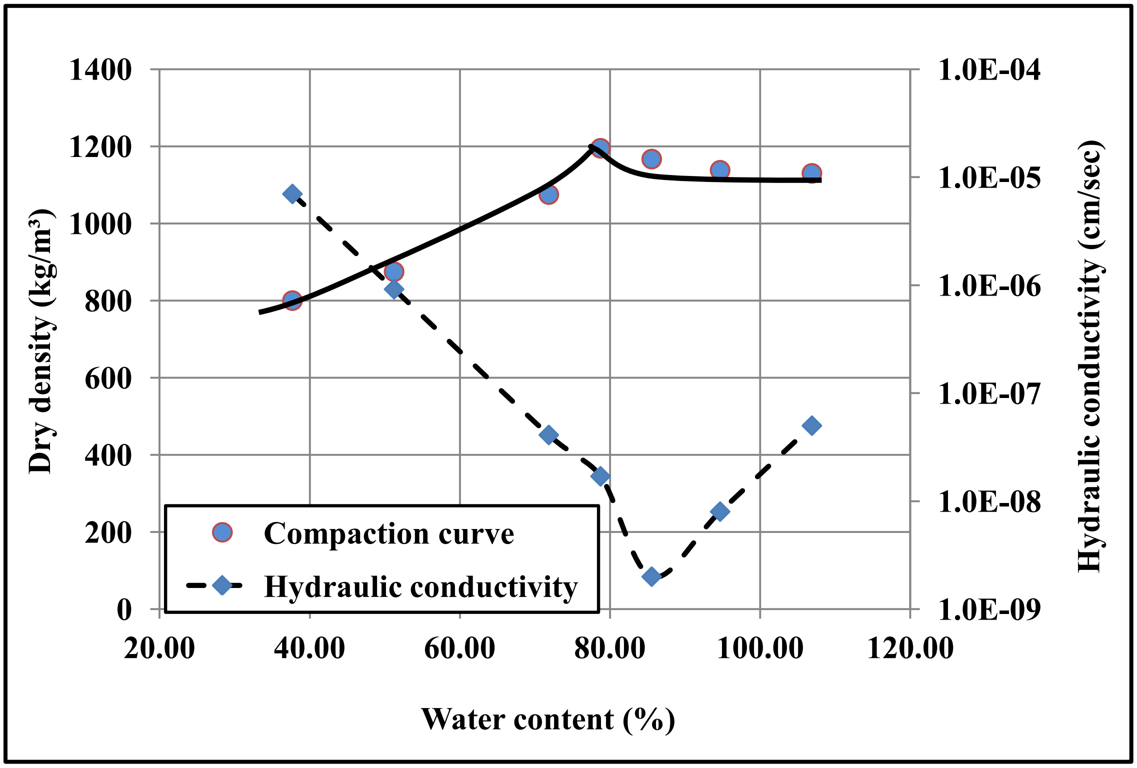


Figure 4-11: Variation of the hydraulic conductivity of compost with the compaction curve

The dry density of compost increases for the dry of optimum with an increase in water content that compels the compost particles to come closer together as reported by Reddy et al. (2009).

As the compost particles come closer together, accordingly, the FAS between the particles is reduced, and the compost sample provides fewer paths for water to flow, and the hydraulic conductivity decreases. Beyond the optimum point, as more water is added to the compost sample for wet of optimum, the dry density decreases, and the compost particles provides an easy path for water to flow. From these results, it can be concluded that the hydraulic conductivity of compost is a function of its compaction degree. In general, the compost provides hydraulic conductivity values in accordance with values suggested by the Resource Conservation and Recovery Act (RCRA, 1976). In addition, many regulatory agencies in the world (e.g., US Environmental Protection Agency (EPA)) require that hydraulic barriers have hydraulic conductivities less than 1 x 10^{-9} m s^{-1}. Based on the aforementioned results, compost can be compacted to achieve sufficiently low hydraulic conductivity.

The data also imply that compacting compost to low hydraulic conductivity can be accomplished for a wide range of water contents (62-110%). However, the water contents needed to achieve low hydraulic conductivity are typically larger than water contents used for compacted clays. Furthermore, it should be emphasized that some physical and structural changes may take place in landfill cover material due to freezing-thawing and some other environmental factors that can lead to the cracking of the cover material after some time and thus changes the hydraulic conductivity values as discussed by Othman and Benson (1993). Furthermore, it should be expected that the compost cover will experience settlement in time. This will result in the refinement of the pore structure of the compost and thus influence the hydraulic conductivity.

4.3.3 Thermal property test results

Figure 4-12 shows a graphical representation of thermal conductivity for compost as a comparison to the compaction curve.

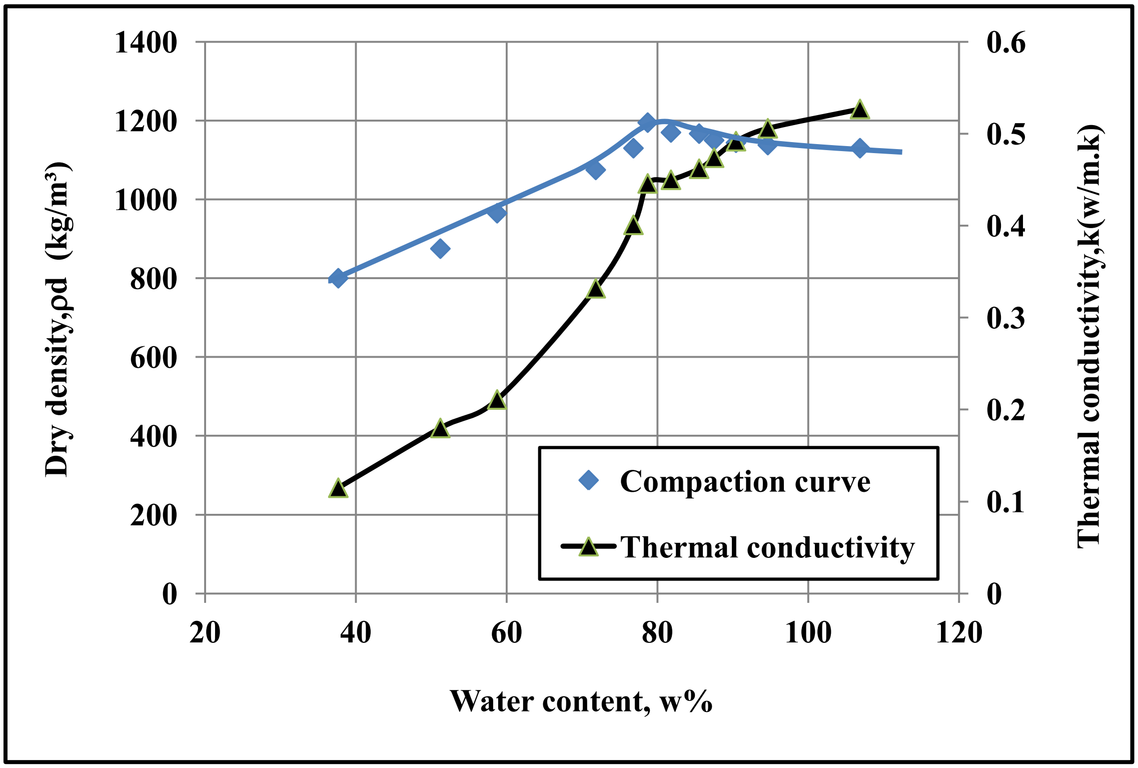


Figure 4-12: Thermal conductivity of compost at different water contents and dry densities

It can be seen that the thermal conductivity values vary from 0.12 to 0.54 w/m.k depending on the compaction degree or water content. Figure 4-12 indicates that thermal conductivity increases with an increase in water content for wet and dry of optimum. However, the nature of the curve is different for dry of optimum in comparison to wet of optimum and the rate of increase in thermal conductivity is more for the dry of optimum than the wet of optimum. The thermal conductivity follows the mechanism of the conduction of heat. According to the Fourier law, the conduction of heat depends on the contact surface area (Li and Yu, 2010). For dry of optimum, the dry unit weight increases with an increase in water content, and the compost particles get closer together. As the particles get closer together, the contact surface area increases which results in an increase in the conduction of heat due to reduction in air pores.

Consequently, an increase in thermal conductivity takes place. An additional factor responsible for this steep increase in thermal conductivity on the dry optimum is the fact that the degree of water saturation of the compost sharply increases as the dry density increases (Figure 4-9), thereby leading to a sharp increase in thermal conductivity. This can be explained by the fact that as the degree of saturation increases, the air in the compost is partially replaced by water. Since water has a thermal conductivity about 25 times that of air, it is obvious that when the water content increases, the thermal conductivity of the compost will also increase. The high rate of increase continues up to the optimal water content; after that, the rate of increase in thermal conductivity decreases with an increase in water.

For dry of optimum, the addition of water first contributes to wetting the surface of the compost particles, but does not play any significant role in filling the pores of the compost sample. For wet of optimum, the compost becomes close to saturation with sufficient additions of water. An increase in water content is used to fill the pores between the compost particles, which results in a decrease of the contact surface area for the compost particles. The reduction in contact surface area, and thus in dry density, results in a lower increase rate of the thermal conductivity on the wet side of the compaction curve compared to the dry side. Table 4-2 shows the thermal conductivity of various materials as a guide.

Table 4-2: Thermal conductivity of different materials

Soil type	**Leaf compost**	**Sandy loam**	**Soil mineral**	**Saw dust**
Thermal conductivity (w/m.k)	**0.6**	**2.74**	**2.6**	**0.202**

(Source : Agnew and Leonard, 2003)

Figure 4-13 shows the relationship between specific heat for a wide range of water content, i.e., from 10% to 106%. The value of specific heat increases with an increase in water content, and follows a linear path. According to equation 3, the specific heat is a function of ash content and water content. The ash content of the compost material is constant for all the samples with various initial water contents as discussed in section 3.3.3. For each addition of water, the degree of saturation increases replacing the air from the samples. The specific heat of water is four times to the air. So the specific heat goes on increasing with an increase in water content. The test results are in agreement with the results obtained by Mears et al. (1975). They carried out research on specific heat of compost material and reported that heat capacity of compost follows a linear relationship for various water contents. It is clear from Figure 4-13 that the specific heat of composting material varies from 1500 $kJkg^{-1}K^{-1}$ to 5700 $kJkg^{-1}K^{-1}$ for water content values between 10% and 106%. The calculated values of specific heat are in close agreement with the values reported by Agnew and Leonard (2003).

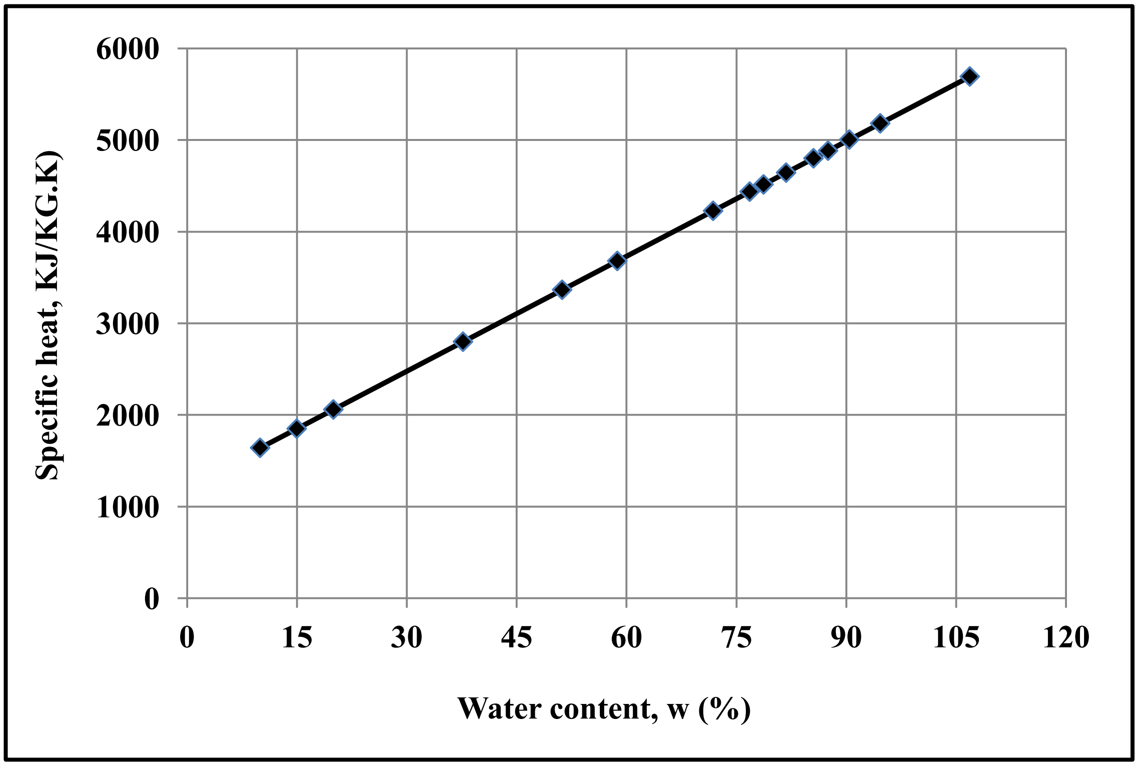


Figure 4-13: Relationship between specific heat and water content of compost

Figure 4-14 depicts the relationship between the thermal diffusivity and water content for the compaction curve. It is obvious from Figure 4-14 that the thermal diffusivity of the compost material increases with an increase in water content. The mechanisms responsible for this increase are the same as those responsible for the increase in thermal conductivity as explained above. A comparison of thermal diffusivity for different materials is presented in Table 4-3.

A comparison of thermal diffusivity in Table 4-3 shows that thermal diffusivity varies in a close range with various waste organic materials. It is clear from Figures 4-12 and 4-14 that an increase in thermal conductivity and thermal diffusivity takes place with an increase in the degree of saturation. The contact surface area is increasing with an increase in the water content of the compaction curve for dry of optimum. However, the rate of increase in thermal conductivity is more for the pre-peak in comparison to the post-peak in relation to constant heat capacity, because the thermal conductivity depends on the contact surface area.

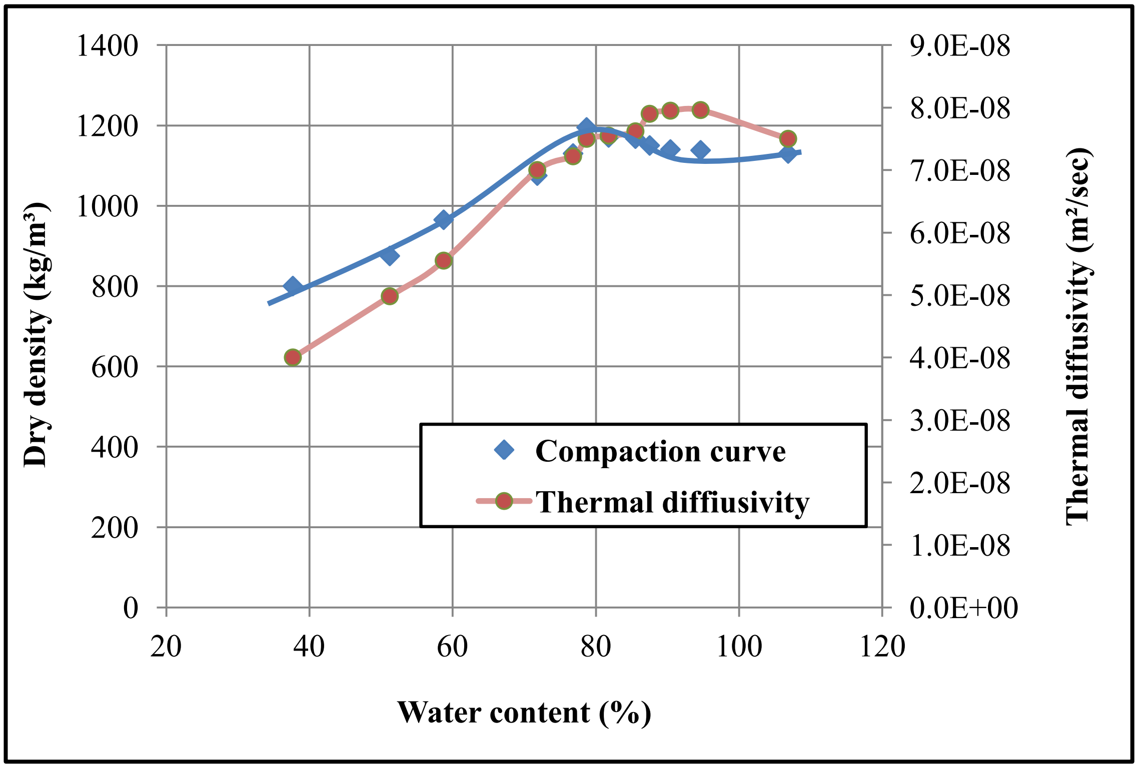


Figure 4-14: Relationship between thermal diffusivity and water content of compost

As a result, the thermal diffusivity decreases after the peak value has been reached. The thermal diffusivity of compost varies from 4.23x10^{-8} to 7.87x10^{-8} m^2/sec for water content values between 35% and 95%.

Table 4-3: Thermal diffusivity of different materials

Soil type	**Beef manure**	**Turkey litter**	**Oat straw**	**Saw dust**	**Sillage**	**Present study (compost)**
Degree of saturation	0.10	0.14	0.14	0.11	0.13	0.26
Thermal diffusivity (m^2/sec)	1.08 x 10^{-7}	7 x 10^{-7}	6 x 10^{-8}	1X 10^{-7}	1 x 10^{-8}	4 X 10^{-8}

(Reference: Ahn et al. 2009; Agnew and Leonard 2003)

4.3.3.1 Various proposed thermal conductivity equations

Various equations have been proposed in the literature to predict the thermal conductivity of porous media. These equations are based on the soil, water and air fractions in the medium. Table 4-4 shows some models used for thermal conductivity determination of various materials.

Table 4-4: Proposed thermal conductivity models

Equations	Material	Model name	Source
$\mathbf{K} = \mathbf{K_a}\,\boldsymbol{\xi}_\mathbf{a} + \mathbf{K_w}\boldsymbol{\xi}_\mathbf{w} + \mathbf{K_s}\boldsymbol{\xi}_\mathbf{s}$	Compost	Electrical circuit analogy model	Cosenza et al. (2003)
$\mathbf{K} = \mathbf{K_s^{(1-\xi)}K_w^{\xi}}$	Saturated media	Geometric law model	Woodside and Messmer (1961)
$\mathbf{K} = (\mathbf{0.8908} - \mathbf{1.0959}\boldsymbol{\xi})\mathbf{K_s} + (\mathbf{1.2236} - \mathbf{0.3485}\boldsymbol{\xi})\boldsymbol{\theta}$	Solids	-	Cosenza et al. (2003)

$\mathbf{K} = \left\{\sqrt{\mathbf{K_s}}(\mathbf{1}-\boldsymbol{\epsilon}) + \sqrt{\mathbf{K_w}\boldsymbol{\xi}_\mathbf{w}} + \sqrt{\mathbf{K_a}\boldsymbol{\xi}_\mathbf{a}}\right\}^2$	Porous media	Quadratic parallel model (QP)	Woodside and Messmer (1961)
$\mathbf{K} = \sum_{\mathbf{i=0}}^{\mathbf{n}} \frac{\mathbf{p_i K_i}\boldsymbol{\xi}_\mathbf{i}}{\mathbf{p_i}\boldsymbol{\xi}_\mathbf{i}}$		Weighted average model	de Varis (1963)

In the above equations $\xi_s = \frac{V_S}{V}$, $\xi_w = \frac{V_W}{V}$ and $\xi_a = \frac{V_a}{V}$ are the volume fractions of solid, water and air, respectively.

The model proposed by Cosenza et al. (2003) was used to theoretically estimate the thermal conductivity and compare it with the experimental data set. Figure 4 – 15 shows a comparison between the theoretical and experimental data test results, and illustrates that the theoretical results are in close agreement with the experimental data set.

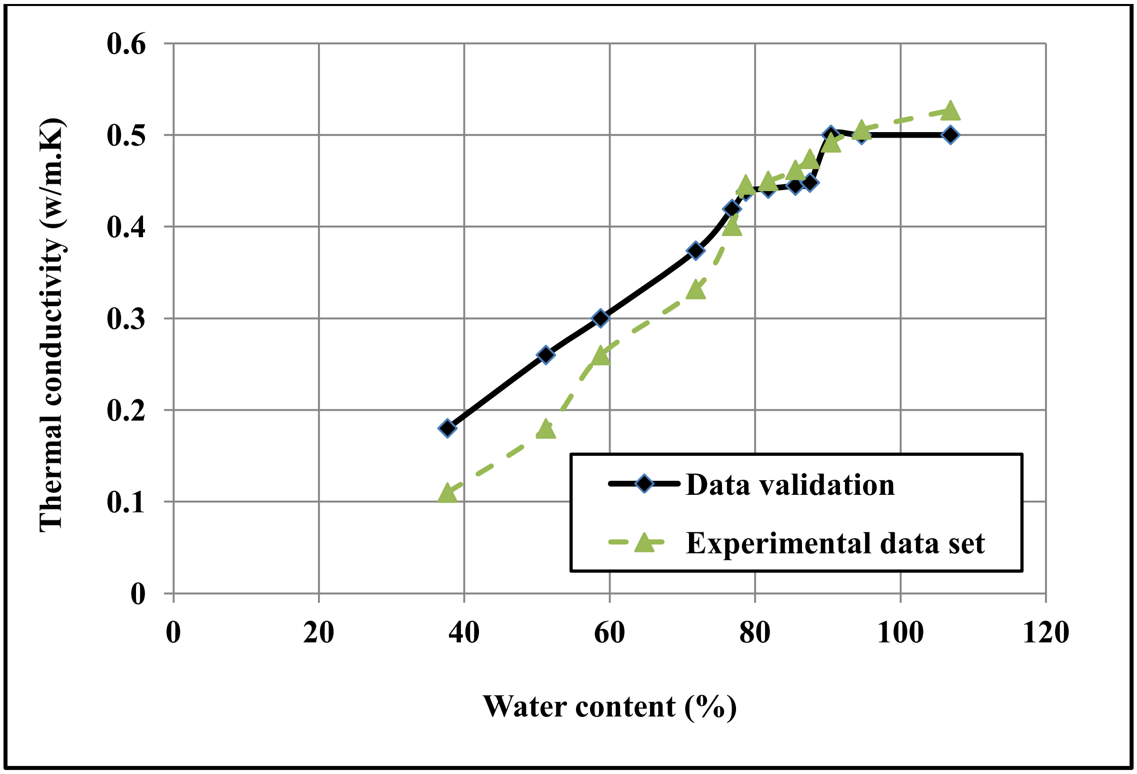


Figure 4-15: Comparison of experimental and theoretical results of compost materials

The model shows a small high peak for low water content, but the percentage difference is small which may be due to the reason that compost is a combination of various ingredients with various properties.

4.3.4 Direct shear test results

The several stress strain diagrams at various initial water contents and loading conditions here provide a pictorial view of the changed behaviour of compost biocover material in detail. The strength envelope of all water contents is also drawn from the test results applying Mohr Coulomb criteria to determine the shear strength at the end. Figure 4-16 shows an example of a typical relationship between shear stress and relative shear displacement at a normal stress of 20 kPa for various initial water contents, such as 46%, 59%, 72% and 79%.

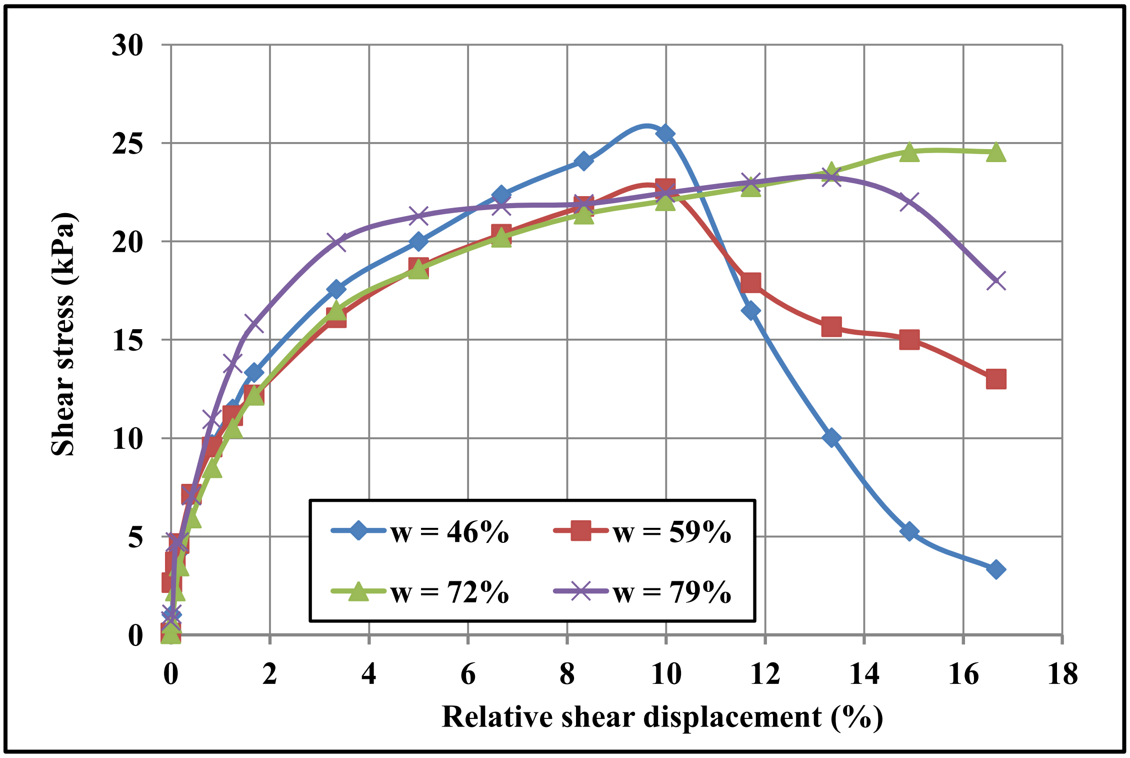


Figure 4-16: Shear stress vs shear displacement for different water contents at a normal stress of 20 kPa.

This figure depicts that shear stress gradually increases with relative shear displacement until it reaches the maximum shear stress at a relative shear displacement of 10% for samples with lower water content (46% and 59%) and around 14% for samples with higher water content values (72% and 79%). The peak shear stress is relatively similar for all water content values (taking into consideration the accuracy of the direct shear test results; the calibration was carried out to determine the deformation of the apparatus in order to check the accuracy of the test apparatus and the deformation was found to be minimal for all normal stresses adding no affect to the deformation value of the samples), except that it has a slightly higher peak for water content of 46%. After the peak value, the curve suddenly drops, which shows the highest drop for lower water content values.

This observed higher relative shear displacement (14%) for samples with higher initial water content can be explained by the fact that at higher water contents, the compost particles are in close interaction with each other due to higher dry density or compaction degree, and mobilize consistent frictional resistance for relatively larger shear displacement, whereas at lower water content, the compost particles are not closely compacted due to a lower mass to volume ratio. This figure depicts that the shear stress gradually increases with relative shear displacement until it reaches the maximum shear stress at a relative shear displacement of 10% for the samples with lower water contents (46% and 59%) and around 14% for the samples with higher water content values (72% and 79%).

Similarly, typical stress strain relationships of compost material are drawn under normal stresses of 40, 60 and 80 kPa for various water contents and dry unit weights. Generally, the cover is top most part of the landfill system and probably, the normal stresses vary from 15 – 20 kPa. However, in case of intermediate layer, the normal stresses are quite high. So a normal stress of 80 kPa is used for the evaluation of direct shear tests. Figures 4-17, 4-18 and 4-19 illustrate the relationship between shear stress and relative shear displacement for water content values of 59%, 72%, and 79%, respectively, under 40, 60 and 80 kPa.

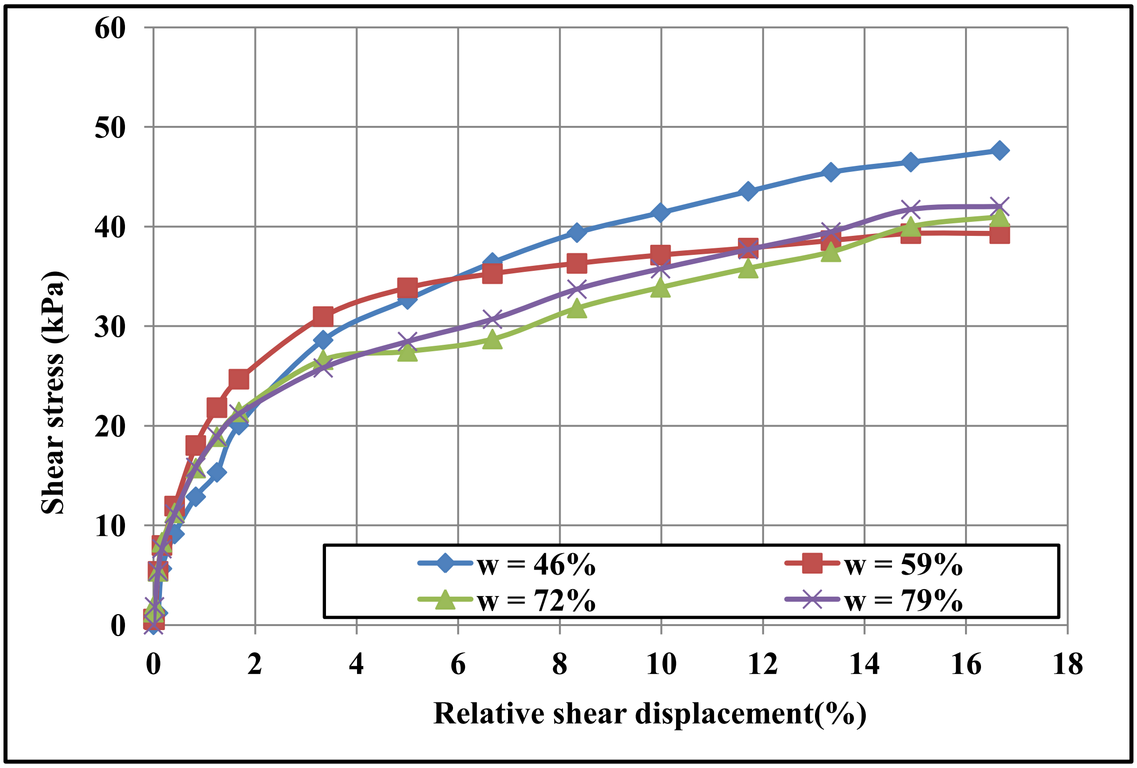


Figure 4-17: Shear stress vs shear displacement for different water contents at a normal stress of 40 kPa.

It is clear from these figures that all the stress-strain curves generally show similar patterns except for the curve with a water content of 79% at normal stresses of 60 and 80 kPa. For water content of 79%, the curves suddenly fail after reaching the peak stress in contrast to all the other curves.

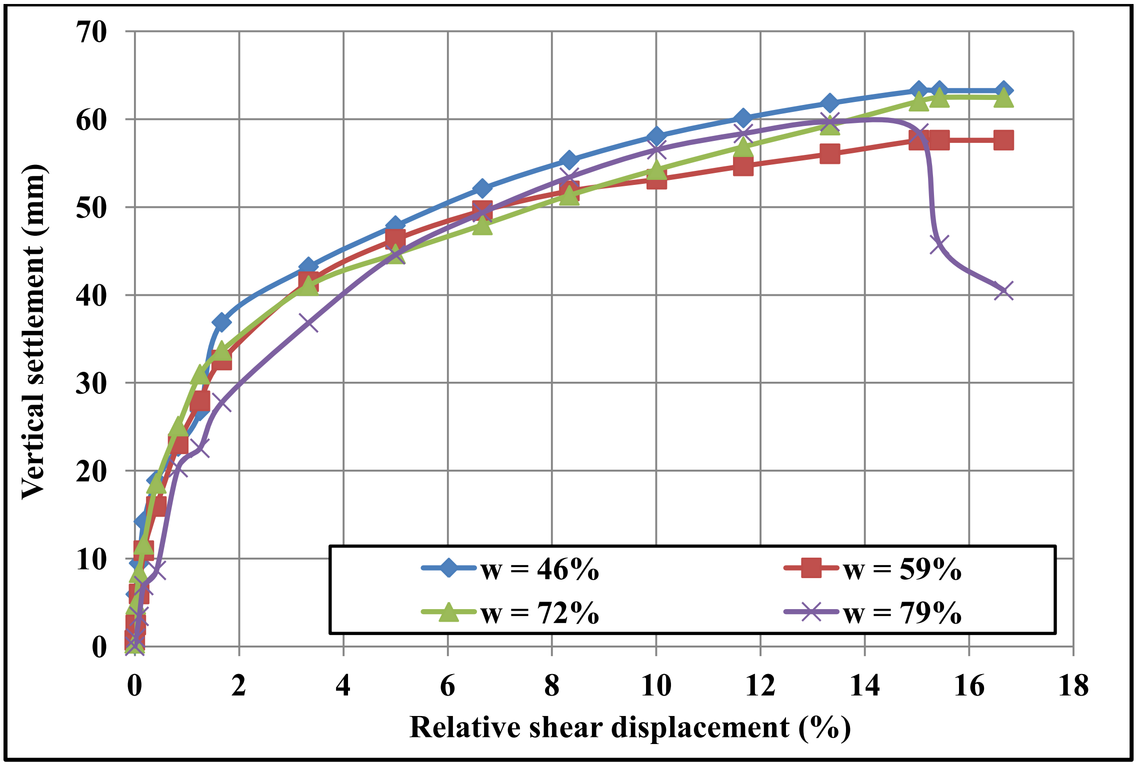


Figure 4-18: Shear stress vs shear displacement for different water contents at a normal stress of 60 kPa.

The shear stress for all the other curves gradually increases with an increase in relative displacement, until it attains peak value. After the peak value, the curves seem to remain relatively horizontal. The strain at the peak stress is approximately 15% for the samples and seems to be independent of the normal stress (except for the samples with a water content of 79%; these samples show a failure strain of 13%). It can be concluded from the above test results that the stress-strain behaviour of compost material is not significantly variable under normal stress (overburden) field loading conditions.

Figure 4-20 shows a typical relationship between shear stress and relative shear displacement under different loading conditions, i.e., 20, 40, 60, and 80 kPa, for a water content of 59%.

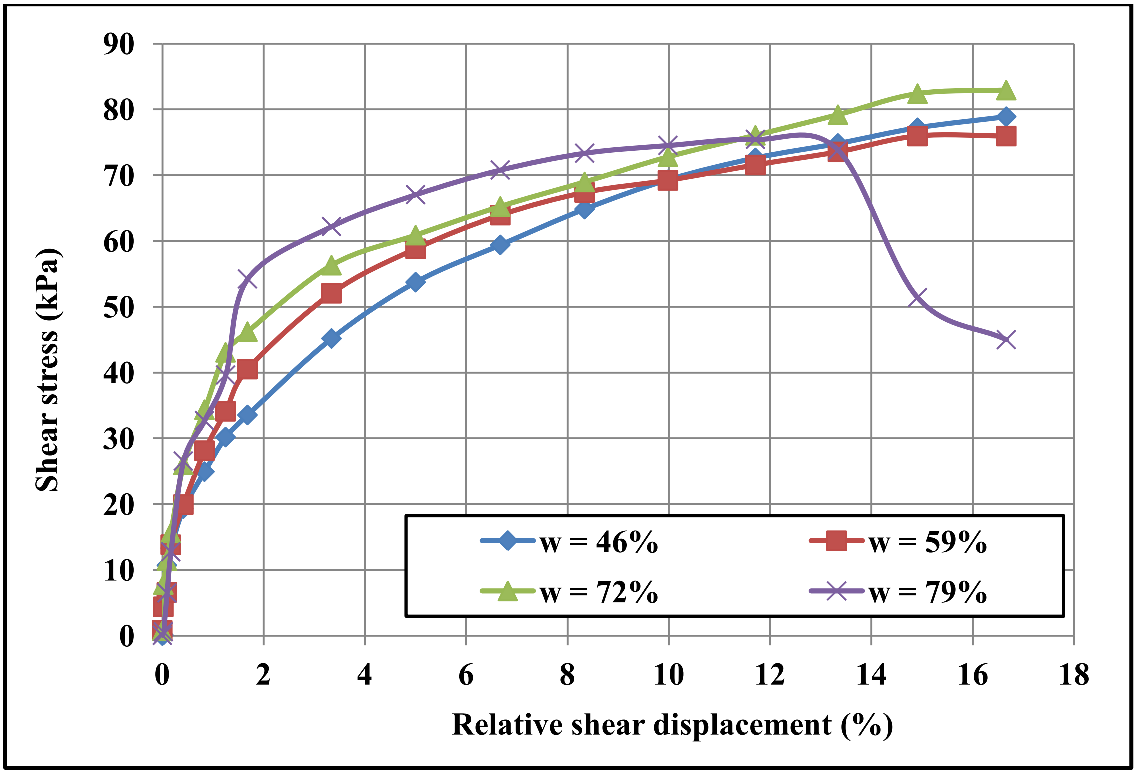


Figure 4-19: Shear stress vs shear displacement for different water contents at a normal stress of 80 kPa

Figure 4-20 shows that the initial portion of all the curves is curvilinear and the shear stress gradually increases with relative shear displacement until it attains the maximum shear stress at a relative shear displacement of around 10% for 20 kPa, and 14% for loading conditions greater than 40 kPa.

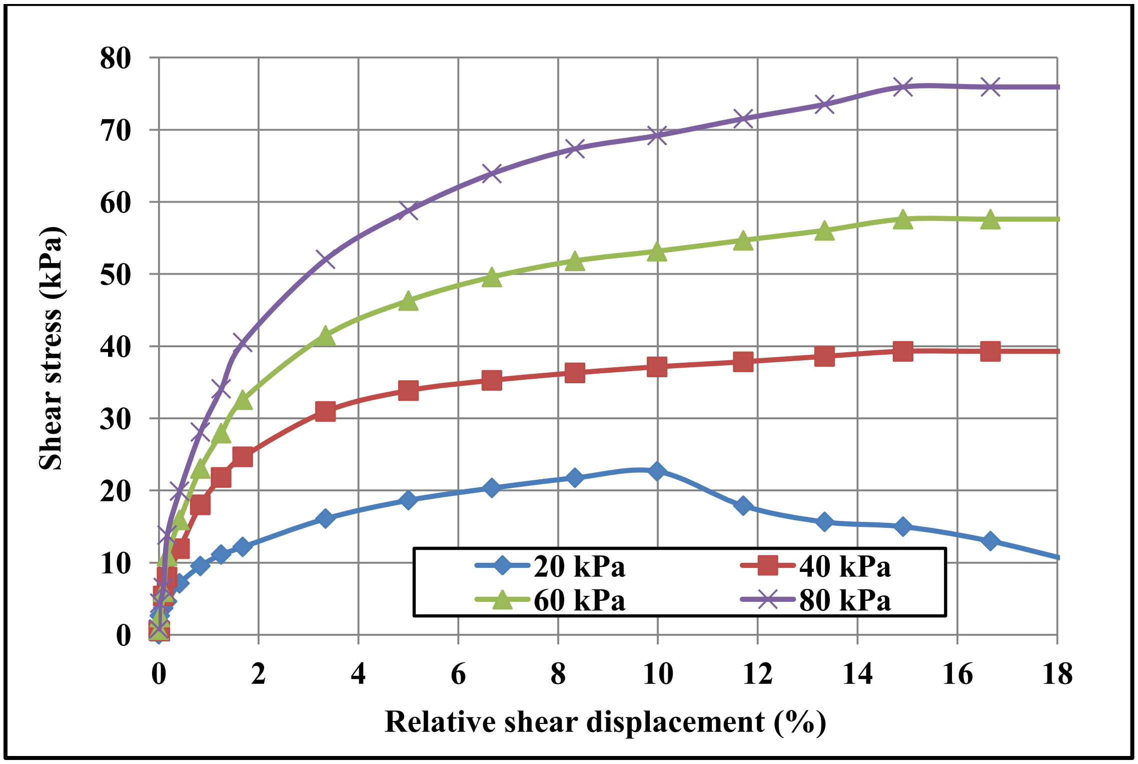


Figure 4-20: Shear stress vs relative shear displacement under different loading conditions for a water content of 59%.

After the peak value, the shear stress remains relatively constant or slightly decreases for normal stresses greater than 40 kPa per increase in relative shear displacement. As shearing is applied, 20 kPa normal stresses mobilize less frictional resistance in comparison to higher normal stresses as the specimen starts to dilate at relatively less shear displacement and fails earlier (Figure 4-20).

The observed increase in peak stress as the normal stress increases can also be explained by the fact that at higher normal stresses, the contact surface area of the compost particles increases. This stabilizes the sample and mobilizes more frictional resistance. As the shearing of the sample takes place, the sample settles more and fails at a larger relative shear displacement in comparison to lower normal stresses. The other reason may be the presence of fibrous constituents in the compost.

Fibrous constituents may stabilize the compost more at high loading conditions in comparison to lower normal stresses. According to Ng and Lo (2007), the behaviour of paper sludge is dependent on the organic, tissue and water contents, and fibre. Benson and Othman (1993) also reported that compacted compost contains fibrous tissues that increase the frictional resistance.

Figure 4-21 shows a typical relationship between relative shear displacement and vertical settlement for a water content of 46% under normal stresses of 20, 40, 60 and 80 kPa. It is clear from the figure that compost settles more at higher normal stresses than at lower normal stresses. The fact is that a higher normal stress leads to reduction in the local voids due to the compression of the compost material. On the other hand, at the beginning of the shear test, all the samples settled in the same way. However, the compost starts to dilate at lower normal stresses (20 and 40 kPa) at a relative shear displacement of 6%-8%. Yet the compost does not show dilating behaviour at higher normal stresses (60 and 80 kPa) for this particular water content (46%).

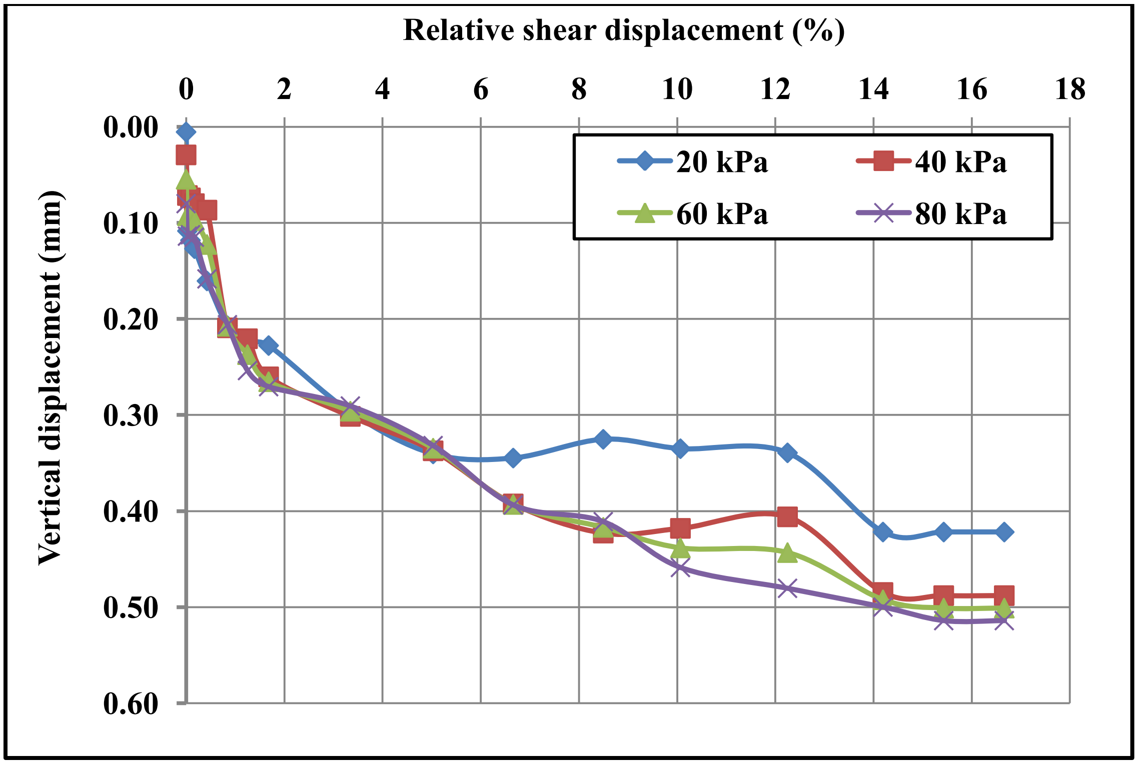


Figure 4-21: Vertical displacement vs relative shear displacement for a water content of 46%

Figure 4-22 shows the relationship between relative shear displacement and vertical displacement for a water content of 59%. It is evident from this figure that the samples experience dilation at lower normal stresses (20 and 40 kPa) and the dilation of the compost sample has slightly increased in comparison to the sample with a water content of 46%. The dilation takes place at a relative shear displacement of 10-13%.

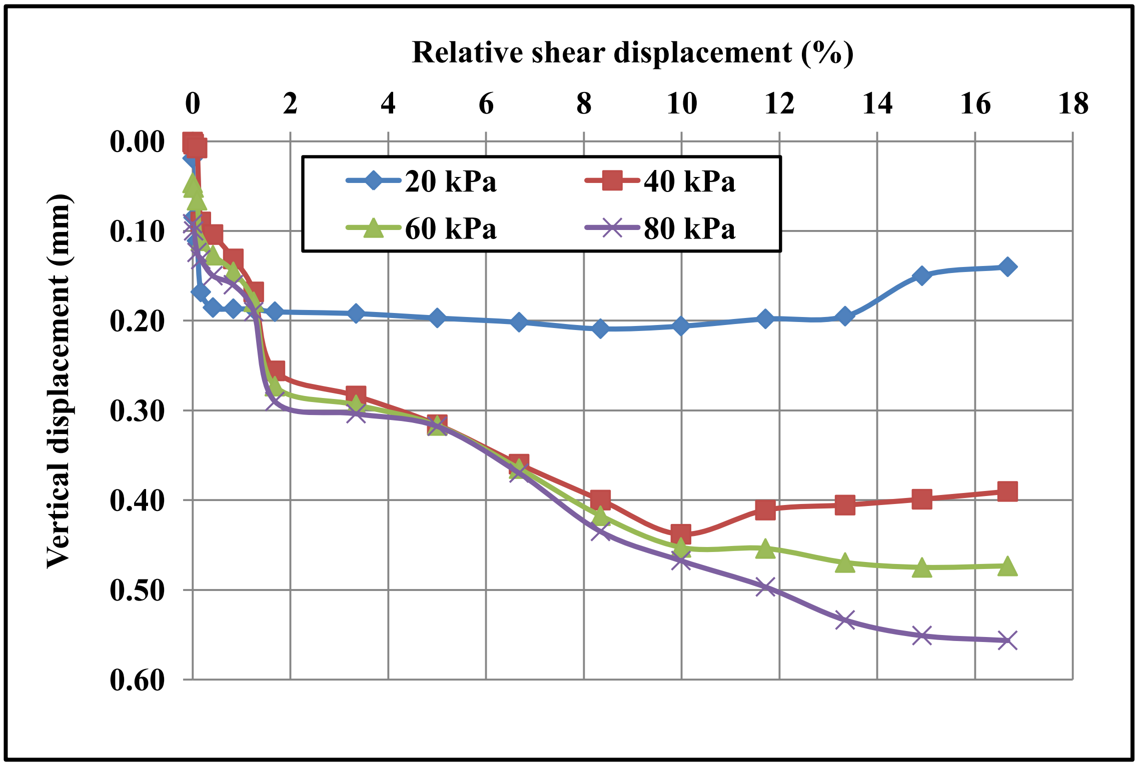


Figure 4-22: Vertical displacement vs relative shear displacement for a water content of 59%

The curves of higher normal stresses (60 and 80 kPa) still do not show any dilating behaviours. As the water content of the sample is increased to 72%, the dilating nature of the compost becomes more obvious and is depicted by Figure 4-23. Figure 4-24 illustrates the relationship between vertical displacement and relative shear displacement for a water content of 79% under various normal stresses. This particular water content corresponds to the optimal water content of the compost in this study. It is clear from the curves that the dilating potential of the compost has significantly increased at this water content, and it is obvious for all loadings.

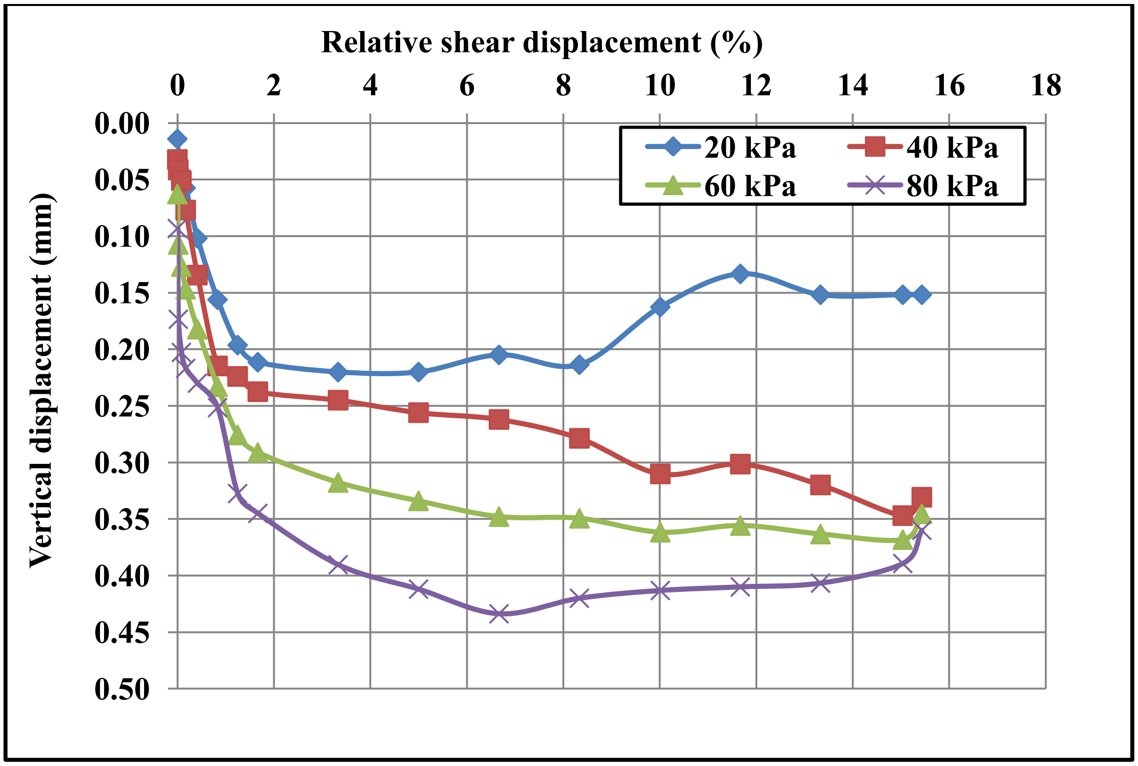


Figure 4-23: Vertical displacement vs relative shear displacement at a water content of 72%

According to Benson and Othman (1993) and Lo et al. (2002), the compost has a fibrous nature, and the fibres have the tendency to swell more at higher water content in comparison to lower water content. The curves start to dilate soon at a relative shear displacement of 5%, whereas for high normal stresses, the dilation takes place at higher relative shear displacements. The dilation is higher at lower normal stresses than higher normal stresses.

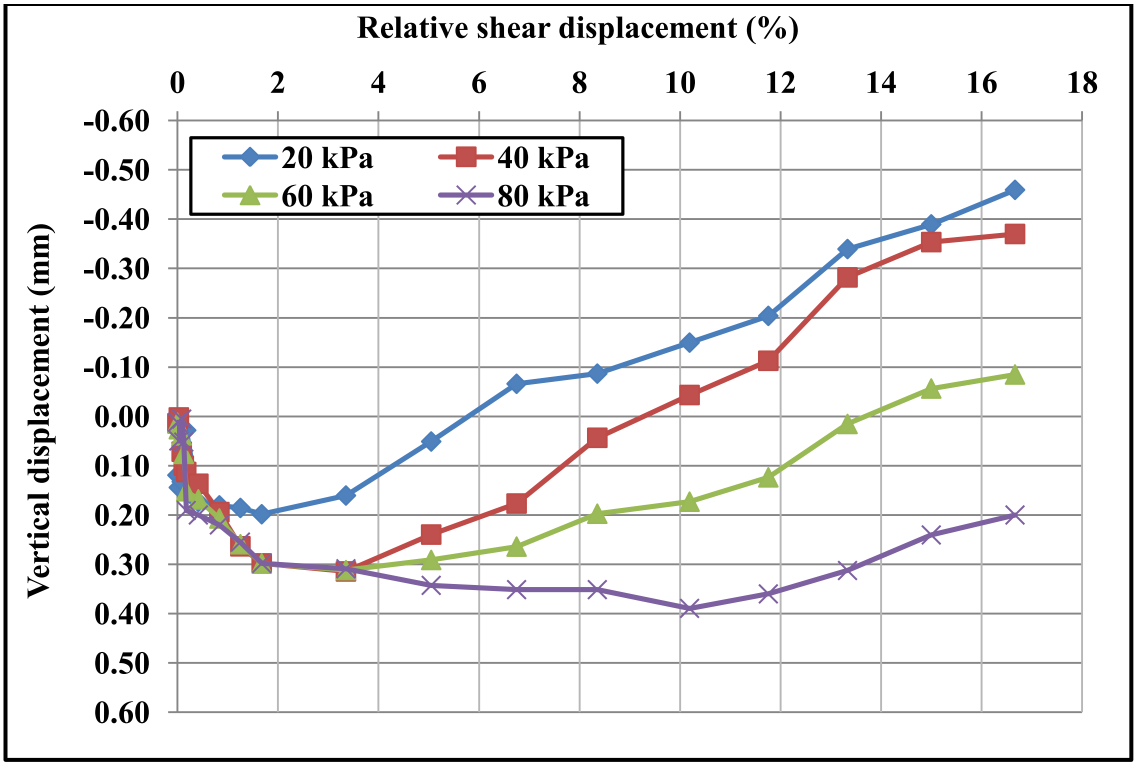


Figure 4-24: Vertical displacement vs relative shear displacement at a water content of 79%

This can be well explained by the fact that for low normal stresses, the particles are not closely packed in comparison to high normal stresses. According to Leo et al. (2002), more contact surface area increases the strength in a sludge type cover material. For higher normal stresses, the compost particles are compressed, which result in more contact surface area. More contact surface area results in stronger attractive interfacial forces that keep the particles intact for a certain range of water content. The compost has a fibrous nature, and the fibres have the tendency to swell more at higher water content in comparison to lower water content (Benson and Othman, 1993; Lo et al. 2002).

Figure 4-25 shows the relationship between shear strength parameters (angle of internal friction and cohesion) and water content of the composting material.

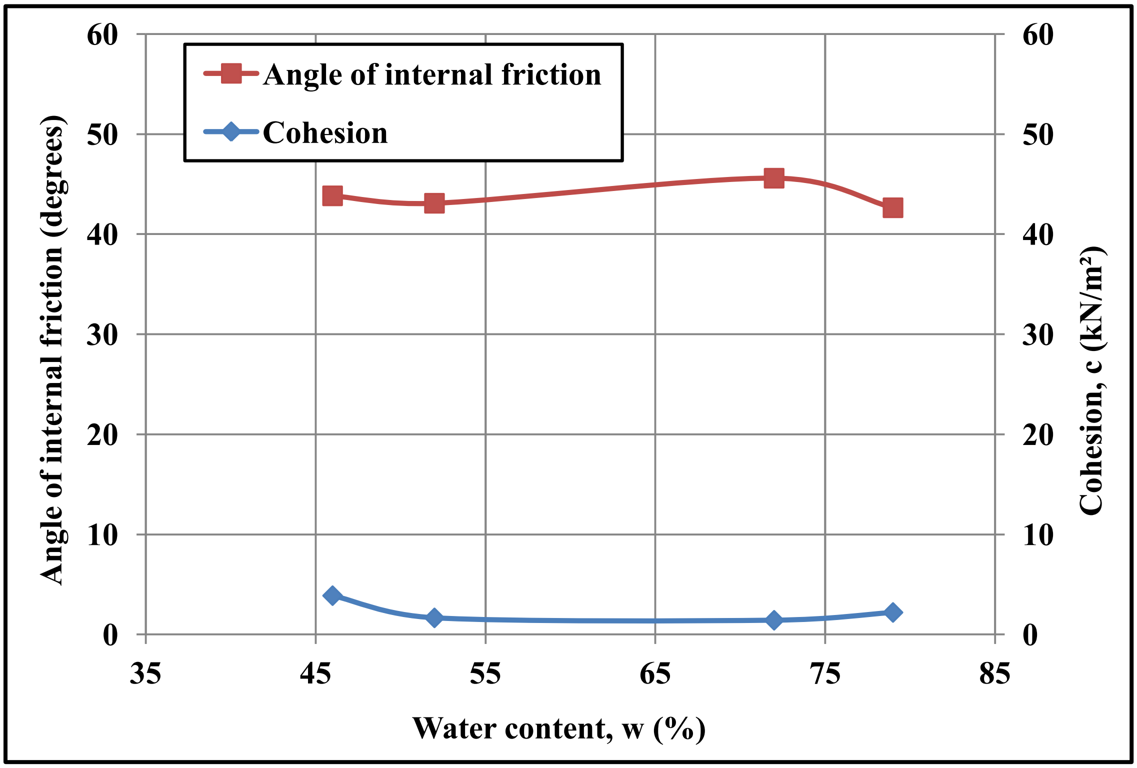


Figure 4-25: Relationship between water content and shear strength parameters of compost materials

The shear strength parameters are obtained by satisfying the Mohr Coulomb failure criterion for the experimental data sets. It is obvious from Figure 4-25 that all the samples have almost the same cohesion and angle of internal friction. The cohesion varies in a close range of 1.4 kN/m² to 3.9 kN/m² whereas the angle of internal friction fluctuates between 42.6 and 43.8 degrees. The friction angle is much greater than normally expected for compacted clays, for which it tends to be in the range of 20-30°

(Mitchell 1976; Benson and Othman 1993). Benson and Othman (1993) stated that this high friction angle is due to the presence of fibers that act as reinforcement in the shear zone. These fibers become entangled in the compost and as a result, increase resistance to deformation. This high friction angle suggests that compacted compost should have appropriate strength to resist shear failures on the slopes of typical landfill covers. It can be concluded from the experimental test results that the shear strength parameters of compost are not significantly influenced by the compaction degree. However, it should be stressed that the compost properties change with time.

It can be concluded from the above discussion that all the samples with different water contents and dry unit weights have the same shear strength parameters. This means that compost does not have any implications with respect to shear strength.

4.3.5 Oedometer test results

Figure 4-26 shows the relationship between vertical deformation and consolidation pressure of the compost specimens at different water contents and dry densities. It is obvious from the figure that all of the compression curves show almost the same nature (shape) for all the water content values; however, the compost dilates more at higher water content in comparison to lower water content, and deforms up to 3.5 mm at a water content of 79% which is 3.04% of the initial height of the sample.

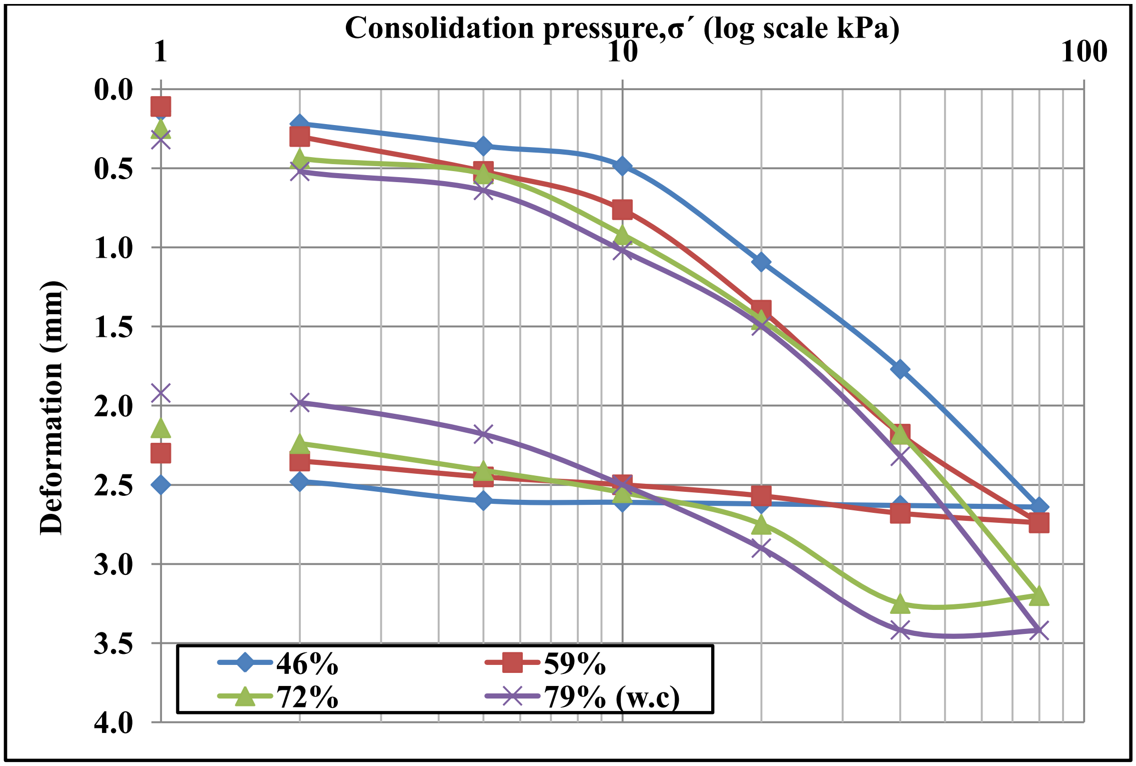


Figure 4-26: Relationship between deformation and consolidation pressure for compost

The maximum deformation for low water content (46%) is 2.6 mm, which is close to a water content value of 59%. Ng and Lo (2007) reported that sludge type material consolidates as well as swells more at higher water content. The study further added that the consolidation is a function of applied stress. On the other hand, the compost swells more as the water content increases irrespective of the dry density.

The compost has a maximum dry density at a water content of 79%, despite that the rebound curve shows a higher peak for this particular water content in comparison to other values. For low water content values, the compost shows less tendency to dilate, and the rebound curve appears to be almost like a straight horizontal line. So, it can be concluded from Figure 4-26 that the dilation/swelling behavior is dependent on the quantity of water content as reported by Ng and Lo, (2007). Figure 4-27 represents the relationship between void ratios versus the logarithm of effective pressure.

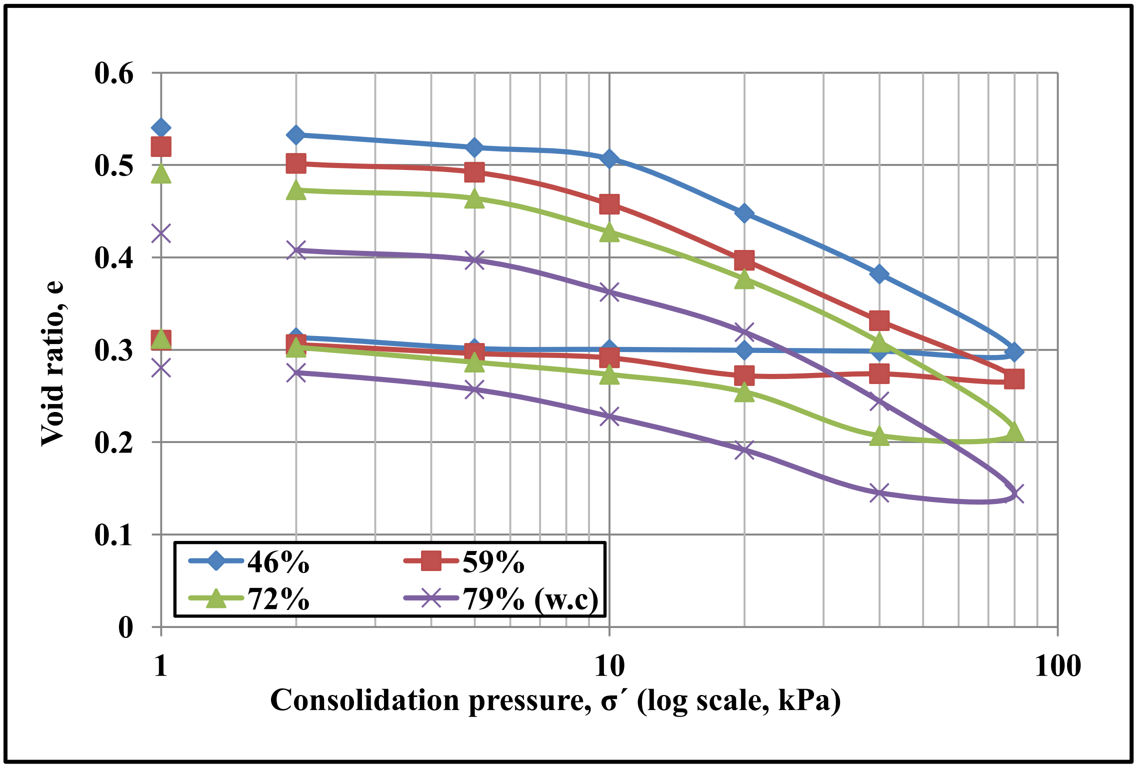


Figure 4-27: Relationship between void ratio and consolidation pressure for compost

Figure 4-27 shows that the void ratio of all the samples decreases with an increase in effective pressure. However, the reduction rate in void ratio for higher water content is relatively more as compared to lower water content values under all loading conditions. The compost sample attains a very low void ratio value (0.15) at a water content of 79% for an effective pressure of 80 kPa. This means that most of the voids are diminished or filled with water, and the sample may provide insufficient free space (f) for the movement of gas flux as a cover material. The same observation was reported by Moo-young and Zimmie (1996) while carrying out research on sludge. The expansion of the consolidated samples was calculated to be 5%, 15%, 35%, and 45% for water content values of 46%, 59%, 72% and 79%, respectively, during the unloading stage. Despite the high swelling potential for high water content samples, the void ratio is still less than that of lower water content values at zero unloading conditions. Ng and Lo (2007) reported that the compression and swelling indices of compost material represent the consolidation behavior of compost.

The computed values of the compression index (C_c) and swelling index (Cs) of compost are calculated as 0.30 and 0.10, respectively. The value of the compression index of compost satisfies the criteria as reported by Ng and Lo (2007) in which the index of natural clay is less than 0.5. The coefficient of consolidation (compressibility) of compost was also estimated to be 8.4 x 10^{-4} cm^2/sec (2.6 m^2/year). Table 4-5 shows the compression and swelling indices of various materials for comparison purposes. It can be seen that the compost has much less compression and a lower swelling index than many of the materials with high water content. Furthermore, it should be emphasized that the value of the Cc for most natural clays is less than 1 and typically less than 0.5 (Aydilek et al. 1999). Table 4-5 depicts that it is difficult to determine the swelling index and coefficient of consolidation for high water content materials. The compost has a lower compression index in comparison with other materials. It can be concluded from the above discussion that lower water content values provide more favorable conditions for compost to be used as a landfill cover material. Compost with lower water content shows less settlement and greater void ratio. The gas flow properties are greatly dependent on FAS, which is a function of CH_4 oxidation potential (Pokhrel, 2006). Compost is a variable natural material, so this study needs to analyze the settlement behavior of compost in the long run in consideration of field conditions.

Table 4-5: Consolidation behavior of high water content materials

Materials	**Coefficient of consolidation (m^2/year)**	**Compression index, C_C**	**Swelling index, Cs**
Paper sludge in Hong Kong	0.54 – 5.54	1.11	0.22
7 types of paper sludge in the US	NA	1.24	NA
Sludge in Japan	NA	1.22	NA
Sewage sludge in Hong Kong	NA	1.66	NA

Present study (compost)	0.27	0.30	0.1

4.4 Summary and conclusions

- Free flux path in a cover is a function of the index properties, including porosity, degree of saturation and air filled porosity. The compost cover significantly consolidates which may result in the reduction of FAS, which influences advection and dispersion processes in the cover. CH_4 oxidation potential is a function of these processes.

- Mechanical test results show that settlement is a function of initial water content and the compost consolidates more at higher water content, showing a significant reduction in air voids; however, the shear strength parameters i.e., angle of internal friction and cohesion, do not show any significant variation in their values for various initial water contents and dry unit weights.

- Hydraulic conductivity is a function of water content, and the hydraulic conductivity values of compacted compost are in good agreement with the requirements of a landfill cover.

- Thermal properties, such as thermal conductivity, thermal diffusivity and specific heat of compost materials, are very important parameters when taking into account the CH_4 oxidation potential. Thermal properties are a function of degree of saturation and dry unit weight.

The next section (Chapter 5) introduces and evaluates coupled THM behaviour of compost materials with a column experiment.

Chapter 5. COUPLED THERMO-HYDRO-MECHANICAL EVOLUTION OF COMPOST MATERIALS IN COLUMN EXPERIMENT

5.1 Introduction

Aside from CH_4 oxidation capacity, the most important properties of compost biocover materials include hydraulic (e.g., hydraulic conductivity, water content, degree of saturation, suction), thermal (e.g., temperature development, thermal properties) and mechanical (e.g., settlement behaviour, shear strength). It is known that the aforementioned properties are coupled. However, technical data that shows the coupling effect of hydraulic, thermal, and mechanical properties is quite limited in the literature. There is the need to obtain more knowledge on the THM behaviour of compost based cover material.

This chapter presents the results of the research carried out to study the coupled THM behaviour of compost material in a column experiment. The objectives of this chapter are:

- to develop a column setup for the study of coupled THM behaviour of compost cover materials, and

- to study the coupled THM evolution of compost biocover material in an unsaturated column experiment.

It should be emphasized that an examination of the CH_4 oxidation capacity of the compost column is beyond the scope of this study.

5.2 Materials and methods

5.2.1 Developed biocover column setup

Figure 5-1 presents a schematic diagram of the developed column to study the coupled THM behaviour of compost material. It should be emphasized that the development of this column setup had been time consuming and necessitated several months of work with regards to the design and the construction of the column.

The developed column has a height of 122 cm and a diameter of 45.6 cm, whereas the height of the compost cover material is 70 cm. An acrylic container was used for the construction of the column. The chamber was surrounded with an insulation sheet to reduce the lateral heat exchange with the surrounding atmosphere. Figure 5-2 shows a view of the acrylic column and insulation material used. According to Humer et al. (2008), a landfill cover can be built up to a height of about 90 cm with a minimum diameter of 10 cm. Tanthachoon et al. (2007) performed their study in acrylic columns with a depth of 60 cm and diameter of 15 cm. Humer et al. (2008) worked on a column experiment by using 1.2 m of mature compost layer underlain by a 0.3 – 0.5 m layer of coarse gravel. Rannaud et al. (2009) used a layer of coarse material that uniformly distributed the CH_4 flux.

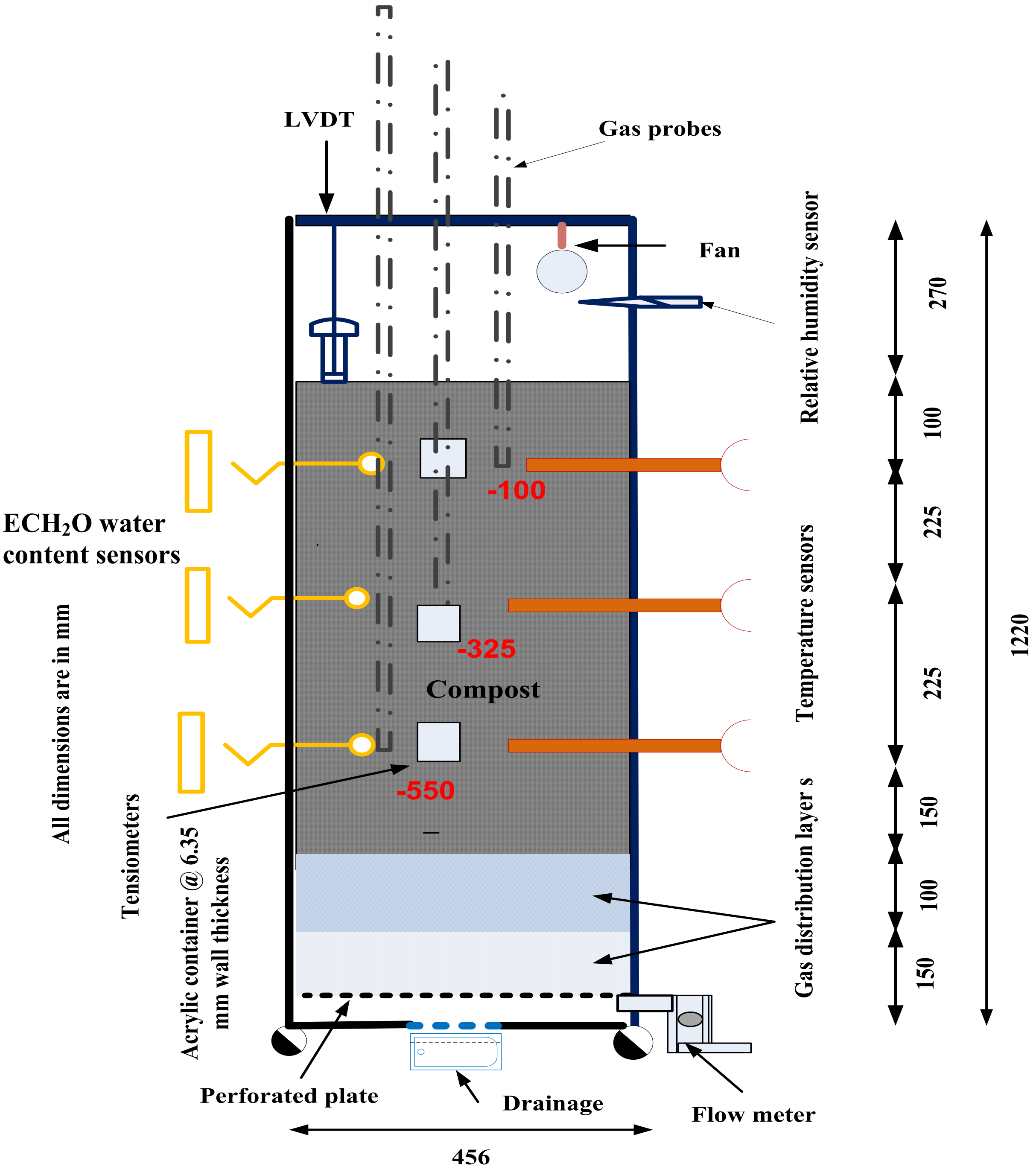


Figure 5-1: Schematic diagram of the developed column to study the coupled THM behavior of compost material

Two distribution layers of gravel with different sizes were used for the distribution of the CH_4 flow (CH_4 flow and oxidation capacity will be studied in future research by using the developed column). A perforated steel plate was placed at the bottom to make the distribution more uniform. Figure 5-3 shows the operational view of the column experiment.

Figure 5-2: View of the acrylic column and insulation material used

Figure 5-3: Operational view of the column experiment

Three ECH_2O sensors coupled with em50 data loggers were fixed in the column to determine the volumetric water content (VWC) and EC. Three thermistors (temperature sensors) were also placed in the column at the same levels as the ECH$_2$O sensors in the cover. Three tensiometers were built in the column to estimate the soil water potential (Figure 5-1). An LVDT connected to a data acquisition system was mounted at the top of the compost materials to determine the settlement behaviour (Figure 5-1). All of the sensors were connected to the data acquisition system. A relative humidity sensor and thermometer were configured outside the column to monitor the relative humidity and room temperature during the experiment. Figure 5-4 shows the test results for relative humidity and room temperature during the column experiment.

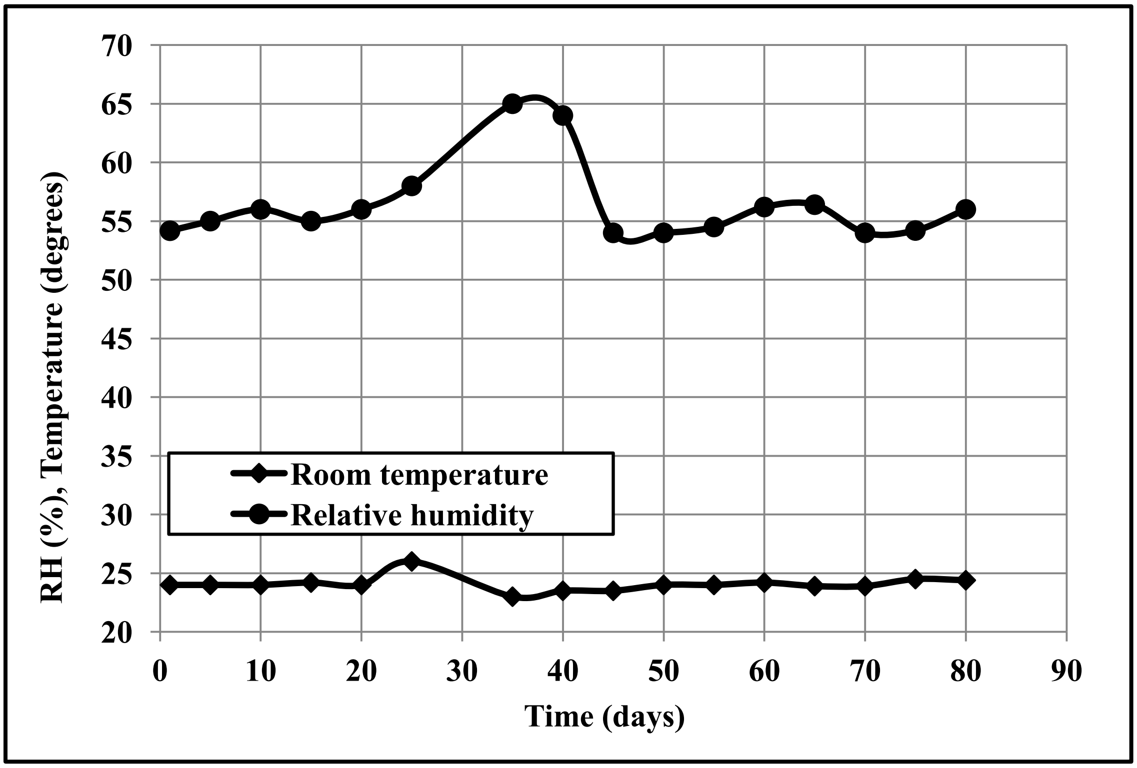


Figure 5-4: Evolution of the room temperature and air RH% during column experiment

Figure 5-4 illustrates that the room temperature falls in a range between 22°C and 24°C whereas the relative humidity varies from 55% to 65%

5.2.2 Calibration and installation of devices

Figure 5-5 shows the arrangement undertaken for the calibration of the devices.

Figure 5-5: Calibration arrangement for water content, soil water potential and temperature sensors

Calibration is considered to be a pre-requisite for any device to be used for data collection. It is important to calibrate devices for the type of soil or porous medium used. This section provides a brief explanation about the calibration of some of the important devices used in the study.

5.2.2.1 Decagon ECH$_2$O EC-5 soil moisture sensor

Figure 5-6 shows an ECH$_2$O EC-5 moisture probe for the measurement of water content. The ECH$_2$O EC-5 moisture probe determines the VWC with a range between 0% and 100%. The probes use capacitance/frequency domain technology to estimate the dielectric constant of the media.

Figure 5-6: Decagon ECH$_2$O EC-5 moisture probe for VWC

Figure 5 - 7 shows the average calibration curve of the ECH$_2$O EC-5 moisture probe. The sensors show a coefficient of correlation almost equal to 1. The ECH$_2$O EC-5 moisture sensors use high frequency oscillation which enables them to precisely determine the VWC in soil or any other medium. The devices take into consideration the minimal effect

of salinity and texture. The VWC depends on the apparent capacitance of the solids that surround the sensors.

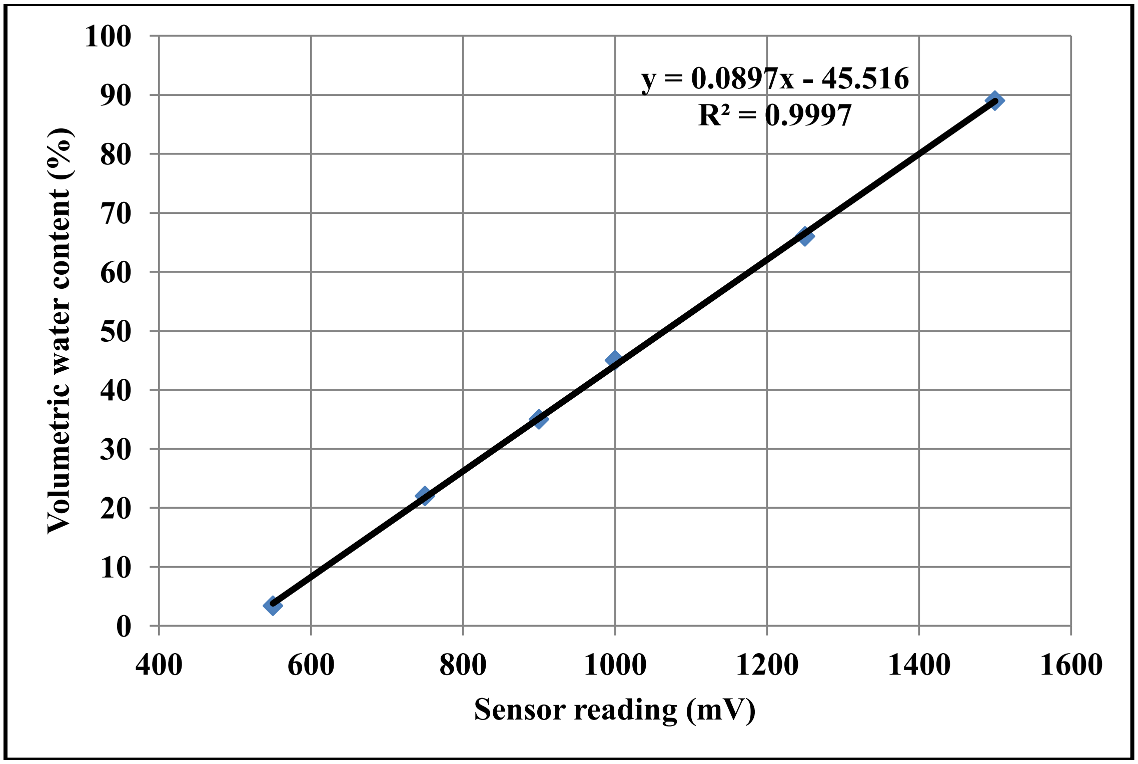


Figure 5-7: Calibration curve of ECH$_2$O EC-5 moisture probe

The ECH$_2$O sensors were calibrated for the compost materials before being placed into the compost cover material.

5.2.2.2 Decagon EC-TM temperature sensor

Figure 5-8 shows the Decagon EC-TM sensors used for the measurement of temperature.

Figure 5-8: Decagon EC-TM probes for temperature monitoring

Figure 5-9 shows the average calibration curve of the EC-TM sensors for the compost material. The EC-TM temperature sensor uses an electromagnetic field to estimate the dielectric permittivity of the surrounding media. The sensor prong receives a 70 MHz oscillating wave from a sensor that produces the charge. The charge depends on the dielectric and water content of the medium. The EC-TM microprocessor measures the charge and outputs a value of dielectric permittivity from the sensor. The EC-TM records the temperature reading in degrees Celsius through surface-mounted thermistors. The curve shows a coefficient of correlation equal to almost 1. It is important to mention that EC-TM establishes a relationship between water content and sensor readings (mV) of the voltmeter for the calibration purpose.

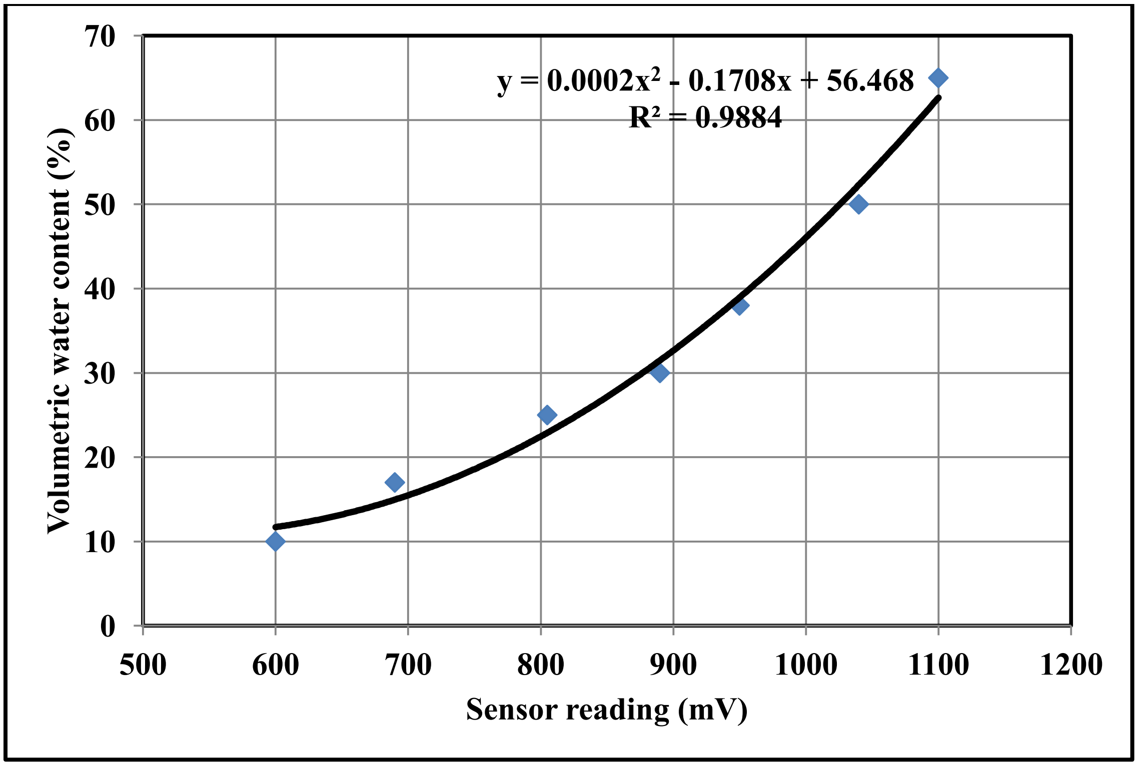


Figure 5-9: Calibration curve for EC-TM probe

5.2.2.3 Tensiometers for soil water potential

Figure 5-10 shows the tensiometers used for the measurement of suction. Large inflexible standard tensiometers are not practical for laboratory research in soil/compost columns with tight corners or near soil surfaces. The Model 2100F soil moisture probe is a specialized unit designed for measuring soil suction values at various levels in soil columns. The tensiometer probe has a tiny porous ceramic cup that is 6 mm in diameter and 2.5 cm in length. The probe is connected to the tensiometer body through 1.8 m of nylon tubing. The tensiometers can measure suction between 0 and 90 kPa. The tensiometer can measure the suction up to 90 kPa, after then the cavitation of water may take place in the tensiometer (Fredlund and Rahardjo 1993)

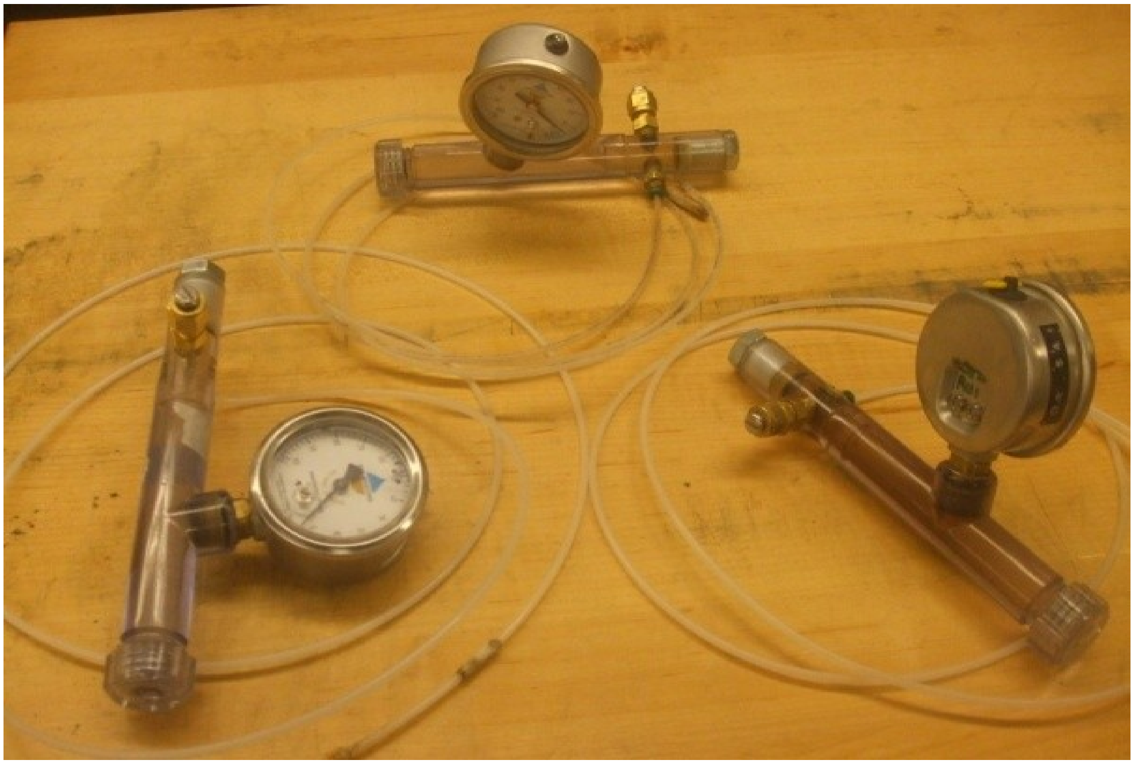


Figure 5-10: Tensiometers for soil water potential

All the tensiometers were calibrated by following the methods as described in the manual. Calibration is essential for air free tensiometer tubes to obtain accurate results and deaired water was used to fill out the tube. The calibration of tensiometers requires matching water contents which are determined by the gravimetric method over a range of soil water contents.

5.2.2.4 LVDT for settlement

Figure 5-11 shows the calibration curve for an LVDT gauge. The LVDT gauge was calibrated by examining the changes in voltage which result from deflection. It was calibrated to determine the voltage based on displacement and vice versa. The LVDT calibration curve shows a coefficient of correlation equal to 1.

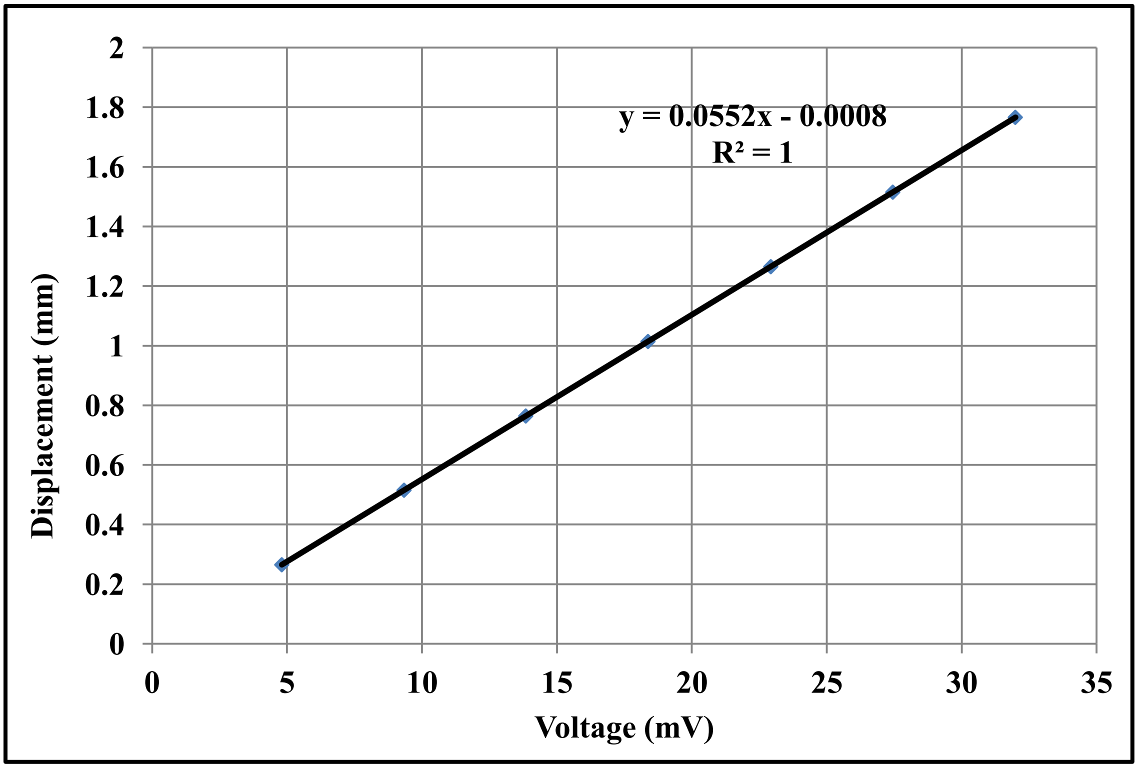


Figure 5-11: calibration curve for LVDT

5.2.3 Characteristics of the compost material studied

The column experiment was carried out with compost material received from Lefleche Environmental Inc., Canada. The various properties of the compost have already been discussed in Chapters 3 and 4 in detail. Table 5 -1 summarizes the characteristics of the compost used in the column experiment.

Table 5-1: Characteristics of compost

Parameters	Value
Gravimetric water content	30%
Degree of saturation	37%
Void ratio	1.38
Porosity	59%
Free air space	37%

The initial water content of the compost was high, so a bulk quantity of the compost was placed on a wooden plank (1.5 m X 1.5 m) for air drying, which brought it to a water content of 30% for use in the column. The compost was thoroughly mixed on the wooden plank until homogeneity of the compost materials was achieved. The homogeneity of the compost was tested by determining the water content. The compost samples were taken out from various locations. It was assured that all the samples have almost the same water content. After then, the compost was taken into column. The compost was compacted into 6 layers of equal thickness to attain the values as mentioned in Table 5-1 and ensure uniform compaction for the biocover.

5.3 **Results and discussions**

5.3.1 Evolution of the temperature in the biocover

Figure 5-12 presents the temperature depth profiles for the compost biocover during the column experiment. Figure 5-12 depicts that the compost cover has a temperature of 20^{o}C at the beginning of the experiment. The temperature profiles for all depths show an increasing trend for the first three weeks of the experimental operation. After that, the temperature profiles start to decrease. The compost cover attains a maximum temperature of 25^{o}C at a depth of 33 cm after 20 days.

The temperature is lower in the upper and lower layers, i.e., 23.5°C and 24.5°C, respectively, in comparison to the middle layer of the cover. However, it should be mentioned that the cover temperatures at depths of 33 and 55 cm are close. The observed temperature in the biocover is in close agreement with the results reported by Cabrel et al. (2010). The noticed increase in temperature (in comparison to the initial compost temperature) can be attributed to the heat generated by the microbial activity. Cabrel et al.

(2010) also confirmed that high temperatures in the cover in comparison to the atmospheric temperature are due to the microbial activity of the methanotrophs.

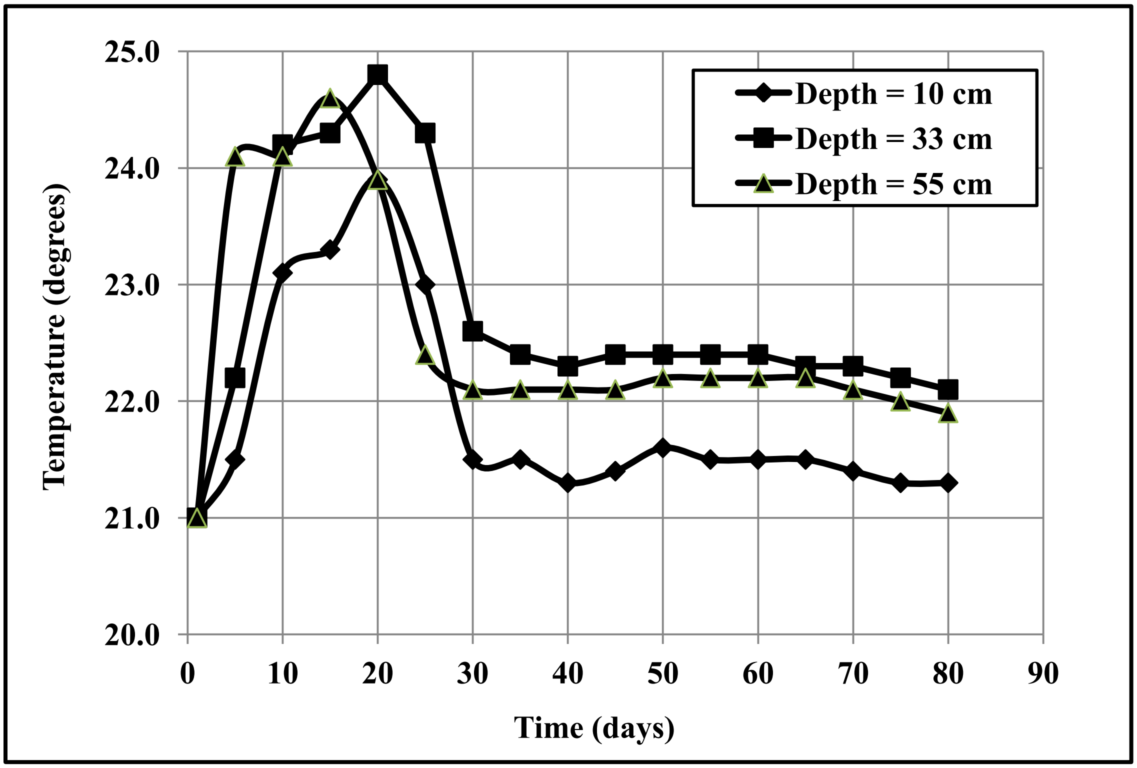


Figure 5-12: Temperature variations of composting material at different depths with time

A decrease in the temperature after reaching the peak could be explained as originating from heat loss. The lower temperatures for the upper layer may be due to higher heat loss and less microbial activities. According to Pokhrel (2006), the optimal temperature for CH_4 oxidation is in the range of 20°C – 50^0C. Visvanathan et al. (2010) reported that an optimal temperature for maximum CH_4 oxidation potential lies between 20°C and 30^0C. This means that the temperature profiles for all the depths are within the maximum oxidation range until now. However, the temperature for the upper layer (10 cm) may lose maximum oxidation potential in the long term or colder regions as the temperature profile continuously decreases. The high temperature in the intermediate and lower layers can be attributed to higher methanotrophic respiration activities as these bacteria release heat upon respiration (Pokhrel, 2006). Thus, in the present study, it can be considered that the most active CH_4 oxidation zone seems to be located between 33–55 cm, exactly within the region where more microbial respiration activities and thus higher temperatures were observed (Figure 5-12).

5.3.2 Evolution of the hydraulic factors in the biocover

5.3.2.1 Volumetric water content (VWC)

Figure 5 -13 shows the evolution of the VWC in the compost cover that was determined at various depths. It can be seen from the figure that the VWC increases for all the depth profiles in the first three weeks. The VWC is quite high for a depth of 55 cm in comparison to the lower depths. The VWC attains a value of almost 26% for a depth of 55 cm in the first week. This higher water content can be explained by the downward movement of water molecules as a result of gravity. After three weeks, the VWC curves for all depth profiles show a slight decreasing trend. This decrease is higher as the depth becomes lower. This decrease can be attributed to water loss due to evaporation (Pokhrel, 2006).

It is well known that the water content has a significant impact on the performance of biocovers with regards to CH_4 oxidation as demonstrated by several studies (Albana 2009, Huber-Humer et al. 2009, Visvanathan, et al. 2009, Yuan 2006, Pokhrel 2006). Pokhrel (2006) suggested a VWC range from 25% to 75% for maximum CH_4 oxidation with respect to the microbial oxidation process. Consequently, from the results presented in Figure 5-13, it can be expected that a depth of 55 cm will have the maximum CH_4 oxidation capacity.

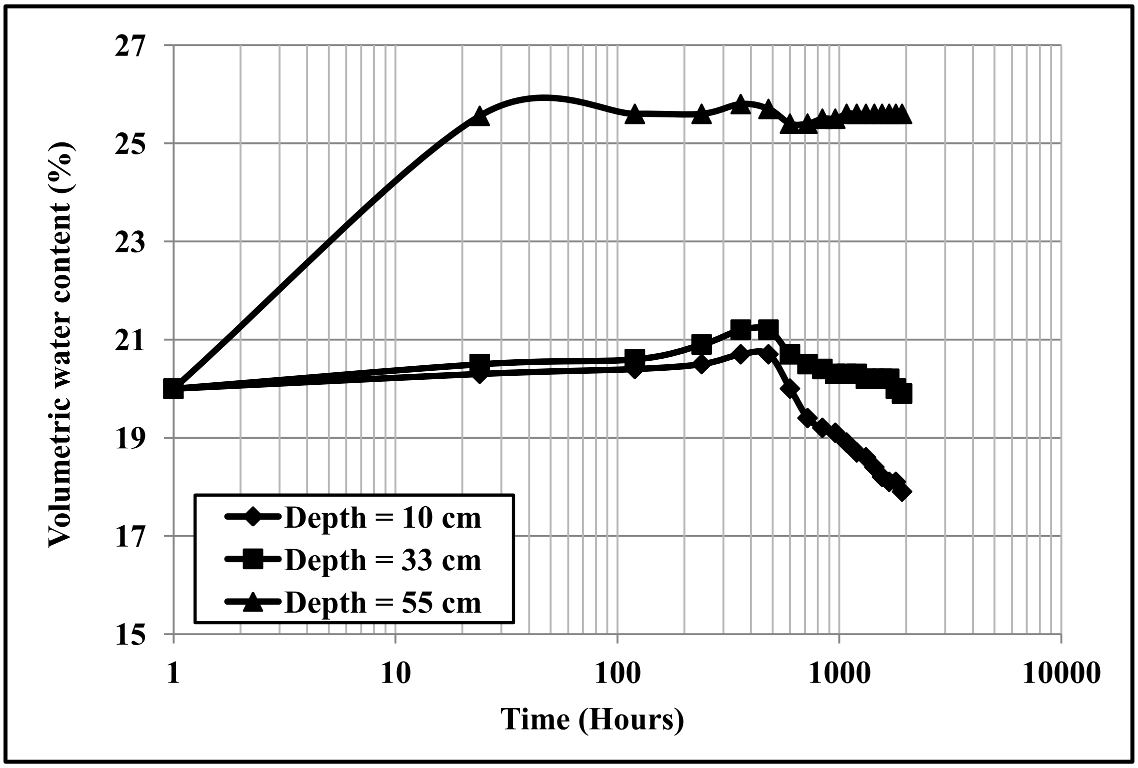


Figure 5-13: Evolution of the volumetric water content in a compost cover at various depth profiles

5.3.2.2 Degree of saturation

Figure 5 -14 shows the degrees of saturation for various depth profiles of a compost cover.

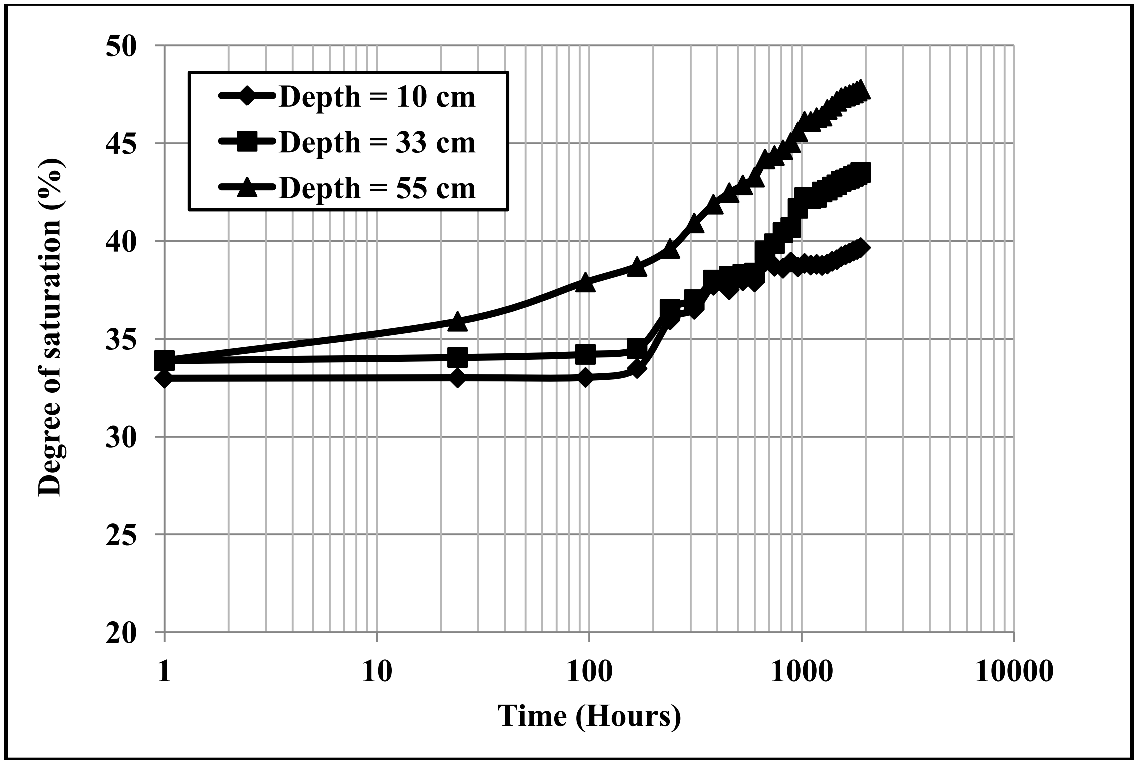


Figure 5-14: Evolution of the degrees of saturation in the compost cover at various depth profiles

It is clear from figure 5 -14 that the degree of saturation is increasing for all depth profiles with time. The degree of saturation is high for 55 cm depth in comparison to lower depths. These results are in good agreement with the conclusions of Cabrel et al. (2010) that reported that compost cover shows high degree of saturation in the bottom layer in comparison to upper layer. The increase of the degree of saturation in the first weeks can be mainly attributed to the increase in volumetric water content. The mechanism responsible for the increase in volumetric water content is already explained above. However, the analysis of Figures 5-13 and 5-14 reveal that after three weeks, the water saturation degree keeps increasing (Figure 5-14) despite a decrease in the volumetric water content (Figure 5-13). This may suggest that the porosity or void ratio of the compost cover is becoming lower, thereby leading to an increase in the saturation degree. This assumption is supported by the results presented in Figure 5-21 (will be discussed later).

From Figure 5-14, it can be noted that regardless of the depth, the values of the degrees of saturation of the biocover column are lower than 85%, which approximately corresponds to the values of the degree of saturation beyond which air becomes occluded in the fine grained soils (Brooks and Corey 1966; Nagaraj et al. 2006). Furthermore, gas fluxes become quite low when the value of the degree of saturation approaches 85% (e.g., Yanful 1993). This means when the degree of saturation reaches approximately 85%, gas diffusion should be completed in the liquid phase which is much slower than the gas phase (Cabral et al. 2004; Scheutz,2009; Moghbel and Fall, 2011). This can radically decrease CH_4 oxidation, due to the lack of both O_2 and CH_4 in the biocover (Scheutz et al., 2009).

5.3.2.3 Suction

Figure 5-15 show the evolution of the suction profile of the compost cover for various depth profiles.

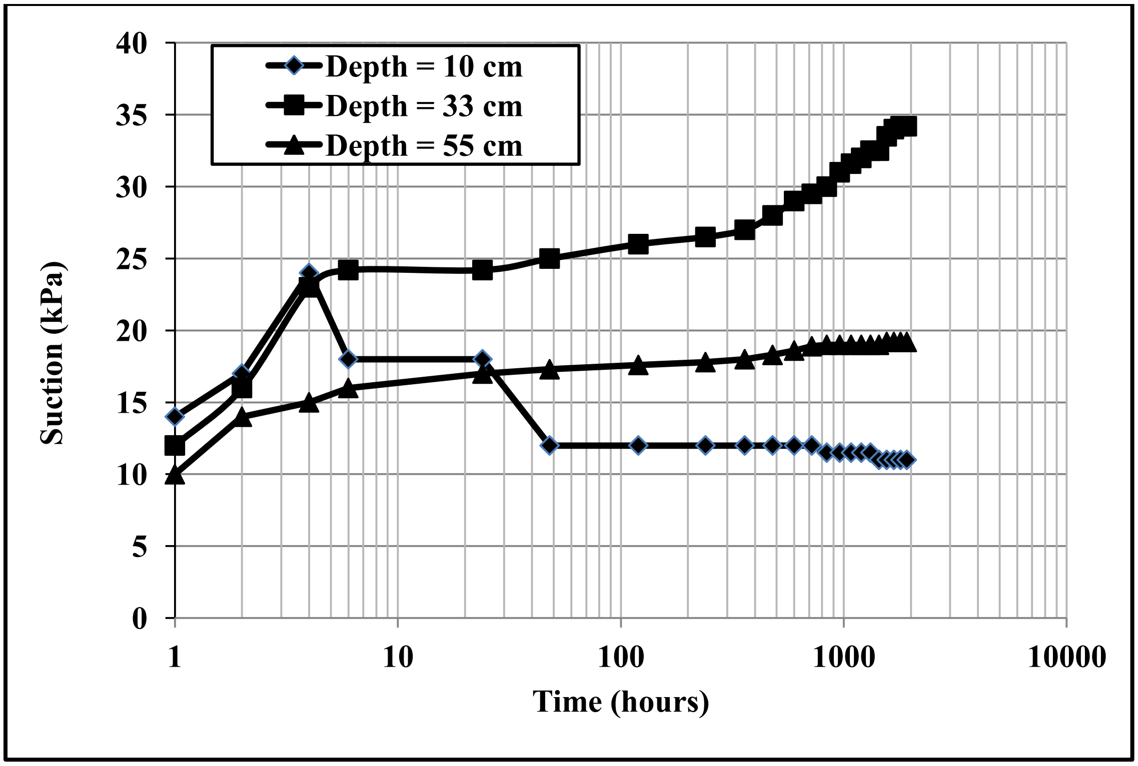


Figure 5-15: Evolution of suction for compost based cover for various depth profiles

It can be seen from Figure 5 -15 that the suction within the compost cover increases fast in the first hours. The suction value for the 10 cm depth profile shows a high peak (24 kPa) in comparison to the other depth profiles at the end of 4 hours. However, the suction curve for this layer (10 cm) starts to decline after 4 hours of the experiment to be operative and falls to 12 kPa which shows a lower value than that of the other depth profiles. This observation of the compost cover (10 cm layer) is in contrast to the fact that the suction increases with a decrease in water content. This may be due to the fact that the tensiometers are exposed close to the surface and air starts to enter them.

The suction reaches 26 kPa for the intermediate layer after 3 days which is a high value in comparison to the other depth profiles. After that, the rate of increase is less and reaches 35 kPa after 80 days, an increase of 11 kPa in 77 days. The increase in the suction value for this particular layer is due to the high tension that results from the loss of water content.

Suction is a function of water content as well as medium texture (Pokhrel, 2006). The lower layer of the compost cover material attains a maximum suction value of 19.5 kPa which corresponds to higher water content after 80 days in the experiment.

A fundamental property of an unsaturated porous medium related to its ability to attract water at various water contents and suctions is characterized by the water retention curve (WRC). This curve is also called soil water characteristic curve (if the porous medium is a soil), capillary pressure saturation curve, moisture retention curve, moisture characteristic curve, desorption and/or sorption isotherm curve, and the suction volumetric water content curve (Abdul-Hussain and Fall 2011). Figures 5-16 and 5-17 show the water retention curve of the compost biocover for intermediate (33 cm) and bottom (55) depth profiles. The air entry value for the water retention curve of the compost biocover is low and its value is close to 0.3 kPa for both layer profiles as shown in Figures 5-16 and 5-17.

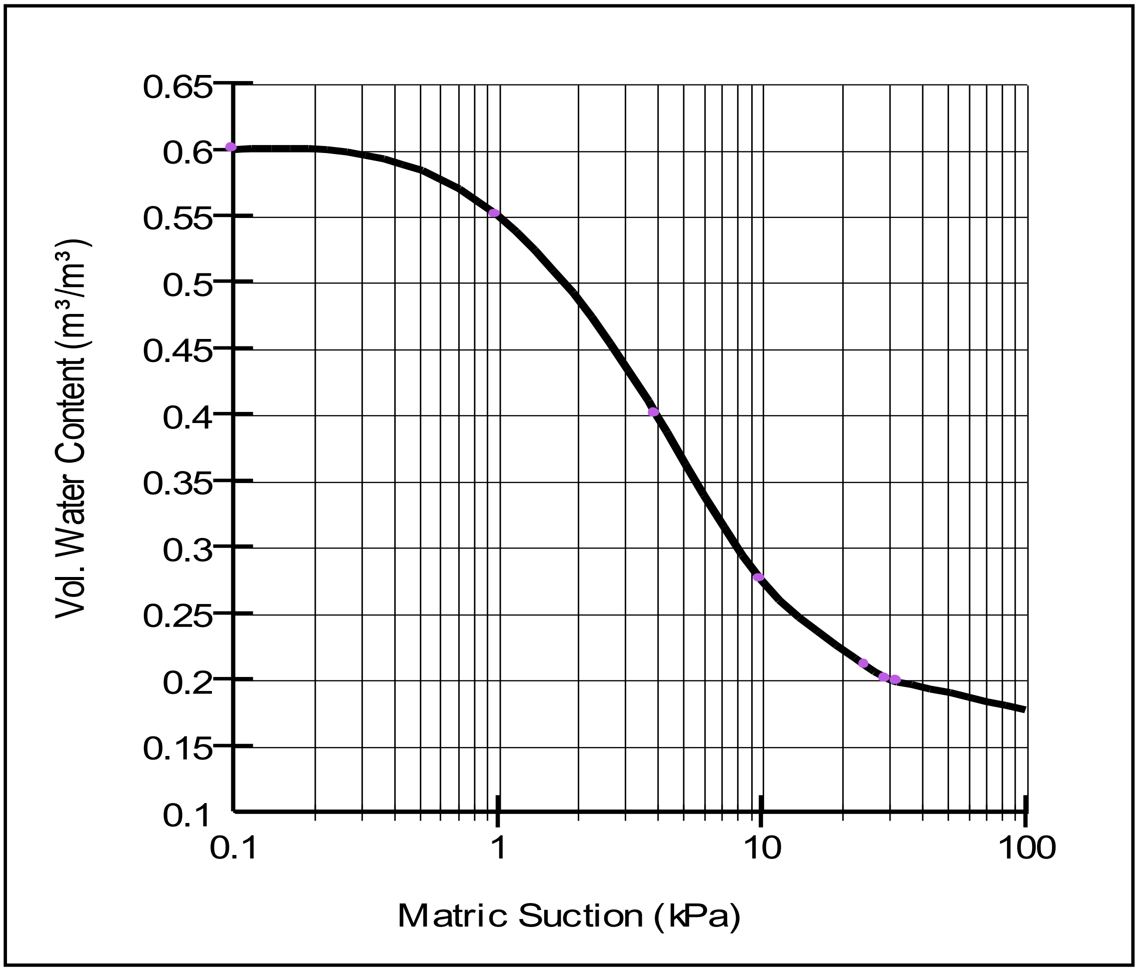


Figure 5-16: Water retention curve of compost cover materials for intermediate depth profile (33 cm)

This low air entry value can be attributed to the coarseness of the grain size of the compost and the high void ratio. The water retention curve of the compost biocover is in well accordance with the water retention curve of solid waste as reported by Wenjie et al. (2007).

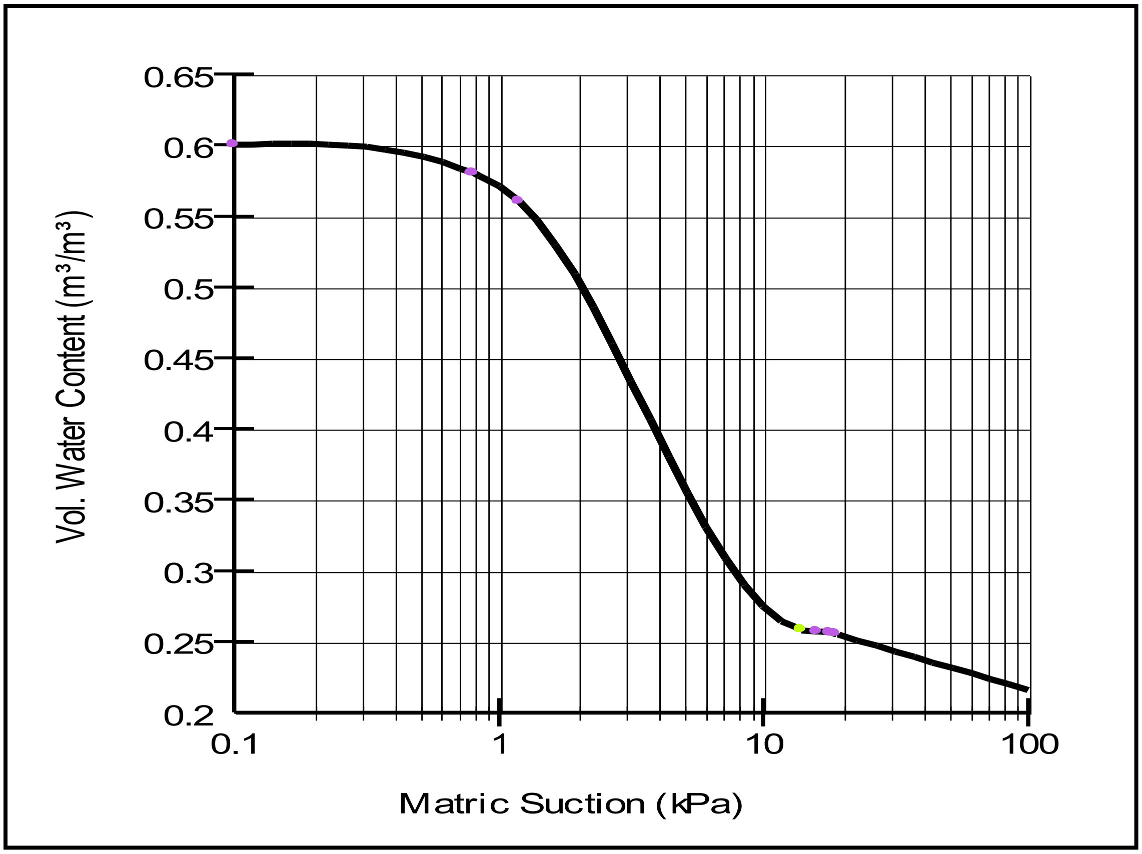


Figure 5-17: Water retention curve of compost cover for bottom depth profile (55 cm)

A large number of models, developed on physical and empirical bases, have been proposed over the years to predict the hydraulic conductivity of unsaturated soil or porous media (e.g., Brooks and Corey 1966; Mualem 1976; van Genuchten 1980; Leij et al. 1997). Common to almost all predictive models is the existence of a mathematical relationship between hydraulic conductivity and the water retention curve. The coefficient of permeability of an unsaturated porous medium is not a constant. The coefficient is strongly influenced by the volumetric water content or suction, which, in turn depends on the porous medium suction (Abdul-Hussain and Fall 2011). Moreover, the compost biocover is mostly characterized by unsaturated flow conditions. The unsaturated hydraulic conductivity obtained by the van Genuchten (1980) model versus suction for the intermediate and bottom layer is plotted in Figure 5-18 and 5-19, respectively. As expected, the unsaturated hydraulic conductivity of the compost decreases as the suction increases. The unsaturated hydraulic conductivity of both (intermediate and bottom) layers are almost the same.

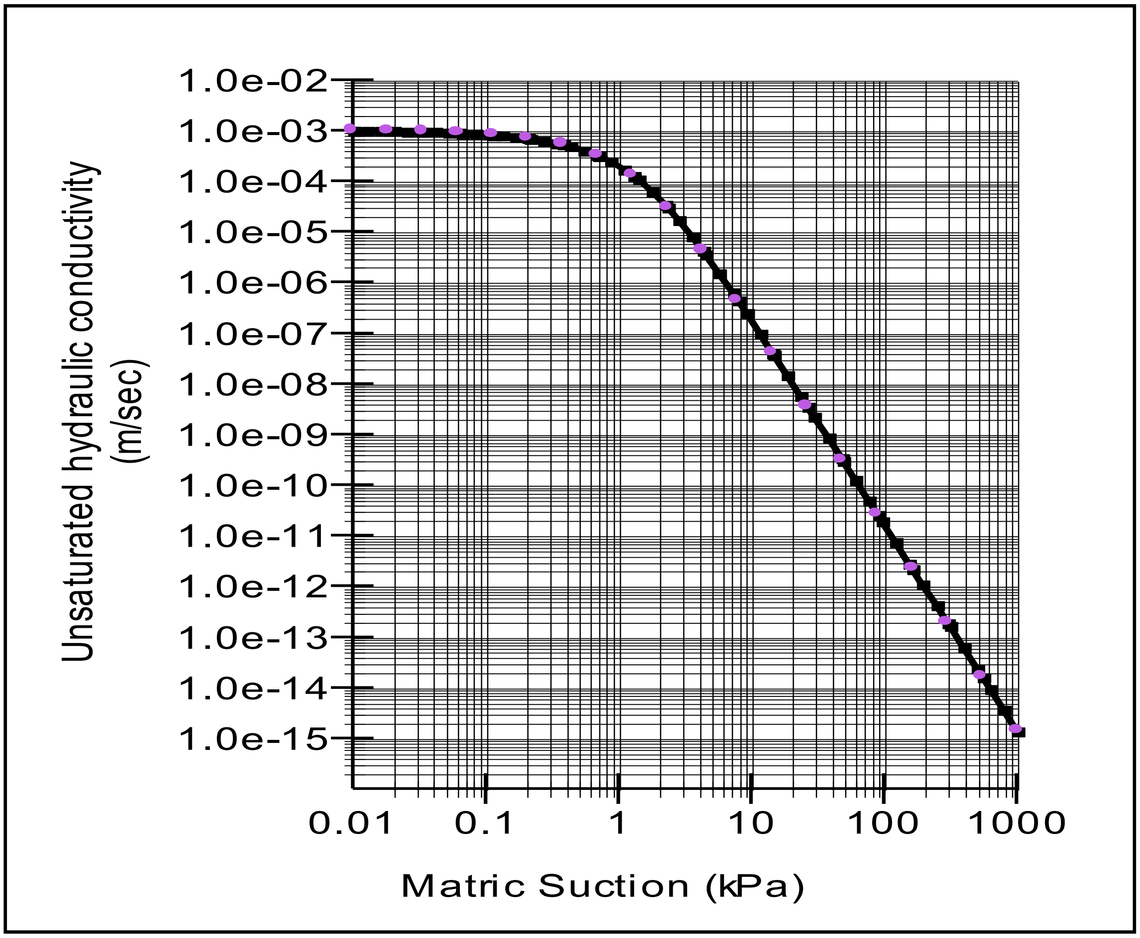


Figure 5-18: Relationship between hydraulic conductivity and matric suction of compost cover for intermediate layer (33 cm in depth)

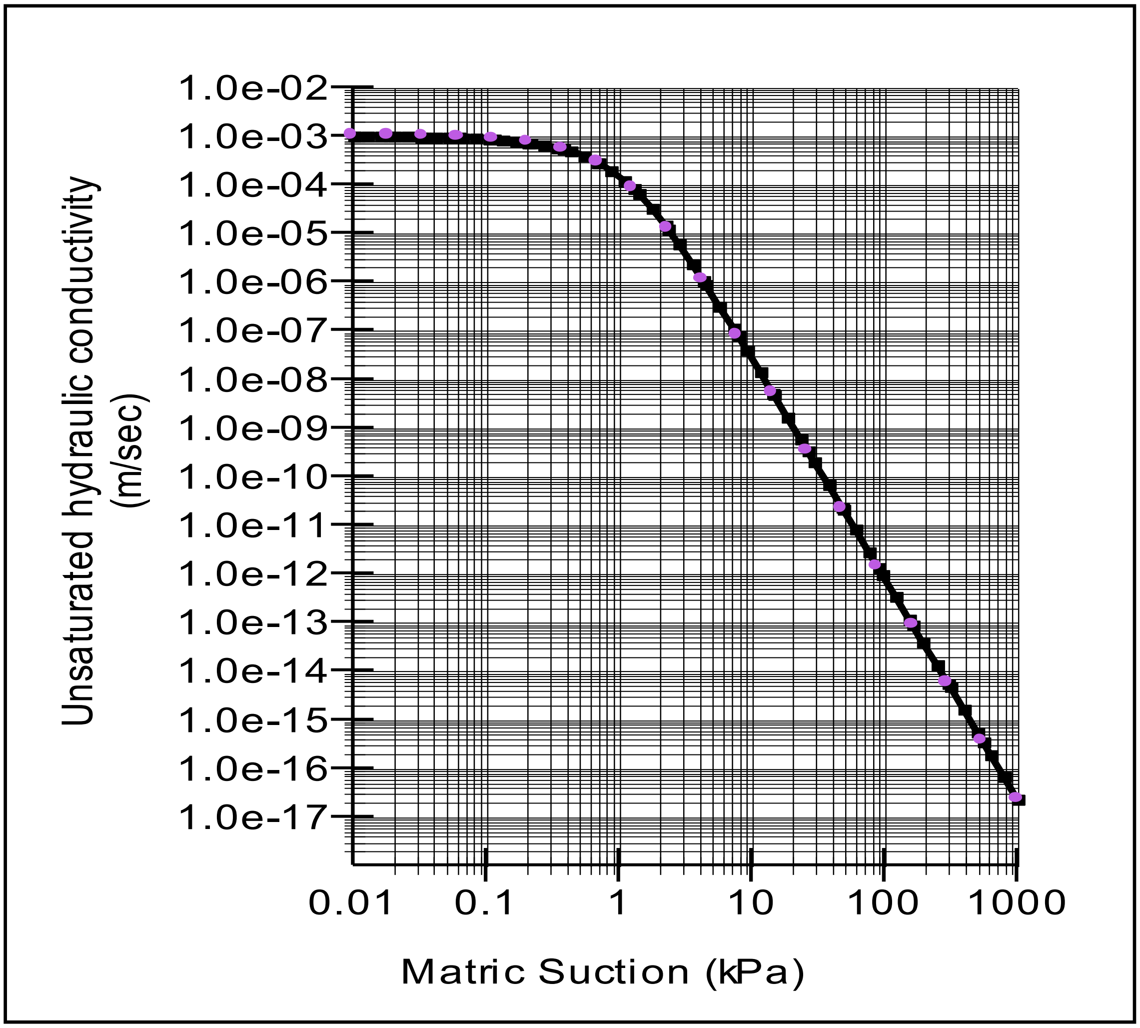


Figure 5-19: Relationship between hydraulic conductivity and matric suction of compost cover for bottom layer (55 cm in depth)

5.3.3 Settlement behaviour of the biocover

Figure 5 -20 represents the settlement behaviour of the compost biocover.

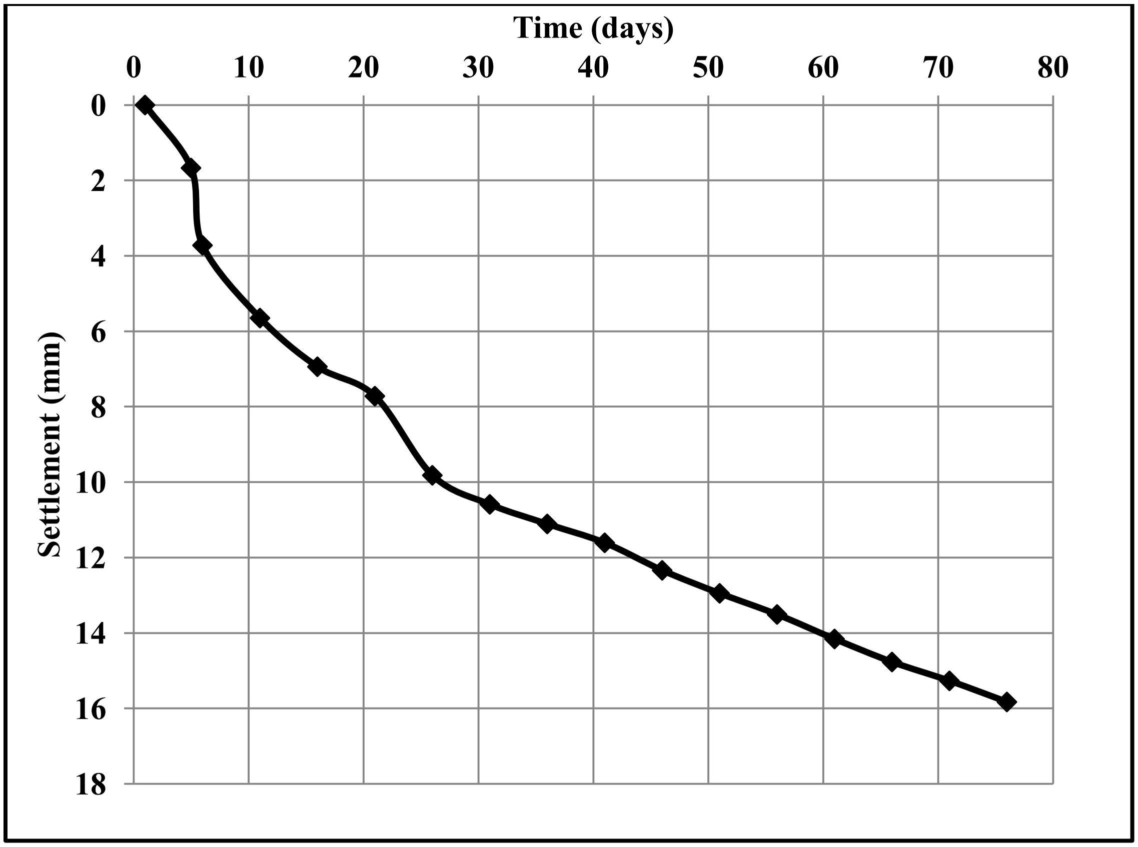


Figure 5-20: Evolution of settlement for the compost material

The compost biocover has settled more in the beginning as observed in Figure 5-20 and the curve follows a steep slope for the first 30 days with a settlement of 11 mm. After that, the rate of increase in the settlement is less and the cover only settles 5 mm for the next 50 days i.e., 22.7% of the value at 30 days. More consolidation for the first 30 days may take place due to an increased number of voids. According to Moo-Young and Zimmie (1996), a greater initial void ratio results in more consolidation of the medium. The compost settled 16 mm in total for the 80 days that the compost cover was placed. The results show that this value is quite significant in that it may considerably reduce the number of voids in the cover material, resultantly affecting the inclusion of O_2 that will surely affect the performance of methanotrophs, which reduces the CH_4 oxidation rate.

5.3.4 Evolution of the total porosity, void ratio and air-filled porosity of the biocover

Figure 5 -21 shows the relationship between porosity, degree of saturation, void ratio and FAS of the compost biocover. Conventional geotechnical relationships as reported by McCarthy (2004) were used to determine these parameters of the compost biocover. The parameters take into account the settlement behavior of the compost biocover as discussed in Section 5.3.3. However, these parameters are calculated for the entire compost, in consideration of the water content variations in the intermediate layer. However, the interaction of all of these factors for the various layers in the compost biocover is discussed in the next section (Section 5.4).

It can be observed from Figure 5-21 that the FAS decreases with an increase in the degree of saturation or decrease in porosity. As the compost consolidates with time as noted in Figure 5-18, the compost particles come closer together, increasing the mass to volume ratio, which results in the reduction of voids in the cover. The reduction in voids may lead to an increase in the degree of saturation. The degree of saturation is a function of void ratio (e) as well as water content. The void ratio of the compost cover varied from 1.40 to 1.05, which resulted in the reduction of FAS from 37% to 29% for the 80 days, hence resulting in an increase in the degree of saturation from 34% to 45% after the application of the compost cover.

The porosity of the biocover was reduced from 58% to 53%. This reduction in FAS is considered to be quite high in a cover material with regards to CH4 oxidation potential. According to Haug (1980), the maximum CH4 oxidation potential takes place with FAS between 21% and 30%. Huber-Humer et al. (2009) reported that the maximum CH4 oxidation takes place with FAS greater than 25%.

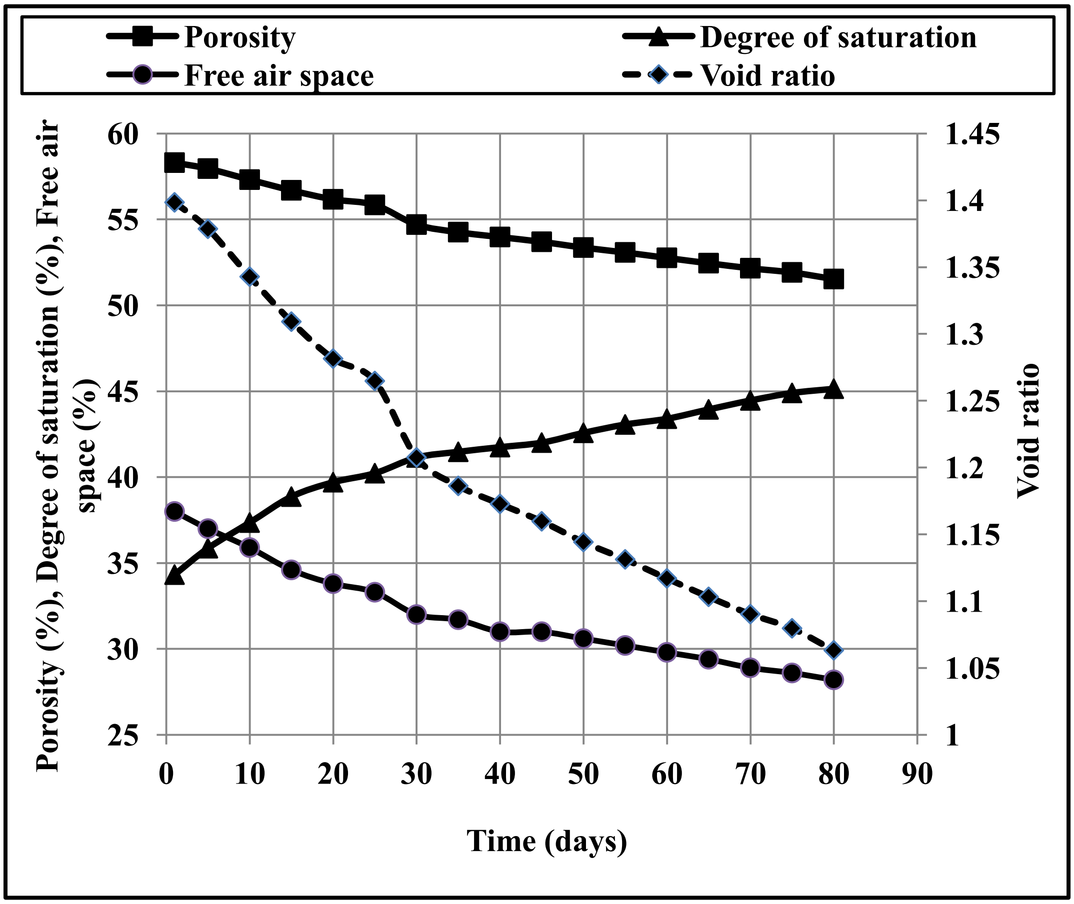


Figure 5-21: Evolution of free air space, porosity, void ratio and degree of saturation of compost cover materials

Thus, it can be concluded that despite the significant reduction in FAS, the compost shows a FAS that is very favorable for high CH_4 oxidation. These results suggest that in the design of landfill compost covers in practice, a decrease in FAS induced by settlement should be taken into account to avoid any decrease below a level that may significantly decrease the CH_4 oxidation of the cover.

5.4 Interactions of the thermal, hydraulic and mechanical (THM) parameters

Figures 5-22 and 5-23 show the interaction of the THM parameters of the compost materials for 30, 60 and 80 days in the experimental operation for various depth profiles. It can be concluded from Figure 5 -22 that the degree of saturation increases for all the depth profiles with time. The lower layer shows a higher degree of saturation in comparison to the upper layer (39%).

The reason for this phenomenon has already been discussed in Section 1.3.2.2. The temperature of the cover fluctuates at a range between 21.5^{o}C and 22.6^{o}C, and reaches the maximum for the intermediate layer. The increase in temperature for the depth profile is not in accordance with the water content and/or degree of saturation profile of the compost (Figure 5 – 22). However, Figures 5 -12 and 5 – 13 indicate that the temperature decreases/increases with a decrease/increase in volumetric water content for a particular depth with time.

This statement verifies the argument of Pokhrel (2006) in that a complex relationship takes place between the volumetric water content and temperature of a compost biocover. In Figure 5 -22, the suction continues to increase for the intermediate and bottom depth profiles with desaturation of the compost cover for all stages and obtains a suction value of 19 and 35 kPa for the mid and bottom layers, respectively. This is in accordance with the argument that suction increases with a decrease in water content (Fredlund and Xing, 1994).

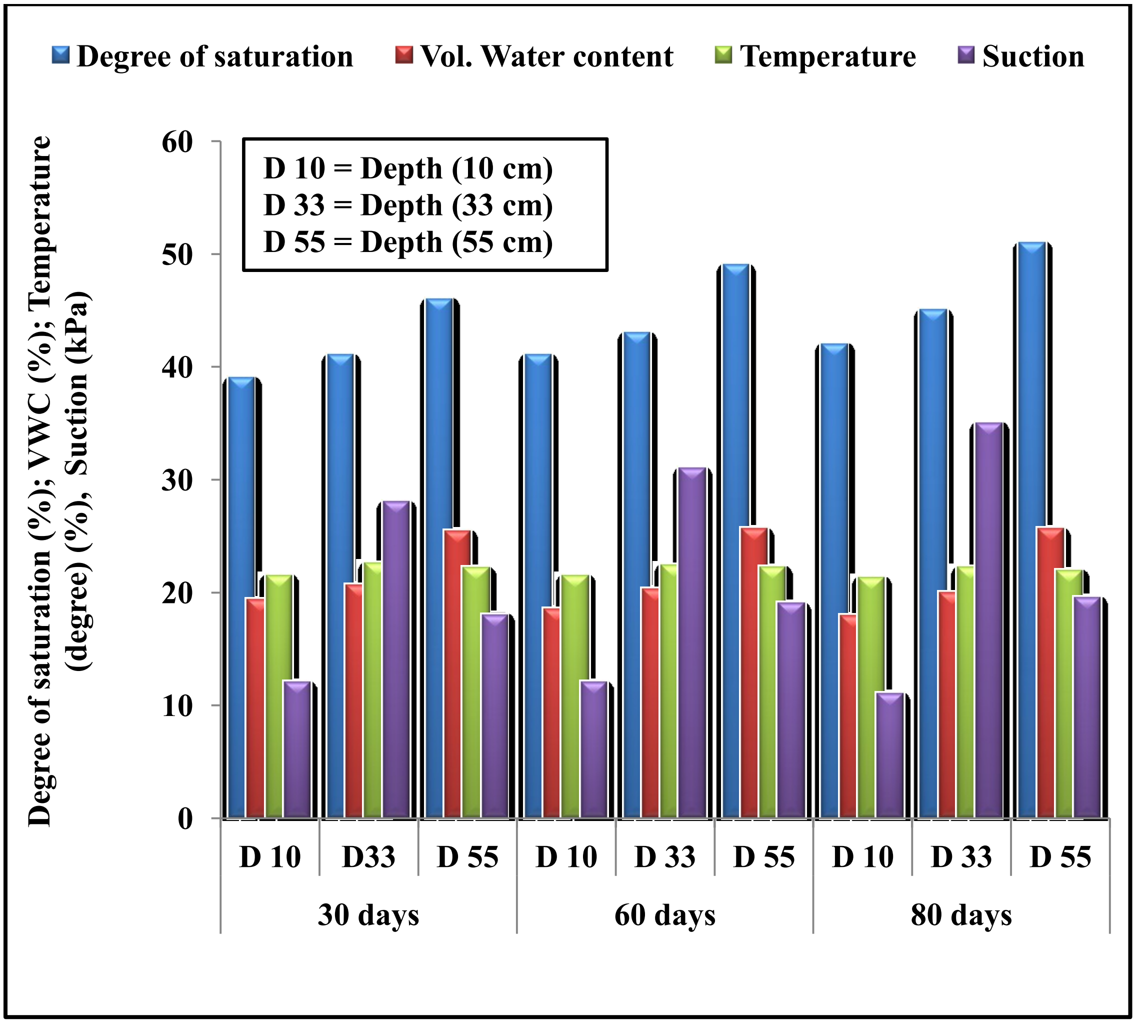


Figure 5-22: Interaction of volumetric water content, degree of saturation, suction and temperature within the compost biocover for various depth profiles

As already discussed (Figure 5 -15), the suction for the top layer cannot be determined because of the entrapped air in the tensiometers. However, in Figure 5-22, all of the parameters show consistent values i.e., decrease or increase in depth profiles at various time stages.

Figures 5 - 23 shows that the degree of saturation consistently increases with an increase in settlement for all depth profiles of the compost biocover at various time stages.

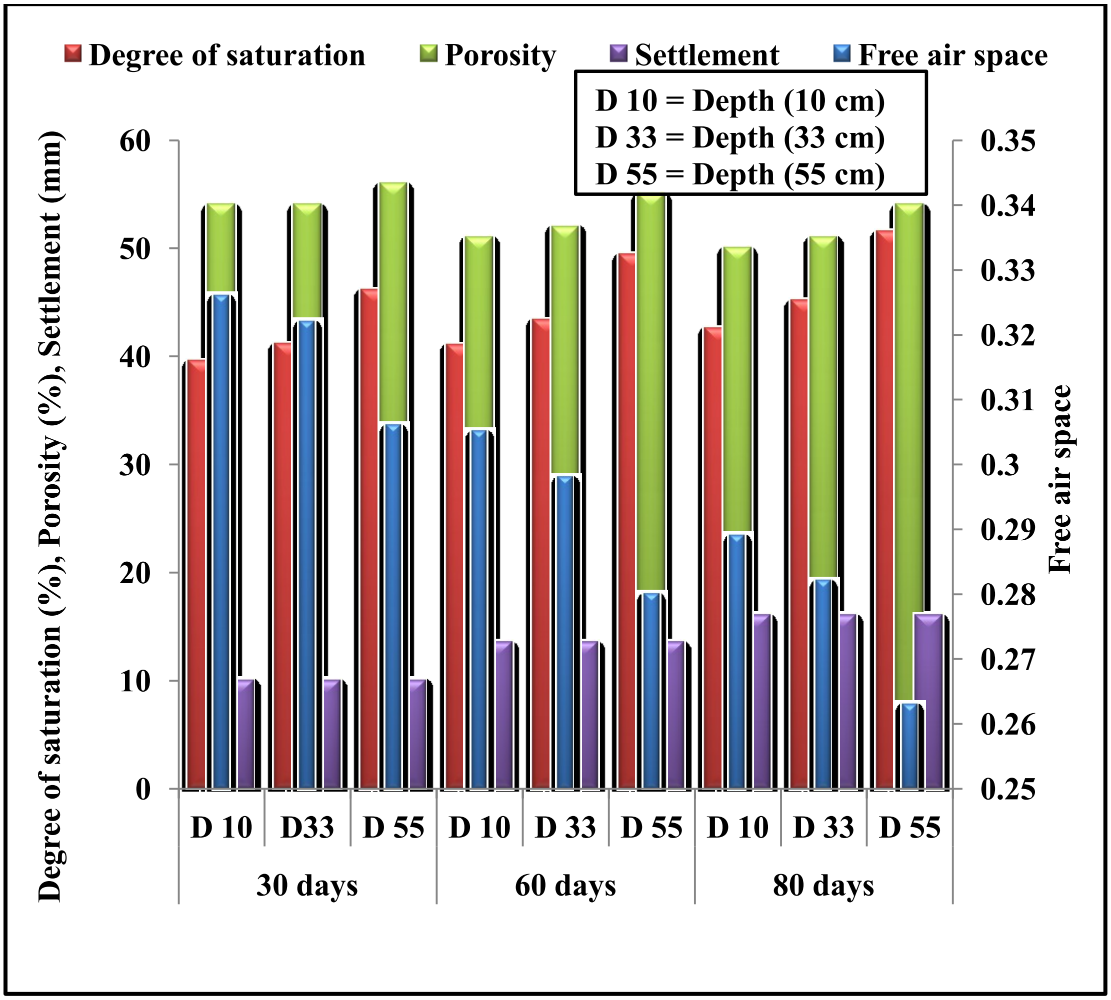


Figure 5-23: Interaction of settlement and index properties in a compost biocover for various depth profiles

The porosity and void ratio show a decreasing trend with time for all the depth profiles. Higher initial water content results in a high void ratio that results in more consolidation (Moo-Young and Zimmie 1996). Therefore, the rate of increase in porosity or void ratio is more for the bottom layer (55 cm) in comparison to the upper layer (10 cm). This means that FAS shows a decreasing trend from the top to bottom of the compost cover materials for various layers due to the associated high degrees of saturation, less porosity and void ratio. It can be concluded from the test results that the FAS, porosity and suction of a compost cover are a function of the degree of saturation, and the degree of saturation depends on the void ratio and settlement. Settlement increases the mass to volume ratio which results in the reduction of FAS, porosity, and void ratio.

Furthermore, the temperature is also dependent on the volumetric water content to some extent as already discussed above. This means that all of these parameters are coupled to each other for compost based cover materials. The increase in degree of saturation, settlement or decrease in porosity with time results in less FAS, which may affect the CH_4 oxidation capability of the biocover, influencing the inclusion of O_2 in the biocover. The microbial organisms also survive well at a certain range of temperature. Furthermore, the water content on the top surface of the compost cover may fall below the specified range.

It can be concluded from the above discussion and test results that the degree of saturation (a hydraulic property) increases with settling (a mechanical property) in a compost cover which results in less FAS (a physical property) and may affect the performance of methanotrophic bacteria due to less inclusion of O_2. This means that the performance properties (thermal, hydraulic, physical and mechanical) of compost cover materials have a strong impact on each other in reference to compost materials used for CH_4 oxidation potential. However, the variation in the vertical profile of the temperature is not well defined in relation to the other properties.

Nevertheless, despite some useful outcomes from the research program, the present study stresses the need to carry out a longer term research program on coupling THM properties to establish some clear relationships among the performance parameters of compost covers that may help designers and policymakers to provide efficient, cost effective compost based landfill covers which could mitigate the emission of CH_4 from landfills to the atmosphere.

Chapter 6. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

6.1 Summary and Conclusions

The following conclusions can be drawn from the present study:

- Compost materials have a liquid limit of 88%; however, it is difficult to determine the plastic limit of compost material, which categorizes compost as a brittle material and classifies it as a well graded silty sand. The compost materials are also classified as organic material that contains 40% organic contents and 60% inorganic contents.

- Compost materials may contain both methanogenes and methanotrophs, depending on the characteristics and age of the compost materials and maturity of the medium which determine the proportions of these microbial organisms.

- The experimental test results show that the free flux path in a cover is a function of the index properties, including porosity, degree of saturation and air filled porosity. The compost cover significantly consolidates which result in the reduction of FAS, which may influence advection and dispersion processes in the cover. CH4 oxidation potential is a function of these processes.

- Mechanical test results show that settlement is a function of initial water content and the compost consolidates more at higher water content, showing a significant reduction in air voids; however, the shear strength parameters i.e., angle of internal friction and cohesion, do not show any significant variation in their values for various initial water contents and dry unit weights. Morevover, the compost cover material with lower water content shows less settlement and greater void ratio. This may suggest that lower water content values provide more favorable conditions for compost to be used as a landfill cover material It is also found that stress-strain behaviour of compost material is not significantly variable under normal stress (overburden) field loading conditions.

- .The hydraulic conductivity of the biocover is a function of compaction degree, and the hydraulic conductivity values of compacted compost are in good agreement with the requirements of a landfill cover. The hydraulic conductivity curve of the compost shows a gradual decrease in value, until it attains a value of around 1.0 E-09 cm/sec at a water content of 82%. The highest hydraulic conductivity value obtained is $1.0x10^{-5}$ cm/sec and corresponds to that of a sample located on the dry of optimum segment of the compaction curve, whereas the lowest hydraulic value reached is equal to $1.0x10^{-9}$ cm/sec at a water content of 82%. This implies that compacting compost to low hydraulic conductivity can be accomplished for a wide range of water contents (62-110%).

- Thermal properties, such as thermal conductivity, thermal diffusivity and specific heat of compost materials, are very important parameters when taking into account the CH4 oxidation potential. Thermal properties are a function of degree of saturation and dry unit weight. The thermal conductivity values vary from 0.12 to 0.54 w/m.k. A simple equation is proposed to predict the thermal conductivity.

- The coupled THM properties indicate that the parameters of these properties are strongly correlated. The degree of saturation increases with settlement of the cover or decrease in porosity. Furthermore, the suction and temperature of a compost biocover are also functions of water content. This coupling effect should be taken into account in the design of compost biocover.

6.2 Recommendations

- Thermal properties, such as thermal conductivity, thermal diffusivity and specific heat of a composting material, are interlinked with each other. Different parameters, such as degree of saturation, dry unit weight, porosity and structural arrangement of compost particles, affect the performance of these parameters. The thermal behavior of a compost cover changes with time and these changes may affect the CH_4 oxidation rate. This demands the need to model thermal behavior of compost to acquire good knowledge of heat flux in biocover.

- The THM properties are interlinked with each other. The test results show that the complex relationships among these properties exist with regards to CH_4 oxidation potential. This study stresses the need to study the coupled THM behaviour of compost columns on a long term basis to establish some clear relationships. The coupling effect of these properties should be carried out, especially taking into account the CH_4 oxidation potential of compost materials.
- A mathematical model needs to be developed to explain the coupled THM behavior of compost biocover.

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Appendices

Appendix A: Small sample laboratory test photographs

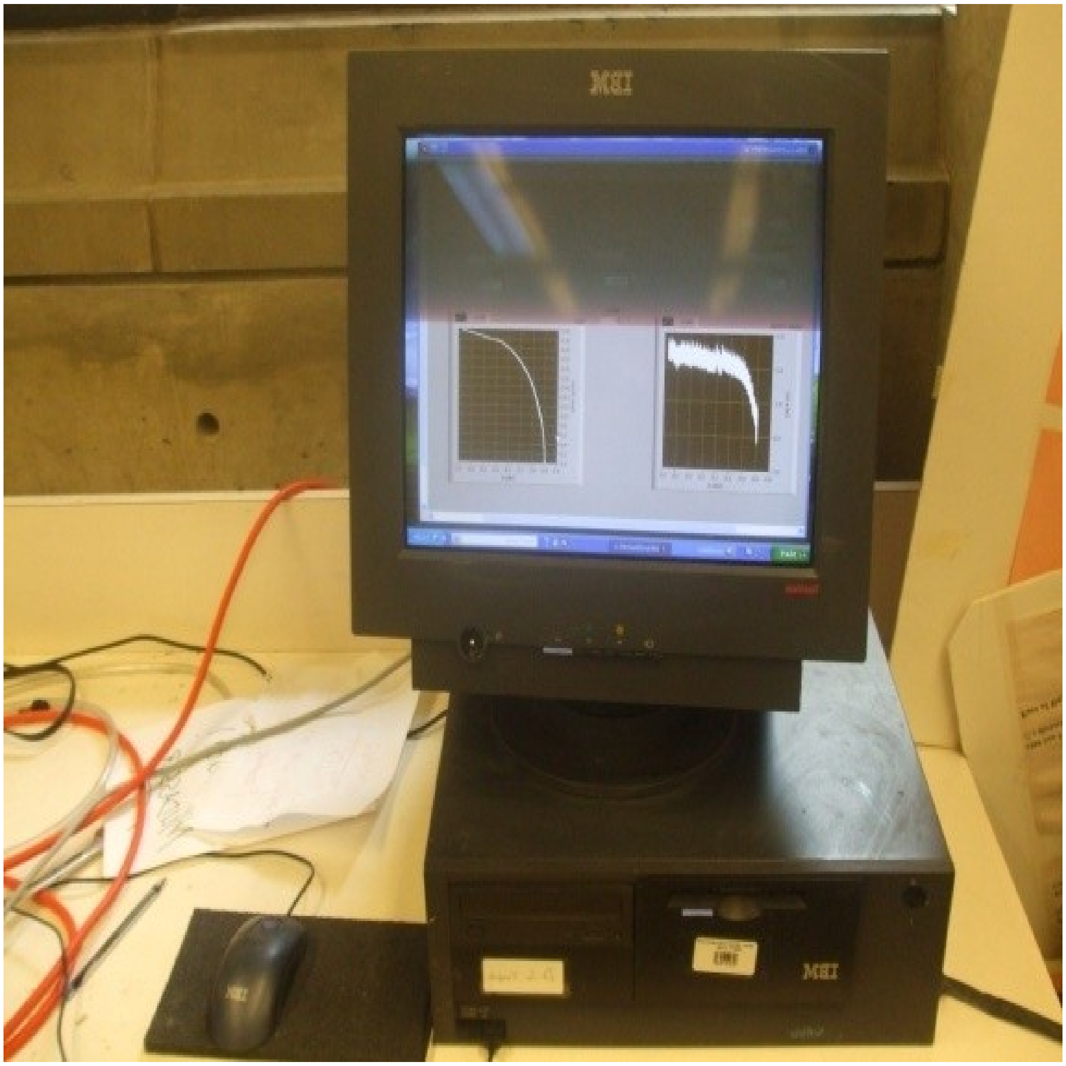
A 1: Particle size distribution tests

A 2: Specific gravity test

A 3: compaction tests

A 4: Hydraulic conductivity tests

A 5: Thermal tests



A 6: Direct shear tests

A 7: Oedometer tests

A 8: Inductively coupled plasma spectrometer tests

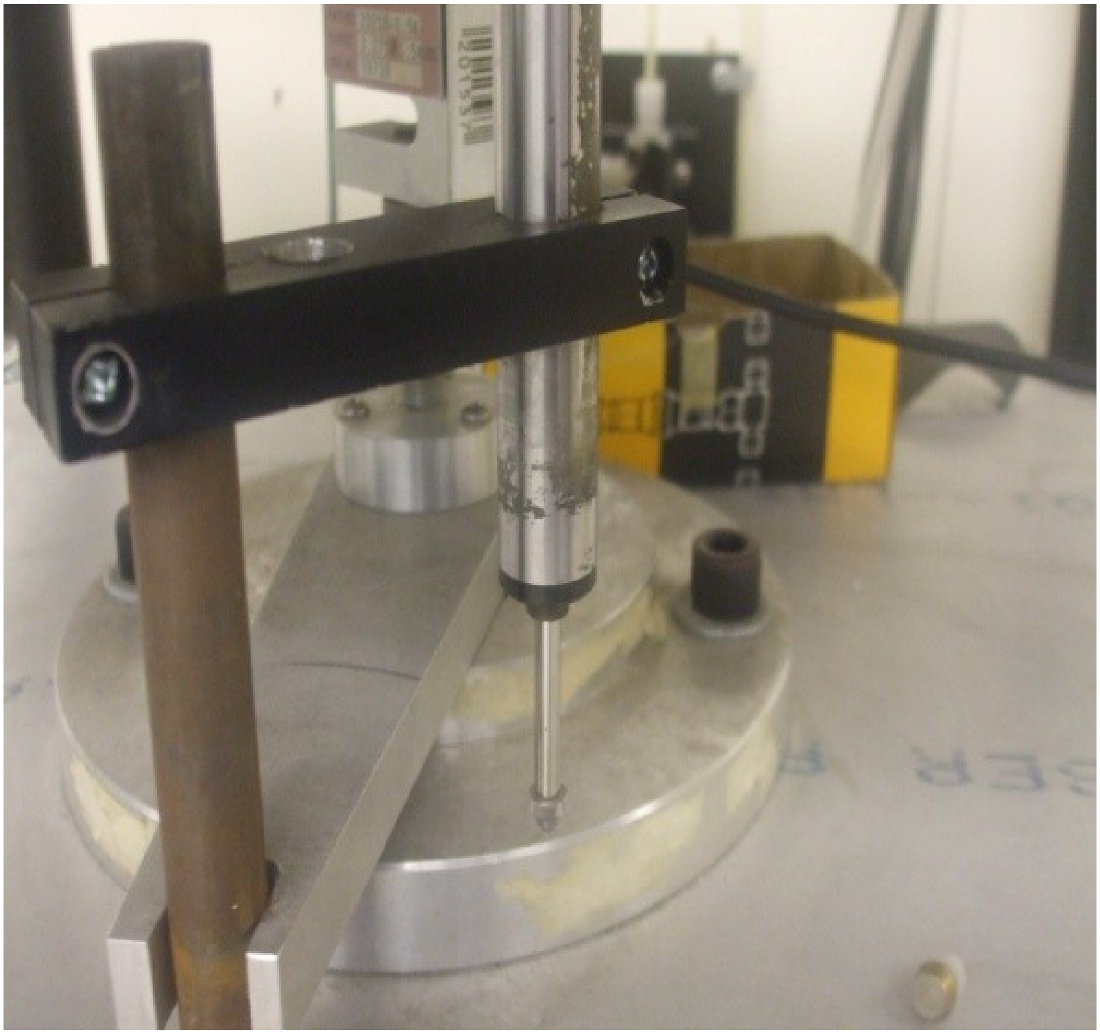
Appendix B: Devices used in column experiement

B 1: Temperature sensors

B 2: Volumetric water content sensors

B3: Tensiometer for soil water potential

B4: Flow meter



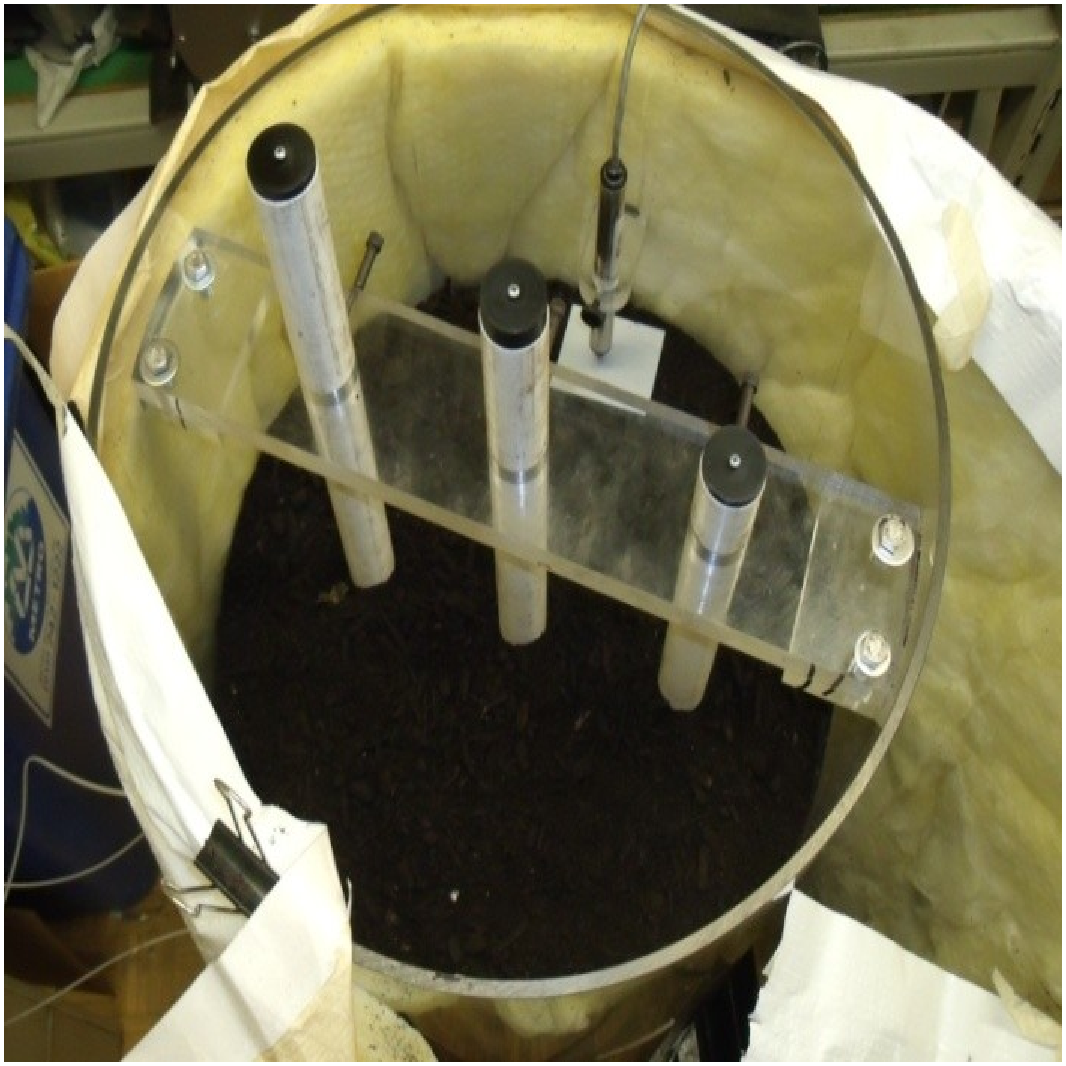
B 5: LVDT for settlement

B 6: Acrylic container

Appendix C: Column experiment photographs

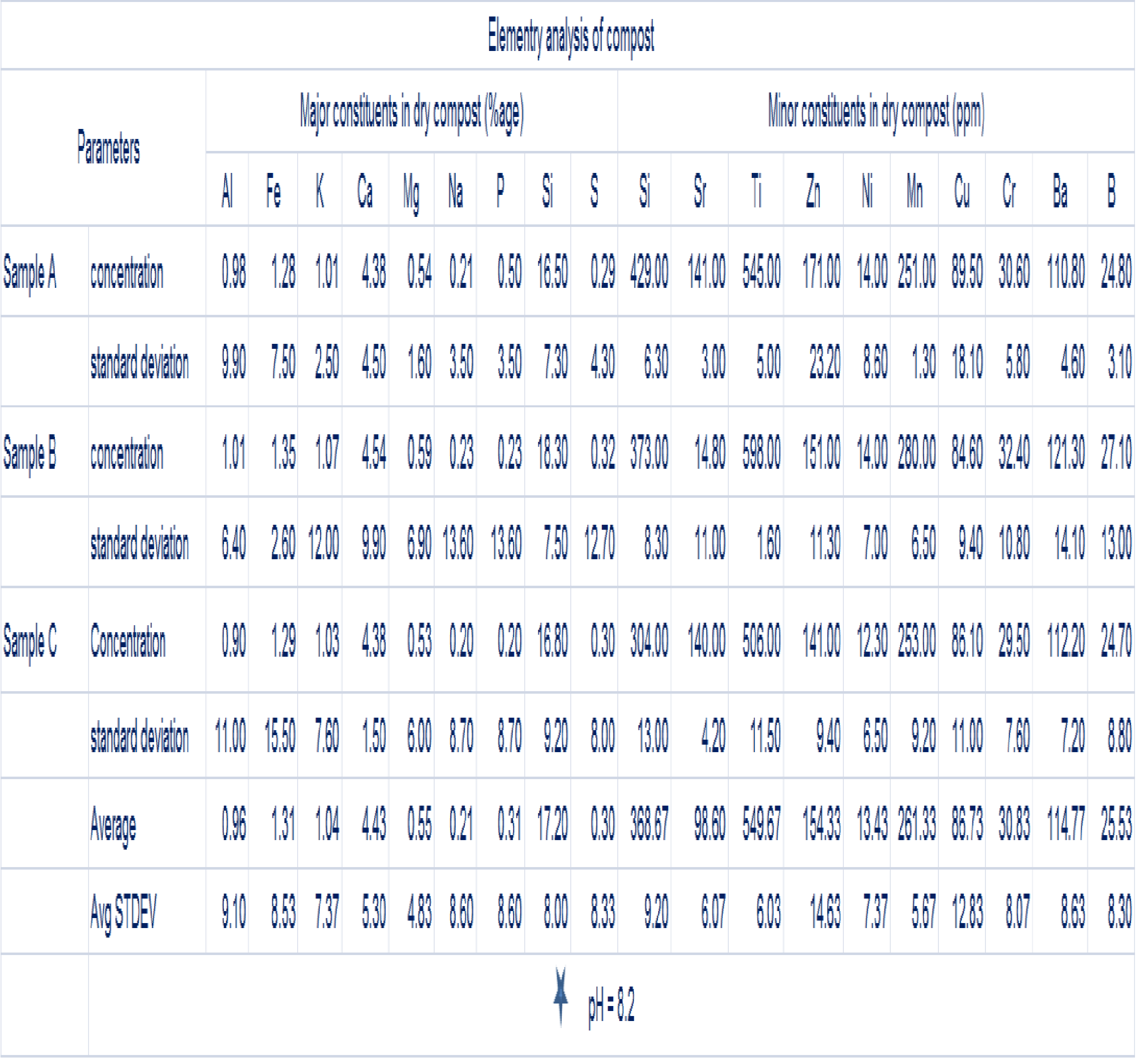
C 1: Placement of compost in the column

C 2: Prepared compost for column experiment



C 3: Top view of the biocover

Appendix D: Elementary analysis of compost



Elementry analysis of compost

Parameters		Major constituents in dry compost (%age)									Minor constituents in dry compost (ppm)									
		Al	Fe	K	Ca	Mg	Na	P	Si	S	Si	Sr	Ti	Zn	Ni	Mn	Cu	Cr	Ba	B
Sample A	concentration	0.98	1.28	1.01	4.38	0.54	0.21	0.50	16.50	0.29	429.00	141.00	545.00	171.00	14.00	251.00	89.50	30.60	110.80	24.80
	standard deviation	9.90	7.50	2.50	4.50	1.60	3.50	3.50	7.30	4.30	6.30	3.00	5.00	23.20	8.60	1.30	18.10	5.80	4.60	3.10
Sample B	concentration	1.01	1.35	1.07	4.54	0.59	0.23	0.23	18.30	0.32	373.00	14.80	598.00	151.00	14.00	280.00	84.60	32.40	121.30	27.10
	standard deviation	6.40	2.60	12.00	9.90	6.90	13.60	13.60	7.50	12.70	8.30	11.00	1.60	11.30	7.00	6.50	9.40	10.80	14.10	13.00
Sample C	Concentration	0.90	1.29	1.03	4.38	0.53	0.20	0.20	16.80	0.30	304.00	140.00	506.00	141.00	12.30	253.00	86.10	29.50	112.20	24.70
	standard deviation	11.00	15.50	7.60	1.50	6.00	8.70	8.70	9.20	8.00	13.00	4.20	11.50	9.40	6.50	9.20	11.00	7.60	7.20	8.80
	Average	0.96	1.31	1.04	4.43	0.55	0.21	0.31	17.20	0.30	368.67	98.60	549.67	154.33	13.43	261.33	86.73	30.83	114.77	25.53
	Avg STDEV	9.10	8.53	7.37	5.30	4.83	8.60	8.60	8.00	8.33	9.20	6.07	6.03	14.63	7.37	5.67	12.83	8.07	8.63	8.30
									pH = 8.2											