Geotechnical and Geoenvironmental Characteristics and Behaviour of Landfill Biocovers

by

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Dedication

I would like to dedicate this dissertation to the soul of my father, Abas Khoshand, who always supported and encouraged me through my life. I wish he was here to see his dream came true.

Abstract

Landfill gas (LFG) which mainly consists of methane (CH_4) and carbon dioxide (CO_2); is produced by the biodegradation of organic waste in landfills. CH_4 is a greenhouse gas with a global warming potential (GWP) 23 to 25 times that of CO_2. Landfills are one of the significant sources of anthropogenic CH_4 emissions and thereby urgent control of CH_4 emissions from landfills is necessary.

One of the most promising approaches for reducing the environmental impacts of landfill emissions is to passively vent LFG through a biological cover soil or biocover in order to oxidize CH_4 into CO_2 through a natural biological process. It is well known that stabilized compost and peat based materials have high porosity and water holding capacity (WHC), as well as appropriate nutrient levels, and therefore can be a suitable medium for CH_4 oxidation.

The geotechnical and geoenvironmental properties of biocovers are of prime importance for the design, construction and maintenance of any type of biocover. Moreover, the performance of biocovers is strongly influenced by the simultaneous evolution of thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) processes, and also interactions between them during the lifetime of a biocover. The geotechnical and geoenvironmental characteristics, evolution of the T, H, M, and C-B processes, and their interactions have been mainly ignored in previous studies, and thus minimally understood.

Therefore, the objective of the present thesis is to address the aforementioned knowledge gaps. This research is categorized into two main parts. In the first part, the geotechnical properties of compost and peat based biocovers are evaluated in order to assess the feasibility of the application of compost and peat based materials as biocover material from a geotechnical viewpoint. In the second part, the simultaneous evolution of T, H, M, and C-B processes and their interactions in compost, compost-sand (with a mix ratio of 3:1 (w/w)), and peat biocovers are studied through laboratory column experiments.

The derived results showed performance of the compost-sand biocover with a mix ratio of 3:1 is steadier over time and no significant decline in CH_4 oxidation rate occurred during the period of operation.

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Table of Contents

List of Figures

List of Tables

List of Symbols and Abbreviations

Symbols	**Defenition**
c	Cohesion (kPa)
C_c	Compression index
c_c	Coefficient of curvature
C_r	Recompression index
c_u	Coefficient of uniformity
C_v	Consolidation coefficient (m^2/year)
D_r	Relative density
G_s	Specific gravity
k	Thermal conductivity (w/m^{o}k)
k_H	Hydraulic conductivity(m/s or cm/s)
SP	Poorly graded sand
S_r	Degree of saturation (%)
SW	Well graded sand
w	Moisture content (%)
ϕ	Friction angle (^{o})

Abbreviation	**Defenition**
C-B	Chemobiological
Cytc	Cytochrome c
EPS	Exopolymeric substance
FADH	Formaldehyde dehydrogenase
FAS	Free air space (%)
FDH	Formate dehydrogenase
GC	Gas chromatography
GHGs	Greenhouse gases
GWP	Global warming potential
H	Hydraulic
LFG	Landfill gas
LL	Liquid limit (%)
LOI	Loss of ignition (%)
M	Mechanical
MDH	Methanol dehydrogenase
MMO	Methane monooxygenase
NADH	Nicotinamide adenine dinucleotide
OM	Organic matter (%)
OMC	Optimum moisture content (%)
PL	Plastic limit (%)

pMMO	Particulate form of methane monooxygenase
RuMP	Ribulose monophosphate path
sMMO	Soluble form of methane monooxygenase
T	Thermal
TCD	Thermal conductivity detector
TLS	transient line source
VOCs	Volatile organic compound
VWC	Volumetric water content (%)
WHC	Water holding capacity

1 Introduction

1.1 Background

Greenhouse gases (GHGs) reabsorb infrared radiation which is reflected from the earth and retain heat in the lower level of the atmosphere. The most abundant GHGs in the atmosphere are water vapour (H_2O), carbon dioxide (CO_2), methane (CH_4), ozone (O_3), and nitrous oxide (N_2O). This natural process regulates the global surface temperature. It should be mentioned that the global surface temperature would be colder than the present average temperature which is about $33^{o}C$ in the absence of GHGs (Peixoto and Oort 1992).

GHGs have both natural and anthropogenic sources, but human induced GHG emissions have increased more than emissions from most natural sinks, particularly after the Industrial Revolution. The continuous increase in concentration of GHGs has caused an increase of over $0.5^{o}C$ in the global surface temperature in the last 150 years (Wuebbles and Hayhoe 2002), a phenomenon known as global warming. Global warming is one the greatest environmental challenges in the 21st century, which has caused global and regional climate changes (Peixoto and Oort 1992).

CH_4 has a strong molar absorption coefficient for infrared radiation and relatively long residence time in the atmosphere among the GHGs (Philopoulos et al. 2009; Scheutz et al. 2009). These properties make CH_4 a very potent GHG such that its global warming potential is 23 to 25 times greater than that of CO_2 in a horizon of 100 years (IPCC 2001 and 2007). CH_4 is released into the atmosphere by both natural and anthropogenic sources (Albanna et al. 2007), but it is estimated that about 70% of the global CH_4 emissions come from anthropogenic sources (IPCC 1996).

A complex anaerobic microbial decomposition of the biodegradable fraction of deposited waste in landfills produces a gaseous mixture, which is known as landfill gas (LFG). LFG primarily consists of CH_4 (approx. 50–55% v/v), CO_2 (approx. 40–45% v/v) (Knaebel and Reinhold 2002; Shin et al. 2002) and trace amounts of VOCs (Allen et al. 1997; Eklund et al. 1998; Rettenberger and Stegmann 1996). Landfills are one of the major sources of anthropogenic CH_4 emissions

(Bogner et al. 1995; Masters 1996) such that about 18% of the global anthropogenic CH_4 emission is related to landfills (Huber-Humer et al. 2009).

The uncontrolled migration of CH_4 from landfills should be prevented due to its high global warming potential, risk of fire hazard, and also ecological hazards. Different approaches have been proposed in the literature for reducing and controlling CH_4 emissions from landfills (Bogner et al. 2008), such as implementation of waste management strategies (Bogner et al. 2008), application of gas recovery systems and burning CH_4 emission by using high temperature flares (Huber-Humer et al. 2008). Recently, researchers have focused on the development of low cost alternative technologies, such as biological methods, to treat LFG (Barlaz et al. 2004; Dever et al. 2007; Stern et al. 2007). One of most promising alternative approaches is to passively vent CH_4 through a reactive biological cover soil or biocover in order to oxidize CH_4 through a natural biological process (Ait Benichou et al. 2009; Cabral et al. 2010; Hilger et al. 2000; IPCC 2007). The biological oxidation process principally relies on the activity of a group of bacteria known as methanotrophs, which use molecular oxygen (O_2) to oxidize CH_4 into CO_2 and cell carbon (Hanson and Hanson 1996).

1.2 Statement of problem

Biocovers are mainly made of a filter material to support methanotrophic activity, which is placed above a gas distribution layer (Pedersen 2010). Previous laboratory and field studies have demonstrated that stabilized and sanitized compost materials (Barlaz et al. 2004; Huber-Humer 2004; Humer and Lechner 2001, 1999; Wilshusen et al. 2004) as well as peat materials (Einola et al., 2009; Kightley et al. 1995; Streese and Stegmann 2003) can be suitable as filter material for supporting methanotrophic activity within biocovers.

However, most of the previous research work available in the literature has focused on compost materials as suitable biocover materials. There is a paucity of comprehensive studies on the performance and feasibility application of peat based materials (pure peat, peat-sand mixtures) as potential biocover materials.

The geotechnical properties of compost and peat based materials are of prime importance for the design, construction and maintenance of compost and peat based biocovers. Absence of a proper understanding of the geotechnical behaviour of compost and peat based biocovers may lead to inaccurate biocover design and consequently, construction of inefficient biocovers. To the best of the knowledge of the author, no such attempts have been made in the literature for investigating the geotechnical behaviour of compost and peat based biocovers and also assessment of the application feasibility of compost and peat based material as biocover material from a geotechnical viewpoint.

The comprehensive understanding of the evolution of thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) processes and also their interactions during the lifetime of a biocover is a prerequisite for the optimal design, construction and maintenance of compost and peat based biocovers. The T, H, M, and C-B processes, which can be controlled either by the material properties of the biocover or environmental conditions, influence the performance of biocovers. There are only limited recommendations in the literature with regards to the evolution of individual T, H, M, and C-B processes in compost and peat based biocovers. To date, no study comprehensively addresses the simultaneous evolution of T, H, M, and C-B processes within biocovers and their interactions.

In consideration of the facts mentioned above, there is a need to acquire sufficient understanding and knowledge about the geotechnical and geoenvironmental characteristics of compost and peat based biocovers, and the evolution of the T, H, M, and C-B processes in these biocovers.

1.3 Research objectives

The main objectives of the current research can be summarized as follows.

1. Evaluating the geotechnical properties of compost based biocovers (pure compost, compost-sand mixture) and investigating the effect of different material compositions on the overall

geotechnical behaviour of compost based biocovers in order to assess the application feasibility of compost based materials as biocovers from a geotechnical viewpoint.

2. Evaluating the geotechnical properties of peat based biocovers (pure peat, peat-sand mixture) and investigating the effect of different material compositions on the overall geotechnical behaviour of peat based biocovers in order to assess the application feasibility of peat based materials as biocovers from a geotechnical viewpoint.

3. Investigating the simultaneous evolution of the T, H, M, and C-B processes and their interactions in a compost biocover through laboratory column experiments in order to evaluate the performance of the compost biocover and its evolution with time.

4. Investigating the simultaneous evolution of the T, H, M, and C-B processes and their interactions in a compost-sand (with a mix ratio of 3:1 (w/w)) biocover through laboratory column experiments in order to evaluate the performance of the compost-sand (with a mix ratio of 3:1 (w/w)) biocover and its evolution with time.

5. Investigating the simultaneous evolution of the T, H, M, and C-B processes and their interactions in a peat biocover through laboratory column experiments in order to evaluate the performance of the peat biocover and its evolution with time.

The results derived from these investigations will contribute to a better understanding of the geotechnical and geoenvironmental behaviours of compost and peat based biocovers and thus towards their cost-effective design.

1.4 Research approach and methodology

The approach adopted in the present research to achieve the aforementioned objectives consists of three main parts.

The first part includes an evaluation of the geotechnical properties of compost and peat based biocovers. The evaluation includes the investigation of compaction, consolidation, and shear strength properties and also the hydraulic and thermal conductivities of compost and peat based materials (compost, compost-sand with a mix ratio of 3:1, 1:1, and 1:3 (w/w), peat, and peat -sand with a mix ratio of 3:1, 1:1, and 1:3 (w/w)). The first part of the approach is explained and covered in Sections 3.2 and 3.3.

The second main part deals with the investigation of the evolution of T, H, M, and C-B processes in compost, compost-sand with a mix ratio of 3:1(w/w), and peat biocovers, and also evaluation of the performance of the studied biocovers in column experiments. In this part, the evolution of T (temperature and thermal conductivity), H (hydraulic conductivity, moisture content, and degree of saturation), M and physical (particle size distribution, settlement, shear strength properties, and consolidation behaviour), and C-B (pH, organic content, and concentration of O_2, nitrogen (N_2), CH_4 and CO_2, CH_4 oxidation capacity) properties is monitored or assessed with time and depth of biocovers made of compost, compost-sand with a mix ratio of 3:1(w/w), and peat. This allows the evaluation of the performance of the studied biocovers. This part is presented and discussed in Sections 4.2, 4.3, and 4.4.

In the third part (as presented in Sections 5.2 to 5.5), the main results derived from the previous sections are discussed and compared with one another in order to identify the most suitable biocover medium among the studied biocovers with respect to a geotechnical perspective as well as performance with regards to CH_4 oxidation (geoenvironmental perspective) .

1.5 Organization of thesis

Fig. 1.1 shows the organization of the present thesis. The thesis is laid out in six chapters in order to facilitate the understanding and presentation of the key findings. It should be noted that both the third and fourth chapters are written in a research paper format and thereby contain related sections (e.g. abstract, introduction, materials and methods, results and discussion, conclusion, and reference sections). The paper based format will result in some repetition, since each paper has to stand alone and be self-sufficient.

Chapter One provides a brief overview of related background information on biocovers and presents a general description of the identified problems as well as research scope. This chapter also reveals the relevance of the adopted approach to achieve the defined research scope.

Chapter Two presents theoretical and technical background information on the contribution of landfills as a source of CH_4 emission in global warming. The different technologies and strategies for controlling and reducing CH_4 emission from landfills are explained in this chapter and an overview on the CH_4 oxidation phenomenon, as well as current knowledge and relevant previous studies on biocover technology are provided. This chapter also presents a comprehensive discussion on the role of the different T, H, M, and C-B parameters in the overall performance of biocovers.

Chapter Three covers a comprehensive laboratory geotechnical investigation on compost based biocovers (pure compost and compost-sand mixtures (3:1, 1:1, and 1:3 w/w)) as well as peat based biocovers (pure peat and peat-sand mixtures (3:1, 1:1, and 1:3 w/w)) in order to determine and assess the compaction, shear strength, compressibility, and hydraulic and thermal conductivity properties of the studied materials.

Chapter Four is designed to study the evolution of the T, H, M, and C-B behaviours of compost, compost-sand with a mix ratio of 3:1(w/w), and peat biocovers with time and depth in laboratory column experiments.

Chapter Five presents a comparative analysis of the obtained results from laboratory investigations which are presented in Chapters Three and Four.

Chapter Six succinctly summarizes the main conclusions from the different studies undertaken through this thesis and links them with the overall research scope. In addition, recommendations that will be useful for future studies on biocover technology are provided.

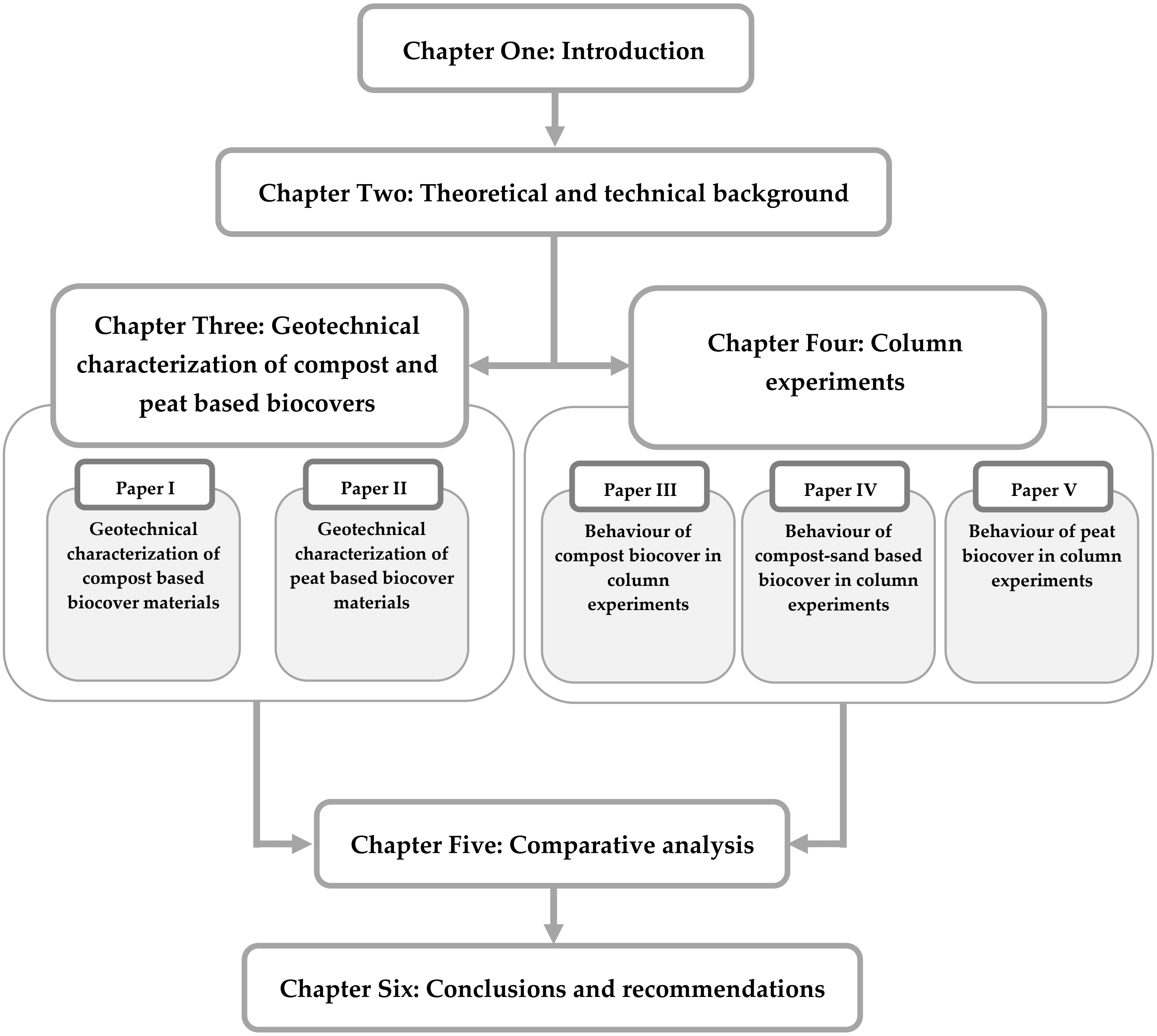

Fig. 1.1. Organization of the thesis.

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2 Technical and theoretical background

2.1 Landfills and global warming

Greenhouse gases (GHGs), which include carbon dioxide (CO_2), methane (CH_4), ozone (O_3), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs), can absorb and emit infrared radiations. The contribution of GHGs to global warming depends on their atmospheric concentration and lifetime as well as global warming potential (GWP) (Lelieveld et al. 1993), which is a relative measure of the amount of heat that gas traps in the atmosphere in comparison to CO_2. The atmospheric concentrations of GHGs have been particularly increased after the Industrial Revolution (Etheridge et al. 1998), such that the atmospheric concentration of CO_2 and CH_4 has increased more than 30% and 150%, respectively, since 1750 (Yuan 2006). Table 2.1 presents the GWP of various GHGs, including CO_2, CH_4, O_3, and N_2O, and their contribution to global warming. It should be mentioned that the major atmospheric constituents, which include nitrogen (N_2), oxygen (O_2), and argon (Ar), are not GHGs.

Table 2.1. GWP, contribution to global warming, atmospheric concentration and lifetime of key GHGs.

Gas	**Chemical formula**	**Atmospheric concentration (ppm)**	**Atmospheric lifetime (years)[1]**	**GWP for given time horizon [2]**			**Contribution (%)[3]**
				20 years	**100 years**	**500 years**	
Carbon dioxide	CO_2	396	Variable	1	1	1	9 – 26
Methane	CH_4	1.7	12	62	23	7	4 – 9
Ozone	O_3	3. 4	N/A	275	269	56	3 – 7
Nitrous oxide	N_2O	3.23	114	289	298	153	5 – 6

[1] IPCC (2007); [2] IPCC (2001); [3] Kiehl and Trenberth (1997)

Among the GHGs, CH_4 has a strong molar absorption coefficient for infrared radiation and relatively long residence time in the atmosphere (Philopoulos et al. 2009; Scheutz et al. 2009). These properties make CH_4 a very potent GHG such that the GWP of CH_4 is 23 to 25 times greater than that of CO_2 in a horizon of 100 years (IPCC, 2001 and 2007). The average atmospheric concentration of CH_4 is 1.7 ppm (Börjesson and Svensson 1997; Humer and Lechner 1999*b*; Le Mer and Roger 2001) with a residence time of 12 years and seasonal concentration variations of about 0.03 ppm (Abichou et al. 2004).

The total amount of annual global CH_4 emissions from both natural and anthropogenic sources is between 500 to 600 Tg (Grübler 1998) (1 Tg $=10^{12}$ g). It is estimated that about 70% of the global CH_4 emissions have anthropogenic sources (IPCC 1996), such as from landfills, agriculture activities, the oil and gas industry, coal mining, combustion processes, wastewater treatment, and specific industrial processes (Huber-Humer 2004).

The biodegradation of the organic fraction of deposited waste in landfills by microbial anaerobic action produces a gaseous product, which is known as landfill gas (LFG). LFG is a potentially harmful mixture, which can migrate to the surface of landfills and become released into the atmosphere (Albanna et al. 2007). The components of LFG are CH_4 (approximately 50% to 55% (v/v)), CO_2 (approximately 40% to 45% (v/v)) (Knaebel and Reinhold 2002; Shin et al. 2002) and trace amounts of different volatile organic compounds (VOCs) (Allen et al. 1997; Eklund et al. 1998; Rettenberger and Stegmann 1996).

Based on the amount of deposited biodegradable waste in a landfill and degradation conditions, such as proper temperature and water content, the production of LFG will continue until the majority of the organic material in the waste has been degraded, which can take up to several decades even after landfill closure and capping (Hilger and Humer 2003). A series of complex biochemical reactions, including hydrolysis, acidogenesis and methanogenesis, are responsible for the biodegradation process of biodegradable waste in landfills (Pokhrel 2006).

Historically, landfills have been perceived to be one of the major sources of anthropogenic CH_4 emissions (Bogner et al. 1995; Masters 1996) and ranked as the third highest source of CH_4 emission after agriculture (livestock farming and rice cultivation), losses from fossil fuel distribution, and processing and mining activities (Huber-Humer et al. 2009). Currently, annual global CH_4 emissions from landfills are in the range of 500 to 800 metric ton CO_2 equivalent (Mt $CO_{2\text{-}e}$), which is about 18% of the global anthropogenic CH_4 emissions (Huber-Humer et al. 2009).

2.2 Counteracting strategies for landfill gas emissions

Among the LFG components, CO_2 is not taken into account in GHG inventories because it has a biogenic origin which is attributed to other sectors (Bogner et al. 2008). Unlike CO_2, CH_4 is a flammable gas and has a high GWP, thus uncontrolled migration of CH_4 from landfills should be prevented due to the associated global and local ecological hazards as well as fire hazards.

There are different approaches for reducing CH_4 emission from landfills (Bogner et al. 2008). One of the approaches emphasizes on the implementation of waste management strategies including composting, recycling and waste incineration, which lead to the reduction of the landfill disposal of biodegradable waste and subsequently decline of CH_4 emission from landfills (Bogner et al. 2008). The implementation of this approach needs time and public support and is more applicable in developed countries with highly regulated waste management policies (Huber-Humer 2004). In developing countries with relatively poor waste management infrastructures, waste management is still mainly the carrying out of untreated waste disposal in poorly controlled landfills (Huber-Humer 2004).

Another strategy is capturing CH_4 emission through a gas recovery system and converting it into energy in the forms of electricity, heat, and steam. Previous studies have shown that gas recovery systems can be an efficient method such that CH_4 emissions can be reduced by a factor of 3 (Bogner et al. 1993) to 10 (Mosher et al. 1999). It should be noted that gas utilization is only applicable for a part of the landfill lifespan with a high rate of CH_4 production. Furthermore, when the CH_4 concentration is reduced to less than 35% to 40% (v/v), this method may become economically and technically unfeasible (Haubrichs and Widmann 2006). Moreover, the burning of CH_4 emission by using high temperature flares is an option when the CH_4 concentration is more than 20% to 25% (v/v) (Huber-Humer et al. 2008). This method converts CH_4 to CO_2 without recovering the energy content which can be harmful due to fire and health hazards.

Even with the application of the mentioned technologies, there is evidence that shows the escape of a significant amount of CH_4 gas into the atmosphere through the landfill cover layer as shown in Fig. 2.1 (Börjesson et al. 2007). Therefore landfills are still one of the main sources of CH_4 emissions, and require technical and regulatory consideration (Huber-Humer 2004).

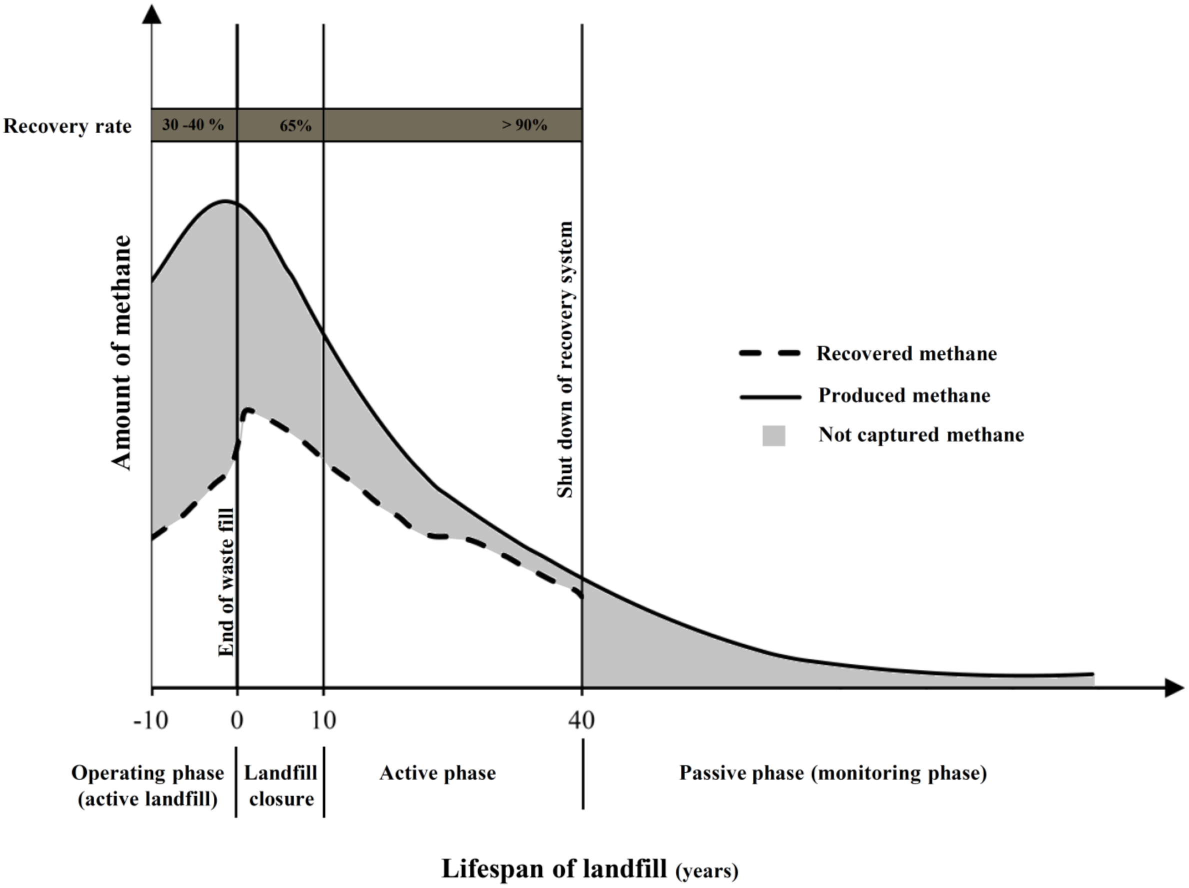

Fig. 2.1. Methane production and recovery over a landfill lifetime

(Reproduced from Huber-Humer et al. 2008).

Currently, attention is focused on the development of low cost alternative technologies such as biological methods, to treat LFG where implementations of the mentioned conventional methods are not economically or technically feasible (Barlaz et al. 2004; Dever et al. 2007; Stern et al. 2007). One of most promising alternative approaches is to passively vent CH_4 through a reactive biological cover soil or biocover in order to oxidize CH_4 through a natural biological process (Ait Benichou et al. 2009; Cabral et al. 2010*b*; Hilger et al. 2000*b*; IPCC 2007).

2.3 Fundamental of biological methane oxidation

A general simplified CH_4 oxidation reaction can be formulated as shown by Eq. 2.1 (Barratt 1995).

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \qquad [2.1]$$

CH_4 oxidation is a chemical exothermic reaction, which releases 883 kJ per mol of oxidized CH_4 (Barratt 1995). The natural CH_4 oxidation process in biocovers is mediated by methanotroph bacteria at the interface of the aerobic and anaerobic zones (Huber-Humer 2004). Methanotroph bacteria have been found in a variety of environments, such as peat lands, landfill soil covers, compost rows, and forest, and agricultural and tundra soils (Bogner et al. 1995; Jackel et al. 2005; Kiese et al. 2003; Mosier et al. 1991; Whalen and Reeburgh 1990, respectively). Methanotrophs are classified into Types I, II, and X according to their pathway, morphology and membrane arrangements (Bowden et al. 1993). Moreover, methanotrophs can be classified based on CH_4 concentration into high affinity (operating at low CH_4 concentration) and low affinity (operating at high CH_4 concentration) (Hanson and Hanson 1996). High and low affinity methanotrophs belong to Types I and II methanotrophs (Scheutz et al. 2009), respectively.

Biotic CH_4 oxidation follows complex biochemical reactions, which are initiated with the oxidation of CH_4 into methanol (CH_3OH) by methane monooxygenase (MMO) enzymes. MMOs can be found in two forms; sMMO which is the soluble form, and pMMO, which is the particulate form of methane MMOs. The pMMO is found in all known methanotrophs, while sMMO is only found in Types II and X methanotrophs (Hanson and Hanson 1996). As presented in Fig. 2.2, methanol is reduced by a periplasmic methanol dehydrogenase (MDH) into formaldehyde (HCHO), which is further converted into cellular biomass by two known pathways of the ribulose monophosphate path (RuMP) and the serine path (Whittenbury et al. 1970).

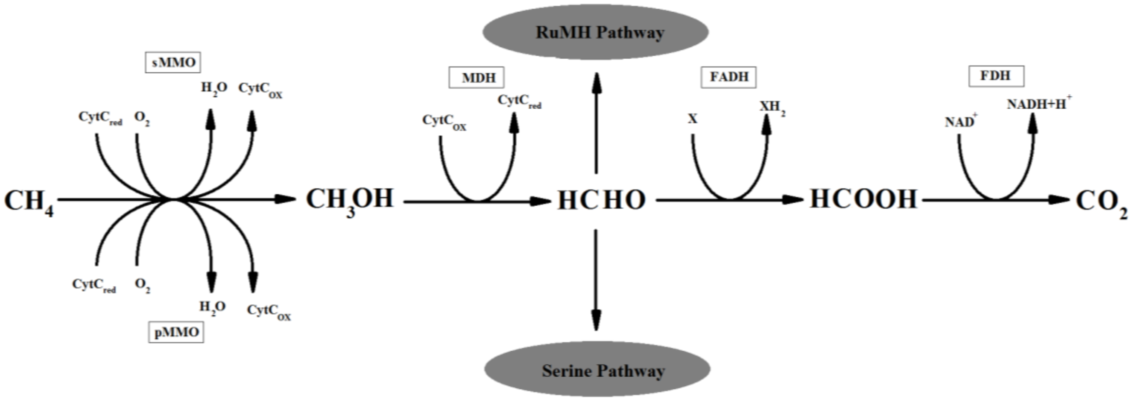

Fig.2.2. Pathways of methane oxidation

(CytC: cytochrome c; FADH: formaldehyde dehydrogenase; FDH: formate dehydrogenase)

(Reproduced from Hanson and Hanson 1996).

Types I and II methanotrophs use RuMP and serine pathways, respectively, while Type X methanotrophs use either one. A part of the formaldehyde is later converted into formic acid (HCOOH) by formaldehyde dehydrogenase (FADH) and then converted by formate dehydrogenase (FDH) into CO_2 (Hanson and Hanson 1996).

Therefore, it should be noted that Eq. 2.1 is stoichiometrically correct, but cannot represent the biological aspect of CH_4 oxidation. A more accurate approach with respect to the biological aspect of CH_4 oxidation is proposed by Van Dijken and Harder (1975) as follows:

$$38.25CH_4 + 3NH_3 + 63.75O_2 \rightarrow 3C_4H_8O_2N + 26.25\ CO_2 + 69H_2O \qquad [2.2]$$

2.4 Biocover technology

An effective means of reducing CH_4 emissions from landfills is to oxidize CH_4 by passively venting LFG through a reactive biological cover soil or biocover (Ait Benichou et al. 2009; Cabral et al. 2010*b*; Hilger et al. 2000*b*; Perez 2009). Biocovers consist of a filter material for supporting methanotrophic activity, which is placed above a gas distribution layer (Pedersen 2010). Fig. 2.3 shows a schematic cross section of a biocover. It should be mentioned that depending on the rate of CH_4 production, biocovers can be solely used or in combination with a gas recovery system to treat fugitive CH_4 emission from landfills (Einola 2010).

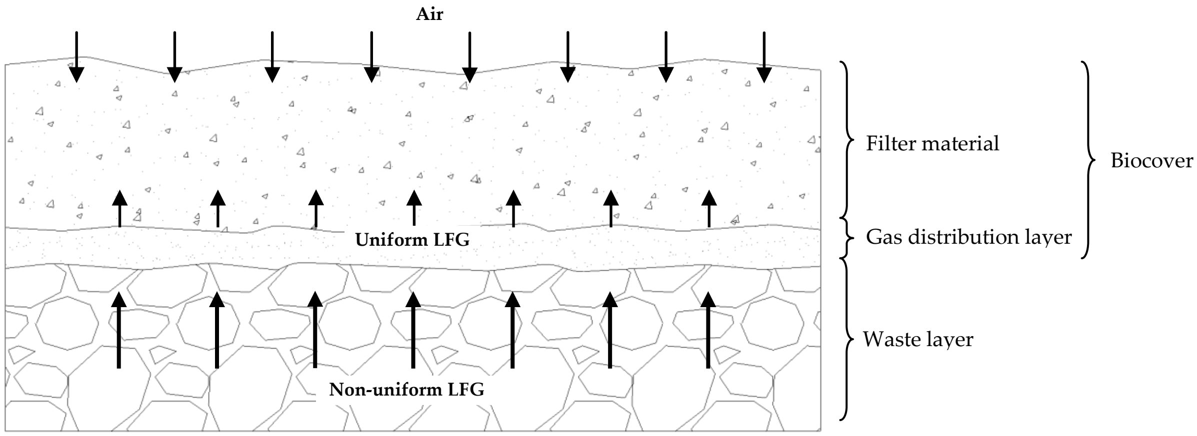

Fig.2.3. Schematic cross section of biocover.

Various materials, which have high porosity, high water holding capacity (WHC), high specific area, low thermal conductivity and appropriate nutrient concenteration can be the support medium for CH_4 oxidation (Hilger and Humer 2003; Kettunen et al. 2006). Table 2.2 is a summary of the recommended properties of biocover material for practical applications. These recommendations are based on the analysis of results derived from laboratory experiments on 41 different potential biocover materials (Huber-Humer et al. 2009).

Table 2.2. Recommended properties of biocover material (Huber-Humer et al. 2009).

Parameter	**Unit**	**Recommended value**
Bulk density	kg/l	0.8–1.1
Moisture content	%	30–50
Water holding capacity (WHC)	%	50–130
Air-filled pore volume	%	>25
Particle size distribution	Fraction in %	0.063–2 mm: 20–30 2-6.3 mm: approx. 40 6.3–20 mm: 20–40 >20 mm: approx. 10
Conductivity	mS/cm	<4
pH	N/A	6.5–8.5
Organic content	%	>15

Previous laboratory and field studies have demonstrated that stabilized and sanitized compost materials (Barlaz et al. 2004; Huber-Humer 2004; Humer and Lechner 2001, 1999a; Wilshusen et al. 2004) as well as peat materials (Einola 2010; Einola et al., 2009; Hanson and Hanson 1996; Kightley et al. 1995; Sly et al. 1993; Stein and Hettiaratchi 2001; Streese and Stegmann 2003; Yavitt et al. 1990) meet the aforementioned criteria and can be suitable for practical applications in mitigating CH_4 emissions.

Compost is a mixture of fragmented organic material, which is formed due to the decomposition of organic substrates in moist and aerobic conditions (Diaz et al. 2007). The decomposition is described as the controlled microbial process of the breakdown of complex organic matter into simple organic matter (Varma and Buscot 2005). Peat is a mixture of stable humus material, which is mainly formed due to the partial humification of biomass (vegetation) in moist and anaerobic conditions over many years (Anggraini 2006; Kazemian et al. 2011; Ulusay et al. 2010). Humification is described as the natural microbial process of transforming biomass into a humus substance (Varma and Buscot 2005). Both peat and compost materials are recognized as porous material with high organic and moisture contents and relatively lower density in comparison to mineral soils (Anggraini 2006; Diaz et al. 2007).

The gas distribution layer in biocovers should be coarse enough to provide a uniform and appropriate distribution of produced CH_4 in the landfill within the filter material (Scheutz et al. 2009). It should be noted that depending on the rate of CH_4 production, biocovers can be solely used or in combination with gas recovery systems in order to treat fugitive CH_4 emission from landfills (Einola 2010).

2.4.1 Laboratory studies

Laboratory studies have generally consisted of a filter substrate, which is packed above a gas distribution in a column. A steady state CH_4 flow is introduced at the bottom of the column to simulate landfill CH_4 flux. The behaviour of a biocover under different conditions is monitored over a period of time in order to evaluate the suitability of the tested material for CH_4 oxidation. Table 2.3 is a summary of the results from different laboratory studies on CH_4 oxidation efficiency as reported in the literature.

Table 2.3. Summary of CH_4 oxidation efficiency obtained from biocover column experiments.

Biocover material	Thickness (m)	Moisture (%)	Organic (%)	CH_4 oxidation efficiency (%)	Duration (day)	Reference
Compost	0.85	100	32.2	100	374	Haubrichs and Widmann (2006)
Compost	0.4	124	46	19	600	Wilshusen et al. (2004)
Compost	1.25	31	20	100	218	Philopoulos et al. (2009)
Compost	0.85	32.2	50	96	396	Haubrichs and Widmann (2006)
Peat	0.8	316	79	85	351	Stein and Hettiaratchi (2001)
Sand	0.3	13	0.4	71	90	Park et al. (2002)
Sand	0.6	18	7	40	53	Humer and Lechner (1999a)
Compost-Sand (1:5)	0.6	45	19	75	53	Humer and Lechner (1999a)
Compost-Sand (1:1)	1.25	15	5	100	218	Philopoulos et al. (2009)

Philopoulos et al. (2009) compared the long term (218 days) performance of two different filter materials under a CH_4 loading flux of 134 g/m^2 day in the laboratory. Each column consisted of 32 cm of drainage stones as the gas distribution layer. The first column was packed with 125 cm of yard waste compost, while the second one was packed with 125 cm of a sand-compost-perlite (SCP) mixture. The initial moisture content of the yard waste compost and SCP mixture was 0.31% and 15%, respectively. Both studied materials had a rapid adaption phase (5 days) and the oxidation efficency varied between 69.6% and 100% for the SCP mixture in the first 96 days. From the 111st day onward, both media showed approximately complete CH_4 oxidation.

Humer and Lechner (1999) investigated the CH_4 oxidation capacity of six different compost and soil mixtures. The columns were packed with 60 cm of filter material and monitored between 51 to 61 days under a constant standard temperature (18°C) and a CH_4 flux of 180 g/m^2 day. The results indicated that the control soil with a CH_4 oxidation efficency of 30% to 45% has the minimum performance, while waste compost (age of 20 weeks) with an initial moisture content of 48.5%, organic content of 27.2% and porosity of 28.7% (by volume) has the maximum CH_4 oxidation efficency (approximately 100%). Also, the temperature was approximately 2°C to 3°C higher in the CH_4 oxidation zone than the rest of the column for all of the samples.

Similar column experiments were conducted by Scheutz and Kjeldsen (2005) on landfill cover soil at room temperature (22°C). The columns were packed with 80 cm of landfill cover soil and continuously fed with artificial LFG at 2.6 mL/min (consisting of 50:50% vol. CH_4:CO_2) for at least 3 weeks, which corresponded to a flux of 250 g/m^{2}day. An atmospheric condition was simulated by passing an airstream at 100 mL/min at the top of the column. The steady state gas profiles were observed after 4 days of column operation (adaption phase). The columns showed a CH_4 oxidation rate up to 184 mole / m^2 day, which corresponds to efficency of 73%. The maximum organic and moisture contents at the end of the column operation, which were 4.3% and 42% respectively, were achieved at depths of 15-20 cm below the surface of biocover.

Perdikea et al. (2008) studied the combined effect of moisture content and thickness on the CH_4 removal capacity of compost and sawdust mixtures in column experiments. Each set of columns were fed an average CH_4 flow rate of 11.3 g/m^{2}day for 40 days at room temperature (22°C). The initial moisture and organic contents were 52.3% and 40% respectively for compost and 6.4% and 99.4% respectively for sawdust. All of the column experiments had a relatively short adaptation phase of 2 to 4 days. The columns with a thickness of 30 cm reached 100% in CH_4 oxidation efficiency, while columns with a thickness of 15 cm had a maximum CH_4 oxidation efficiency of 64% to 77%. In the mentioned study, the column of pure compost with a thickness of 30 cm and a moisture content of 52% had the best overall performance.

The effect of soil properties on the CH_4 oxidation rate of sedge peat, landfill loam, and agricultural soils were also studied by Stein and Hettiaratchi (2001) in column experiments. The thickness of the filter material was 76 cm and columns were fed through the bottom with CH_4 (99% pure) at flow rates from 2.5 to 5.2 ml/min and through the top of the columns with an air flow rate of 300 ml/min in order to simulate an atmospheric condition. The initial organic content and WHC were 3.1% and 24.6% for the landfill loam soil, 4.7% and 39.8% for the agricultural soil and 79% and 505% for the sedge peat, respectively. After 19 days of carrying out the column operation, the sedge peat column, which was subjected to a CH_4 flow rate of 319 g/m^{2}day, showed an increase in the rate of CH_4 oxidation and reached an approximate maximum efficiency value of 100%. For the landfill loam soil column, the steady state condition occurred after 28 days of carrying out the column operation and finally reached 120 g/m^{2}day. The agricultural soil, which was subjected to a CH_4 flow rate of 310 g/m^{2}day, showed a low oxidation rate of 10 g/m^{2}day due to the low initial moisture content. The CH_4 oxidation efficiency increased to 40% (124 g/m^{2}day) in the agricultural soil after 14 days by increasing the moisture content (up to 10%).

Kightley et al. (1995) investigated the capacity of the CH_4 oxidation of landfill cover soil in column experiments. Each column was packed with 90 cm of landfill cover soil and fed with CH_4 (99% pure) at a flow rate of 271.2 g/m^{2}day and an airflow of 300 ml/min was passed across the top column. After 13 days of column operation, the CH_4 oxidation efficiency rapidly increased and reached 61%. Then, the CH_4 oxidation efficiency was increased to steady state efficiency of 65% and 66% after 2 and 4.5 months, respectively. The authors also reported that amendment with sewage sludge increases the CH_4 oxidation efficiency by 26% while amendment with K_2HPO_4 and NH_4NO_3 respectively has no effect and decreases the CH_4 oxidation efficiency to 64%, respectively.

Wilshusen et al. (2004) evaluated the long term (over 220 days) CH_4 oxidation behaviour of municipal leaf and garden composts, and unscreened composted wood chips and municipal solid waste (MSW). The columns consisted of 50 cm of filter material and were fed with CH_4 (99% pure) at a flow rate of 520 g/m^{2}day from the bottom of the column and an air flow from the top of the column. The initial moisture and organic contents were 124% and 46% for the leaf compost, 122% and 78% for the garden compost, 123% and 34% for the composted wood chips, and 123% and 49% for the MSW compost, respectively. The leaf and MSW compost columns reached a steady state CH_4 oxidation rate after a quick adaptation phase and remained there for approximately 100 days. The leaf compost column had the highest average CH_4 oxidation rate of 360 g/m^{2}day in comparison to the MSW and wood composts, which reached approximate peak oxidation rates of 260 g/m^{2}day and 270 g/m^{2}day throughout the high rate composting phase, respectively. Conversely, the garden compost column did not exhibit a similar high rate of CH_4 oxidation. All of the columns demonstrated similar trends in decline in CH_4 oxidation rate after approximately 100 days of column operation.

Further to the mentioned studies, De Visscher et al. (1999) investigated the performance of agricultural soil and a landfill cover soil in CH_4 oxidation. In this research, cylinders were filled with filter material to a height of 50 cm. A CH_4/CO_2 gas mixture (50:50% vol.) with a flow rate of 13.4 mol /m^2_{column} day and 23 mol/m^2_{column} day was introduced to the bottom of the agricultural soil and landfill cover soil columns, respectively. After 5 days of column operation, the CH_4 oxidation rate reached a steady rate of 8 mol/m^2_{column} day for the agricultural soil. Then, the CH_4 oxidation rate slowly increased with time, and a value of 10.7 mol/m^2_{column} day was observed on the 28th day. The average and maximum CH_4 oxidation rates of the landfill cover soil were 15 and 18.1 mol/m^2_{column} day, respectively, which are considerably higher than those of the agricultural soil. Also, the authors reported that amendment with sugar beet leaves caused temporary enhancement of the CH_4 oxidation capacity while mixing in wheat straw resulted in a permanent increase.

2.4.2 Field studies

Laboratory studies can evaluate the CH_4 oxidation capacity of different filter media and the effect of various factors on the performance of oxidation layers. However, the efficient design of biological CH_4 oxidation layers also needs to comprehensively take into consideration the field conditions in different climates (Chanton et al. 2009). Table 2.4 presents the CH_4 oxidation efficiency of field scale studies available in the literature.

Table 2.4. Summary of CH_4 oxidation efficiency obtained in field studies.

Biocover material	Thickness (m)	Area (m^2)	CH_4 oxidation efficiency (%)	Reference
Compost	1.5	9.3	76	Philopoulos et al. (2009)
Compost	2.5	20.9	35	Philopoulos et al. (2009)
Compost	0.9	625	99	Huber-Humer et al. (2009)
Peat-Compost (2:3)	0.5	39000	25-84	Einola et al. (2009)
Compost-Woodchips (5:1)	1.2	9	67	Dever (2000)
Compost-Woodchips (1:1)	0.9	625	85	Huber-Humer et al. (2009)
Compost-Sand (5:1)	0.9	26.8	11	Cabral et al. (2010*a*)
Compost-Gravel (1:1)	0.4	26.8	72	Cabral et al. (2010*a*)

Several techniques have been developed to estimate the CH_4 oxidation in landfills, such as the use of a flux chamber, mass balance calculation, isotope fractionation, plume tracers, and the aircraft and tower method. It should be noted that each technique has some limitations and different levels of simplicity (Nozhevnikova et al., 2003).

Philopoulos et al. (2008) conducted a field scale experiment in Leduc, Alberta, Canada for 10 months to evaluate the CH_4 oxidation capacity of yard waste compost with initial moisture and organic contents of 31% and 18% respectively, at three different sites. The thickness of the filter medium was 1.5 m, which was placed above a 0.8 m layer of tire shreds as the gas distribution layer. The first site was located on a slope and in a non active section of the landfill. The second site was located at the top of the landfill (20 m) and in an active section which was equipped with a gas well. The last site was similar to the second site and located at the top of the landfill (20 m), but in a non active section. In this study, the rate of CH_4 oxidation was calculated by using carbon mass balance. The average calculated influent CH_4 loads were 37.4, 53.5, and 12 g/m^2day, for Sites 1, 2, and 3, respectively. The monitored results demonstrated that CH_4 surface emissions were less than 15 g/m^2day at the first and second sites, and less than 5 g/m^2day at the third site. Also, the average CH_4 oxidation efficiencies were 76%, 68%, and 35% for Sites 1, 2, and 3, respectively.

Barlaz et al. (2004) investigated the CH_4 oxidation capacity of a soil cover (1 m of clay) and a biocover in combination with a gas collection system over a period of 14 months at a field scale. The studied biocover system consisted of 1 m of yard waste compost, which was located above 15 cm of tire chips (gas distribution layer). Both the soil cover and biocover were placed on a sloped and flat section of the landfill, where the average ambient temperature and pressure during the monitoring period were 26.3°C and 760 mmHg respectively. The initial and final moisture contents were 16.6% and 14.6% for the soil cover and 63% and 53.1% for the biocover, respectively. CH_4 emissions were measured by using the stable isotope method. CH_4 emission from the biocover reached up to 1.33 g/m^2day while that from the soil cover was higher than 15 g/m^2day. The results indicated that the operation of a gas collection system has no significant effect on the performance of biocovers, but in contrast, caused a dramatic reduction of the CH_4 oxidation rate in the soil cover.

Cabral et al. (2010*b*) studied the performance of a passive CH_4 oxidation biocover, which was constructed within an existing final cover in a landfill (an area with 5 year old waste) in Quebec, Canada. The studied biocover had a dimension of 2.75 m (width) x 9.75 m (length) and consisted of 80 cm of compost and sand mixture (5:1 v/v) above 10 cm of 6.4 mm gravel, which served as the gas distribution layer and underlain by 30 cm of 12.7 mm of net gravel. CH_4 was fed through a gas distribution system and steadily increased from 9.3 to 250 g/m^{2}day during the 6 months of study. The CH_4 surface fluxes in this research were measured by the static chamber method. The results indicated that by increasing CH_4 loading until 2.5 months after the biocover operation, the CH_4 oxidation efficiency increased and reached approximately 100%. During the steady state period of CH_4 loading from 2.5 to 5.5 months in the biocover operation, the CH_4 oxidation efficiency was relatively constant (almost 100%). Then, by increasing the CH_4 loading rate after 5.5 months, the studied biocover responded well and the performance increased back again to 100% in less than 15 days. It should be mentioned that the major oxidation zone in this study was located at a depth between 0.6 m to 0.8 m below the surface of the biocover.

For over 2 years, Humer and Lencher (2001) studied the performance of a MSW biocover at field scale in an Austrian landfill. This field test included the construction of four cells with a dimension of 25×25 m on fresh household waste and one control cell with the same dimension. The primary used filter materials were sewage sludge and MSW composts with the same initial organic content of 27%, and moisture content of 120% and 97%, respectively. The base for all of the cells was 10-15 cm of MSW. The first and second cells consisted of 30 cm of gravel above the MSW layer as the gas distribution layer. The first cell was composed of 90 cm of sewage sludge compost above the gas distribution layer, while the second cell consisted of 90 cm of MSW compost. In this study, the CH_4 emissions were measured by using an open tunnel system. The average total gas flux (including both CH_4 and CO_2) was in the range of 30 to 60, 20 to 90, 30 to 960, 30 to 370, and 50 to 1960 l/m^{2}d respectively for the first to fifth cells. The authors reported fluxes of 98.7, 48.6, and 232.88 g/m^{2}day, respectively, at the surface of the third to fifth cells while the CH_4 oxidation efficiency of the first and second cells was 100%.

Moreover, Abichou et al. (2009) monitored a field experiment which was set up over an area that was covered in 8 years of waste in Leon County, Florida. In this study, three biocovers and three control cells were studied for 1 year and the CH_4 oxidation rate was measured by the stable isotope method. Each biocover had a dimension of 7.6 m x 7.6 m and consisted of a 10 cm layer of glass cullet above a 3.8 m layer of yard compost. The average and peak CH_4 fluxes were 11 and 77 g/m^{2}day respectively before the biocover implementation and 0.04 and 0.06 g/m^{2}day after the biocover implementation. Also, the mean CH_4 oxidation was 79% for the biocovers and 29% for the control cells.

2.5 Controlling factors on biological methane oxidation

Generally, methanotrophic activities and thereby biological CH_4 oxidation are strongly regulated by different factors. Some of these factors are affected by the material properties of biocovers (Einola 2010) while others through certain environmental factors (Huber-Humer 2004). This section summarizes the impact of different factors on the CH_4 oxidation process of compost based substrates.

2.5.1 Thermal factors

2.5.1.1 Temperature

Temperature has a significant effect on methanotrophic activity and subsequently CH_4 oxidation processes (Scheutz et al. 2009). The CH_4 oxidation rate increases with temperatures up to the maximum oxidation rate and then decreases with increasing temperatures (Czepiel et al. 1996). The temperature in biologically active soil is affected by the temperature of the LFG, atmospheric temperature, rainfall, and microbial activity (Jäckel et al. 2001).

Most methanotrophs are mesophiles and multiply best at a temperature range of 25°C to 35°C (Scheutz et al. 2009). Scheutz and Kjeldsen (2004) and Stein and Hettiaratchi (2001) reported 30°C as the optimum temperature for CH_4 oxidation in loam soil. Laboratory studies conducted by Park et al. (2009) on landfill cover soil showed that the optimum temperature for CH_4 oxidation is in the range of 25°C to 35°C. Börjesson (1997) and Whalen et al. (1990) found that the optimum condition for the growth of methanotrophic bacteria is at a temperature of about 31°C in sandy soil mixed with clay and silty loam.

Moreover, there are different findings on the degree of dependency of CH_4 oxidation on temperature. Kettunen et al. (2006) found that when the temperature declined from a range of 21°C to 23°C to a range of 4°C to 6°C, the CH_4 oxidation efficiency in a sand and sewage sludge compost mixture and bark chips drops by 50% and 75%, respectively. Whalen et al. (1990) reported a significant decrease in CH_4 oxidation rates by decreasing the temperature from 35°C to 5°C. Albanna and Fernandes (2009) found a similar behaviour in landfill cover soil such that the CH_4 oxidation rates were reduced by half when the temperature decreased from 35°C to 5°C. Batch studies conducted by De Visscher et al. (2001) indicated that an increase in the temperature from 5°C to 35°C leads to an exponential increase in the CH_4 oxidation rate.

Methanotroph bacteria are adaptative to different temperatures (Hanson and Hanson 1996) such that CH_4 oxidation has been observed at temperatures as high as 45°C (Scheutz and Kjeldsen 2004; Visvanathan et al. 1999). This phenomenon can be attributed to the specific population of methanotrophic bacteria, which are thermophile and capable of growing at temperatures up to 50°C (Hanson and Hanson 1996). Moreover, several laboratory investigations have shown that methanotrophic bacteria are still active at low temperatures of 1°C to 2°C (Börjesson 1997; Christophersen et al. 2000; Einola 2002). Experimental investigations conducted by Börjesson et al. (2004) revealed that all of the found bacteria at low temperatures belong to Type I methanotrophs and temperature has a selective effect in determining the type of methanotroph that will predominate in a given temperature.

2.5.1.2 Thermal conductivity

As previously mentioned, methanotrophic activity and consequently, CH_4 oxidation, is profoundly affected by temperature (Börjesson and Svenssen 1997; Chandrakanthi et al. 2005; Chanton and Liptay 2000; Dobbie and Smith 1996). Thermal conductivity indicates the rate of heat flux dissipation and thereby temperature dissipation (Al Nakshabandi and Kohnke 1965). Thus, the thermal conductivity of biocover materials can be described as one of the decisive physical factors that controls the suitability of the thermal conditions for methanotrophic activity and influences CH_4 oxidation in various climatic and thermal loading conditions.

Thermal conductivity is influenced by texture (size and type of soil particles), organic content, bulk density and moisture content (Hettiarachchi 2005). Bajwa (2012) studied the thermal conductivity of compacted compost material at different moisture contents and observed that the thermal conductivity varies at a range of 0.12 to 0.54 W/m°K, while the moisture content varies at a range of 38% to 107%.

Chandrakanthi et al. (2005) studied the effects of moisture content and bulk density on the thermal conductivity of leaf compost. The obtained results showed that the thermal conductivity of compost increases with increase in the moisture content and bulk density. Moreover, Iwabuchi and Kamide (1993) reported a thermal conductivity of 0.051 W/m°C for dry compost (dairy cattle manure and saw dust mixture) and 0.096 W/m°C at a moisture content of 57%. Ahn et al. (2009) investigated the dependency of the thermal properties of various compost materials on particle size distribution, moisture content and bulk density. They found a linear relationship between bulk density and thermal conductivity such that an increase in the bulk density leads to an increase in the thermal conductivity. This means that coarse materials conduct heat at lower rates in comparison with dense materials (Hettiarachchi, 2005).

Despite the significant contributions of the previous studies towards the understanding of the thermal properties of biocovers and the factors that can affect thermal properties, there is still a paucity of data on the thermal properties of biocover materials, such as compost-sand mixtures, peat, and peat-sand mixtures.

2.5.2 Hydraulic factors

2.5.2.1 Hydraulic conductivity

The water infiltration and gas exchange processes through biocovers are strongly influenced by the hydraulic conductivity of the biocover material (Pokhrel 2006). High hydraulic conductivity of the medium results in an increase in the gas transport properties and subsequently enhancement of CH_4 oxidation. Conversely, high hydraulic conductivity accelerates water infiltration, which can lead to an increase in leachate generation, saturation of the base of the biocover and thereby drastic reduction in gas migration and CH_4 oxidation through the biocover. The optimum hydraulic conductivity supports an appropriate gas exchange process and also prevents water infiltration.

Benson and Othman (1993) reported a minimum hydraulic conductivity of 6×10^{-9} m/s for compacted compost material. According to a laboratory investigation on the hydraulic conductivity of compost material by Bajwa (2012), the hydraulic conductivity of compacted compost material varies over a range of 2×10^{-7} m/s to 7×10^{-10} m/s depondes on moisture contents. Puppala et al. (2006) investigated the hydraulic conductivity of different compacted compost mixtures and reported a range of 4.2×10^{-10} m/s to 9.7×10^{-11} m/s for the studied materials. Similar results have been observed by Banavathu (2003) in laboratory experiments where the hydraulic conductivity of different compost and biosolid mixtures ranged from 1.2×10^{-9} m/s to 9.7×10^{-11} m/s.

Huat et al. (2011) found a hydraulic conductivity range of 10^{-5} m/s to 10^{-13} m/s for peat material; material which is applicable as biocover material (Einola 2010; Stein and Hettiaratchi 2001). Mesri and Ajlouni (2007) also found similar results and reported that the hydraulic conductivity of peat ranges from 10^{-7} m/s to 10^{-14} m/s. In contrast, Colley (1950) and Miyakawa (1960) obtained a lower range of 10^{-9} m/s to 10^{-12} m/s for the hydraulic conductivity of peaty soils.

It should be noted that the hydraulic conductivity of other potential biocover materials such as compost-sand and peat-sand mixtures, has not been comprehensively investigated in the literature. Thus, there is a need for further studies.

2.5.2.2 Moisture content

Moisture is essential for methanotrophic activity which acts as a transport medium for nutrient supply and also metabolite removal (Scheutz et al. 2009). Microorganisms are impacted by physiological stress under low moisture contents which lead to the reduction of CH_4 oxidation efficiency (Huber-Humer 2004; Scheutz et al. 2009). Accumulation of small amounts of nitrite at low moisture contents also reduces the CH_4 oxidation rate (Boeckx et al. 1996).

Moreover, excessive moisture slows down gaseous transport processes and impacts CH_4 oxidation capacity. This is because gases have to diffuse into the liquid phase under high moisture conditions, which is about 10^4 times slower than molecular diffusion in the gas phase (Cabral et al. 2004). Furthermore, the accumulation of ammonium at high moisture conditions in organic soils contributes to the reduction of the CH_4 oxidation rate (Börjesson et al. 1998). Therefore, CH_4 oxidation is significantly reduced under conditions of both high and low moisture contents (Pokhrel 2006).

The moisture content that supports the maximum gas phase molecular as well as microbial activity is referred to as the optimum moisture content for CH_4 oxidation (Einola 2010). The optimum moisture content depends on the soil texture (Scheutz et al. 2009) and can be expressed in a volumetric and mass basis or proportion of the WHC. It should be noted that the range of optimum moisture content for CH_4 oxidation when expressed in a volumetric or mass basis is variable among different soils due to their different water retention characteristics (Einola 2010).

Batch studies conducted by Park et al. (2005) showed that the optimum moisture content for CH_4 oxidation is 10% (w/dw) for sandy soil. Similar results were derived by Whalen et al. (1990) on sand and clay mixtures where the optimum moisture for growth of methanotrophic bacteria was 10% (w/dw). Park et al. (2009) found that the optimum moisture content for CH_4 oxidation in landfill cover soil is in the range of 10% to 15% (w/dw). Contrary to the mentioned studies, Börjesson (1997) reported optimum moistures of 61% and 35% (w/dw) for silty loam and sandy loam soils, respectively. Mor et al. (2006) also observed that the maximum CH_4 oxidation rate in compost occurs with moisture contents over 110% (w/dw).

In terms of the WHC, Whalen and Reeburgh (1996) observed an optimum moisture content of 50% WHC for CH_4 oxidation in bog soil. Humer and Lechner (1999) recommended a moisture content between 40% and 80% WHC as the optimum moisture content for CH_4 oxidation. Boeckx et al. (1996) also found that the highest CH_4 oxidation rate is achieved at a moisture content of 50% WHC. Moreover, CH_4 oxidation dramatically decreases at moisture contents below 13% WHC (Bender, 1992). Based on a laboratory investigation by Jäckel et al. (2001) on paddy soil, it was found that methanotroph bacteria become inactive at moisture contents less than 20% WHC and there is also rapid reduction in CH_4 oxidation when the moisture content is in a range of 75% to 82% WHC.

The presented literature review reveals that several studies have been conducted to determine the optimal moisture content for methanotrophic activity within biocovers. However, it should be emphazised that the moisture content of biocovers changes with time during their lifetime. The time dependent changes of the moisture content of biocovers and associated effects on the performance of biocovers were mostly not addressed in the previous studies. Thus, there is a need to comprehensively address these issues.

2.5.2.3 Degree of saturation and water potential

The degree of saturation (S_r) can affect degradation and gas transport processes through the medium as well as the geotechnical stability of biocovers (Bajwa, 2012). In terms of gas flow, the S_r expresses the relative pore volume available for gas exchange at different moisture contents. At relatively low S_r, most of the gas transport processes occur through partially air filled pores because of the much higher air diffusion coefficients in comparison with aqueous diffusion coefficients (Aachib et al. 2004). The continuity of air phases is reduced by increasing the S_r (Nagaraj et al. 2006). Beyond an S_r of 85%, air filled voids are no longer interconnected (Cabral et al. 2004) and occluded air tends to be in the form of air bubbles (Aachib et al. 2004; Cabral et al. 2004; Nagaraj et al. 2006). This condition causes gas to diffuse into the liquid phase as dissolved species which result in quite low gas fluxes (Aachib et al. 2004; Cabral et al. 2004) and consequently, gas occlusion and reduction of the CH_4 oxidation rate (Cabral et al. 2010*a*) take place.

Roncato et al. (2010) presented a preliminary discussion about the importance of the S_r in the behaviour of biocovers. They observed the minimum and maximum CH_4 oxidation efficiencies in laboratory experiments at S_r of 63% and 45%, respectively, while in field tests, the minimum efficiency occurred at an S_r of 70%. Moreover, the average value of the S_r in field studies, which were conducted by Cabral et al. (2010*b*) varied in a range of 59.5% to 77.5% and there was no correlation between the CH_4 oxidation efficiency and S_r.

Another parameter which can describe the dependency of microorganisms to soil moisture is water potential (Mancinelli, 1995). Water potential can be defined as the potential energy of water relative to the free energy of pure water in reference conditions (Huber-Humer 2004). The water potential of pure free water is zero while unsaturated soils have negative water potential according to the definition by Mancinelli (1995).

There are different scientific views on the dependency of microorganism activity and consequently, the CH_4 oxidation rate on water potential. Mancinelli (1995) reported that due to insignificant resistance posed by the microbial cell wall, the water potential of a microbial cell in soil should be near equilibrium with the surrounding environment. Conversely, Schinner and Sonnleitner (1996) stated that microorganisms prefer water potential at a range of -0.1 to -4 bars. The MMO enzyme oxidizes CH_4 in the stages of CH_4 oxidization, and methanol, formaldehyde and formate- dehydrogenations. Dehydrogenase activity (DHA) is one of the most imperative biological processes during CH_4 oxidation (Brzezińska et al. 2004). Biological investigations (Paradelo and Barral 2009) have revealed that the highest values of DHA and consequently, CH_4 oxidation rate, are obtained at a water potential of -0.1 bar and lower DHA values are obtained at pressures above and below the mentioned water potential.

2.5.3 Mechanical and physical factors

2.5.3.1 Particle size distribution

Particle size distribution provides the first insight into material suitability for biocover construction (Huber-Humer et al. 2009) and produces a strong impact on microbial CH_4 consumption (Huber-Humer 2004). Particle size distribution should be fine enough to provide a high specific surface (Stein 2000), which maximizes the sorption capacity and potential reaction sites for methanotrophic activity per unit volume (Swanson and Loehr 1997). Conversely, fine particle size distribution causes restrictions in the gas transport process which have a negative impact on CH_4 oxidation process (Delhoménie et al. 2002).

Börjesson et al. (2004) investigated the effect of particle size distribution on CH_4 oxidation rate and reported that the CH_4 consumption rate is strongly influenced by the coarse sand content (particle size between 0.2 to 2 mm) of the oxidizing layer (Yuan 2006). Pawlowska et al. (2003) observed that coarse sand has higher CH_4 oxidation than coarse gravel, which can be attributed to insufficient methanotrophic reaction sites in the latter. Huber-Humer et al. (2009) recommended compost material with a content of 20% to 30% sand and 40% fine gravel, and 30% to 40% coarse gravel as the biocover medium. Bender and Cornad (1994) reported that sand material with a particle size between 0.5 and 2 mm is a favourable soil matrix for methanotrophic activity. Kightley et al. (1995) carried out experiments on coarse and fine sands, and demonstrated that CH_4 consumption in coarse sand is approximately 20% higher than that in fine sand. Similar observations were made by Boeckx et al. (1997) who demonstrated that coarse textured soils show higher CH_4 oxidizing capacity (6.74 to 16.38 μg CH_4/m^2 per hour) in comparison to fine textured soils which have a CH_4 oxidation capacity of 4.66 to 5.34 μg CH_4/m^2 per hour.

Furthermore, particle size distribution influences the retention time for both O_2 and CH_4 gases within substrates, such that fine textures enhance the retention time while coarse textures provide shorter retention time (Huber-Humer 2004). The dissolved form of CH_4 and O_2 can only be consumed by methanotroph bacteria in the CH_4 oxidation process. CH_4 has a diffusion coefficient in water of 1.49×10^{-5} cm^2/s, which is slightly lower than that of oxygen (2.3×10^{-5} cm^2/s) (Huber-Humer 2004). Therefore, a certain contact time (retention time) is required for the conversion of CH_4 and O_2 into a dissolved form (Huber-Humer 2004; Humer and Lechner 1999). It should be considered that particle size distribution also indirectly affects CH_4 consumption by controlling the WHC (Wilshusen 2002). It should be noted that, generally, the application of very coarse material with low thermal conductivity in biocover construction increases the risk of high temperatures (Pedersen 2010) and moisture loss within the biocover (Huber-Humer 2004), which have negative effects on the CH_4 oxidation process.

Biological degradation can also influence the particle size distribution of biocover material during the operation of biocovers. It can be concluded that the determination of the proper particle size distribution of biocovers has been shrouded in controversy and depends on either local climate conditions or substrate properties. Moreover, the time-dependent evolution of the particle distribution of compost and peat based biocovers is still not well known.

2.5.3.2 Thickness

CH_4 oxidation capacity is also regulated by the thickness of the substrate layer (Pokhrel 2006). As presented in Tables 2.3 and 2.4, several laboratory and field studies have investigated the performance of various potential biocover materials with different thicknesses.

Determination of the proper thickness of a biocover strongly depends on local climate conditions (i.e. precipitation and frost penetration depth) as well as substrate properties (i.e. density and moisture content) (Pokhrel 2006). Einola (2010) stated that increasing the thickness of the oxidation layer can enhance the rate of CH_4 oxidation due to the remaining favourable conditions for methanotrophic activity and also higher volume of substrate available for the growth of methanotrophs. Furthermore, a thicker oxidation layer can provide protection against desiccation (Huber-Humer et al. 2008).

Hilger and Humer (2003) found that CH_4 oxidation can proceed under more stable moisture and temperature conditions at greater depths. Albanna et al. (2007) investigated the effect of thickness on the CH_4 oxidation capacity of landfill cover soil. They reported that the layer with a thickness of 200 mm has higher CH_4 oxidation efficiency than that with a thickness of 150 mm. The same authors explained that the higher CH_4 oxidation rate of the thicker layer can be attributed to the larger population of methanotrophic bacteria and also longer retention time for CH_4 in the thicker layer. Stern et al. (2007) also carried out field experiments on composted garden waste and demonstrated that increasing the thickness causes increasing retention times for CH_4 gas transport and consequently, higher CH_4 oxidation.

It can be concluded from the aforementioned studies that increasing the thickness of the oxidation layer results in higher CH_4 oxidation rate. However, the O_2 penetration depth is an imperative factor, which influences the effective thickness of biocovers, and should also be taken into consideration in the optimal design of biocovers (Hilger and Humer 2003; Pokhrel

2006). Moreover, it should be noted that the application of a thick layer of substrate increases the involved costs (Einola 2010).

2.5.3.3 Shear strength properties

Biocovers should be physically stable and have sufficient shear strength to resist sliding and rotation on the slope (Benson and Othman 1993). Also, biocovers should have enough tensile capacity to prevent cracking during local subsidence (Benson and Othman 1993). The stability assessment of biocovers is based on shear strength parameters. Shear strength is defined in terms of cohesion and angle of friction which are the basic parameters of the Mohr-Coulomb failure criterion.

Previous studies on compost (Bajwa 2012; Bajwa and Fall 2011; Banavathu 2003; Benson and Othman 1993; Ho et al. 2011; Puppala et al. 2006; Thiem et al. 1990) and peat (Edil and Dhowian 1981; Farrell and Hebib 1998; Kazemian et al. 2011; Mesri and Ajlouni 2007; Ulusay et al. 2010) have demonstrated that direct shear testing is applicable to determine the shear strength properties of compost and peat as biocover media.

Benson and Othman (1993) studied the shear strength properties of compost by direct shear testing. In this study, the compost samples were compacted at a water content of 44% and consolidated under pressures of 14, 41 and 69 kPa, and finally, the samples were sheared at a rate of 4×10^{-8} m/s to prevent the generation of pore water pressure. The authors reported a friction angle of 61° and cohesion of 20 kPa.

Banavathu (2003) carried out direct shear testing on compacted dairy manure and Dillo Dirt (a type of compost material, which consists of treated municipal sewage sludge and yard trimmings) under a normal stress of 100 kPa. The dairy manure had a cohesion of 58.7 kPa and friction angle of 26° at optimum moisture content (25.9%). The cohesion of the Dillo Dirt-control soil mixture (mix ratio of 1:5) was 144 kPa and 116 kPa at optimum (32.2%) and the wet side of the optimum moisture content (35.3%), respectively. The corresponding friction angles of the Dillo Dirt-control soil mixture (mix ratio of 1:5) were 22.5° and 19°, respectively.

Bajwa (2012) investigated the shear strength properties of compacted compost material at the optimum moisture content (79%) and three different initial moisture contents on the dry side of the optimum moisture content (46%, 59% and 72%). The shearing rate was 0.0277 m/s in this research and the cohesion ranged from 1.4 to 3.9 kPa, while the angle of friction ranged from 42.6° to 43.8°.

The shear strength properties of compost mixtures were also studied by Thiem et al. (1990). The samples were compacted at optimum moisture content to reach 90% of the maximum dry density. The measured friction angles were 27.8° and 50.2° for Bridgewater and West Warwick composts, respectively. The results indicated that the latter has a higher cohesion (21.1 kPa) in comparison to the former, which has a cohesion of 13 kPa. The same authors also investigated the effect of compost amendment on the shear strength of soil. They found that the high cohesion and friction angle values of the studied compost material have a dominant effect on the shear strength behaviour of soil compost mixtures.

Ulusay et al. (2010) also conducted direct shear and triaxial testing on undisturbed peat samples which were collected from two different boreholes. They found friction angles and cohesions of 59.8° and 2.9 kPa and 42.6° and 5.8 kPa for the first and second samples, respectively. The results also indicated that the direct shear tests showed higher shear strengths than those from the triaxial tests.

It should be noted that the previous studies on the shear strength properties of biocovers mostly focused on those of compost and peat materials. The shear strength properties of compost-sand and peat-sand mixtures as potential biocover materials and also time-dependent changes of the shear strength properties of the biocover material were not investigated in the literature. Thus, these issues need to be addressed.

2.5.3.4 Consolidation properties

Changes in the stress of biocovers can cause continued settlement and drainage of pore water from the compressible matrix of the biocover particles. Settlement can result in the reduction of free air space (FAS) and development of cracks in the biocover, which have significant effects on the O_2 penetration and CH_4 oxidation potential of the biocover. Furthermore, the consolidation affects the void ratio or porosity of the biocover, which has direct influence on the fluid (e.g., O_2 and CH_4) transportability capacity of the biocover.

Bajwa (2012) conducted a series of consolidation tests on compost material in order to investigate the consolidation behaviour of biocovers at different initial moisture contents (46%, 59%, 72% and 79%) and dry densities under normal stresses of 2.5, 5, 10, 20, 40, and 80 kPa. The results indicated that the compressibility of compost material increases by increasing the moisture content. Also, the studied samples showed the lowest void ratio values at the highest moisture contents and a consolidation pressure of 80 kPa. The author concluded that compost material with low moisture content has less settlement and a greater void ratio, which result in the proper condition for CH_4 oxidation with regards to the gas exchange process.

The consolidation behaviour of compost material was also studied by Perez (2009) under different normal stresses (5, 10, 20, 40 and 80 kPa) and moisture contents of 7%, 25%, 50%, 75%, and 100%. In this study, a higher moisture content resulted in greater deformation of the compost material. The author also reported that the void ratio is a function of the compressive stress and moisture content such that the void ratio of the compost material with an initial moisture content of 100% is 0.75 and 0.19 under compressive stresses of 5 and 80 kPa, respectively, while at an initial moisture content of 75%, the void ratio is 0.4 and 0.1 under the same compressive stresses.

Ulusay et al. (2010) carried out experiments on peaty soils under normal stresses that ranged between 10 and 1600 kPa, and reported that the compression index (C_c) varies in a range from 0.49 to 2.42 while the coefficient of consolidation (C_v) ranges from 0.52 to 7.09. They found that lower organic contents generally result in lower C_c values in comparison to the figures reported in the literature.

Despite the significant contribution of the previous studies to the understanding of the consolidation characteristics of biocover materials, most of them have focused on the consolidation behaviour of compost and peat materials. The consolidation characteristics of compost-sand and peat-sand mixtures, and the time dependent evolution of the consolidation characteristics of biocover materials were mostly not addressed.

2.5.4 Chemo-biological factors

2.5.4.1 pH

Basically, microbial growth is affected by the concentration of hydrogen ions (H^+) which is expressed in terms of the pH (Sternenfels 2012). The pH value of the microenvironment depends on the characteristics of the used biocover material (Scheutz et al. 2009). The optimum pH values for CH_4 oxidation are consistent with those of methanotrophic growth and vary between 6.7 and 8.1 (Bender and Conrad 1995; Scheutz and Kjeldsen 2004).

The degree of responsiveness of CH_4 oxidation to the pH varies among different materials. Heyer and Suckow (1985) observed CH_4 oxidation at pH values of 3.7 to 4.4 in peaty soils. Born et al. (1990) found that there is no significant change in the CH_4 oxidation rate when the pH is increased from 3.5 to 8.0. Based on the investigations conducted by Dunfield et al. (1993), the optimum pH value for CH_4 oxidation is 3.5 in acidic peaty soils. Hanson and Hanson (1996) stated that the CH_4 oxidation rate is only slightly influenced by variation in the pH values between 4.0 and 6.0, but sharply decreases beyond this range. It can be seen that methanotroph bacteria can grow in a fairly wide pH range due to their adaptive capability to prevailing environmental conditions (Hanson and Hanson 1996).

Moreover, changes in the pH value were reported in column laboratory studies with a trend toward more acidic conditions, particularly near the top of the biocovers (Hilger et al. 2000*a*). The acidification can be attributed to the dissolution of generated CO_2 during the oxidation process in the aqueous phase (Scheutz et al. 2009) and accumulation of products of the serine and RuMP metabolic reactions (Hilger et al. 2000*a*). Hilger et al. (2000*a*) also stated that accumulation of generated methanol and formic acid during the CH_4 oxidation process could lead to declines in the pH.

2.5.4.2 Methane concentration

Biological CH_4 oxidation is profoundly affected by the CH_4 concentration. Previous studies have demonstrated that the population of methanotrophic bacteria noticeably increases with increasing CH_4 concentration in a substrate (Jones and Nedwell 1993; Mancinelli 1995). Based on studies conducted by Jones and Nedwell (1993), it was found that the effect of CH_4

concentration on the number of methanotrophic bacteria is more significant in the top layer of the substrate. They found that the population of methanotrophic bacteria in landfill soil at a CH_4 concentration of 25% (v/v) and depth of 5 cm is more than 17 times higher than that at a CH_4 concentration of 7% (v/v) and depth of 35 cm.

Moreover, an increase in CH_4 concentration accelerates methanotrophic activity, which can lead to higher CH_4 oxidation rates (Bender and Conrad, 1992). Visvanathan et al. (1999) found that a higher CH_4 concentration can significantly increase the CH_4 oxidation rate. Kravchenko et al. (2002) also reported similar results for arable soils in batch experiments. Huber-Humer (2004) investigated the effect of CH_4 concentration on the rate of CH_4 oxidation in compost materials. They reported that under the same environmental conditions, the CH_4 oxidation rate is enhanced by increasing the CH_4 concentration until a certain CH_4 load (240 to 250 l/m^2d), which is attributed to the maximum CH_4 oxidation capacity of the studied material. Bender (1992) observed methanotrophic activity at CH_4 concentrations as low as 2 ppmv. Kightley et al. (1995) stated that methanotrophs are capable of surviving during CH_4 starvation and oxidation rates rapidly recover to a steady state after interruption in the CH_4 supply.

Furthermore, previous studies have shown that CH_4 concentration has a selective effect in determining the type of methanotroph that will predominate in a certain concentration of CH_4 (Amaral and Knowles 1995; Hanson and Hanson 1996; Huber-Humer 2004; Wilshusen 2002). Hanson and Hanson (1996) stated that Type I methanotrophs are favoured under low CH_4 concentrations and show high affinity kinetics while a high concentration of CH_4 enhances the growth of Type II methanotrophs which exhibit low affinity kinetics. According to field incubation research by Bogner et al. (1997), methanotrophs can be divided into CH_4 and O_2 limited groups.

The CH_4 oxidation process exhibits first order kinetics at low CH_4 concentrations according to the Michaelis-Menten kinetics which is described by Eq. 2.3. In contrast, the rate of CH_4 oxidation is independent of CH_4 concentration at high CH_4 concentrations (Hettiarachchi 2005; Stein 2000).

$$\nu = \nu_{\max} \frac{S}{K_m + S} \qquad [2.3]$$

In the above equation, ν is the CH_4 oxidation rate, ν_{max} is the maximum CH_4 oxidation rate, K_m is a half saturation constant and S is the CH_4 concentration. It can be seen that the CH_4 oxidation rate is linearly proportional to the CH_4 concentration at low CH_4 concentrations (Hettiarachchi 2005; Stein 2000).

2.5.4.3 Oxygen concentration

Methanotrophic bacteria can be classified as obligate aerobes microorganisms (Hanson and Hanson 1996; Huber-Humer 2004). A previous study by Mancinelli (1995) showed that high rates of CH_4 oxidation can be achieved at very low O_2 concentrations, which imply that the growth of methanotrophic bacteria is favoured under microaerophilic conditions. A simple stoichiometric calculation (Eq. 2.1) indicates that 4 grams of O_2 is needed for the oxidation of 1 gram of CH_4 (4 g O_2/ 1 g CH_4) by methanotroph bacteria. It should be noted that actually less O_2 is needed for CH_4 oxidation due to carbon conversion into biomass during the oxidation process (Huber-Humer 2004). There are different scientific views about the accurate amount of required O_2 for CH_4 oxidation which are summarized in Table 2.2.

Table 2.5. Accurate amount of required oxygen for methane oxidation.

Medium	Required O_2 g / 1g CH_4	Reference
Landfill soil	3.5	Kjeldsen et al.(1997)
Organic landfill cover	2-3.8	Börjesson et al. (1998)
Laboratory basal medium	2-2.5	Whittenbury et al. (1970)
Landfill recultivation soil	2.2-3.4	Figueroa (1998)
Sediment, swamp and humisol	3.2-3.9	Amaral and Knowles (1995)
Compost	2.1-4	Humer (1996)

Both high and low O_2 concentrations accelerate the formation of exopolymeric substances (EPS). EPS formation has a negative effect on the CH_4 oxidation process (Chiemchaisri et al. 2001; Costa et al. 2001).

Based on the experimental studies conducted by Czepiel et al. (1996), it was found that CH_4 consumption rapidly decreases below O_2 concentrations of 3% in the gaseous phase. Bender (1992) arrived at similar results and reported that CH_4 oxidation significantly drops at O_2 mixing ratios below 2% (v/v), while constant CH_4 oxidation rates are achieved when the O_2 concentration is varied in a range between 2% and 20% (v/v). Gebert et al. (2003) observed CH_4 oxidation in a biofilter medium at O_2 concentrations greater than the range of 1.7% to 2.6% (v/v). Ren et al. (1997) reported that maximum CH_4 oxidation occurs when O_2 concentrations range between 0.45% and 20% (v/v). The same authors also found that the CH_4 oxidation efficiency declines more than 20% when the O_2 concentration is more than 60% in the gaseous phase.

Stein and Hettiaratchi (2001) conducted laboratory experiments on loamy landfill soil and showed that optimum CH_4 oxidation rates are achieved at O_2 concentrations between 0.75% and 1.6% (v/v). They also reported that the CH_4 oxidation rate is independent of the O_2 concentration at O_2 concentrations above 2% to 3% (v/v). Bender and Conrad (1994) also reported an O_2 concentration of 3% (v/v) as the optimum O_2 concentration for methanotrophic activity. Furthermore, they observed no significant change in CH_4 oxidation when the O_2 concentration is varied in a wide range from 3% to 99% (v/v).

Furthermore, O_2 concentration can cause competition between Types I, II and X methanotrophs (Huber-Humer 2004). This phenomenon is attributed to the difference in the O_2 requirements of pMMO and sMMO enzymes (Huber-Humer 2004). The growth of Types II and X methanotrophs, which contain sMMO enzymes, are favoured under low O_2 conditions (Mancinelli, 1995) and the mentioned types are mainly located in deep regions. Conversly, Type I methanotrophs are mostly found in high altitude regions with high O_2 concentrations (Hanson and Hanson, 1996).

The vertical distribution of O_2 concentration is affected by soil gas diffusivity, because downward O_2 movement in the oxidation layer is mostly caused by O_2 diffusion from the air (Huber-Humer 2004). Another factor which influences O_2 availability is gas pressure inside the oxidation layer. The CH_4 oxidation process causes pressure reduction in the CH_4 oxidation layer (Christoffersen et al., 2001; DeVisscher, 2001; Maurice, 2001). A reduction in pressure drives the flow of the air through the substrate and increases O_2 availability. In contrast, high pressure reduction due to methanotrophic activity can lead to a slow down of the upward gas flow and negatively affect the CH_4 oxidation rate.

2.5.4.4 Nitrogen compounds

Some of the N_2 compounds are able to inhibit the CH_4 oxidation process (Scheutz et al. 2009) through different mechanisms, such as enzyme inhibition (Boeckx et al., 1996), contribution to the production of toxic components (Cai and Mosier 2000; King and Schnell 1994) or changes in the pH value (Pokhrel 2006).

Methanotrophic bacteria are able to take up N_2 with both serine and RuMP pathways (Hilger and Huber-Humer 2003). This is because MMO enzymes which are responsible for the oxidation of CH_4, also contribute to nitrification and are able to co-oxidize ammonium (NH_4^+) into NH_2OH (Neufeld and Knowles 1999). Ammonia monooxygenase (AMO) enzymes of nitrifiers have a dehydrogenase/oxidase and reductive dehalogenation activity and also capable of oxidizing CH_4 (Neufeld and Knowles 1999) at a low capacity (Bedard and Knowels 1989). Both groups are present and active in the aerobic region and responsible for O_2 depletion (Neufeld and Knowles 1999). Therefore, one possible reason for the inhibition effect of N_2 on CH_4 oxidation can be O_2 competition between the AMOs and MMOs (Mosier et al. 2004). Another reason can be attributed to the competition for MMO enzymes between the N_2 compounds and CH_4, particularly at low CH_4 concentrations (Boeckx and van Cleemput 1996). Nitrogen compounds have a more aggressive nature (Boeckx and van Cleemput 1996) and outcompete CH_4 in the competition for MMO enzymes which results in the inhibition of CH_4 oxidation (Pokhrel 2006). Further studies by Kightley et al. (1995) concluded that the inhibitory effect of N_2 compounds on CH_4 consumption follows a very complex process.

Moreover, the co-oxidizing of ammonium by MMOs can lead to the formation of toxic compounds and byproducts which have negative impacts on the CH_4 oxidation process (Huber-Humer 2004).

Several researchers have demonstrated that high ammonium concentrations have an inhibitory effect on CH_4 oxidation. Whittenbury et al. (1970) studied the effect of ammonium concentrations on CH_4 oxidation rates in a laboratory basal medium. They reported that the CH_4

oxidation rate declined when the ammonium chloride concentrations were increased from 0 to 1700 ppm. Scheutz and Kjeldsen (2004) also observed no significant change in the CH_4 oxidation rate by increasing ammonium concentrations up to 14 mg N/kg, but higher concentrations than that resulted in the reduction of the CH_4 oxidation rate. Based on laboratory experiments conducted by Humer and Lechner (2001), ammonium has an inhibition effect on the CH_4 oxidation rate at concentrations higher than 350 ppm. Further studies on arable soil carried out by Hütsch (1998) demonstrated that a concentration of 40 mg N/kg causes more than 90 percent inhibition of CH_4 oxidation. An investigation by Boeckx and van Cleemput (1996) on landfill cover soil revealed that ammonium concentrations over 25 mg N/kg lead to the inhibition of CH_4 oxidation. Similar results were also obtained by Bronson and Mosier (1993) who found that an increase in ammonium concentration more than 25 μg NH_4Cl/g in aerobic soils results in the reduction of the efficiency of CH_4 oxidation between 78% and 89%. Moreover, De Visscher (2001) cited that MMOs and consequently CH_4 oxidation is inhibited by free ammonia (NH_3) rather than ammonium. Hanson and Hanson (1996) stated that the CH_4 oxidation rate is unaltered in sediment slurries at ammonia concentrations below 4 millimolar (mM) while concentrations between 4 and 10 mM cause an approximate 30% reduction in the CH_4 oxidation efficiency. The same authors reported that ammonia concentrations above 20 mM completely stop CH_4 oxidation. Hanson and Hanson (1996) concluded that the inhibitory effect of ammonia on the CH_4 oxidation process is complex.

In contrast to the mentioned studies, Bodelier and Laanbroek (2004) stated that the limitation of N_2 compounds has a negative effect on the growth of methanotrophic bacteria which can lead to the reduction of CH_4 oxidation rate. This phenomenon is attributed to the fact that methanotroph bacteria require 0.25 mol of N_2 to assimilate each mole of CH_4 (Anthony 1982). Therefore, limitations due to the availability of inorganic N_2 can limit the growth of methanotrophs and thereby cease CH_4 oxidation particularly in environments with high molar ratios of CH_4 to N_2 (Bodelier and Laanbroek 2004).

2.5.4.5 Inhibition compounds

Several substrates have an inhibitory effect on the CH_4 oxidation process. The inhibitory effect can be related to the formation of toxic components and/or competition for MMO enzymes (Scheutz et al. 2009). The degree of inhibition is also influenced by methanotroph bacteria composition and concentration of inhibitor compounds.

Börjesson (2001) observed that the inhibition of CH_4 oxidation in landfill cover soils is due to the presence of methanethiol (CH_4S) and carbon disulphide (CS_2). Boeckx et al. (1998) and Scheutz et al. (2009) investigated the inhibitory effect of various pesticides. They found that Lenacil ($C_{13}H_{18}N_2O_2$), Mikado ($C_{14}H_{13}ClO_5S$) and Oxadixyl ($C_{14}H_{18}N_2O_4$) in sandy soils, and Atrazine ($C_8H_{14}ClN_5$) and Dimethenamid ($C_{12}H_{18}ClNO_2S$) in clayey soils have negative impacts on CH_4 oxidation process. Based on studies conducted by Arif et al. (1996), 2,4 dichlorophenoxy acetic acid ($C_8H_6Cl_2O_3$) also has a partial inhibitory effect on CH_4 consumption. Further studies carried out by Scheutz and Kjeldsen (2004) demonstrated that increasing the concentration of hydrochlorofluorocarbons (HCFCs) to 1600 μg/L caused a 30% reduction in the CH_4 oxidation efficiency. It should be noted that inhibition compounds are not limited to the mentioned substrates; for more details, a review of Scheutz et al. (2009) is recommended.

2.5.4.6 Exopolymeric substances

Methanotroph bacteria under certain environmental conditions can produce EPS (Huber-Humer 2004). EPS are high molecular weight substances which mostly consist of polysaccharides (Scheutz et al. 2009) as well as anionic hetero-polysaccharides and can be produced in the form of capsules, slime and biofilms (Jensen and Corpe 1991). Huber-Humer (2004) stated that the type of EPS formation can have an imperative effect on growth conditions as well as the metabolism of the bacteria.

Various possible functions are defined in the literature for EPS, such as protection from desiccation, provision of a shield against predators (Hilger et al. 2000*b*), protection from toxic compounds and starvation (Wilshusen 2002), promotion of nutrient accumulation and immobilization of metals due to their cation exchange properties (Wilshusen 2002). However, the main function of these compounds is to serve as anchorage to soil surfaces (Scheutz et al. 2009).

Environmental conditions and microbial species strongly influence the nature of EPS formation (Scheutz et al. 2009). Costerton et al. (1995) stated that EPS formation is a response to induced metabolic stress through sub optimal-environmental conditions, such as temperature, O_2, desiccation and starvation. Linton et al. (1986) suggested that EPS are produced by methanotroph bacteria in the case of carbon excess to prevent the accumulation of formaldehyde during the CH_4 oxidation process.

Some specific methanotroph bacteria are able to accumulate intracellular polysaccharides, which is the main component of EPS and later metabolized as a carbon source (Huber-Humer 2004). However, it should be noted that EPS cannot be considered as an energy source for methanotrophic activity because generally, methanotrophic bacteria are not able to metabolize EPS (Huber-Humer 2004).

EPS can be produced by Type I and II methanotrophs with the use of both RuMP and serine pathways (Malashenko et al. 2001). The RuMP pathway is more energetically favourable and less NADH limited than serine pathways (Wilshusen 2002). Therefore, EPS formation by the RuMP pathway which is used by Type I methanotrophs has a higher rate in comparison with other types of methanotroph bacteria (Malashenko et al. 2001).

Several studies have reported the formation and accumulation of EPS in biologically active soil. However, there are still uncertainties about the inhibitory effect of EPS on the CH_4 oxidation process.

Hilger et al. (2000*b*) reported a decrease in methanotrophic activity in column experiments on landfill cover soil due to EPS formation. They found that EPS production has a negative effect on gas diffusion, which results in a reduction of the CH_4 oxidation rate. Wilshusen et al. (2004) also observed a decreasing CH_4 oxidation rates which was correlated with the accumulation of EPS in the upper layers of biocover columns. Similar observations were made by Chiemchaisri et al (2001) on landfill soil columns. Haubrichs and Widmann (2006) carried out column experiments on compost and reported EPS formation after 105 days of column operation. It should be noted that no significant changes in the CH_4 oxidation rate was reported time. Based on a laboratory investigation which was conducted by Huber-Humer (2004), the EPS clogged the pores of the compost and limited the diffusion of CH_4 and O_2 into the cells which probably led to a reduction in the CH_4 oxidation efficiency. However, EPS production was observed in their experiments after about 42 days of the column operation, and a decline in the CH_4 oxidation rates was measured after about 80 days. Furthermore, Hilger et al. (2000*b*) reported EPS accumulation in actual landfill cover samples which implies that EPS formation is not limited to only laboratory column tests.

In contrast to the above studies, Gebert et al. (2006) reported no indications of any EPS formation during 6 years of operating a biofilter that consisted of porous clay pellets.

2.6 Coupled THMC-B processes

Porous medium can be host to chains of coupled processes which continually take place at varying rates. The rate of the process depends on the nature and strength of the sources and also the driving energies in the system. Coupled processes imply that one process affects the initiation and progress of another process and are formed by at least a pair of individual processes. In contrast to individual processes, coupled processes are the basis of developing theories and have been raised as a main field for further development.

The main processes which are involved in coupled processes can be classified as thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B). In a porous medium, these processes are related to each other through interactions. The individual processes can be classified as affecting processes (agent) and affected processes (objects) depending on how they are affecting or being affected by other processes. Fig. 2.4 shows a general format of coupled THMC-B processes in porous media.

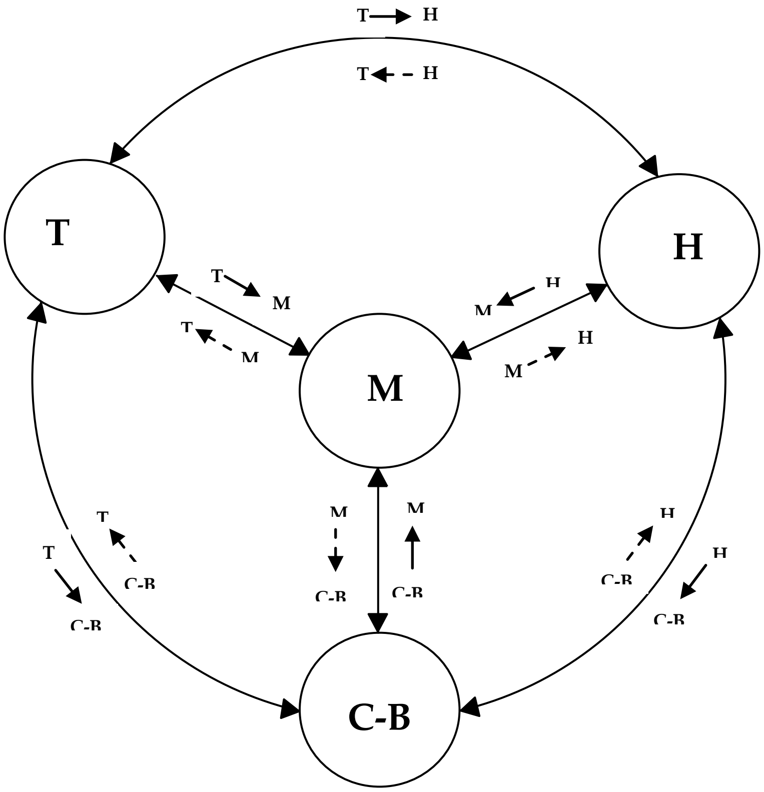

Fig. 2.4. General format of coupled THMC-B processes in porous media.

In biocovers, T, H, M, and C-B processes that simultaneously occur are related to each other through interactions (Bajwa 2012). It should be noted that the interactions of not all the involved processes can be equally important in controlling the behaviour of biocovers. With regards to the importance of different processes, only particular processes and their interactions should be taken into account and considered as controlling the coupled processes in biocovers. Table 2.6 is a summary of the main interactions between different T, H, M, and C-B processes within biocovers which have been reported in the literature (Bajwa 2012; Pokhrel 2006; Stein and Hettiaratchi 2001).

Table 2.6. Main coupling processes in biocovers
(Bajwa 2012; Pokhrel 2006; Stein and Hettiaratchi 2001).

Object \ Agent	T	H	M	C-B
T	N/A	Thermal conductivity Thermal diffusivity Thermal resistivity	Thermal conductivity Thermal diffusivity Thermal resistivity	Thermal conductivity Thermal diffusivity Thermal resistivity Temperature
H	Moisture content Degree of saturation Water potential	N/A	Degree of saturation Hydraulic conductivity Water potential	Moisture content Degree of saturation Hydraulic conductivity Water potential
M	Thermal stress Thermal strain	Shear strength Compressibility	N/A	Shear strength Compressibility Particle size distribution
C-B	CH_4 oxidation potential	CH_4 oxidation potential	CH_4 oxidation potential	N/A

The main effects produced from one process onto another process are indicated in terms of the increment of the controlling variables in Table 2.6. It is clear from Table 2.6 that coupling effects in one direction may be different from those in the opposite direction in biocovers.

2.7 Conclusion

From the literature review presented above, it can be concluded or observed that the previous studies on biocovers have mainly focused on their biochemical response. There are a limited number of studies that have addressed the T, H and M properties of biocover materials. There is a paucity of data on the geotechnical properties and behaviour of biocover materials and their time dependent-evolution. Moreover, most of the research in the literature has focused on pure compost as a suitable biocover material with high CH_4 oxidation potential. There is a rarity of studies on other types of biocover materials, such as compost-sand mixtures, peat and peat-sand mixtures. A comprehensive investigation on the geotechnical and geoenvironmental properties and behaviour of biocovers as well as their time-dependent evolution is critical for the assessment of the long term behaviour of biocovers and their cost-effective design as well.

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3 Geotechnical characterization of compost and peat based biocovers

3.1 Introduction

For the design, construction and maintenance of any type of biocover, an evaluation of the geotechnical properties of biocover materials is essential. The geotechnical properties of biocover materials can have a decisive impact on the CH_4 oxidation process and thereby on the overall performance of biocovers. Most of the previous research has focused on the biochemical properties of biocovers and there have been minimal recommendations in the literature with regards to the geotechnical behaviour of biocovers. Furthermore, previous studies on the behaviour of biocover materials mostly focus on compost and peat as the biocover materials. There is a paucity of studies on the geotechnical behaviour of other potential biocover materials, such as a mixture of compost and peat with more inert materials (sand).

This chapter primarily addresses the results of an extensive laboratory geotechnical investigation on compost based biocovers (pure compost and compost-sand mixtures (3:1, 1:1, and 1:3 w/w)) (Section 3.2) and peat based biocovers (pure peat and peat-sand mixtures (3:1, 1:1, and 1:3 w/w)) (Section 3.3). The aims of this chapter are to characterize and evaluate the geotechnical behaviour (compaction, shear strength, compressibility, and hydraulic and thermal conductivities) of compost and peat based biocovers in order to develop a suitable biocover medium from a geotechnical perspective. The obtained laboratory geotechnical results will be discussed with reference to the data and the published literature.

3.2 Geotechnical characterization of compost based biocover materials[1]

Afshin Khoshand and Mamadou Fall

Abstract

Landfills are one of the major sources of methane (CH_4) emission which is a very potent greenhouse gas. The use of a natural process for microbial CH_4 oxidation through biocovers provides a source reduction of CH_4 emission. Previous studies have mostly focused on biochemical properties, and limited research has been conducted with regards to the geotechnical characterization of compost based biocovers. This paper presents the results of a comprehensive laboratory investigation on pure compost and compost-sand mixtures (with mix ratio of 3:1, 1:1, and 1:3 w/w) to determine the compaction, shear strength, compressibility, and hydraulic and thermal conductivity properties of compost based biocovers. Direct shear and ring shear tests have shown that the cohesion (c) and friction angle (ϕ) are in the range of 2.1 to 19.7 kPa and 44.1° to 54.7°, respectively. Based on the results of one dimensional consolidation tests, the coefficient of consolidation (C_v) values are in the range of 1.71 to 0.63 m^2/ year, which is a function of the moisture and organic contents of the samples. The lowest hydraulic conductivity ranges from 6.09×10^{-8} to 1.78×10^{-7} cm/s which occur at optimum moisture contents. Thermal conductivity is measured under various porosities and moisture contents. By increasing the dry density and sand content of the mixtures, thermal conductivity increases. The results presented in this paper will contribute to a better understanding of the geotechnical behaviour of compost based biocover, and thus to a more cost-effective design of biocovers.

Keywords: biocover, compost, shear strength, compressibility, hydraulic conductivity, thermal conductivity

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[1] Accepted for publication in Geotechnical and Geological Engineering Journal

3.2.1 Introduction

Global surface temperature has increased over 0.5°C in the last 150 years (Wuebbles and Hayhoe 2002) principally due to the increase in the concentration of greenhouse gases (GHGs). Among the GHGs, methane (CH_4) is a very potent GHG with the global warming potential of 23 times than that of carbon dioxide (CO_2) (IPCC 2007).

Historically, landfills are estimated to be one of the major sources of anthropogenic CH_4 emissions (Bogner et al. 1995). Currently, annual global CH_4 emissions from landfills are in the range of 500–800 metric ton CO_2 equivalent (Mt $CO_{2\text{-}e}$) which is about 18% of the global anthropogenic CH_4 emission (Huber-Humer et al. 2009).

Biodegradation of the organic fraction in waste disposed in landfills produces a gaseous product which is known as landfill gas (LFG). The components in LFG are CH_4 (55–60% v/v), CO_2 (40–45% v/v) (Shin et al. 2002) and numerous volatile organic compounds (VOCs). LFG is a flammable and potentially harmful mixture which can migrate to the surface of a landfill and released into the atmosphere (Albanna et al. 2007). Extraction and utilization of LFG as a potential fuel are common options for reducing CH_4 emission from landfills. But the costs involved in the aforementioned technologies are high and mainly feasible for large landfill sites (Albanna et al. 2007). Therefore, many researchers have focused on the development of cost effective methods where these technologies have not been implemented or are not technically and economically feasible (Barlaz et al. 2004, Dever et al. 2007, Stern et al. 2007).

One of the important and cost effective methods to reduce CH_4 emissions from landfills is natural process of microbial CH_4 oxidation through reactive biological cover soils (Cabral et al. 2010) or biocovers. This oxidation process principally relies on the activity of a group of bacteria known as methanotrophs, which are able to use molecular oxygen to oxidize CH_4 into CO_2 and cell carbon. The use of biocovers provides a complementary strategy for controlling CH_4 emissions that escape gas collection systems and can also be an alternative option for emission mitigation at small or old sites where the CH_4 production is too low for energy recovery or flaring, (Huber-Humer et al. 2009).

Different materials which have high porosity, high water holding capacity and appropriate nutrient levels can support the medium for CH_4 oxidation (Kettunen et al. 2006). Previous laboratory studies (Humer and Lechner, 1999; Wilshusen et al. 2004) and field trials (Huber-Humer 2004; Bogner et al. 2005) have demonstrated that stabilized and sanitized compost materials generally meet these criteria and can be suitable for practical application in mitigating CH_4 emissions

Biochemical behaviour of compost based biocovers has been studied extensively in the literature (Huber-Humer 2004; Bogner et al. 2005). It should be noted that besides biochemical behaviour, geotechnical (mechanical, hydraulic, thermal) properties of compost based materials are of prime importance for the design, construction and maintenance of biocovers as briefly explained below..

The CH_4 oxidation rate in biocovers is controlled by gas exchanges process which is strongly affected by porosity of biocover's medium. Compaction of biocover's medium due to field installation and maintenance activities (Philopoulos et al. 2009) can affect porosity and subsequently performance of biocover. Biocovers should also be physically stable and have sufficient shear strength (Benson and Othman 1993). Stability of biocovers can be assessed based on shear strength parameters which are cohesion (c) and angle of friction(ϕ). Sudden changes in the stress in biocovers can cause consolidation settlement, reduction of porosity, drainage of pore water and finally development of cracks in a biocover. This will have significant negative effect on the performance of biocovers.

Optimum hydraulic conductivity of biocover can support an appropriate gas exchanges process and also minimize rainfall infiltration and subsequent biocover saturation which can result in a drastic reduction of CH_4 oxidation rate (Pokhrel 2006; Scheutz 2009). CH_4 oxidation in biocovers is profoundly influenced by temperature (Chanton and Liptay 2000). Thermal conductivity expresses the rate of heat dissipation (Al Nakshabandia and Kohnke 1965) and can control temperature (Chandrakanthi et al. 2005). Thereby, thermal conductivity can control the suitability of the thermal conditions and subsequently the performance of biocovers in various climatic and thermal loading conditions.

To the best of our knowledge, there are limited recommendations in the literature with regards to geotechnical behaviour of compost based biocovers. Therefore, the main goal of the present paper is to evaluate the geotechnical (mechanical, hydraulic, thermal) characteristics of compost and compost-sand mixtures (with mix ratio of 3:1, 1:1, and 1:3) as a potential biocover medium by conducting a comprehensive laboratory experimental study. It should be noted that determination of CH_4 oxidation capacity of the studied biocover materials is out of scope of the current research. The obtained results are used for assessment of the suitability of the studied materials as a potential biocover medium with regards to their compaction, shear strength, compressibility properties and thermal and hydraulic conductivity.

3.2.2 Materials and methods

3.2.2.1 Material selection and characterization

The experiments were conducted with compost and compost–sand mixtures at ratios of 1:3, 1:1 and 3:1 (w/w). These ratios are suggested by previous studies which investigated the CH_4 oxidation of different mixtures (Pokhrel 2006).

The compost used in this research is sampled from an open windrow operation at the Lafleche landfill site in Moose Creek (Ontario), Canada, which is owned and operated by Lafleche Environmental lnc. Ottawa sand is used in this experiment and supplied by Unimin Canada Inc. As recommended by Wolf et al. (1989), used sand was oven dried prior to experiments in order to eliminate any methanotrophic bacteria that may be present in the sand. The sand was free of organic matter (OM) based on the results of the laboratory tests performed according to ASTM D2974.The chemical compositions of the compost material and compost–sand mixtures are presented in Table 3.1. The geotechnical index properties of the sampled compost and compost-sand mixtures were determined in accordance with American Society of Testing and Materials (ASTM) standards (ASTM 2010). The moisture content was determined by drying the samples in an oven at a temperature of 110 ± 5°C in accordance with ASTM D 2216.

Table 3.1. Chemical composition of compost material and its mixtures used in this study.

Constituents	**Contents (%)**			
	Compost	**Compost – Sand (3:1 w/w)**	**Compost – Sand (1:1 w/w)**	**Compost – Sand (1:3 w/w)**
SiO_2	30.20	45.27	60.34	75.41
Al_2O_3	6.20	6.01	5.83	5.64
Fe_2O_3	2.77	2.10	1.43	0.76
Na_2O	1.49	1.30	1.10	0.91
MgO	1.37	1.03	0.70	0.36
CaO	8.47	6.44	4.41	2.39
K_2O	2.36	2.40	2.45	2.49
TiO_2	0.31	0.24	0.16	0.09
P_2O_5	1.32	0.99	0.66	0.33
Cr_2O_3	0.02	0.02	0.01	0.01
MnO	0.05	0.04	0.03	0.01
V_2O_5	<0.01	<0.01	<0.01	<0.01
LOI[1]	44.00	33.08	22.16	11.24

[1] LOI: Loss of Ignition

ASTM D422 was used for particle size analysis. Fig. 3.1 shows the grain size distributions of the samples. It can be seen that pure compost has the finest particle distribution and all samples consist of particles with sizes that range from 0.07 to 5 mm.

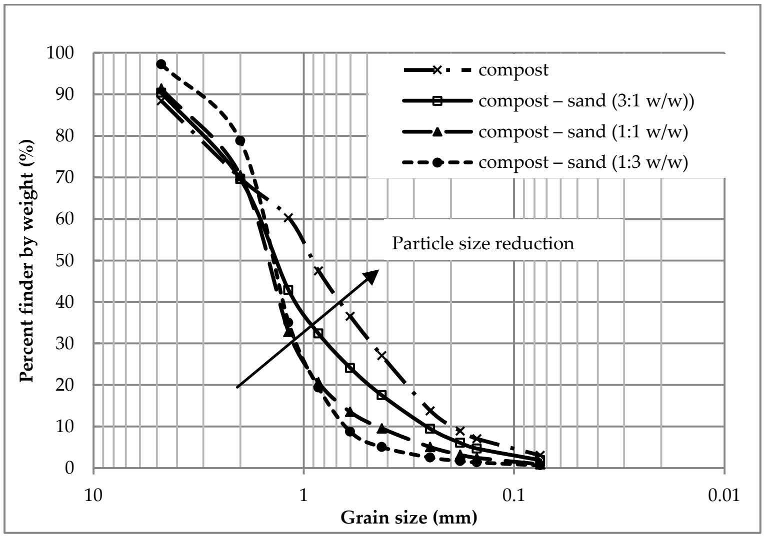


Fig. 3.1. Particle size distribution of compost and its mixtures.

The compost has a coefficient of uniformity (C_u) of 5.5 and a coefficient of curvature (C_c) of 1.1 which means that the compost can be described as well graded. Based on the measurements, the compost can be described as organic, well-graded sand and classified with the symbol SW in the Unified Soil Classification System.

Measurements of specific gravity, Atterberg limits (liquid and plastic limits), organic content and pH were performed in accordance with ASTM D854, ASTM D4318, ASTM D 2974 and ASTM D 4972, respectively. A summary of the geotechnical index properties and pH of the samples are shown in Table 3.2. High Atterberg limits are common for compost materials, and Benson and Othman (1993) obtained similar results for their compost materials.

Table 3.2. Geotechnical index properties and pH of the compost and its mixtures.

Parameters		**Compost**	**Compost – Sand (3:1 w/w)**	**Compost – Sand (1:1 w/w)**	**Compost –Sand (1:3 w/w)**
Initial moisture content, w (%)		75.4	58.4	38.2	19.7
Organic content (%)		29.4	22	14.7	7.4
pH		6.7	6.7	6.8	6.8
Specific gravity, G_s		2.05	2.2	2.3	2.5
WHC[1] (%)		108.7	97.6	75.5	42.7
Atterberg limits	PL[2]	-	-	-	-
	LL[3]	78	69	55	48
Soil gradation	C_u	5.5	6.3	3.8	2.7
	C_c	1.1	1.3	1.4	1.1
	Symbol	SW	SW	SP	SP

[1]WHC: Water Holding Capacity; [2]PL: Plastic Limit (PL could not be measured because of the brittleness of the samples); [3]LL: Liquid Limit; [4]SW: well-graded sand; [5]SP: poorly graded sand.

3.2.2.2 Methods

3.2.2.2.1 Compaction test

Standard compaction tests were performed by following ASTM procedure D698 to evaluate the compaction characteristics and variation of dry density with moisture content of the compost and compost-sand mixtures (with mix ratio of 3:1, 1:1, and 1:3). Each compaction test was repeated twice for all samples to ensure the accuracy of the obtained results.

3.2.2.2.2 Shear test

Previous researches on compost (Benson and Othman 1993; Puppala et al. 2006; Bajwa 2012; Ho et al. 2011) and peat (Mesri and Ajlouni 2007; Ulusay et al. 2010; Edil and Dhowian 1981), a material with properties that are comparable to those of compost (Benson and Othman 1993), have demonstrated that the direct shear test is applicable for determination of the shear strength properties of compost based biocovers. Therefore, direct shear tests were conducted in this study to investigate the shear strength parameters and behaviour of the compost and its mixtures. Moreover, the ring shear tests were performed to determine the shear strength parameters and behaviour of the aforementioned materials.

a. Direct shear test

Consolidated drained direct shear tests were conducted on the samples which were compacted at OMC, the dry side and wet side of optimum in accordance with ASTM D 3080. The shear strength parameters (cohesion (c) and friction angle (ϕ)) of compost and its mixtures were determined based on the Mohr–Coulomb failure criteria. Previous studies reported that normal stresses in landfill covers vary from 10 to 40 kPa which include the self weight of cover materials (Rajesh and Viswanadham 2011). Therefore, in this experiment, to simulate field conditions, the samples were tested at normal stresses of 10 kPa, 20 kPa and 40 kPa. To prevent generation of excess pore water pressure during testing and satisfying recommended criteria by ASTM D 3080, shearing was conducted at a slow rate (0.0025 mm/min).

b. Ring shear test

The Bromhead ring shear apparatus was used in this study to obtain consolidated drained shear strength parameters. The annular samples (with inside to outside diameter ratio of 7:10) were moistened and compacted at optimum moisture content according to recommended method by (Sedano 2006). The compacted samples were consolidated prior to shearing. Once consolidation was complete, specimens were sheared at a speed of 0.02 mm/min under the 10 kPa, 20kPa and 40kPa normal stress conditions until failure plane occurred.

3.2.2.2.3 Consolidation test

In order to determine the consolidation behaviour of the studied biocover materials, consolidation tests were performed in a floating ring oedometer in accordance with ASTM D2435. The circular samples (with diameter to thickness ratio of 3:1) were moistened and compacted to achieve the desired densities for specific moisture contents on the dry side of OMC. Each sample was subjected to 5 increments of loading (5, 10, 20, 40, and 80 kPa) and each loading was held constant for 24 hours. Moo-Young and Zimmie (1996) showed that load duration of 24 hours provides a good estimation of long-term compressibility in consolidation testing. Also, calculation of coefficient of consolidation (C_v) was performed based on the square root time (Taylor's) method.

3.2.2.2.4 Hydraulic conductivity

To determine the hydraulic conductivity, constant head tests were performed on the compost and its mixtures at various moisture contents (OMC, on the dry and wet sides of OMC) and related density by a flexible wall permeameter in accordance with ASTM D5084. The measurement of hydraulic conductivity was conducted on cylindrical samples (with diameter of 50 mm and height of 115 mm), which were moistened and compacted to achieve the desired densities for specific moisture contents. The test was conducted by using a TRI-FLEX II standard panel, which was equipped with pressure gages and regulators, electronic pressure transducers, and graduated pipettes. The prepared samples were saturated and to ensure that anomalies did not affect the measurements, a low hydraulic gradient (approximately 5) was maintained in the tests (Benson and Othman 1993). Each hydraulic conductivity test was repeated twice and the average value was considered as the saturated hydraulic conductivity of the sample tested.

3.2.2.2.5 Thermal conductivity

In this study, the non-steady state method was used to determine the thermal conductivity of the compost and its mixtures. The thermal conductivity test was performed on cylindrical samples (with diameter of 100 mm and height of 115 mm) which were compacted to reach the desired densities in accordance with the compaction curves. The thermal conductivity of the compost was determined once thermal equilibrium was achieved under isothermal conditions with a transient heat dissipation device KD2 (Decagon Devices 2012) and thermal probe SH-1. To carry out the thermal conductivity measurements, a thermal probe was slowly and steadily inserted into the samples. To take an accurate reading, the needles remained parallel to each other during insertion and a minimum of 15 mm of sample surrounded the needles in all directions. Also, each test was repeated three times and the average value was considered as the thermal conductivity of the samples.

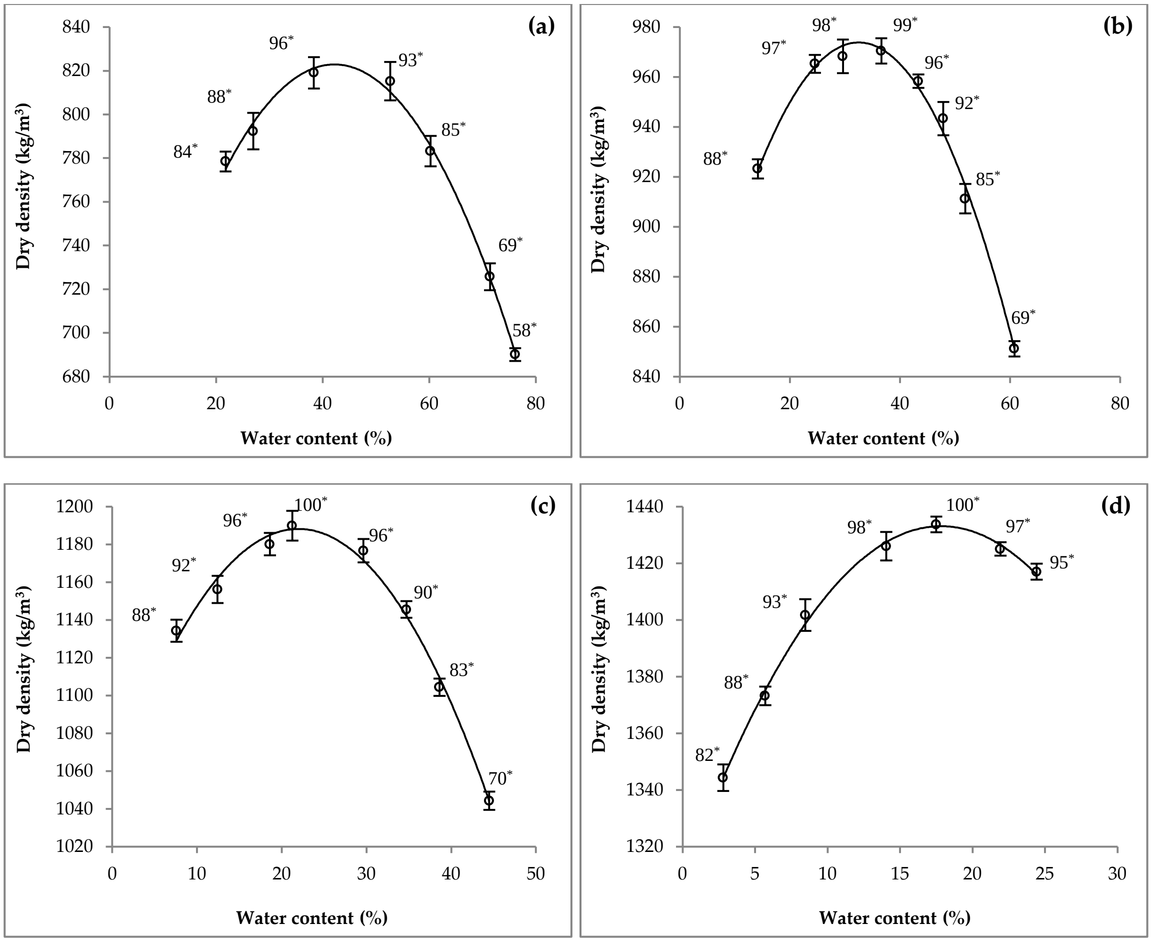
3.2.3 Results and discussion

3.2.3.1 Compaction characteristics

The compaction tests were conducted over a broad range of moisture contents. Fig. 3.2 illustrates the compaction curves (moisture contents plotted against dry densities) for the compost and its mixtures. Moreover, relative density (D_r) of samples is presented in Fig 3.2 in order to evaluate the state of compactness of samples with regards to level of compaction.

The compaction curves shown in Fig. 3.2 are similar in shape to curves that were reported in previous studies (Benson and Othman 1993; Puppala et al. 2006). Also, it can be found that the compaction behaviours of the compost materials are very similar to soils in terms of physical behaviours. The OMCs of the compost and compost-sand mixtures with mix ratios of 3:1, 1:1 and 1:3 are 40, 32, 22, and 17.5%, respectively, and the corresponding maximum dry densities determined from the compaction curves are 842, 967, 1188, and 1428 kg/m^3, respectively.

According to Fig. 3.2, by increasing the sand content of the samples, the maximum dry density is increased which is attributed to the higher specific gravity (2.65) of the sand in comparison with compost (2.05). The compost-sand mixtures have higher maximum dry densities and lower OMCs which indicates the compost-sand mixtures can be more readily compacted to a higher density in comparison to pure compost.



*Relative density of samples in percentage (%)

Fig. 3.2. Compaction curve of compost based materials

((a) compost; (b) compost – sand (3:1 w/w); (c) compost – sand (1:1 w/w); (d) compost – sand (1:3 w/w)).

Moreover, CH_4 oxidation is a function of oxygen (O_2) penetration through biocovers (Scheutz et al. 2009). The degree of saturation (S_r) and free air space (FAS) of materials can influence O_2 penetration and therefore, the CH4 oxidation potential of biocover materials. By taking into consideration the importance of mentioned parameters, the variation of these factors with the moisture content of the studied materials is illustrated in Fig. 3.3.

It can be seen from Fig. 3.3 that S_r sharply increases by increasing the moisture content up to the OMC. After OMC, the saturation curve remains almost constant for the wet side of OMC. Moreover, Fig. 3.3 shows that by increasing the moisture content up to OMC, FAS decreases and air filled voids reduce. Then, the FAS continues slow decrease with an increase in the moisture content until it reaches a value close to zero.

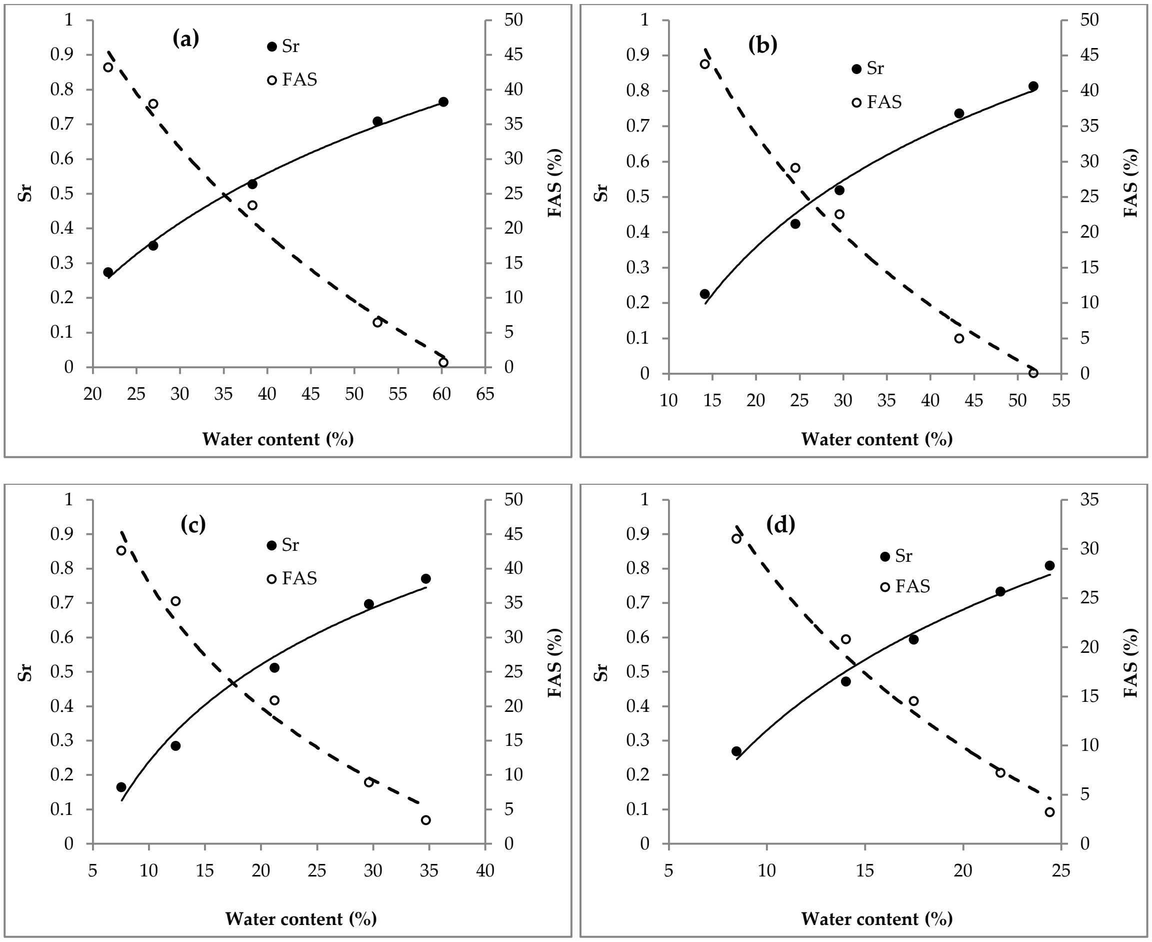


Fig. 3.3. Relationship between degree of saturation, free air space and moisture content of compost based materials

((a) compost; (b) compost – sand (3:1 w/w); (c) compost – sand (1:1 w/w); (d) compost – sand (1:3 w/w)).

With high moisture content, the air filled voids are no longer interconnected and the O_2 has to diffuse in the liquid phase as dissolved specie (Scheutz et al. 2009). Since the O_2 diffusion in liquid phase is about 10^4 times slower than O_2 diffusion in the gas phase (Cabral et al. 2004; Cussler 1997), so gaseous exchange processes slow down and CH_4 oxidation decreases due to the lack of O_2 and gas occlusion (Cabral et al. 2010).Tim (1993) found that the maximum O_2 consumption rate is attained when the FAS value is between 20% and 35%. Therefore, when the moisture content is between 41% and 27%, 30% and 20%, 19% and 12%, and 14% and 7% for the compost and compost-sand mixtures with mix ratios of 3:1, 1:1 and 1:3, respectively, the maximum O_2 consumption and CH_4 oxidation rate can be expected.

3.2.3.2 Shear strength characteristics

3.2.3.2.1 Direct shear test

Fig. 3.4 shows the direct shear test results for the compost and its mixtures which were carried out under normal stresses of 10 kPa, 20 kPa, and 40 kPa with moisture contents less than the optimum, at optimum and more than OMC. It can be seen that with the same values of normal stresses, the peak strength increases with an increase in the moisture content up to OMC (Cokca et al. 2004) on the dry side of the compaction curve. This can be attributed to a rearrangement and deformation of the compost particles when the moisture content is increased on the dry side (result in higher density). Then, the peak strength decreases on the wet-side of optimum due to the breakdown of aggregations with high moisture content (Malomo 1983). The dependence of the peak strength on the moisture content of soils was also observed by Malomo (1983).The cohesion (c) and friction angle (ϕ) values of studied samples are summarized in Table 3.3. It can be seen from Table 3.3 that the cohesion of the compost and its mixtures vary from 2.1 to 19.7 kPa, while the friction angle ranges from 45.8° to 54.7°.

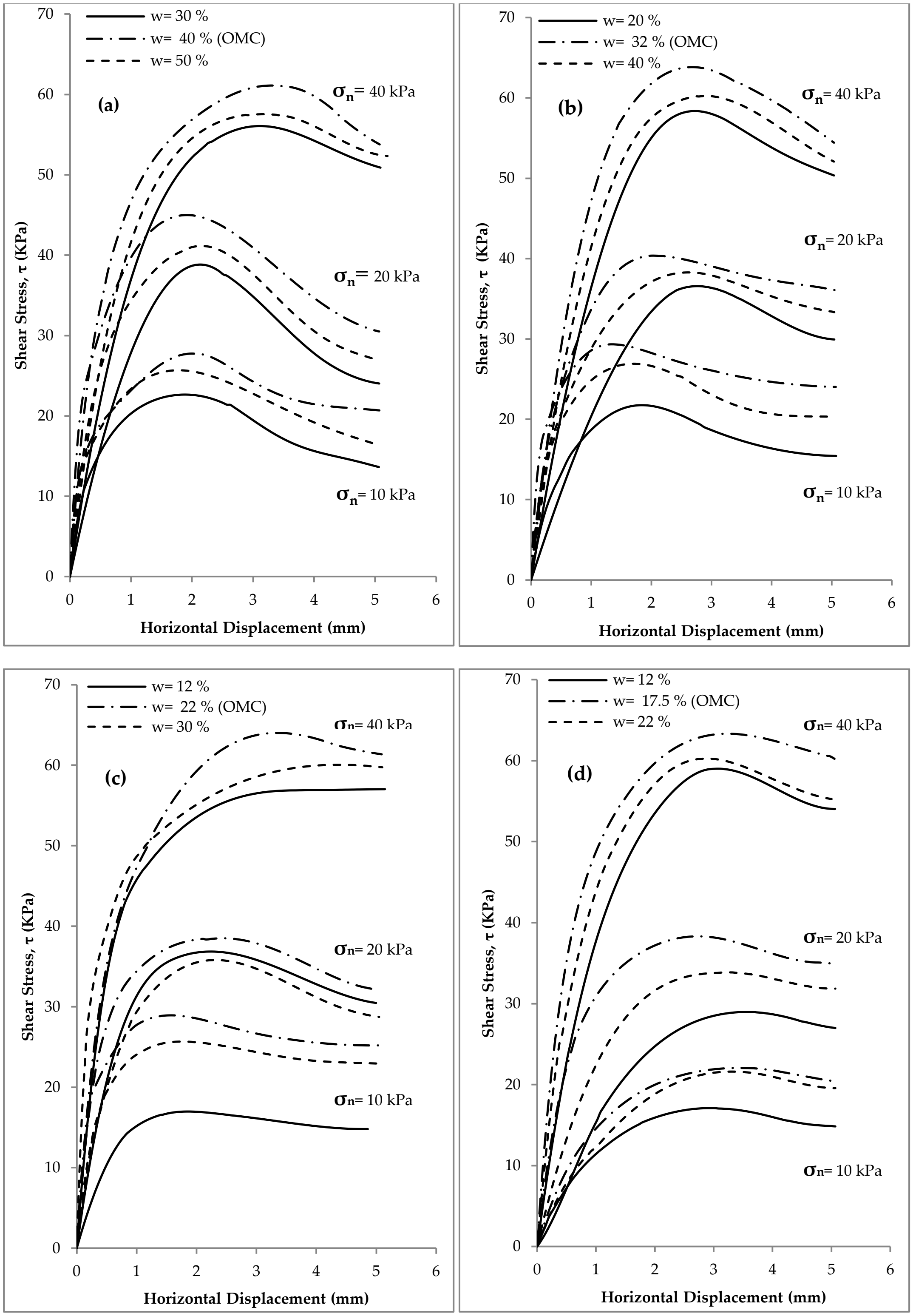


Fig. 3.4. Variation of shear stress versus displacement in direct shear test of compost based materials ((a) compost; (b) compost – sand (3:1 w/w); (c) compost – sand (1:1 w/w); (d) compost – sand (1:3 w/w)).

Table 3.3. Shear strength parameters of the compost and its mixtures at different moisture contents.

Soil type	**Moisture content, w (%)**	**Cohesion, c (kPa)**	**Angel of friction, φ (°)**
Compost	30 (dry side of OMC)	14	47.1
	40 (OMC)	19.7	46.9
	50 (wet side of OMC)	17.5	45.8
Compost – Sand (3:1 w/w)	20 (dry side of OMC)	10.9	50.2
	32 (OMC)	17.6	49.1
	40 (wet side of OMC)	15.9	48
Compost – Sand (1:1 w/w)	12 (dry side of OMC)	6.9	52.4
	22 (OMC)	16.2	49.8
	30 (wet side of OMC)	13.5	49.1
Compost – Sand (1:3 w/w)	12 (dry side of OMC)	2	54.7
	17.5 (OMC)	9.5	53.6
	22 (wet side of OMC)	8.4	52.3

The friction angles of compost and its mixtures are greater than those expected for compacted clays (Mitchell 1976), which are normally in ranges of 20-30°. These results are in agreement with those in literature. Benson and Othman (1993) performed direct shear test on compacted compost material and reported angle of friction of 61° for studied material. Also Bajwa and Fall (2011) and Thiem et al. (1990) respectively found the range of 42-44° and 40-69° for compacted compost materials with plant origin.

In contrast, Ho et al. (2011) reported that the friction angel is in the range of 23° to 30° for un-compacted compost. Generally, compaction procedures reduce the voids ratio which causes larger interlock between the soil particles and subsequently increases the friction angle (Mouzai and Bouhadef 2011). Thereby, it is obvious that the friction angle of compacted samples should be significantly higher than un-compacted ones.

These high internal friction angles are due to the presence of fibers that act as reinforcement and become entangled in the compost and as a result, they increase the resistance to deformation (Cola and Cortellazzo 2005; Benson and Othman 1993). Moreover, Banavathu (2003) and Puppala et al. (2006) observed angle of friction that varies between 13° to 26° for compacted compost with animal origin (dairy manure compost). It should be noted that shear strength properties of different compost materials can differ due to the origin of fibers.

In the field, lower shear strength may result from internal seepage erosion, which will eventually lead to the failure of the biocover slope; therefore, the cohesion and angle of friction obtained from laboratory tests should be reduced by 15–25% or a higher safety factor (1.5–2) should be used, as suggested by Bagchi (1990). By considering the aforementioned safety factors, all of the friction angles of the compost and its mixtures are larger than 25°. Therefore, the compost and its mixtures should have adequate strength to resist shear failures on slopes less than 20° (under drained conditions).

Moreover, the results imply that the shear strength parameters are dependent on the moisture conditions. Samples with lower moisture content have a higher friction angle. The reduction of the friction angle with increased moisture content is attributed to the fact that the particles of the compost and its mixtures loosen their bonding upon an increase in moisture content which form thicker water films around the particles, so that the particles becomes more and more slippery and hence the angle of internal friction is reduced (Cokca et al. 2004).

Also, the cohesion gradually increases up to the OMC on the dry side of OMC, and then gradually decreases on the wet side. It is noted that the peak value of cohesion is obtained at around OMC (19.7, 17.6, 16.2 and 9.5 kPa for the compost, and compost-sand mixtures with mix ratios of 3:1, 1:1 and 1:3, respectively).This behaviour is similar to the standard compaction curve.

The variations of the angle of friction and cohesion with the sand content of the mixtures can be found in Table 3.3. The composts with moisture content less than the optimum (30%), OMC (40 %) and more than optimum (50%) have relatively higher cohesion values (14, 19.7 and 17.5 kPa, respectively) in comparison with those of the compost-sand mixtures. This shows that increasing the sand content of the mixtures decreases cohesion values due to decreases in the plasticity of the mixtures. The interlocking mechanism of the aggregates is responsible for the variation of the friction angle (Ng and Lo 2007). The interlocking force between sand and compost particles is greatly enhanced by increasing the sand content in the samples. Therefore, angle of friction of samples increases with increasing the sand content as shown in Table 3.3.

3.2.3.2.2 Ring shear test

In this study ring shear tests were performed on samples to confirm the obtained results of direct shear tests. Fig. 3.5 illustrates the ring shear test results for compost and its mixtures at optimum moisture content and normal stresses of 10 kPa, 20 kPa, and 40 kPa.

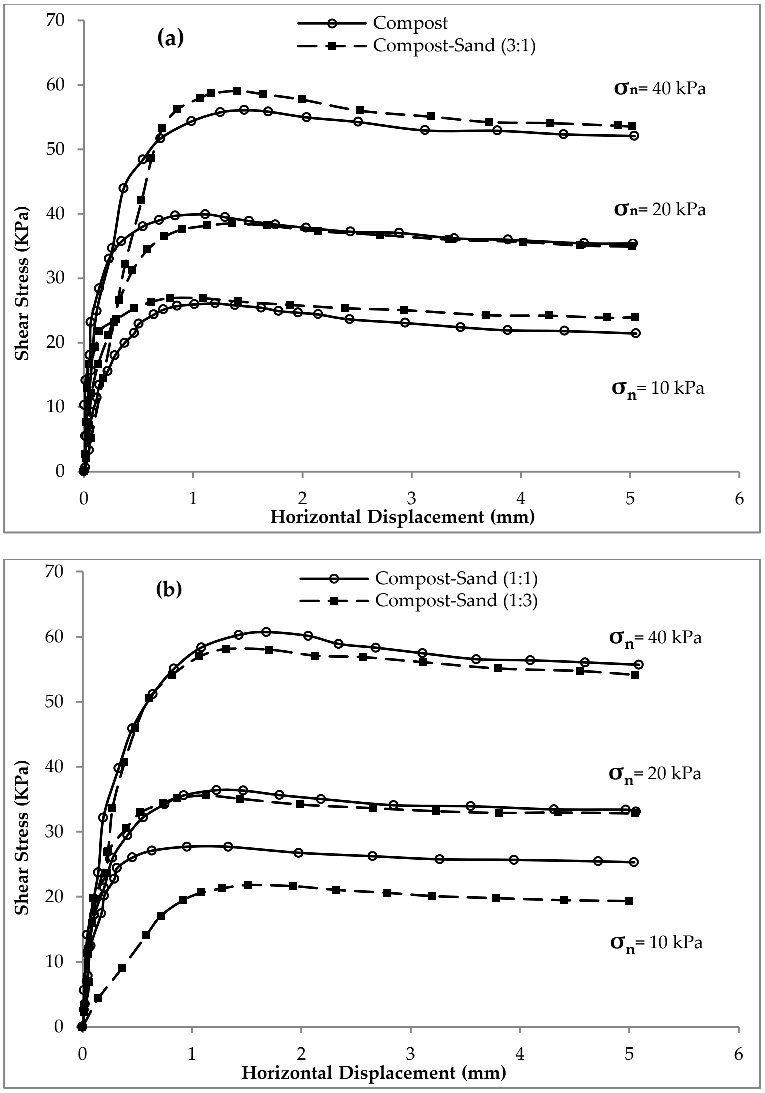


Fig. 3.5. Variation of shear stress versus displacement in ring shear test of compost based materials at optimum moisture content

((a) compost and compost – sand (3:1 w/w); (b) compost – sand (1:1 w/w) and compost – sand (1:3 w/w)).

Hvorslev (1939) found that in ring shear test when the ratio of inner to outer diameter of sample is greater than 0.5, the peak shear stress is close to that obtained from direct shear test. The ring shear device used in this study has a diameter ratio of 0.7. It can be seen from Fig. 3.5 that there is a small difference between the values of peak shear stress which are obtained from direct shear test and ring shear test (less than 8 %). Moreover as demonstrated in Fig. 3.5, there is a difference in shear displacement at which peak shear stress is occurred for direct shear test and ring shear test. This difference can be due to non-uniform shear displacement across the ring shear sample (Eid 1996).

Based on Mohr-Coulomb shear strength envelopes, the cohesion values of compost and compost-sand mixtures with mix ratios of 3:1, 1:1, and 1:3 were 17.9, 16.6, 15.5, and 10.5 kPa, while the friction angle values were 44.1°, 46.6°, 47.9°, and 49.9°. It can be found that the results of ring shear test and direct shear test are similar.

3.2.3.3 Consolidation test

Table 3.4 presents the coefficient of consolidation (C_v) values of the compost and its mixtures over applied pressures at moisture contents less than the OMC. It is observed that the C_v of the compost and its mixtures vary from 1.71 to 0.63 m^2/ year, while the moisture contents range from 8% to 34%. It should be noted from Table 3.4 that there is a general trend of reduction in the C_v values with increasing consolidation pressure and moisture content. This trend is in agreement with previous research which has been carried out on peat soils by Sing et al. (2008).

Table 3.4. Coefficient of consolidation of compost and its mixtures.

Load	Compost		Compost-sand (3:1)		Compost-sand (1:1)		Compost-sand (1:3)	
	w (%)	C_v (m^2/year)	w (%)	C_v (m^2/year)	w (%)	C_v (m^2/year)	w (%)	C_v (m^2/year)
5	24	1.71	18	1.64	10	1.47	8	1.37
	34	1.68	26	1.52	18	1.42	14	1.33
10	24	1.56	18	1.49	10	1.38	8	1.31
	34	1.54	26	1.43	18	1.36	14	1.27
20	24	1.35	18	1.28	10	1.17	8	1.12
	34	1.33	26	1.25	18	1.14	14	1.09
40	24	1.09	18	1.10	10	1.03	8	0.97
	34	1.09	26	1.07	18	1.00	14	0.92
80	24	0.81	18	0.78	10	0.72	8	0.66
	34	0.79	26	0.74	18	0.67	14	0.63

Fig. 3.6 illustrates the variation of void ratios with logarithm of pressure for the compost and its mixtures at different moisture contents. As shown in Fig. 3.6, the void ratios of the samples decrease with increasing consolidation pressure and initial moisture content. It can also be seen that the reduction rate of the void ratios is dependent on the organic content of the samples and reduced with decreases in the organic content.

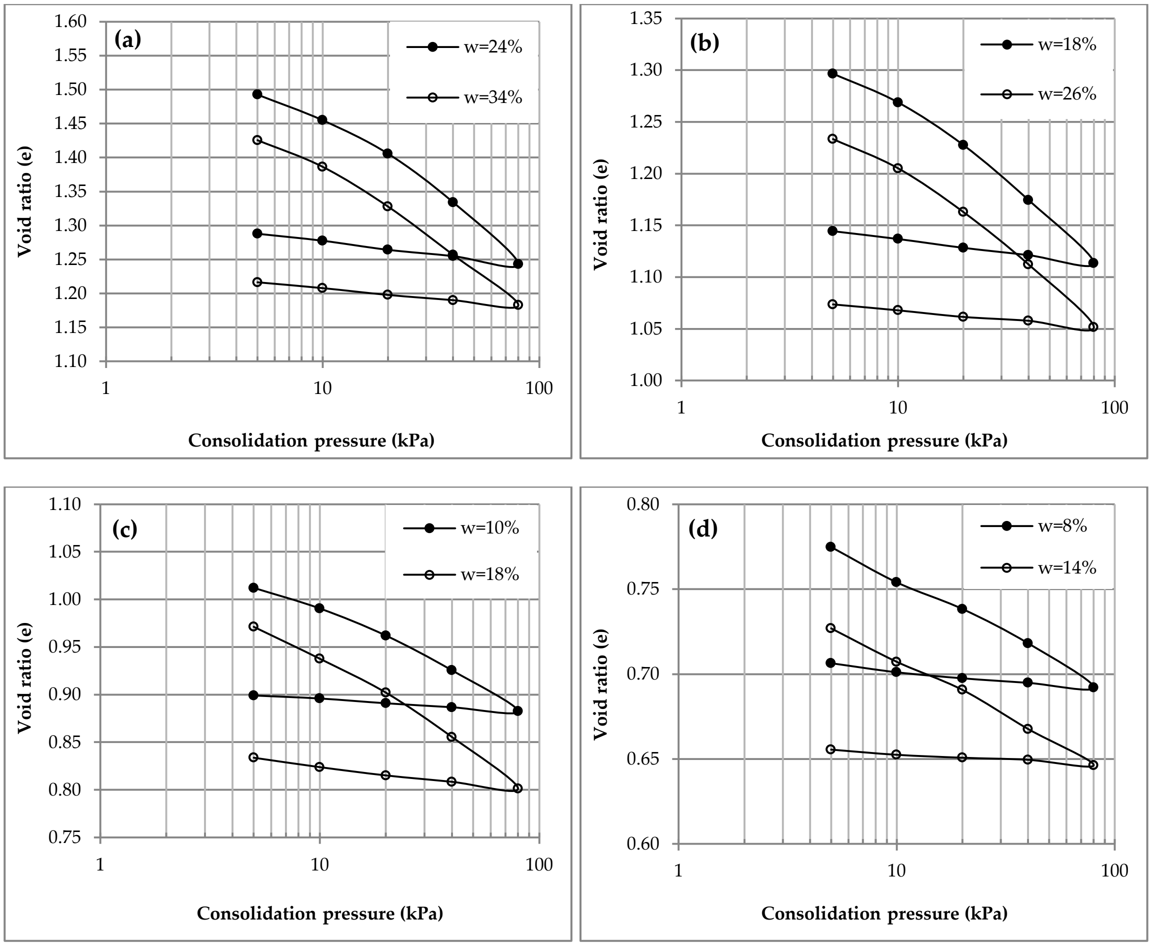


Fig. 3.6. Consolidation curves of compost based materials ((a) compost; (b) compost – sand (3:1 w/w); (c) compost – sand (1:1 w/w); (d) compost – sand (1:3 w/w)).

Also, it is observed that all the samples have the lowest void ratio value, (1.18, 1.05, 0.8, and 0.65 for compost, and compost-sand mixtures with mix ratios of 3:1, 1:1, and 1:3, respectively) with higher initial moisture contents and a consolidation pressure of 80 kPa. This means that the air filled voids are reduced and the samples provide insufficient FAS for the gas exchange process through the biocover. Bajwa and Fall (2011) and Moo-young and Zimmie (1996) have made the same observation respectively on compost materials and sludge.

The compression (C_c) and recompression indexes (C_r), which are the slopes of the consolidation curves (Fig. 3.6) for the loading and unloading stages during the consolidation process, are presented in Table 3.5.

Table 3.5. Compression and recompression indexes of the compost and its mixtures.

Sample	w (%)	C_c	C_r
Compost	24	0.225	0.027
	34	0.234	0.038
Compost-sand (3:1)	18	0.17	0.018
	26	0.171	0.025
Compost-sand (1:1)	10	0.119	0.014
	18	0.151	0.024
Compost-sand (1:3)	8	0.067	0.006
	14	0.068	0.01

The value of C_c which reflects the compressibility of the materials and consequently consolidation settlement is decreased by increasing sand content of the samples. Samples with higher sand content have lower void ratio (as shown in Fig. 3.6). Following the saturation prior to consolidation test, samples with higher sand content have lower free water content which can be removed by external loading. Since consolidation settlement can be due to the reduction of free water, so less consolidation settlement was observed for materials with higher sand content in comparison to samples with lower sand content.

The maximum deformation of compost material with initial moisture content of 34% was found at 2.25 mm (11.25% of the initial height of the sample) while the maximum deformation of the compost-sand mixture with a mix ratio of 1:3 and initial moisture content of 14% was found at 0.8 mm (0.4% of the initial height of the sample). These results are in agreement with those obtained by Hilger et al. (2000) and Philopoulos et al. (2009) who reported that the use of a sand based medium minimizes the settlement of biocovers.

As tabulated in Table 3.5, the C_r, which reflects the swelling potential of the materials, decreases with a decrease in the organic content (or an increase in the sand content) of the samples. This means that the samples with lower organic content have less swelling potential. Moreover, more consolidation settlement will occur for compost based biocover materials with higher organic content (or lower sand content) in comparison to samples with lower organic content (or higher sand content).

3.2.3.4 Hydraulic conductivity

The hydraulic conductivity values are presented in Fig. 3.7. This figure shows that the hydraulic conductivity values vary and range from 1.65×10^{-7}– 8.67×10^{-8} cm/s when the compaction moisture content varies in an approximate range of 7–60 %. It can be seen that the hydraulic conductivities of each sample are decreasing with increasing compaction moisture content up to OMC then for compaction moisture contents that exceed optimum, the hydraulic conductivities start to slightly increase. The results indicate that the minimum hydraulic conductivities (6.09×10^{-8}, 8.4×10^{-8}, 1.43×10^{-7} and 1.78×10^{-7} cm/s respectively for the compost and compost-sand mixtures with mix ratios of 3:1, 1:1 and 1:3) are achieved at OMC. This general trend is in agreement with the data published by Moo-Young and Zimmie (1996).

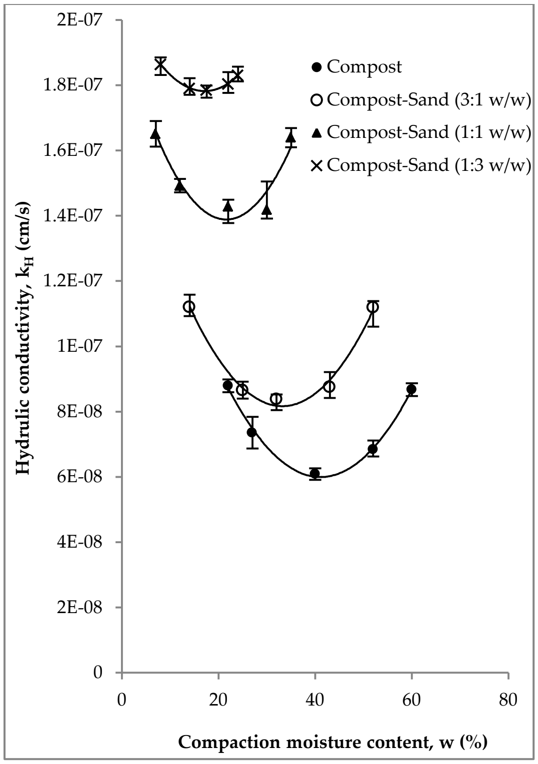


Fig. 3.7. Variation of hydraulic conductivity versus compaction moisture content of compost based materials.

The pure compost has lower hydraulic conductivities than the compost-sand mixtures and by increasing the percentage of sand in the samples, the hydraulic conductivity increases. The minimum hydraulic conductivity of the pure compost is about 6.09×10^{-8} cm/s, while that for the compost-sand mixture with a mix ratio of 1:3 is about 1.78×10^{-7} cm/s. Three possible reasons could account for such a phenomenon.

Firstly, the interlinked floc structure of the pure compost can induce a "clogging" effect and also OM retains water and prevents water from flowing, thereby reducing its hydraulic conductivity (Nemes et al. 2005). Secondly, as shown in Fig. 3.1, the compost- sand mixtures have coarser materials and fewer but larger voids than those of the pure compost. In contrast, in the pure compost, more and more fine particles fill the voids created by the coarse fraction, and the pore-size distribution becomes finer (Sivapullaiah et al. 2000). Finally, OM may also affect the pore size distribution of the soil through soil structure development (Ghanbarian-Alavijeh et al.

2010). By increasing OM content (compost) in the samples, the compost particles fill the pore structure of the sand which significantly affects the hydraulic conductivity.

3.2.3.5 Thermal conductivity

Fig. 3.8 illustrates how thermal conductivity varies with moisture content and dry density of the compost and its mixtures.

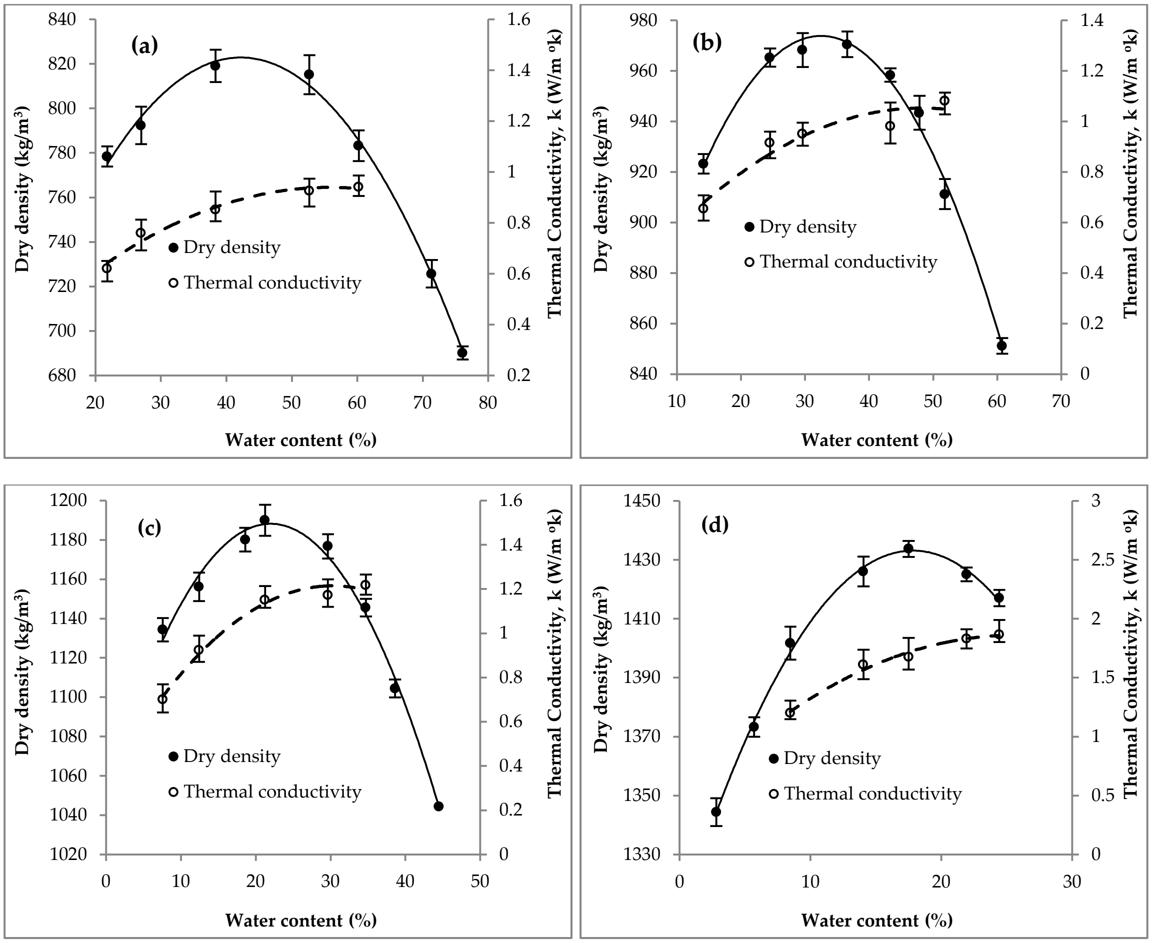


Fig. 3.8. Variation of thermal conductivity versus moisture content and dry density of compost based materials

((a) compost; (b) compost – sand (3:1 w/w); (c) compost – sand (1:1 w/w); (d) compost – sand (1:3 w/w)).

The results indicate that minimum thermal conductivities (0.621, 0.655, 0.701, and 1.202 W/m°K respectively for compost and compost-sand mixtures with mix ratios of 3:1, 1:1, and 1:3) are achieved at minimum moisture contents. It can be seen that the thermal conductivities of each sample are increasing with increases in moisture content and dry density on dry side of optimum moisture content. By increasing the moisture content, the water films around the soil particles, which are relatively larger than the particles themselves, are completed, which increase the indirect contact area between particles, causing the thermal conductivity to increase (Abu-Hamdeh and Reeder 2000). Chandrakanthi et al. 2005 also reported increasing in thermal conductivity of soil due to an increasing in moisture content.

Moreover, the degree of interparticle surface contact which is determined by particle packing efficiency has an important role in controlling the thermal conductivity in soils (Hall and Allinson 2009). As the density of a given soil increases up to the maximum dry density due to compaction, the contact between individual particles becomes more intimate which results in facilitating heat movement through the soil and an increase of thermal conductivity.

After the maximum density was reached, in contrast to moisture content, densities is decreased which results in reduction of direct contact between individual particles due to the presence of water between the soil particles. Whereas water has a thermal conductivity (0.59 W/m^{o}k) that is smaller than that of mineral soil particles (e.g., 2.9 for silt and clay, 3 for sand stone and 3.8 for dolostone (Côté and Konrad 2005)) (Ramires et al. 1995), the thermal conductivity therefore slightly increased after OMC was reached. This trend is in agreement with the results published by Al Nakshabandia and Kohnke (1964), who reported that the effect of moisture variation on thermal conductivity is more significant in comparison to the effect of density variation on thermal conductivity.

The relationship between thermal conductivity and degree of saturation is plotted in Fig. 3.9. It can be seen that the thermal conductivity increases with an increase in the saturation degree the samples. The thermal conductivity of water is significantly higher than that of air and the water layer around the solid particles conducts the heat from one solid (mineral, organic) grain to the other (Al Nakshabandia and Kohnke 1964). So, heat conduction through soil particles is mostly electrolytic (Singh and Devid 2000). In dry conditions, sufficient molecules of water are not available to bridge the air gaps between individual particles and thermal conductivity is low.

However, by increasing the degree of saturation, the voids are gradually filled with water and indirect contact between particles is made, so that the thermal conductivity begins to rise (Al Nakshabandia and Kohnke 1964). Therefore, it can be concluded that thermal conductivity should be increased by increasing the degree of saturation.

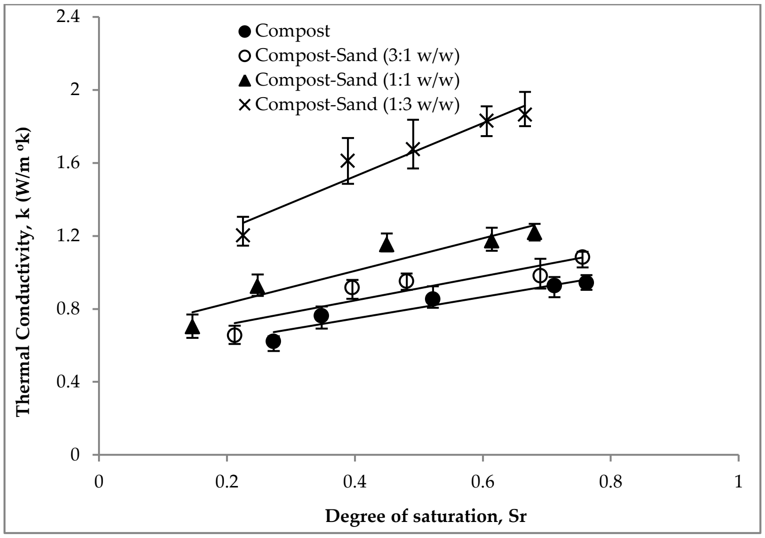


Fig. 3.9. Variations of thermal conductivity versus degree of saturation of compost based materials.

Also, as Hettiarachchi (2005) found, the results confirmed that the thermal conductivity of the compost based material is significantly lower than that for a range of mineral soils (e.g., 2.9 for silt and clay, 3 for sand stone and 3.8 for dolostone (Côté and Konrad 2005)). This means that mentioned materials are able to conduct heat at a lower rate and therefore heat will be stored in them compared to more mineral materials (Hettiarachchi 2005). In winter, when the atmospheric temperature is low, the low thermal conductivity of compost based materials means that it insulates well and ensures a stable temperature for the activities of microorganisms and thus, CH_4 oxidation should be able to proceed right through a long period in the winter (Mor et al. 2006).

3.2.4 Conclusions

In this paper, the geotechnical properties of four different types of compost based biocovers have been determined through a comprehensive laboratory investigation for the evaluation of the index properties, compaction properties, shear strength parameters, hydraulic conductivity, and thermal conductivity. The following key conclusions are drawn about the geotechnical properties of the studied compost based biocovers from the laboratory results.

The maximum dry density and OMC vary, ranging from 841.8 to 1428.5 kg/m^3 and 40% to 17.5%, respectively. The maximum dry density increases with an increase in the sand content due to the lower specific gravity of the compost in comparison with sand.

The drained cohesion of the samples varies from 2.08 to 19.7 kPa, while the angles of friction are in the range of 45.77^o to 54.69°. The high cohesion values of the pure compost may be attributed to the presence of fibers that act as reinforcement and become entangled in the compost. Also, the peak strength increases with an increase in the moisture content up to OMC and later decreases on the wet-side of optimum.

The C_c and C_r values range from 0.234 to 0.067 and 0.038 to 0.006, respectively. Also, higher organic contents result in higher compressibility.

The hydraulic conductivity values vary in a relatively wide range from 1.65×10^{-7} to 8.67×10^{-8} cm/s when the moisture contents vary in an approximate range of 7–60 %. The hydraulic conductivities decrease when the moisture content is increased up to OMC and minimum hydraulic conductivities are observed at OMCs. Thermal conductivity increases with increasing dry density and sand content. Also, minimum thermal conductivity is achieved at a minimum void ratio.

The presented study has shown that mixing compost with sand promotes shear strength, incompressibility, and porosity of compost based biocovers. The compost-sand mixture with mix ratio of 1:3 has relatively high hydraulic and thermal conductivities which are not favored characteristics, particularly in cold climate conditions with high rate of precipitations. Based on the obtained results, it could be concluded that the compost-sand mixtures with mix ratio of 3:1 and 1:1 have mechanical, hydraulic and thermal properties which are desirable for a biocover medium. Despite the presented results, more detailed study and field investigation on long term performance and CH_4 oxidation capacity of studied samples are required before making definite conclusions.

3.2.5 References

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3.3 Geotechnical characterization of peat based biocover materials[2]

Afshin Khoshand and Mamadou Fall

Abstract

Natural methane (CH_4) oxidation through biocovers is a promising method for reducing CH_4 emission from landfills. Previous studies concerning peat based biocovers have focused on their biochemical properties (e.g., methane oxidation capacity). However, utilization of peat as biocover materials requires also solid understanding of their geotechnical properties (thermal, hydraulic, mechanical), which are critical to the performance of any biocover. Therefore, the focus of this paper is to gain insight into geotechnical properties of peat based materials to assess their suitability for use as biocover media from geotechnical point of view. The objective of this research is to investigate and assess the geotechnical properties of peat based cover materials including compaction, consolidation, and hydraulic and thermal conductivity. This paper also evaluates and compares the suitability of peat-sand based biocovers (peat and peat-sand mixtures with mix ratio of 3:1, 1:1, and 1:3) in terms of their geotechnical properties. The studied materials displayed high compressibility to the increase of vertical stress, with compression index (C_c) values in the range of 0.160 to 0.358. The compressibility was function of sand content such that peat-sand mixture (1:3) had the lowest C_c value. Both thermal and hydraulic conductivities were function of moisture content, dry density, and sand content. The hydraulic conductivity varied in a range of 1.74×10^{-9} to 7.35×10^{-9} m/s and increased with increase in sand content. The thermal conductivity of the studied samples varied between 0.54 and 1.41 W/m°K and there is general trend of increase in thermal conductivity with increase in moisture and sand contents. Increasing sand content generally promotes mechanical behaviour of peat based biocover; however, causes relatively high hydraulic and thermal conductivities which are not favored properties for biocovers. On the basis of derived results, peat-sand mixtures with mix ratio of 3:1 and 1:1 have more desirable mechanical, hydraulic and thermal characteristics as biocover medium among all studied biocover mediums.

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[2] Submitted to the Geotechnical and Geological Engineering Journal

Keywords: biocover, peat, sand, compaction, compressibility, hydraulic conductivity, thermal conductivity.

3.3.1 Introduction

Methane (CH_4) is a potent greenhouse gas (GHGs) with a global warming potential 23 to 25 times that of carbon dioxide (CO2) (IPCC 2001 and 2007). Anaerobic biodegradation of municipal solid waste (MSW) in landfills is one of significant global sources of anthropogenic CH_4 emission. The current global CH_4 emissions from landfills are in the range of 500 to 800 metric ton (Mt) $CO_{2\text{-}e}$ ($CO_{2\text{-}e}$ or equivalent CO_2 is the concentration of CO_2 that causes the same level of radiative forcing as a given type and concentration of GHGs) per year and estimated to reach 1500 Mt $CO_{2\text{-}e}$ per year in 2030 based on waste statistics and demographic evolution (IPCC 2007). Therefore, urgent mitigation actions in order to reduce CH_4 concentration in the atmosphere are necessary (Stern and Kaufman 1996).

The extraction and utilization of landfill gas (LFG) are common technologies for controlling CH_4 emission from landfills. However, there are evidences that large amounts of CH_4 escape at sites equipped with extraction and utilization systems (Börjesson et al. 2007).

One of the most promising methods for reducing CH_4 emissions from landfills is the natural processing of microbial CH_4 oxidation through active biological cover soil or biocover (Scheutz et al. 2009*a* and 2011). This oxidation process principally relies on the activity of a group of bacteria known as the methanotrophs, which are able to use molecular oxygen (O_2) to oxidize CH_4 into CO_2 and cell carbon. Biocovers are an alternative effective option for CH_4 emission mitigation where the implementation of LFG extraction and utilization systems is not technically and economically feasible (Scheutz et al. 2011).

Previous studies have demonstrated that various organic soils (e.g., compost, peat, loam soil) can support growth and activity of methanotrophs bacteria (Humer and Lechner 1999; Stein and Hettiaratchi 2001; Wilshusen et al. 2004; Einola 2010), and can be suitable for practical applications in mitigating CH_4 emissions. Peat is one of the promising biocover materials. Indeed, peat is able to provide environmental conditions suitable for proliferation and activity of methanotrophic bacteria (Einola 2010; Stein and Hettiaratchi 2001; Streese and Stegmann

2003). Furthermore, many researchers (e.g., Stein and Hettiaratchi 2001; Einola et al. 2009) have experimentally demonstrated that peat materials show a high CH_4 oxidation efficiency (up to 90%) as illustrated in Table 3.6. The latter summarizes the CH_4 oxidation efficiency of various biocover materials. It can be noted that the CH_4 oxidation efficiency of peat (up to 90%) is close to that of compost (up to 100%) and much higher than those observed in other types of biocover materials (loam soil, topsoil, agricultural soil, and sand). However, for the peat biocover material to be of interests, aside from having a high CH_4 oxidation efficiency (Table 3.6), it should show geotechnical properties, which are comparable to or better than those of the existing biocover materials (particularly compost) available in the construction practices.

Table 3.6. Summary of CH_4 oxidation efficiency in different organic soils.

Biocover material	CH4 oxidation efficiency (%)	Reference
Loam soil	50	Stein and Hettiaratchi (2001)
	65	Scheutz et al. (2003)
	65	De Visscher et al. (1999)
Topsoil	40	Kightley et al.(1995)
	37	Humer and Lechner (1999)
Sand	41	Kightley et al.(1995)
	63	Powelson et al. (2006)
Peat	85	Stein and Hettiaratchi (2001)
	90	Einola et al. (2009)
Agricultural soil	32	Stein and Hettiaratchi (2001)
	45	De Visscher et al. (1999)
Compost	53	Humer and Lechner (2001)
	96	Haubrichs and Widmann (2006)
	100	Philopoulos et al. (2009)

The geotechnical properties (mechanical, hydraulic, and thermal) of biocover materials are of prime importance for the design, construction and maintenance of any biocover as discussed later. However, to date, the geotechnical characteristics of the peat based biocover material are not understood. There have been little comprehensive recommendations in the literature with regards to compaction properties, consolidation behaviour, and the hydraulic and thermal conductivities of peat based biocover material (pure peat, peat-sand mixtures). This is because previous studies concerning peat based biocovers have mainly focused on their biochemical properties (methane oxidation capacity). Therefore, the goal of this paper is to gain insight into geotechnical properties of peat based biocover materials and to assess their suitability for use as biocover media from geotechnical point of view.

The current paper describes the results of a comprehensive laboratory study on the geotechnical characteristics (compaction and consolidation, hydraulic and thermal conductivity) of peat based biocover materials and evaluates variations in the relative proportion of sand and peat on the overall geotechnical properties of peat based biocovers.

3.3.2.1 Material selection and characterization

Mixing potential biocover materials with sand minimizes the settlement and compaction of biocovers (Powelson et al. 2006; Philopoulos et al. 2009; Scheutz et al. 2009*a*; Khoshand and Fall 2013). The issue of compaction is especially important when consideration is given to any field installations, as there will be some traffic on the medium's surface (e.g. maintenance) (Philopoulos et al. 2009). Therefore, laboratory investigations in the current study were conducted on peat and peat–sand mixture samples at ratios of 1:3, 1:1, and 3:1 (w/w). The aforementioned ratios are suggested in the literature by Pokhrel et al. (2011) who studied the CH_4 oxidation capacity of different mixtures of potential biocover materials.

In this research, Ottawa sand, obtained from Unimin Canada Ltd., was used. The sand was oven dried prior to experiments in order to eliminate any methanotrophic bacteria that may be present in the sand. Also, the sand was free of organic content based on the results of the laboratory tests performed according to ASTM D2974. The peat soil samples were collected from the Moose Creek Bog in Moose Creek, Canada which is owned and operated by Lafleche Environmental lnc. The peat samples were transported to a laboratory and stored at a temperature of 3^{o}C before further characterization.

Since the mineralogical composition of a soil can significantly affect its geotechnical behaviour, the mineralogical composition of the peat material and peat–sand mixtures were determined by X-ray diffraction analyses and the results are presented in Table 3.7.

Table 3.7. Chemical composition of peat material and its mixtures used in this study.

Constituents	Contents (%)			
	Peat	Peat-Sand (3:1 w/w)	Peat-Sand (1:1 w/w)	Peat -Sand (1:3 w/w)
SiO_2	11.7	31.51	51.2	70.79
Al_2O_3	2.49	3.25	3.97	4.71
Fe_2O_3	1.04	0.8	0.57	0.35
Na_2O	0.62	0.65	0.67	0.69
MgO	0.85	0.66	0.45	0.24
CaO	5.13	3.96	2.76	1.56
K_2O	0.68	1.15	1.61	2.08
TiO_2	0.09	0.07	0.06	0.04
P_2O_5	0.3	0.22	0.15	0.08
Cr_2O_3	<0.01	<0.01	<0.01	<0.01
MnO	0.03	0.02	0.01	<0.01
V_2O_5	<0.01	<0.01	<0.01	<0.01
LOI	76.1	57.16	38.21	19.27

The selected geotechnical index properties of all the samples were determined in accordance with the procedures described by the American Society of Testing and Materials (ASTM) standards (ASTM 2010). Grain size analysis was performed according to ASTM D422. It can be seen from Fig. 3.10 that all samples consisted of particles with sizes that range from 0.07 to 5 mm and the grain size distribution of the samples becomes coarser as the sand ratio increases.

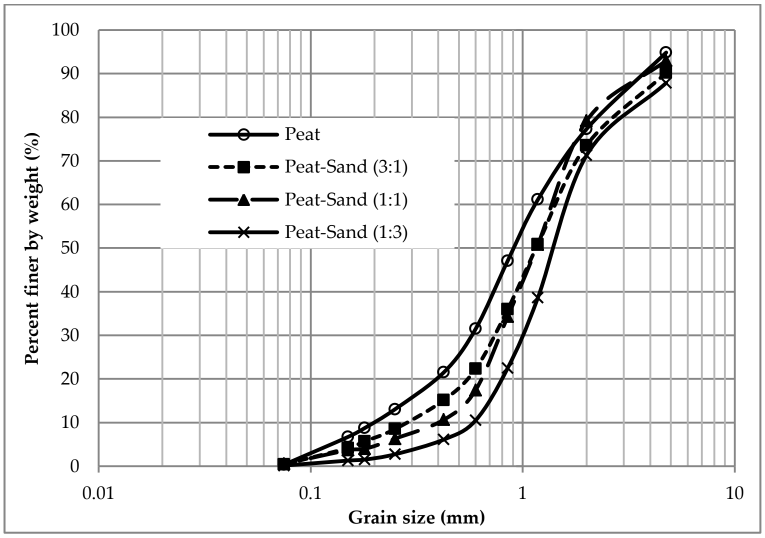

Fig. 3.10. Particle size distribution of peat and its mixtures.

The grain size distribution of the peat samples indicated that the percentage of grains that passed through sieve numbers 10, 40 and 100 were 79%, 22% and 7%, respectively. The pure peat sample in this study was classified as organic SW (well graded sand) and the rest of samples were classified as organic SP (poorly graded sand) based on the Unified Soil Classification System (USCS). Classifying soils into groups with similar behavior, in terms of simple indices, can provide engineers a general guidance about engineering properties of the soils. However, this USCS classification system is not well suited for organic soils and considers samples as peat only when organic content is more than 75%. In this study, a classification system proposed by Wüst et al. (2003), which is based on the ash and organic contents of peats, was also used. Based on this classification, peat and peat-sand mixture with a mix ratio of 3:1 were considered as peat, while peat-sand mixtures with mix ratios of 1:1 and 1:3 were considered as muck. A summary of the index properties and the pH of the samples are shown in Table 3.8. The pH value of the peat sample was 6.72 and this value falls within the range quoted by Cola and Cortellazzo (2005). The liquid limit of the tested samples ranged between 74% and 128%. This high range of liquid limits for the peat materials are in good agreement with those quoted in the literature (Deboucha and Hashim 2009). It should be emphasized that the peat specimens are non plastic and the measurement of the plastic limit is impossible for most kinds of peat as reported by Ulusay et al. (2010).

Table 3.8. Geotechnical index properties and pH of peat and its mixtures.

Parameters	**Peat**	**Peat-Sand (3:1 w/w)**	**Peat-Sand (1:1 w/w)**	**Peat-Sand (1:3 w/w)**
Initial moisture content, w (%)	195.48	145.43	98.63	48.93
Organic content (%)	69.73	51.92	35.35	19.12
pH (in H_2O)	6.72	6.75	6.81	6.91
Specific gravity, Gs	1.65	1.90	2.15	2.4
Dry bulk density (kg/m^3)	375.4	659.5	943.7	1227.8
WHC^1 (%)	218.86	166.67	137.08	94.41
LL^2 (%)	128	105	88	74

^{1}WHC: water holding capacity; ^{2} LL: liquid limit.

3.3.2.2 Methods

3.3.2.2.1 Compaction test

In order to experimentally determine the values of optimum moisture content and corresponding maximum dry density of the studied materials, standard proctor compaction tests were performed in accordance with ASTM D698.

3.3.2.2.2 Consolidation test

Conventional consolidation tests were performed on the samples at the dry side of the optimum moisture content and optimum moisture content according to ASTM D2435 to determine the consolidation characteristics of the peat and its mixtures samples. The dried samples were moistened and compacted to reach the desired densities for specific moisture contents that correspond to standard proctor compaction results. Each test consisted of five increments of loading (5, 10, 20, 40 and 80 kPa) and the duration of each loading was 24 hours to ensure that long term compressibility of the samples has been properly simulated (Moo-Young and Zimmie, 1996). Each test was repeated twice.

3.3.2.2.3 Hydraulic conductivity

Hydraulic conductivity testing was performed on all of the samples in accordance with the procedures that are outlined in ASTM D5084. The measurement of hydraulic conductivity was conducted by a flexible wall permeameter on samples (with dimensions of 115 mm in height and 50 mm in diameter) at optimum, dry of optimum, and wet of optimum moisture content and related densities based on compaction curves. In order to prevent anomalies during the flow rate measurements, low hydraulic gradient (approximately 10) was maintained in all of the tests (Benson and Othman 1993). Also, for each sample, hydraulic conductivity testing was repeated until three values were derived which fell within ±10% (minimum three and maximum five replicates for each sample). The average value was considered as the saturated hydraulic conductivity of the sample tested.

3.3.2.2.4 Thermal conductivity

In this testing, the materials were first air dried and kept in a dry condition for 10 days to reach thermal equilibrium. Afterwards, the samples were moistened and compacted to reach the desired densities in accordance with the compaction curves. The thermal conductivity of the samples was determined based on the non-steady state method under isothermal conditions by using the device KD2 (Decagon Devices 2012). Each thermal conductivity test was performed twice to four times to ensure the repeatability of the results obtained.

3.3.3 Results and discussion

3.3.3.1 Compaction characteristics

In this study, compaction tests were carried out over a broad range of moisture contents and dry densities. Fig. 3.11 illustrates the compaction curves of peat and its mixtures. The maximum dry densities of the peat and peat-sand mixtures with mix ratios of 3:1, 1:1 and 1:3 were 402, 570, 709 and 1004 kg/m^3 and the corresponding optimum moisture contents were 96%, 82%, 77% and 64%, respectively. Said and Taib (2009) also report similar compaction behaviour (similar range of maximum dry density and optimum moisture content) for peaty soils.

The maximum dry density increased when the sand content in the mixtures increased. Pure peat had the lowest value of maximum dry density in comparison with the other mixtures which can be attributed to the lower specific gravity (1.65) of peat. During the compaction procedure, samples with lower sand content required more water to be added and were still compactable while those with higher sand content required less water and were less compactable. Compared with pure peat, peat-sand mixtures have lower optimum moisture contents and were less compactable (Stone and Ekwue 1993).

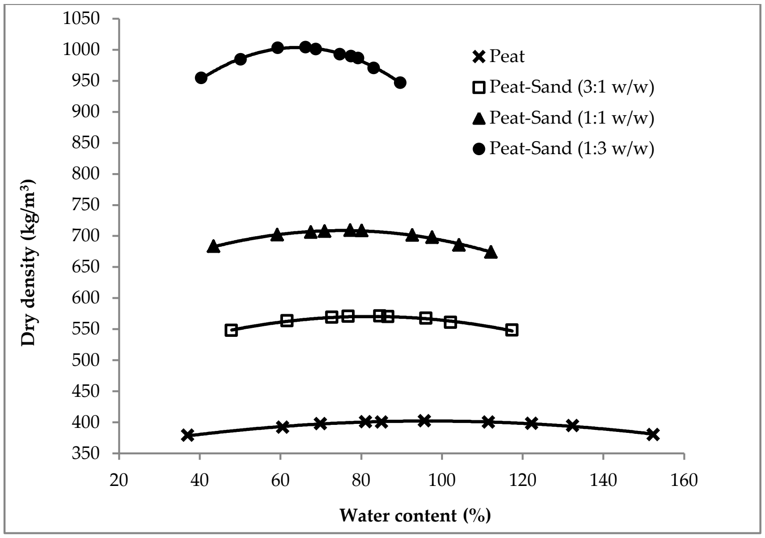

Fig. 3.11. Compaction curve of peat based materials.

In biocovers, the CH_4 oxidation rate is greatly influenced by O_2 penetration depth. The parameters that can control oxygen penetration and therefore CH_4 oxidation rate through biocovers are free air space (FAS) and degree of saturation (Sr) of biocover media. The diffusivity of biocover media is strongly regulated by the saturation degree (Sr) (Gebert et al. 2011). Saturation causes discontinuing diffusion pathways by creating water menisci (Moldrup et al. 2001). In considering the significance of the mentioned parameters, variations of FAS and Sr with moisture content for the studied materials are presented in Fig. 3.12. This figure shows that as the moisture content increased, FAS decreased until it reached a value close to zero at the wet side of the optimum moisture content. In this condition, the air phase in the pores becomes occluded (Nagaraj et al. 2006) and gases have to diffuse in the liquid phase. The gaseous diffusion in the liquid phase is greatly less than air (Gebert et al. 2011) which causes a slowdown of the diffusive migration of O_2 through the biocover media and drastic reduction in the CH_4 oxidation rate. The O_2 consumption rate reaches a maximum value when the FAS is between 20% and 35% (Tim 1993). So, it can be concluded from Fig. 3.12 that the maximum O_2 consumption rate (thereby highest CH_4 oxidation) in peat and peat-sand samples with mix ratios of 3:1, 1:1 and 1:3 should be expected when the moisture content is between 85% and 110%, 70% and 85%, 80% and 95%, and 65% and 75%, respectively.

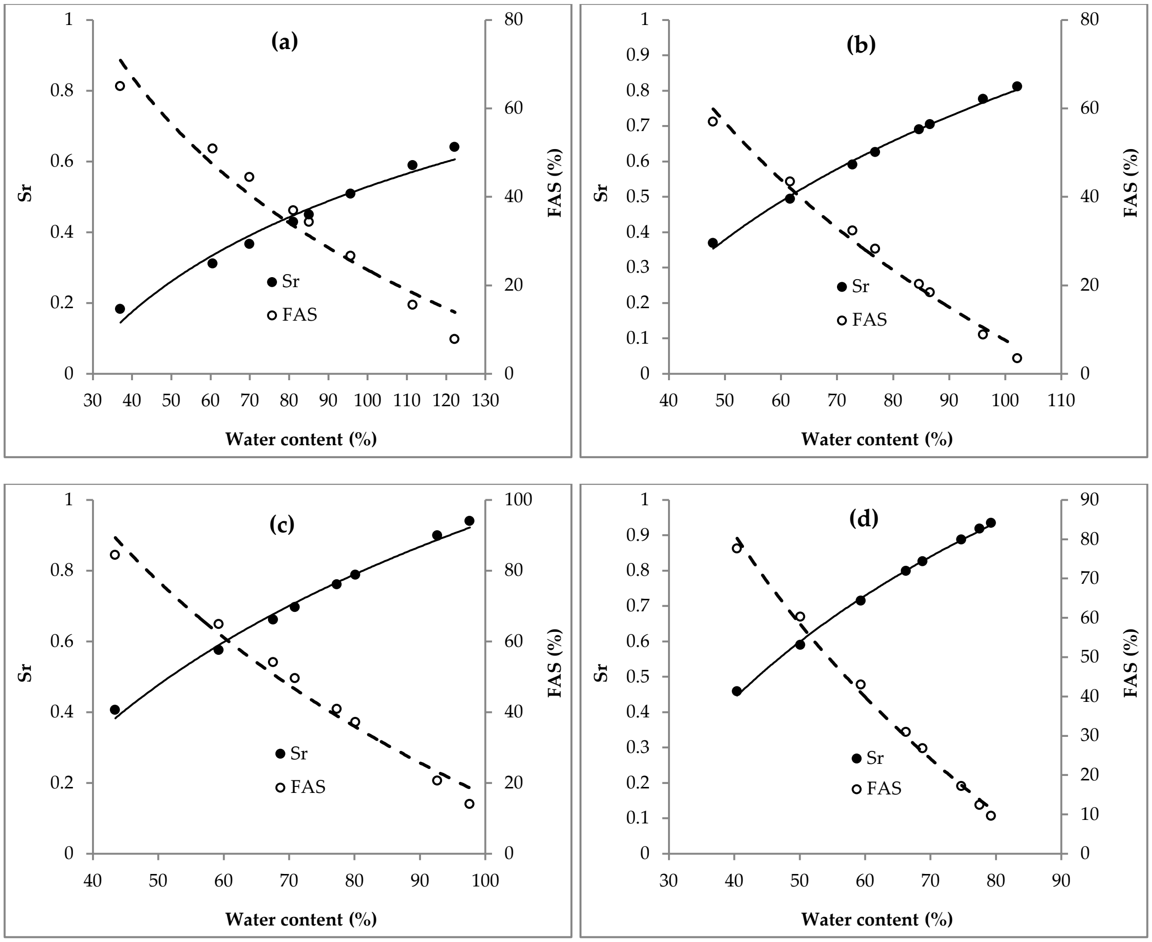

Fig. 3.12. Relationship between degree of saturation, free air space, and moisture content of peat based materials

((a) peat; (b) peat – sand (3:1 w/w); (c) peat – sand (1:1 w/w); (d) peat – sand (1:3 w/w)).

It can be clearly seen that range of moisture content associated to the maximum O2 consumption rate in studied samples generally decreased with increase in sand content.

3.3.3.2 Consolidation characteristics

Consolidation can significantly change the porosity of the biocover. The gas transport process in biocover (e.g., advection flux of CH_4 (upward) and the diffusion flux of oxygen (downward) into the CH_4 oxidation zone) and consequently the performance (methane oxidation capacity) of biocover is strongly affected by its porosity (Pedersen 2010). Moreover, the strain due to consolidation could also translate into crack development in the biocover which can affect its physical stability (Bajwa 2012) as well as the amount of methane emitted to the atmosphere. These cracks may create preferential pathways for methane to escape to the atmosphere. Thus, there is a need to understand the consolidation characteristics of peat-based biocover materials. The compressibility of materials can be divided into primary and secondary consolidation.

3.3.3.2.1 Primary compression

The primary consolidation can be explained by the variation of the void ratio and a logarithm of the consolidation pressure as shown in Fig. 3.13.

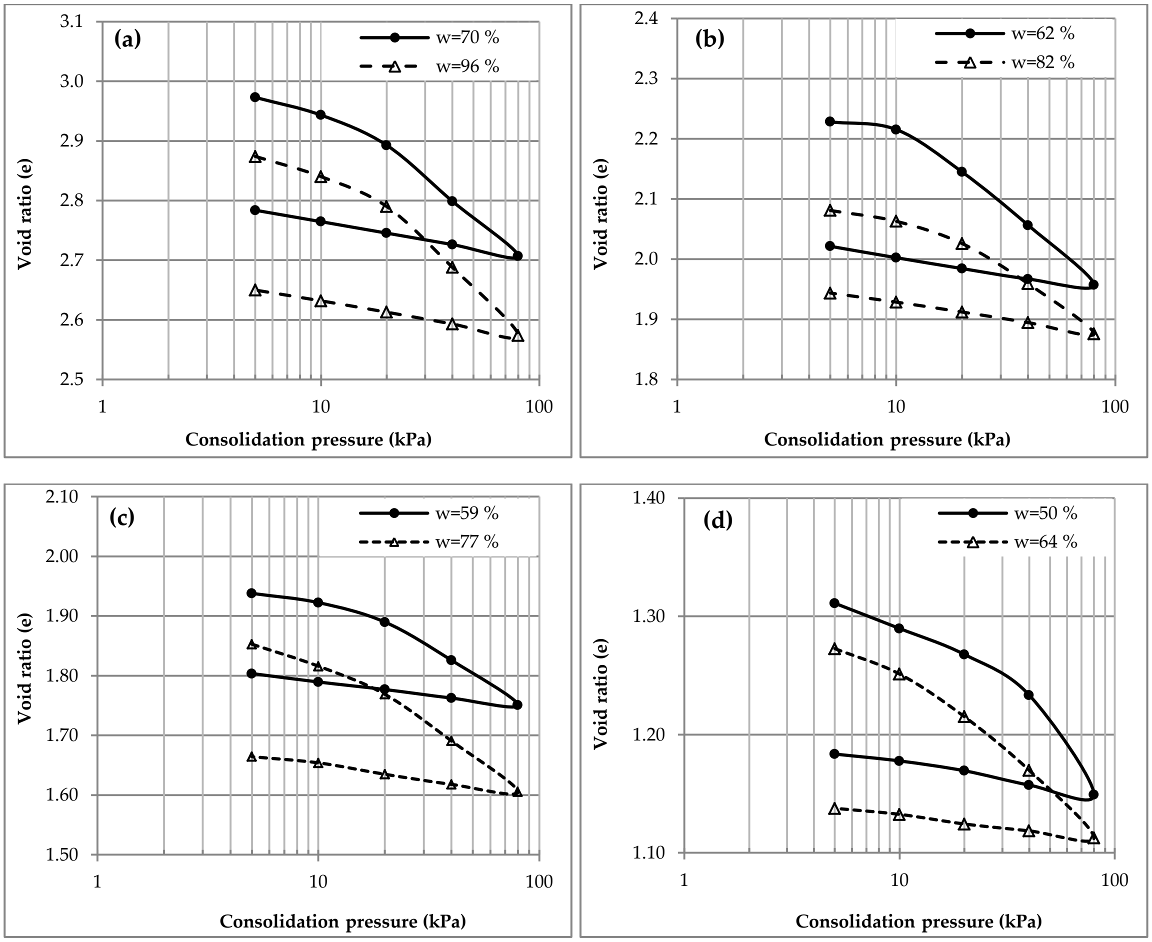

Fig. 3.13. Consolidation curves of peat based materials

((a) peat; (b) peat – sand (3:1 w/w); (c) peat – sand (1:1 w/w); (d) peat – sand (1:3 w/w)).

It is clear from Fig. 3.13 that the void ratio of the samples decreased when the moisture content and consolidation pressure increased. The lowest void ratio values of the samples (2.57, 1.87, 1.61 and 1.11 for peat, and peat-sand mixtures with mix ratios of 3:1, 1:1, and 1:3, respectively) were observed at high moisture content conditions and a consolidation pressure of 80 kPa.

Calculation of the coefficient of consolidation (Cv) was carried out based on square root of time (Taylor's) method. It is evident from Table 3.9 that there was a significant reduction in the Cv value of the samples with an increase in consolidation pressure, and this reduction was more pronounced in samples with less sand content. The compression index (Cc) and recompression index (Cr) values are presented in Table 3.10. The Cc value, which reflects the compressibility of the materials, ranges from 0.35 to 0.13 in this study. This range is lower than that obtained by Kazemian et al. (2011) and Ulusay et al. (2010).

Table 3.9. Coefficient of consolidation of peat and its mixtures.

Load	**Peat**		**Peat -sand (3:1)**		**Peat-sand (1:1)**		**Peat-sand (1:3)**	
	w (%)	**C_v (m²/year)**	**w (%)**	**C_v (m²/year)**	**w (%)**	**C_v (m²/year)**	**w (%)**	**C_v (m²/year)**
5	70	3.34	62	3.09	59	2.92	50	2.64
	96	3.24	82	3.01	77	2.83	64	2.52
10	70	3.06	62	2.75	59	2.71	50	2.40
	96	2.89	82	2.69	77	2.54	64	2.26
20	70	2.79	62	2.59	59	2.55	50	2.15
	96	2.70	82	2.52	77	2.42	64	2.10
40	70	2.65	62	2.42	59	2.31	50	2.01
	96	2.50	82	2.34	77	2.23	64	1.95
80	70	2.34	62	2.28	59	2.17	50	1.91
	96	2.25	82	2.19	77	2.06	64	1.83

The primary consolidation and associated settlement can be explained by Cc value such that a higher value of Cc results in higher primary settlement. It can be clearly observed from Table 3.10 that there is a general trend of decreasing Cc with increase in sand content. The peat samples had the highest value of Cc among the studied materials (Table 3.10) and subsequently would experience higher primary settlement that could increase the risk of crack formation and/or significantly reduce the FAS, and thereby decrease the efficiency of CH4 oxidation. It is clear from Table 3.10 that the Cc values generally increased when the initial moisture content increased. This can be explained by the fact that the high moisture content of peat is related to the presence of high pore water outside the peat particles (Huat et al. 2011). The pore water can easily be dissipated during consolidation due to increase of vertical stress. As presented in Table 3.10, the Cr values of the samples that display the swelling potential of materials were low for studied materials. The obtained Cr values in the current study are also consistent with the published data by Mesri and Ajlouni (2007). It is also clear that the Cr decreased as the sand content increased which means the samples with higher sand contents have less swelling potential.

Table 3.10. Compression index and recompression index of peat and its mixtures.

Sample	w (%)	C_c	C_r
Peat	70	0.308	0.034
	96	0.358	0.063
Peat -Sand (3:1)	62	0.312	0.053
	82	0.249	0.056
Peat -Sand (1:1)	59	0.231	0.044
	77	0.272	0.048
Peat -Sand (1:3)	50	0.134	0.029
	64	0.160	0.021

3.3.3.2.2 Secondary compression

Secondary compression can be completely described by the ratio of coefficient of secondary compression (C_α) to C_c (Mesri and Ajlouni 2007). The variations in C_α/C_c for peat and peat-sand mixtures at different stress levels (5 to 80 kPa) are illustrated in Fig. 3.14. This figure indicates that the values of C_α/C_c for the studied samples decreased when the consolidation pressure increased. Ulusay et al. (2010) also reported the similar observations for peat materials.

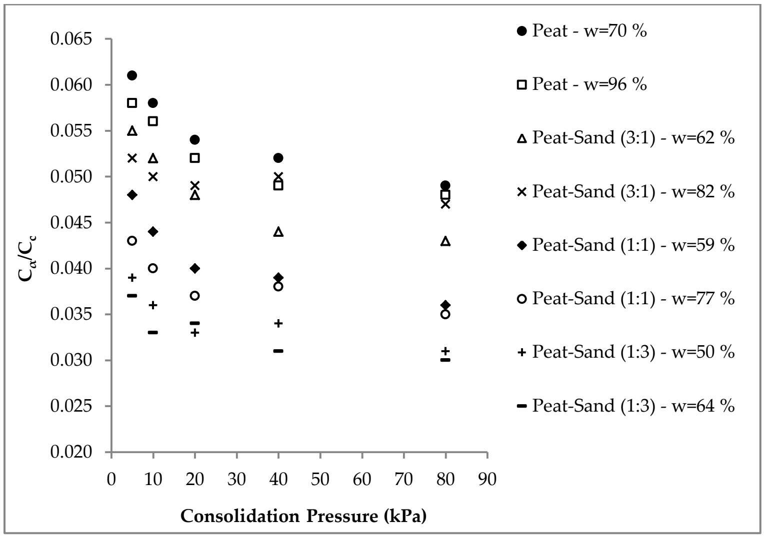

Fig. 3.14. Variations of the C_α/C_c ratios versus consolidation pressure of peat based materials.

However, most of the previous studies obtain values of $C_\alpha/C_c = 0.06 \pm 0.01$ or higher (up to 0.1) for peat materials (Mesri and Ajlouni 2007 and Ulusay et al. 2010). Duraisamy et al. (2007) report lower values of C_α/C_c (0.027 and 0.038) for some peat samples. In the current study, the values of C_α/C_c for the peat samples were in range of 0.048 to 0.061, and the obtained values are close to those of Mesri and Ajlouni (2007). The values of the C_α/C_c for different geotechnical materials vary in a narrow range of 0.01 to 0.1 (Ulusay et al. 2010). The magnitude of the C_α/C_c can be used to explain the deformability and compressibility of the soils (Mesri and Ajlouni 2007). In the current research, peat samples consist of deformable particles and thereby are highly compressible and display the highest values of C_α/C_c. Increasing sand content resulted in lower range of C_α/C_c because sand granular materials such as sands are less deformable with $C_\alpha/C_c = 0.02 \pm 0.01$ (Mesri and Vardhanabhuti 2009).

Secondary compression not only has a negative effect on gas exchange process and thereby CH_4 oxidation potential of biocover, but also affects the pore structure (Bajwa 2012) and consequently physical stability of biocovers. Based on the obtained values of C_α/C_c in the current research, the peat experienced the highest secondary settlement among the studied materials which could increase the risk of physical failure of peat biocover mainly due to crack development and changes in the pore structure.

3.3.3.3 Hydraulic conductivity

Biocovers should also have appropriate hydraulic conductivity in order to minimize rainfall infiltration and subsequent biocover saturation, which can result in a drastic reduction of the CH_4 oxidation rate (Pokhrel 2006; Scheutz 2009; Khoshand and Fall 2013). Therefore, changes in the hydraulic conductivity of biocovers have important effects on the rate of CH_4 oxidation and water intrusion. Fig. 3.15 shows the saturated hydraulic conductivity test results for peat and its mixtures in the current study.

It is observed that the hydraulic conductivity values ranged from 1.74×10^{-9} to 7.35×10^{-9} m/s while the compaction moisture contents varied in an approximate range of 45–132%. As illustrated in Fig. 3.15, the hydraulic conductivity of specimens decreased when the compaction moisture content and dry density increased until the optimum moisture content and maximum dry density were reached. Afterward, the hydraulic conductivity increased for compaction moisture contents that exceed optimum. The minimum hydraulic conductivities (1.74×10^{-9} m/s, 2.62×10^{-9} m/s, 4.45×10^{-9} m/s, and 6.26×10^{-9} m/s respectively for peat and peat-sand mixtures with mix ratios of 3:1, 1:1, and 1:3) were achieved at optimum moisture content.

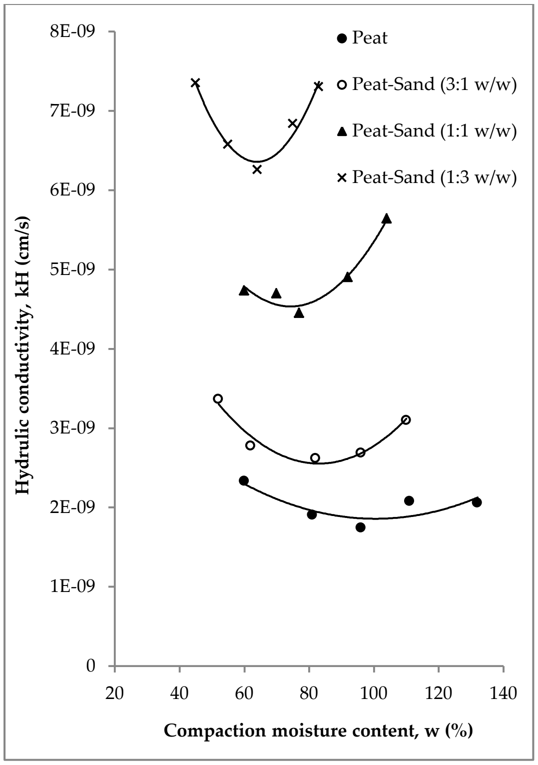

Fig. 3.15. Variation of hydraulic conductivity versus compaction moisture content of peat based materials.

Moo-Young and Zimmie (1996) who studied the geotechnical behaviour of potential landfill covers reported a similar trend in variation hydraulic conductivity with moisture content. The hydraulic conductivity of peat is a function of the void ratio and the size and shape of the flow channels (Mesri and Ajlouni 2007). Naturally, peat particles are porous and subsequently have large pore sizes which result in high initial hydraulic conductivity at low dry density conditions (Huat et al. 2011). The increase in dry density up to the maximum dry density due to compaction causes smaller pores, tortuous flow channels through the samples which eventually results in a drastic reduction in hydraulic conductivity to a comparable value to that of clay soils (Huat et al. 2011).

The hydraulic conductivity of peat varied in the range of 1.74×10^{-9} – 2.33×10^{-9} m/s while hydraulic conductivity peat-sand mixture with a mix ratio of 1:3 were in the range of 6.29×10^{-9}-7.35×10^{-9} m/s. The hydraulic conductivity of peat is controlled by the physical and structural arrangement of the constituent particles (Edil 2003), which can affect pore size distribution and the size and shape of the flow channels. Increasing the sand content of the samples causes larger void ratios, pores and straight flow channels through the specimens which result in higher hydraulic conductivities. The interlinked fibrous structure of pure peat which has a clogging effect (Edil 2003) is as another possible reason of lower hydraulic conductivity of peat in comparison to those of peat-sand mixtures. However, increasing sand content increases the hydraulic conductivity and consequently promotes the gas exchange process within peat based biocovers; hydraulic conductivity of biocover should also be low enough to prevent the water infiltration.

3.3.3.4 Thermal conductivity

Thermal conductivity expresses the rate of heat dissipation (Al Nakshabandia and Kohnke 1965) and can control temperature (Chandrakanthi et al. 2005) and subsequently the performance of biocovers in various climatic and thermal loading conditions. To assess and predict the evolution and distribution of temperature in biocovers, the knowledge of the thermal conductivity of the biocover material is a prerequisite.

The simultaneous variation of thermal conductivity and dry density with moisture content is shown in Fig. 3.16. The thermal conductivities of the peat samples varied from 0.54 to 0.71 W/m^{o}K when the moisture contents ranged from 60% to 132% (Fig. 3.16). The obtained results are close to those reported by Dissanayaka et al. (2012) for pure peat in wet conditions (0.1 to 0.6 W/m^{o}K). It is clear from Fig. 3.16 that the thermal conductivity of studied peat based materials is influenced by moisture content such that the thermal conductivity consistently increased as the moisture content increased.

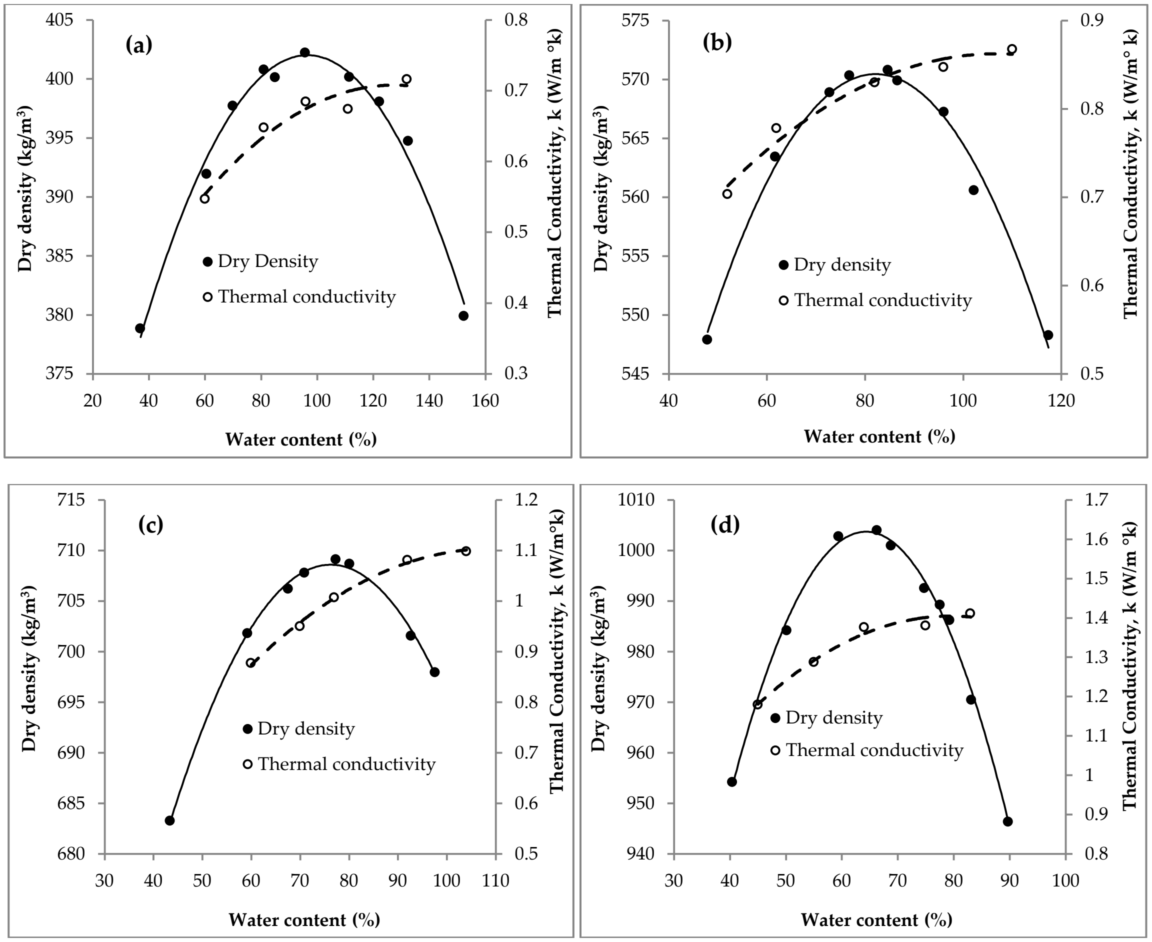

Fig. 3.16. Variation of thermal conductivity versus moisture content and dry density of peat based materials

((a) peat; (b) peat – sand (3:1 w/w); (c) peat – sand (1:1 w/w); (d) peat – sand (1:3 w/w)).

It can be seen from Fig. 3.16 that the minimum thermal conductivities (0.54, 0.7, 0.87 and 1.17 W/m°K respectively for peat and peat-sand mixtures with mix ratios of 3:1, 1:1 and 1:3) were achieved at minimum moisture contents. This is caused by the fact that thermal conductivity of water (0.59 W/m°K) is more than 20 times greater than that of air (0.025 W/m°K) (Holman 2002). By increasing the moisture content, the volume fractions of air are decreased and the portion of the pore spaces filled with water is increased (Ahn et al. 2009). So, water films around soil particles become completed and enhance the contact area between particles which result in increases in the thermal conductivity (Abu-Hamdeh and Reeder 2000). A similar trend for the variation of thermal conductivity with moisture content is reported in previous studies (Ahn et al. 2009; Chandrakanthi et al. 2005).

Furthermore, Fig. 3.16 indicates that thermal conductivity increased when the dry density of the samples increased. This can be explained by the fact that, generally, when the density of soil samples increases up to the maximum dry density due to compaction, the degree of inter particle surface contact increases and contact between the individual particles becomes more intimate (Al Nakshabandi and Kohnke 1965) which results in facilitating heat movement through the soil and an increase in thermal conductivity. After the maximum density is reached, excess water causes higher pore water pressures that result in less compactability and subsequently density reduction (Ekwue et al. 2011). However, as the densities decline, the moisture contents still increase and contact between the individual particles becomes less due to the presence of water between the soil particles. Whereas water has a thermal conductivity greater than air and considerably smaller than that of mineral soil particles (e.g., 2.9 for silt and clay, 3 for sand stone and 3.8 for dolostone (Côté and Konrad 2005)) (Ramires et al. 1995), thermal conductivity continued to slightly increase after the optimum moisture content was reached (Fig. 3.16). Ekwue et al. (2011) also reported that the effect of density variation on thermal conductivity is considerably less than that of moisture variation.

Fig. 3.17 shows the variation of thermal conductivity as a function of the S_r. It can be seen that in peat based biocovers, thermal conductivity increased when the S_r increased. As mentioned above, the thermal conductivity of water is significantly higher than that of air. At low S_r, there are insufficient molecules of water to fill the air gaps between particles and thermal conductivity is low. However, by increasing the S_r, air gaps are filled by water and contact between particles is increased and subsequently, thermal conductivity increases (Al Nakshabandia and Kohnke 1965).

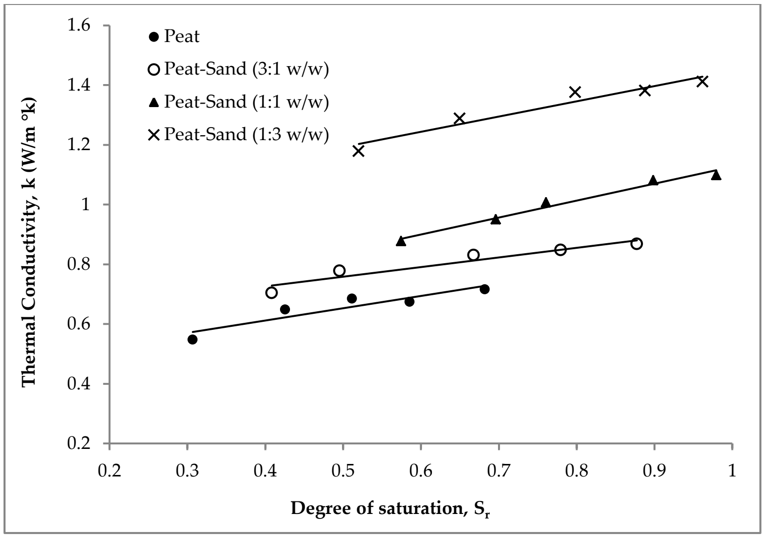

Fig. 3.17. Variation of thermal conductivity versus degree of saturation of peat based materials.

The obtained results indicate that thermal conductivity of studied materials is strongly influenced by sand content such that thermal conductivity significantly increased with increase in sand content. This is caused by the lower thermal conductivities of peat materials in comparison to those of mineral soils (e.g., 0.05 to 0.6 (Dissanayaka et al. 2012) and 0.2 to 0.52 (Kujala et al. 2008) for peats versus 2.9 for silt and clay, 3 for sand stone and 3.8 for dolostone (Côté and Konrad 2005)).

It can be concluded that peat material in comparison with peat-sand mixtures can conduct heat at lower rates and thereby provides better temperature insulation. The temperature insulation guarantees the proper and stable temperature for methanotrophic bacteria within the biocover which is especially important in cold climate when atmospheric temperature is low.

3.3.4. Conclusion

In this research, a comprehensive assessment and comparison of the compaction and consolidation behaviours, hydraulic conductivity and thermal conductivity of the studied peat based biocover materials peat and peat-sand mixtures with mix ratio of 1:3, 1:1, and 3:1) are made. The key conclusions based on the analyses of the obtained results can be drawn as follows:

The optimum moisture content of the peat based materials varies from 64% to 96% while the maximum dry density is in the range of 402 to 1004 kg/m^3. The maximum dry density and compactability decrease with increasing sand content. Moreover, the analysis of the results of variations in FAS with moisture content suggests that the maximum O_2 consumption rate (thereby highest CH_4 oxidation potential) in peat and peat-sand samples with mix ratios of 3:1, 1:1, and 1:3 should be expected when the moisture content is between 85-110%, 70-85%, 80-95% and 65-75%, respectively.

The studied peat based materials are compressible. The samples displayed high compressibility to an increase of consolidation pressure, and higher initial moisture contents and organic contents result in higher compressibility. It should be noted that after loading, the primary consolidation of the studied samples was completed in a relatively short time and followed by secondary compression. The value of the C_α/C_c of the samples is in the range of 0.061 to 0.03; this parameter is a function of the consolidation pressure and organic content. The obtained values of C_α/C_c suggest that pure peat has the highest secondary settlement among the studied materials (peat-sand mixtures) which results in higher potential of failure of the pure peat based biocovers due to crack development or changes in the pore structure. This can be mitigated by increasing the sand content.

The hydraulic conductivity values range from 1.74×10^{-9} m/s to 7.35×10^{-9} m/s while the moisture contents vary in an approximate range of 45% to 132 %. The minimum hydraulic conductivities were achieved at optimum moisture contents and decreased when moisture content increased at the wet side of the optimum moisture content.

Thermal conductivity increased with increasing bulk density, moisture content and sand content. However, the effect of the variation in bulk density on thermal conductivity was considerably less than that of moisture content variation. It is found that pure peat material can provide better temperature insulation and consequently more stable temperature within biocover than the peat-sand biocover materials due to their low thermal conductivity which is particularly important in cold climate.

On the basis of derived results, peat-sand mixtures with mix ratio of 3:1 and 1:1 have more desirable mechanical, hydraulic and thermal characteristics as biocover medium (from geotechnical point of view) among all studied biocover mediums. Despite the presented results, detailed study and field investigation on CH_4 oxidation potential and long term performance of the studied peat biocover materials are required.

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4 Behaviour of biocovers in column experiments

4.1 Introduction

A proper understanding of the behaviour of biocovers, including the evolution of thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) processes and their interactions is critical for the effective design, construction and maintenance of biocovers. The main objective of the current chapter is to provide insight into the behaviour of compost and peat based biocovers during their lifetime.

The evaluation of the T (temperature and thermal conductivity), H (hydraulic conductivity, moisture content, and degree of saturation), M (grain size distribution, shear strength and consolidation) and C-B (pH, organic content, gas profile and CH_4 oxidation rate) properties of compost and peat based biocovers and their interactions in two dimensions of time and depth are investigated in the current chapter.

To study the behaviour of biocovers, extensive laboratory column experiments and post analysis and tests have been carried out and the obtained results are discussed.

4.2 Behaviour of compost biocover in column experiments[3]

Afshin Khoshand and Mamadou Fall

Abstract

The anaerobic biodegradation of the organic fraction of deposited waste in landfills produces methane (CH_4), which is a potent greenhouse gas. Methane can be oxidized by a natural biological process when it passes through reactive biological cover soils or biocovers. The optimal design, construction, and maintenance of biocovers require the precise evaluation of geotechnical and geoenvironmental properties, which includes the assessment of the thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) properties of biocovers during their lifetime. In the current paper, the geotechnical and geoenvironmental behaviour of a compost biocover has been investigated through laboratory column tests (over a period of five months) and post experiment analysis. Samples are extracted from the biocover columns at different times and depths, and the geotechnical and geoenvironmental properties are tested. The characterization tests indicate that the biocover medium becomes compacted and the organic content increases with time and depth. The studied samples are frictional in nature and exhibit continuous strength gain with an increase in horizontal deformation during direct shear testing. The shear strength parameters, cohesion (c) and friction angle (φ) are found to vary from 4.2 to 11.6 kPa and 34.9^{o} to 46.3^{o}, respectively. Based on the results of the consolidation tests, the coefficient of consolidation (C_c) values range from 0.23 to 0.76 m^2/year, which generally decrease with depth in each column due to the increase in the bulk density. The hydraulic conductivity of the samples is progressively reduced by two orders of magnitude from the top to the bottom of each column due to compaction. The CH_4 oxidation rate over 153 days shows that the studied compost material is capable of an oxidation efficiency of 84% (209.7 g/m^2 day) of the influent CH_4 flux. The findings presented in the current paper will contribute to a better understanding of the geotechnical and geoenvironmental behaviour of compost

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[3] Submitted to the Acta Geotechnica

biocovers and thus towards the determination of the criteria that enable the efficient design, construction, and maintenance of biocovers.

Keywords: biocover, compost, thermal, hydraulic, mechanical, chemo-biological

4.2.1 Introduction

Landfill gas (LFG) is produced by the anaerobic biodegradation of the organic fraction of disposed waste in landfills (Scheutz and Kjeldsen 2003). LFG consists of about 50-55% methane (CH_4), 40-45% carbon dioxide (CO_2) (Shin et al. 2002), and trace amount of volatile organic compounds (VOCs; Eklund et al. 1998). Methane is a greenhouse gas with the global warming potential 23 to 25 times that of CO_2 (IPCC 2001 and 2007). Landfills are one of the significant sources of anthropogenic CH_4 emissions (Huber-Humer et al. 2009). It is now estimated that 10%-20% of worldwide anthropogenic CH_4 emissions are attributed to landfills (IPCC 2001). CH_4 can migrate to the surface of landfills and be released into the atmosphere due to pressure and concentration gradients even after landfill closure (Scheutz and Kjeldsen 2003). So, urgent control of CH_4 emissions in landfills is necessary for reducing CH_4 concentration in the atmosphere (Stern et al. 2007).

Some of the advanced technologies, such as the extraction and utilization of LFG in the form of energy, can reduce the environmental impacts of landfill emissions (Albanna et al. 2007). However, there is evidence of the escape of large amounts of CH_4 gas at sites which are equipped with the mentioned technologies (Börjesson and Svensson 1997). Also, the costs involved in the technical degasification of old landfills are high (Humer and Lechner 1999) and these technologies are mainly feasible for large and new landfill sites (Albanna et al. 2007).

The current attention is now focused on the development of low cost alternative technologies where implementations of the conventional mentioned methods are not economically or technically feasible (Stern et al. 2007; Barlaz et al. 2004). One of the most promising alternative approaches to the conventional methods is to passively vent LFG through a reactive biological cover soil or biocover in order to oxidize CH_4 by a natural biological process (Ait-Benichou et al. 2007; Philopoulos et al. 2009). The natural CH_4 oxidation process in biocovers is mediated by methanotroph bacteria at the interface of the aerobic and anaerobic zones (Huber-Humer 2004). The methanotroph bacteria use molecular oxygen (O_2) to oxidize CH_4 into CO_2 (Albanna et al. 2007), which has a lower global warming potential than CH_4. The CH_4 oxidation reaction through biocovers can be described by Eq. 4.1 (Van Dijken and Harder 1975):

$$38.25\ CH_4 + 3\ NH_3 + 63.75\ O_2 \rightarrow 3\ C_4H_8O_2N + 26.25\ CO_2 + 69\ H_2O + \text{Heat} \qquad [4.1]$$

A suitable support medium for CH_4 oxidation should have high porosity, high water holding capacity and appropriate stable nutrient levels (Hilger and Humer 2003). Previous laboratory research (Humer and Lechner 1999; Wilshusen et al. 2004) and field studies (Barlaz et al. 2004; Huber-Humer 2004) have reported that generally stabilized and sanitized compost materials meet these criteria and can be a suitable medium for CH_4 oxidation.

Generally, the performance of biocovers is strongly regulated by different geotechnical and geoenvironmental factors. The main influencing factors can be classified as thermal (T) (temperature and thermal conductivity), hydraulic (H) (hydraulic conductivity, moisture content, and degree of saturation), mechanical (M) and physical (grain size distribution, shear strength, and consolidation), and chemo-biological (C-B) (pH, organic content, gas concentration and composition) factors.

Previous studies on biocovers have mostly focused on biochemical behaviours (i.e. CH_4 oxidation capacity) (Humer and Lechner 1999; Kightley et al. 1995; Wilshusen et al. 2004) or the isolated effects of one influencing factor (T, H, M, or C-B) on the performance of biocovers (Hilger et al. 2000; Stein 2000; Huber-Humer 2004). Furthermore, there have been few comprehensive recommendations in the literature with regards to the geotechnical and geoenvironmental behaviour of compost biocovers. Moreover, no previous studies on compost biocovers have investigated the simultaneous evolution of the influencing factors (T, H, M, and C-B) and their interactions. There is a need to acquire sufficient understanding of the geotechnical and geoenvironmental behaviours, and interactions between the T, H, M, and C-B properties of biocovers in order to determine the criteria that enable their optimal design, construction and maintenance.

The objective of the current paper is to experimentally investigate and discuss the simultaneous evolution of the main influencing geotechnical and geoenvironmental factors (T, H, M, and C-B) and their interactions in a compost based biocover by conducting column experiments.

4.2.2 Materials and methods

4.2.2.1 Materials

In the current research, mature and stabilized compost is used as the biocover medium. The compost used was collected from an open windrow operation at the Lafleche landfill site in Moose Creek, Canada. The composting process at the mentioned facility includes well mixing the organic compounds of municipal solid waste (MSW) by rotating drums followed by screening. The materials, which are passed through sieves, are continually turned in windrows to promote uniform degradation. Finally, the materials are stored outdoors on curing pads in order to achieve complete maturation.

The compost material was transported to a laboratory and air-dried at room temperature in order to bring the moisture contents to the same level. Before the experiment, the compost material was sieved through a 9.5 mm mesh and any remaining plant material or large stones were removed by hand. Then, the compost material was moistened to reach a gravimetric moisture content of 35%. This moisture content was recommended by previous studies as the optimum moisture content for methanotrophic activity (Humer and Lechner 1999; Huber-Humer 2004; Huber-Humer et al. 2009).

4.2.2.2 Methods

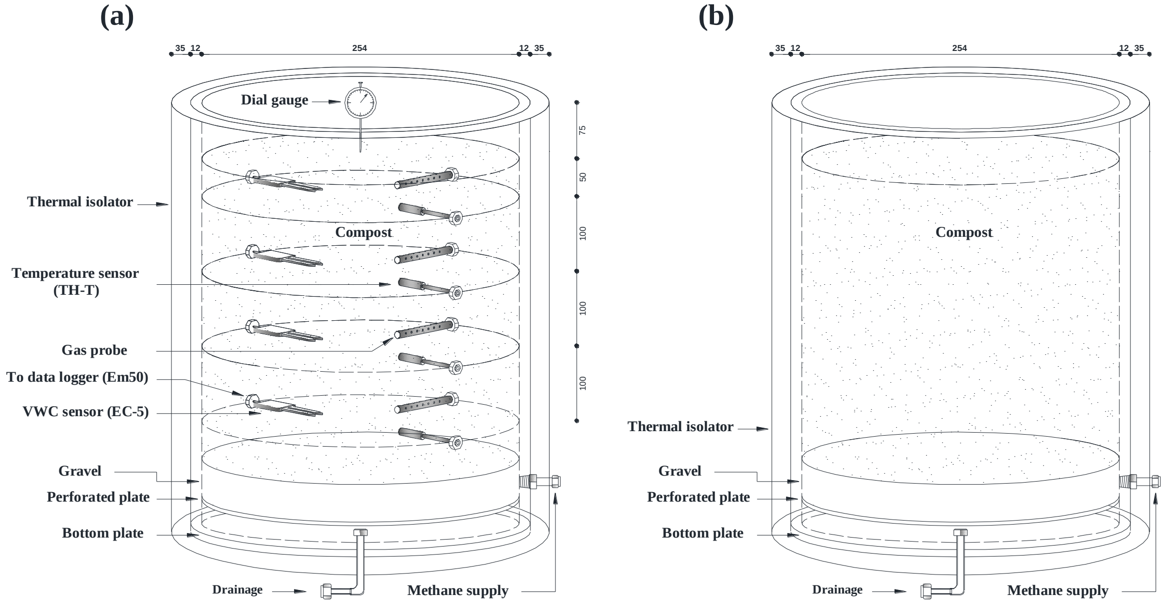
4.2.2.2.1 Column experiment set up, instrumentations and monitoring

Fig. 4.1 presents the schematic diagram of the developed experimental column set-up. The column set-up consists of two columns (A and B), including one instrumented column (A) and one column (B) for sampling. Both columns were manufactured with Plexiglas tubes (inner diameter of 25.4 cm and height of 60 cm). A perforated aluminum plate was installed above a drain at the bottom of each column to support the compost material. A layer of fine and clean gravel was placed as the gas distribution layer to provide a uniform distribution of CH_4 over the entire area of the biocover. The columns were insulated with expansive insulation foam in order to minimize the lateral heat exchange between the compost material within the column and the surrounding atmosphere. An inlet CH_4 flow (99% purity) of 250 g/m^{2}day (equal to 13.21 ml/min) was uniformly injected into the middle of the gas distribution layer of each column. The selected inlet is similar to the mid to high range of reported landfill CH_4 fluxes. The inlet CH_4 flow rate was monitored by a Mass Stream D5111 mass flow controller (M+W Instruments 2011) which was connected to an NI 9219 data acquisition system (National Instruments 2009).

Column A was equipped with four gas sampling ports along the column at intervals of 10 cm from the first port. The gas sampling ports were penetrated into the middle of the column cross-section for monitoring the gas profile through the biocover. The sampling ports were equipped with a plastic fitting and septa which enabled the taking of gas samples via a gastight syringe needle.

In addition to the gas sampling ports, Column A was also equipped with different sensors to continuously monitor the evolution of temperature, volumetric water content (VWC), and vertical settlement of the biocover.

The VWC was monitored by using four calibrated EC-5 dielectric soil moisture sensors (Decagon Devices 2012*a*) at heights of -5, -15, -25, and -35 cm from the surface of the biocover. The EC-5 sensors were placed at the centre of the column cross-section and connected to the EM 50 data loggers (Decagon Devices 2012*b*). Also, the evolution of the temperature for the column depths with time was measured by using TH-T temperature sensors (Roctest Ltd. 2005), which were installed at the same level where the EC-5 sensors were located. All of the sensors were horizontally installed through the wall of the column and their wall connections equipped with a fabricated brass fitting and butyl rubber O ring that completely sealed them. Furthermore, in order to measure the settlement of the biocover medium over time, a dial gauge with a sensitivity of 0.01 mm was installed perpendicular to the surface of the biocover in Column A.



Note: All of the dimensions are in millimetres (mm).

Fig. 4.1. Schematic diagram of the developed biocover column set-ups ((a) Column A (monitoring column); (b) Column B (sampling column)).

4.2.2.2.2 Material characterization tests

Extensive laboratory testing was carried out to evaluate the T, H, M, and C-B properties of the compost material used before beginning the column tests (Phase I). Columns B and A were dismantled after 87 days (Phase II) and 153 days (Phase III) of operation, respectively, and their materials were removed in four undisturbed layers (at depths of -5, -15, -25, and -35 cm from the surface of the biocover) in order to prepare samples for post experiment analysis or tests.

The characterization of all the samples was performed in accordance with the procedures described by the American Society of Testing and Materials (ASTM) standards (ASTM 2010). Measurements of the Atterberg limits, organic content and pH were performed according to ASTM D 4318, D 2974, and D 4972, respectively. A particle size analysis was carried out by following ASTM procedure D 422 for the entire column at the mentioned phases.

4.2.2.2.3 Hydraulic conductivity

Constant head hydraulic conductivity tests were carried out on undisturbed samples by using the flexible wall technique in accordance with ASTM standard procedure D 5084. The undisturbed cylindrical specimens were trimmed from thin-walled metal tubes and then placed into triaxial cells with minimal disturbance. A standard TRI-FLEX II panel, equipped with pressure gauges, regulators, electronic pressure transducers and graduated pipettes, was used in the testing. The specimens were saturated by flushing water under a constant hydraulic gradient and applying back pressure which facilitated saturation. A low hydraulic gradient of 5 kPa was maintained in the testing to avoid anomalies during measurement. The flow measurements were taken in predetermined elapsed periods of time when the samples were saturated and recorded in order to calculate the hydraulic conductivity. Also, the completion of saturation was verified by examining the degree of saturation of the samples at the end of the hydraulic conductivity tests. Each hydraulic conductivity test was repeated at least twice and the average value was considered as the saturated hydraulic conductivity value of the sample.

4.2.2.2.4 Direct shear testing

Direct shear testing is an appropriate method to determine the shear strength properties of compost biocovers (Benson and Othman 1993; Puppala et al. 2006; Bajwa 2012; Ho et al. 2011). Thereby, consolidated drained direct shear tests were performed on undisturbed samples in accordance with ASTM D 3080 in order to investigate the shear strength behaviour of the compost material at different depths (-5, -15, -25, and -35 cm from the surface of the biocover) and times (Phases I (0 day), II (87th day), and III (153rd day)).

To simulate field conditions, the samples were sheared at three normal stresses of 10, 20 and 40 kPa, which are in the range of induced normal stresses in landfills in field conditions (Rajesh and Viswanadham 2011). In order to prevent the generation of excess pore water pressure during shearing and also satisfy the recommended criteria by ASTM D 3080, shearing was performed at a slow rate of 0.0025 mm/min. The shear strength parameters, cohesion (c) and angle of friction (φ) of the compost material were determined based on the Mohr–Coulomb failure criteria.

4.2.2.2.5 Consolidation testing

Consolidation testing was performed by using a floating ring oedometer on the undisturbed samples and following ASTM procedure D 2435 to evaluate the consolidation behaviour of the studied biocover materials. The undisturbed circular specimens (with diameter to thickness ratio of 3:1) were carefully placed into the ring to avoid disturbance. Each sample was consolidated under 5, 10, 20, 40 and 80 kPa of stress and each loading was continuously monitored for 24 hours.

4.2.2.2.6 Thermal conductivity

In this study, a portable KD2 thermal properties analyzer (Decagon Devices 2012*c*) and dual stainless-steel needle SH-1 thermal sensor (30 mm in length, 1.28 mm in diameter, with spacing of 6 mm) were used to measure the thermal conductivity of the undisturbed samples under isothermal conditions.

The KD2 thermal properties analyzer, which employs the transient line source (TLS) method, calculates thermal conductivity by monitoring heat dissipation from a line heat source given a known voltage. For the measurement of thermal conductivity, the SH-1 thermal sensor was slowly and steadily inserted into the undisturbed samples and allowed to reach thermal equilibrium for at least 15 minutes before taking the reading. Also, for accurate measurement, the needles remained parallel to each other during insertion and a minimum of 15 mm of the sample surrounded the needles in all directions. The default reading time for the SH-1 sensor is 2 minutes and the thermal conductivity was measured with a relative error of 10% (Decagon Devices 2012*c*). Also, each test was repeated three times and the average value was considered as the thermal conductivity value of the samples.

4.2.2.2.7 Gas analysis

The gas samples (1 mL) were analyzed by manual injection via a Series 400 isothermal gas chromatograph (GC) instrument (Gow-Mac Instrument 2011), which was equipped with a thermal conductivity detector (TCD) and two stainless steel columns. O_2 and nitrogen (N_2) were analyzed on a Molsieve 13X, 80/100 mesh column, while a HayeSep Q, 80/100 mesh column was used to quantify CH_4 and CO_2. The carrier gas was high purity helium (99.999% He, vol. basis), and column, injector, and detector temperatures were respectively 120°C, 130°C, and 130°C. Standard gas samples which were directly made from a cylinder of a known volumetric concentration were used for calibration.

4.2.3 Results and discussion

4.2.3.1 Material characteristics

The evolutions of the pH, bulk density, porosity (n), Atterberg limits, and organic content with time and depth are shown in Figs. 4.2a-e, respectively. As illustrated in Fig. 4.2, the compost used in this study has an initial porosity of 79.4%, a high organic content (initial organic content of 29.4%), and neutral pH (initial pH of 6.7). These properties are similar to those which are recommended as properties of suitable biocover materials in the literature (Huber-Humer et al. 2009).

It can be seen from Fig. 4.2a (pH profiles) that the pH values remain relatively constant (with a narrow range of variation from 6.55 to 6.75) with time, but there is a slight decrease of the pH values with depth throughout the study period. This trend is similar to that reported by Einola (2010). The bulk density profiles (Fig. 4.2b) indicate that the bulk density values increased, and the compost medium became compacted with depth. Also, the bulk density of the compost medium increased with time from Phase II (87th day) to III (153rd day) which is the result of the rearrangement of the orientation of the compost particles and organic content degradation (Pokhrel 2006). The compaction due to the settlement of the biocover resulted in a general reduction of the porosity (Fig. 4.2c) with depth and time which could affect gas transport and CH_4 oxidation rate over time through the biocover medium (Pokhrel 2006).

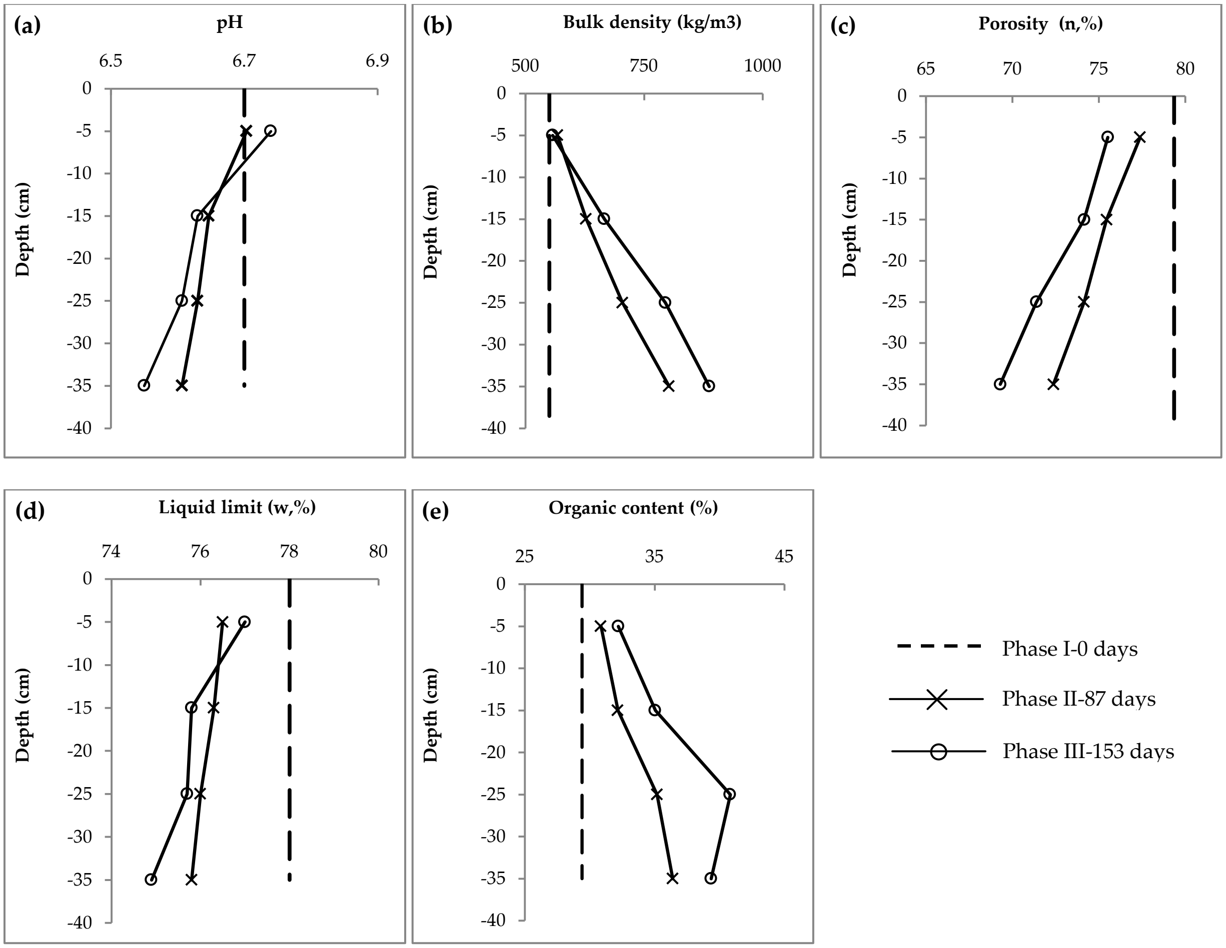


Fig. 4.2. Variation of pH, bulk density, porosity, LL, and organic content of compost biocover medium with depth at different times.

((a) pH, (b) bulk density, (c) porosity, (d) LL, and (e) organic content).

It can be seen from Fig. 4.2d that the liquid limit of the compost medium is 78% in Phase I (0 days) and varies between 75.8% - 76.5%, and 74.9% - 77% for Phases II (87th day), and III (153rd day), respectively. There is no significant change in the liquid limit values with depth. These high ranges of the liquid limits for the compost material show good agreement with those quoted in the literature (Benson and Othman 1993).

Fig. 4.2e presents the organic content depth profile at different times. The maximum organic contents of the biocover medium are 29.4% before beginning the column operation, 36.4% after 87 days and 40.8% after 153 days of column operation which are observed at column depths of

-35 to -25 cm, respectively. This increase in the organic content with time is attributed to the formation of exopolymeric substances (EPS; Pokhrel 2006). The EPS are long chain organic compounds which are produced by methanotroph bacteria under certain environmental conditions (Huber-Humer 2004). The formation of EPS was clearly observed after approximately six weeks in the transparent columns. Therefore, a higher organic content of the compost medium after 87 and 153 days of column operation (36.4% and 40.8% at column depths of -35 and -25 cm, respectively) in comparison to the initial value of 29.4% implies the presence of methanotrophic activities at these depths. Similar higher organic contents at depths with maximum CH_4 oxidation were also reported by Kightley et al. (1995) and Wilshusen et al. (2004) in soil and compost columns, respectively. The organic content profile can be a surrogate to determine the depth for maximum CH_4 oxidation (Pokhrel 2006).

4.2.3.2 Mechanical and physical properties

4.2.3.2.1 Grain size distribution

The evolution of the grain size distribution of the compost is presented in Fig. 4.3. The compost samples in Phases I (0 day), II (87th day) and III (153th day) were classified respectively as organic well-graded sand (SW), organic well-graded sand (SW), and organic poor-graded sand (SP) based on the Unified Soil Classification System (USCS). It can be seen that the samples became finer with time due to the mineralization of the compost material over time (Huber-Humer 2004). The reduction of the particle size of the compost material as the biocover medium during column testing over time has also been reported by Huber-Humer (2004).

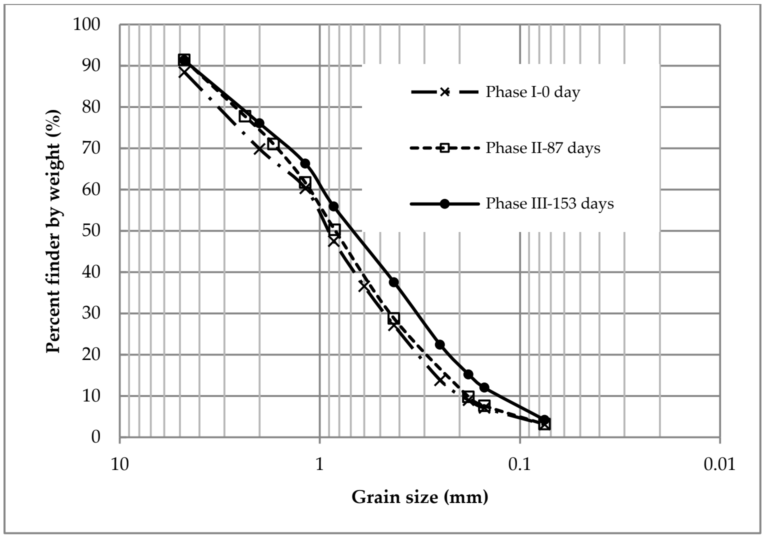


Fig. 4.3. Particle size distribution of compost biocover medium at different times.

4.2.3.2.2 Shear strength characteristics

Bicovers should be physically stable and have adequate shear strength to resist cracking during local subsidence and sliding failures (Benson and Othman 1993). The physical stability of biocovers is controlled by the shear strength parameters. The shear strength is assessed in terms of the φ and c, which are the basic parameters of the Mohr-Coulomb failure criteria.

Figs. 4.4 and 4.5 illustrate horizontal displacement versus shear stress response under normal stresses of 10, 20 and 40 kPa for the studied material at different depths and for Phases II and III. As shown in Figs. 4.4 and 4.5, all of the samples exhibit continuous increases in strength with increases in horizontal deformation. In the absence of reaching the peak strength, the shear stress at 15% horizontal deformation was selected to establish the Mohr-Coulomb shear strength envelopes (Reddy et al. 2011). The shear stress at 15% horizontal deformation versus normal stress was plotted and the shear strength parameters (c and φ) were calculated in accordance with the Mohr-Coulomb failure criteria.

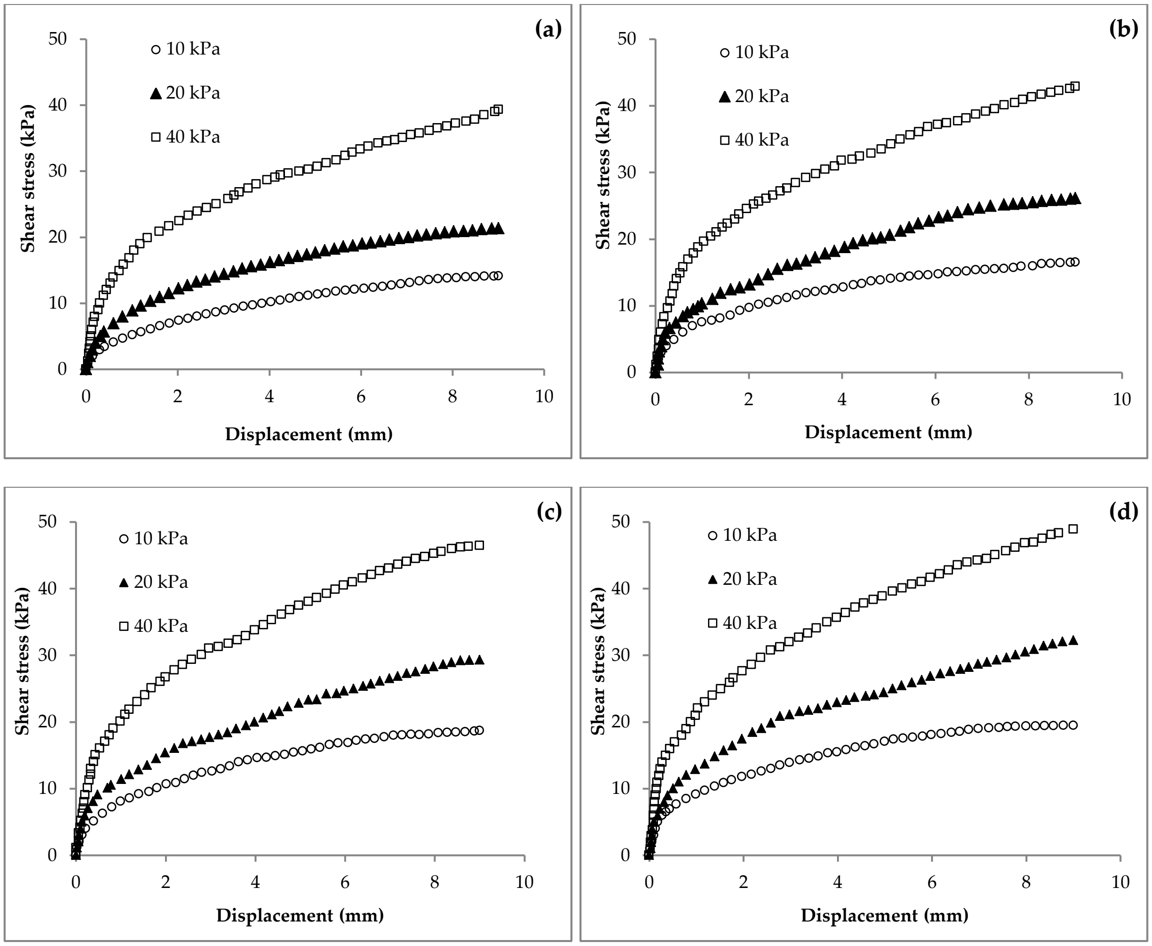


Fig. 4.4. Variation of shear stress versus horizontal displacement of compost biocover medium samples at different depths in Phase II (87 days)
((a) -5 cm; (b) -15 cm; (c) -25 cm; and (d) -35 cm).

The biocover medium changed from a loose to dense condition (Fig. 4.2b) due to the rearrangement and deformation of the compost particles with depth and time. Therefore, as shown in Figs. 4.4 and 4.5, the ultimate strength increases at the same values of the normal stress with depth and time. It should be noted that the difference between the ultimate strengths decreases with time due to the decreasing rate of compaction. The difference of the ultimate strengths at a normal stress of 40 kPa between Phases I and III is 38%, and 7% between Phases II and III at the same normal stress.

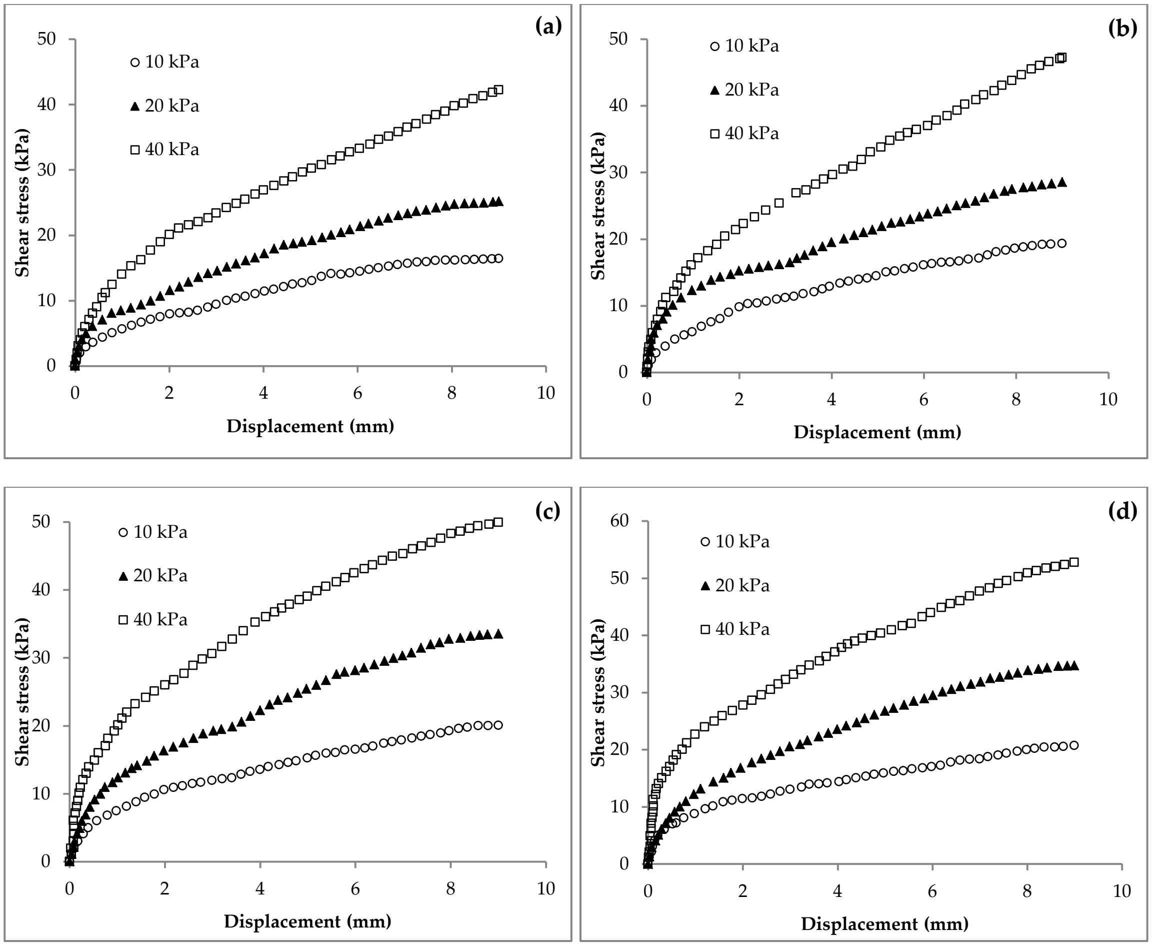


Fig. 4.5. Variation of shear stress versus horizontal displacement of compost biocover medium samples at different depths in Phase III (153 days)

((a) -5 cm; (b) -15 cm; (c) -25 cm; and (d) -35 cm).

The values of c and φ of the samples at different depths and the three phases are presented in Table 4.1. In this study, the φ and c of the studied material in Phase I are 34.9° and 4.2 kPa, respectively, which are similar to those reported in the literature by Ho et al. (2011) for uncompacted compost material. It can be clearly observed from Table 4.1 that the studied materials are frictional in nature and φ improves with depth and time, which is favourable for the mechanical stability of sloped biocovers. This trend is attributed to the compaction of the biocover medium due to settlement with depth which causes larger interlocks between the compost particles and subsequently increases the φ (Mouzai and Bouhadef 2011).

Table 4.1. Shear strength parameters of the biocover medium at different depths and time.

Sample	Depth (cm)	Cohesion, c (kPa)	Angle of friction, φ (°)
Phase I	All depths[1]	4.2	34.9
Phase II	-5	5.2	40.3
	-15	8.2	41.1
	-25	10.1	42.5
	-35	11.1	43.8
Phase III	-5	7.9	40.6
	-15	10	42.9
	-25	11.9	44.1
	-35	11.6	46.3

[1] Includes -5, -15, -25, and -35 cm.

Nimmo (2004) and Annabiabc et al. (2007) found that organic materials exert forces through surface tension or electrical charges, and increase cohesion through the binding of soil particles. Therefore, in Table 4.1, an increase in cohesion can be progressively observed with increasing organic content from the top to the bottom of the columns in Phases II (87 days) and III (153 days).

In field conditions, internal seepage erosion causes lower shear strength which can eventually result in the slope failure of the biocover. Therefore, the obtained laboratory values of c and φ should be reduced by 15–25% as suggested in the literature (Bagchi 1990). However, the laboratory obtained φ of the used material under drained conditions ranged between 34.9° and 46.3°, so by applying the mentioned safety factor, the compost material has adequate strength to resist shear failure on slopes less than 25°.

4.2.3.2.3 Consolidation behaviour

Strains due to sudden stress changes in biocovers could translate into continued settlements and crack development in biocovers. Settlement has significant effects on physical stability, O_2 penetration and therefore the CH_4 oxidation rate of biocovers (Bajwa 2012). So, proper knowledge of the amplitude and rate of consolidation with respect to the stress level is of prime importance for evaluating the mechanical behaviour of biocovers.

In this study, the calculation of the coefficient of consolidation (C_v) is carried out based on the square root of time (Taylor's) method and the results are presented in Table 4.2. The C_v values of the compost material range from 1.55 to 2.12 m^2/year before the beginning of the column operation (Phase I), 1.78 to 2.27 m^2/year after 87 days (Phase II) and 1.85 to 2.34 m^2/year after 153 days (Phase III) of column operation. It can be seen that in general, by increasing the organic content from the beginning (29.4%) to the end of the column operation (30.9-36.4%), the C_v values are increased (1.55 to 2.12 m^2/year versus 1.85 to 2.34 m^2/year).

Table 4.2. Coefficient of consolidation of biocover medium at different times and depths.

Load	Depth (cm)	C_v (m^2/year)		
		Phase I (0 days)	Phase II (87 days)	Phase III (153 days)
5	-5	2.12	2.18	2.26
	-15		2.21	2.27
	-25		2.24	2.3
	-35		2.27	2.34
10	-5	2.01	2.08	2.16
	-15		2.1	2.18
	-25		2.11	2.21
	-35		2.15	2.24
20	-5	1.93	1.98	2.02
	-15		2.01	2.07
	-25		2.03	2.09
	-35		2.06	2.14
40	-5	1.76	1.87	1.93
	-15		1.9	1.95
	-25		1.92	1.98
	-35		1.95	2.00
80	-5	1.55	1.78	1.85
	-15		1.79	1.88
	-25		1.82	1.9
	-35		1.84	1.92

The increase in the C_v values in Phases I to III (1.55 to 2.12 m^2/year versus 1.85 to 2.34 m^2/year) is more than that of Phases II to III at the same depth. This difference is related to fewer changes in the organic content in Phases II to III in comparison to Phases I to III as illustrated by Fig. 4.2e. Islam et al. (2006) also reported variations of the coefficient of consolidation with organic content soils. Furthermore, based on the theory of consolidation, the coefficient of consolidation decreases with increasing consolidation pressure (Leonards and Girault 1961). It is clear from

Table 4.2 that there is a reduction in the C_v values of the samples with an increase in the consolidation pressure.

Fig. 4.6 shows the void ratio (*e*) variation versus the logarithm of the consolidation pressure (*σ*) curve of the samples at the four different column depths (-5, -15, -25 and -35 cm) and different times (Phases I, II, and III). It can be seen from Fig. 4.6 that the studied biocover materials are compressible with considerable reductions in the void ratio with increasing consolidation pressure. Also, the void ratio of the samples decreases as the depth increases at the same consolidation pressure. This is because the biocover medium becomes more compacted with increasing depth (Fig. 4.1b) which results in lower void ratios.

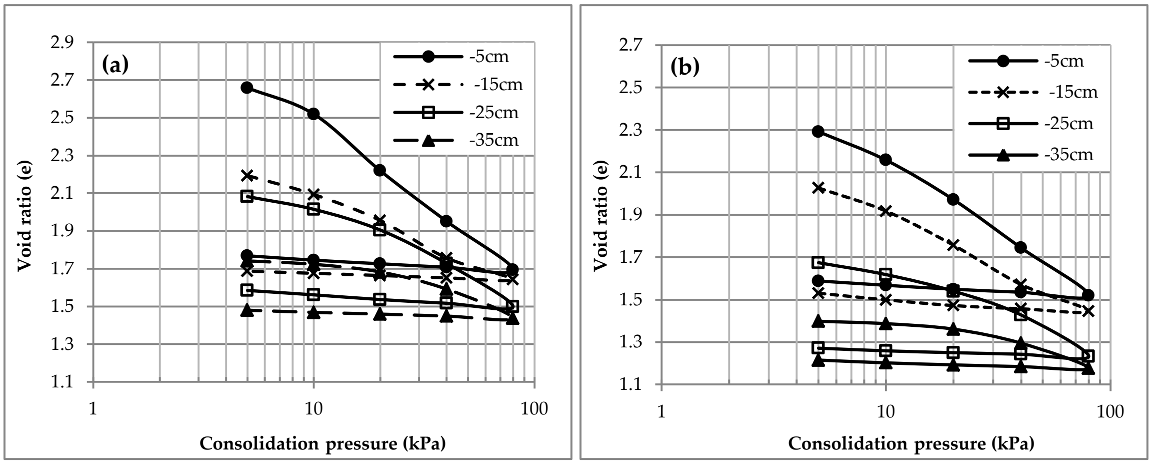


Fig. 4.6. Consolidation curves of compost biocover medium at different depths and times ((a) Phase II (87th day), and (b) Phase III (153rd).

The compression index (C_c) and recompression index (C_r) of the samples which are the slopes of the consolidation curves (Fig. 4.6) for the loading and unloading stages during the consolidation process, respectively, are shown in Table 4.3.

The consolidation behaviour and associated settlement of the biocover medium can be explained by the C_c values such that a higher value of the C_c results in higher settlement. Mesri and Ajlouni (2007) found that the compressibility of organic soils is significantly controlled by the organic content and dry bulk density. The C_c value of the biocover medium at the beginning of the column operation (Phase I) is 0.85 which is greater than that in Phases II and III at all depths (Table 4.3). This difference is attributed to the lower bulk density and organic content of the compost material in Phase I (which is respectively 550.3 kg/m^3 and 29.4%) in comparison to those of the biocover medium in Phases II and III at all depths (Figs. 4.2b and e).

Table 4.3. Compression and recompression indexes of the biocover medium at different depths and times.

Sample	Depth (cm)	C_c	C_r
Phase I	All depths[1]	0.85	0.079
Phase II	-5	0.76	0.067
	-15	0.50	0.040
	-25	0.48	0.071
	-35	0.32	0.035
Phase III	-5	0.71	0.059
	-15	0.48	0.070
	-25	0.43	0.032
	-35	0.23	0.031

[1]Includes -5, -15, -25, and -35 cm.

It can be seen from Table 4.3 that the C_c value which reflects the compressibility of the material ranges from 0.76 to 0.32 and 0.71 to 0.23 for Phases II and III, respectively. Generally, the compression index decreases with increases in the dry bulk density such that the compression index is decreased with depth due to the increasing bulk density in each phase.

Moreover, the C_r value which reflects the swelling potential of the material ranges from 0.067 to 0.035 and 0.059 to 0.031 respectively for Phases II and III. The recompression index generally shows decreases with depth due to compaction.

Furthermore, the vertical settlement of the biocover medium was monitored over 153 days in the column operation and the result is shown in Fig. 4.7.

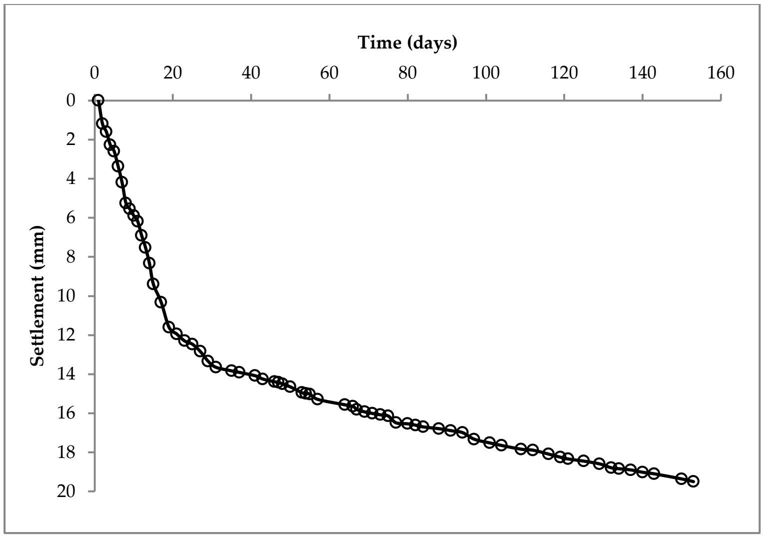


Fig. 4.7. Vertical settlement of compost biocover medium over 153 days.

The settlement rate of the bicover medium in the first 30 days is 0.45 mm/day followed by lower increments in the following 123 days (0.05 mm/day). It can be observed that after 30 days of column operation, the settlement curve maintains a relatively straight line with time. This behaviour can be attributed to the rearrangement of the compost particles which is due to the decrease in the pressure due to self-weight over time. The obtained results are compatible to those obtained by Huber-Humer (2004) and Bajwa (2012). The observed settlement did not affect the CH_4 oxidation rate (Fig. 4.12). However, in the determination of the minimum thickness of the biocover and also if a minimum thickness is required by regulatory agencies, biocover designers must account for the reduction of the thickness of the biocover induced by settlement or consolidation.

The studied biocover materials were relatively compressible with an average deformation of 20% of the initial height during consolidation tests. In field conditions, sudden changes of stresses due to field installation and maintenance activities can cause natural consolidation and settlement of biocovers. Such natural consolidation and settlement are more significant when the biocovers are placed without any artificial compaction.

4.2.3.3 Hydraulic properties

4.2.3.3.1 Saturated hydraulic conductivity

The performance of biocovers is strongly influenced by gas transport processes which support CH_4 advection flux (upward) and O_2 diffusion flux (downward) into the CH_4 oxidation zone (Bajwa 2012). The gas transport processes are significantly regulated by the hydraulic conductivity of the porous media (Pedersen 2010) such that higher hydraulic conductivity results in better gas exchanges through the biocover and enhances the CH_4 oxidation rate. Conversely, in order to minimize rainfall infiltration which contributes to leachate production, biocover saturation and subsequently drastic reduction of the CH_4 oxidation rate (Pokhrel 2006; Scheutz et al. 2009), biocovers should have low hydraulic conductivity. Therefore, a proper hydraulic conductivity value of the biocover medium is a key factor which influences the rate of CH_4 oxidation and water intrusion through a biocover.

The variation of the hydraulic conductivity of the biocover medium with depth is presented in Fig. 4.8. It can be observed that the hydraulic conductivity values are 4.7×10^{-5} m/s in Phase I, 2.14×10^{-5} to 2.4×10^{-7} m/s in Phase II, and 9.1×10^{-6} to 9.34×10^{-8} m/s in Phase III.

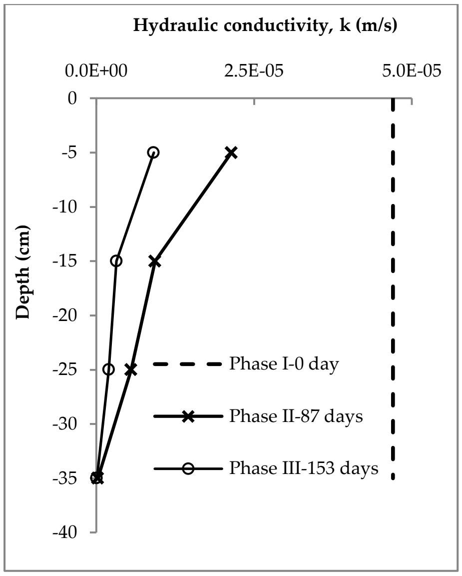


Fig. 4.8. Variation of hydraulic conductivity of compost biocover medium with depth at different times.

As shown in Fig. 4.8, there is a significant drop in the hydraulic conductivity of the biocover after 87 days of column operation (from 4.7×10^{-5} m/s to a range of 2.14×10^{-5} to 2.4×10^{-7} m/s). Also, the saturated hydraulic conductivity value is decreased from 3.2×10^{-6} m/s (at a depth of -5 cm) by two orders of magnitude to reach 9.34×10^{-8} m/s (at a depth of -35 cm) in Phase III. The reduction in the saturated hydraulic conductivity with depth and time is attributed to physical compression (Fig. 4.7) and creep processes over time (Abdolahzadeh et al. 2011), which change the porosity and pore structure of the compost biocover. This is supported by the results of the evolution of the porosity with time and depth as shown in Fig. 4.2c. The hydraulic conductivity is strongly regulated by the physical and structural arrangements of the constituent particles (Edil 2003); void ratio, and size and shape of the flow channels (Mesri and Ajlouni 2007). The compost particles are porous and large, and subsequently have large pore size and high void ratios or porosity (Fig. 4.2c) which contribute to a high initial hydraulic conductivity prior to the column operation. As time progressed, the medium became more compacted (as shown in Fig. 4.7) and finer (as illustrated in Fig. 4.3), respectively, due to self-weight pressure and mineralization of the compost material over time (Huber-Humer 2004). These processes cause a reduction in coarse pores and porosity (Fig. 4.2c), destruction of pore continuity (Dec et al. 2008) and finally, a drastic reduction of the hydraulic conductivity (Huat et al. 2011; Ankeny et al. 1990; Fuentes et al. 2004; Horn and Smucker 2005). An analysis of the results presented in Fig. 4.8 for relationships as those shown in Fig. 12 (will be discussed later) reveals that the observed significant reductions in the hydraulic conductivity or permeability are not associated with a significant reduction in the CH_4 oxidation capacity of the biocover, This means that the CH_4 oxidation capacity of biocovers with permeability values as low as those presented above would be satisfactory. In, addition, these low permeabilities will reduce the infiltration of water into biocovers. Such infiltration would not only contribute to the generation of leachate, but also increase the degree of saturation (Sr) of the biocover to a value higher than 85%. It is well known that when Sr approaches 85%, the air phase in the pores of the biocover material start to become occluded, (Brooks and Corey 1966; Nagaraj et al. 2006), thus leading to a strong reduction in gas migration, and thereby decreasing the effectiveness of the biocover.

4.2.3.3.2 Degree of saturation and moisture content evolution

The CH_4 oxidation rate in biocovers corresponds to the gas permeability of the medium, which is affected by the degree of saturation (S_r) (Huber-Humer 2004). A high S_r causes aqueous diffusion of CH_4 and O_2 through the biocover medium which is much slower (10^{-4} folds less rapid) than gaseous diffusion. So, the CH_4 oxidation rate of biocover is drastically reduced at high S_r (Huber-Humer 2004). Moreover, the growth of microorganisms is strongly regulated by water availability. Low moisture content causes inactivation of methanotrophic microorganisms which leads to the reduction of the CH_4 oxidation rate (Huber-Humer 2004; Sternenfels 2012; Humer and Lechner 1999).

The evolution of S_r in the biocover for Phases I, II and III is illustrated in Fig. 4.9a. It can be seen that the S_r in the top layer (-5 cm) is reduced to 14% and 7% after 87 and 153 days of column operation respectively. This can be attributed to evaporation induced surface desiccation with time in the top layer.

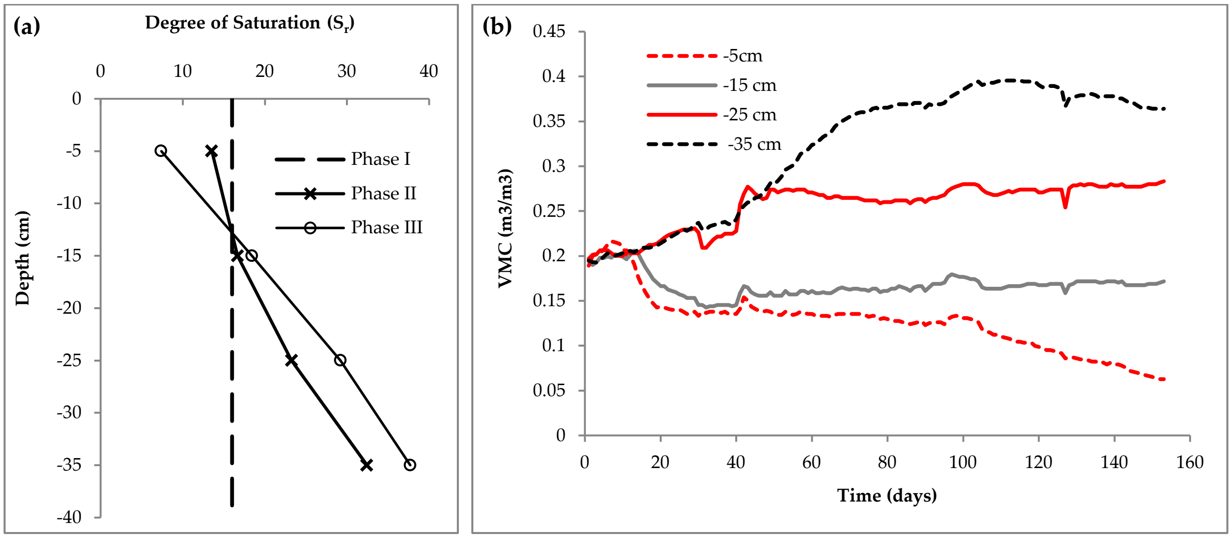


Fig. 4.9. Variation of degree of saturation and VWC of compost biocover medium with depth at different times.

((a) degree of saturation, and (b) VWC)).

Furthermore, the S_r progressively increases from the top layer (14% and 7% respectively in Phases II and III) to the bottom layer (32% and 38% respectively in Phases II and III) and this increase is more significant at the end of the column operation. This can be explained by downward moisture movement and more methanothrophic activity in the bottom layer. Other researchers (Bajwa 2012; Cabral et al. 2010) also reported high S_r in the bottom layer of the studied biocovers.

Moreover, the degree of saturation was always less than 85%, which is, as explained above, the S_r threshold, beyond which air becomes occluded in the soil (Brooks and Corey1966; Nagaraj et al. 2006), gas fluxes become quite low (Nicholson et al. 1989; Yanful 1993; Aachib et al. 2004; and Cabral et al. 2004) and subsequently, there are reductions in the microbial oxidation activity (Cabral et al. 2010).

Fig. 4.9b presents the variations of the volumetric water content (VWC) with time at different depths of the biocover. The initial VWC throughout the depth of the biocover was 19% which consistently dropped in the top layer (-5 cm) with time and reached a minimum value of 6.2% on day 153. The top 5 cm of the biocover was noticeably drier due to evaporation induced surface desiccation (Stein and Hettiaratchi 2001; Stein 2000). The low VWC of the upper layers indicates a lack of methanotrophic activity within those depths which can affect the biocover performance (Wilshusen et al. 2004). Unlike the surface layer, the VWC in the bottom layer continuously increased with time and was higher than the initial value (37% and 36.4% respectively in Phases I and II in comparison to the initial value of 19%). This high VWC value is attributed to the downward migration of moisture (Stein 2000; Bajwa 2012) and production of water during the CH_4 oxidation process (Pedersen 2010) due to high methanotrophic activity in this region (Stein 2000).

4.2.3.4 Thermal properties

4.2.3.4.1 Temperature

Temperature has a significant effect on CH_4 oxidation processes (Scheutz et al. 2009), especially at very low and high temperatures (Pokhrel 2006). The CH_4 oxidation rate increases with temperature up to the maximum oxidation rate and then decreases with increasing temperatures (Czepiel et al. 1996).

Various researchers have cited different optimum temperatures for methanotrophic activity. Börjesson and Svensson (1997) observed a range of 25-35ºC as the optimum temperature for CH_4 oxidation while Dunfield et al. (1993) and Mor et al. (2006) reported optimum temperatures around 20°C and 25°C respectively. Moreover, CH_4 oxidation can occur at 4ºC as well as 55ºC (Humer and Lechner 2001; Hanson and Hanson 1996) at a lower rate compared to the optimum temperature range. Therefore, proper knowledge about the evolution of temperature in biocovers is essential in order to enhance the CH_4 oxidation rate.

Fig. 4.10 illustrates the development of the temperature of the studied material with time at selected depths. It can be seen that the average temperature was 24.7°C at the beginning of the experiment.

There is an increasing trend in the temperature for the 10 days of column operation at all depths. The highest temperature during this period of time was 37.8°C at a depth of -5 cm where O_2 availability was not a limiting condition. The increase in temperature during the first 10 days of column operation can be attributed to the aerobic degradation of available carbon sources in the compost (Sternenfels 2012). A similar trend was also observed by Bajwa (2012) who studied the behaviour of compost based biocovers.

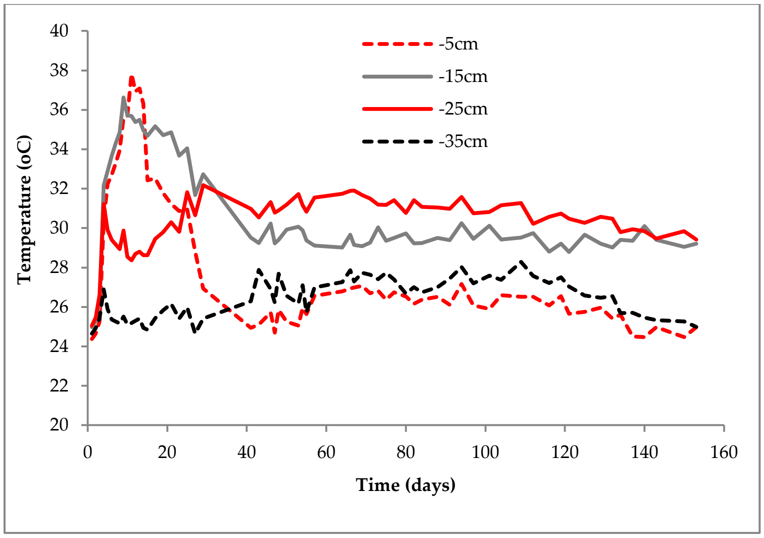


Fig. 4.10. Variation of temperature at different depths of compost biocover with time.

The CH_4 oxidation process is an exothermic one which releases 780 kJ per mol of oxidized CH_4 (Scheutz et al. 2009). This leads to an increase in the temperature in the active oxidation layer (layer with accumulated visible water vapor and orange colored biofilm) (Pedersen 2010). The obtained results indicated that the average temperature of the middle layers (30.7°C and 30.3°C at depths of -15 and -25 cm, respectively) is higher than those of the bottom (-35 cm) and surface (-5 cm) layers (26.3°C and 28°C respectively).

Moreover, the evolution of the temperature at different levels inside the column can be analyzed to obtain further information on the CH_4 oxidation process and vertical zonation of the microbial activity inside the column. Fig. 4.10 shows the development of a zone between the -15 and -25 cm layers of the studied biocover that has a high temperature (3.3°C higher in comparison to the rest of the substrate), which is an indication of the intense microbial activity and consequently higher CH_4 oxidation rate. The CH_4 oxidation rate (Fig. 4.12) is consistent with this observation and the zone with the highest rate of CH_4 oxidation was localized in the middle layer.

The average temperature in the column (28.9°C) was generally higher than the average ambient temperature (24.3°C). The heat generated by the microbial activity is the reason for the difference in temperature (Huber-Humer 2004). A similar difference between the ambient and column temperatures has been also reported in the literature (Huber-Humer 2004; Pedersen 2010; Berger et al. 2005).

The temperature and consequently CH_4 oxidation process within the biocover are influenced by the atmospheric temperature (Dever et al. 2010). In field conditions, the CH_4 oxidation process may slow down during winter when the atmospheric temperature commonly falls below 10°C (Dever et al. 2010). However, the temperature increase within the biocover due to the exothermic process of the methanotrophic activity could maintain temperatures within the biocover high enough to enable the CH_4 oxidation process in cold climates (Humer and Lechner 2001). In contrast, for biocovers located in warm climates, this temperature increase may result in increasing evaporation, drying out the upper layers of the biocover, and consequently, reduce the CH_4 oxidation rate (Dever et al. 2010). Also, it could lead to excessive temperatures in the biocover, which is detrimental to its effectiveness. Indeed, at temperatures higher than 40°C, the oxidation ability of the bacteria severely decreases, and at 50°C, practically no oxidation takes place (Zeiss 2006).

4.2.3.4.2 Thermal conductivity

The thermal conductivity reflects the rate of the heat flux dissipation (Al Nakshabandia and Kohnke 1964) and influences the temperature in biocovers (Chandrakanthi et al. 2005). The evolution of the thermal conductivity in biocovers has an important effect on the rate of CH_4 oxidation in various climatic and thermal loading conditions.

The variations of the thermal conductivity at selected depths and times are presented in Fig. 4.11. The thermal conductivity is influenced by the moisture content, bulk density (Chandrakanthi et al. 2005) and organic content. The results indicated that the minimum thermal conductivity (0.23 W/m° K) is achieved in the top layer of column at the end of the column operation due to the minimal VWC (Fig. 4.9b) of this layer in the mentioned phase. This is caused by the fact that the thermal conductivity of water (0.59 W/m° K) is more than 20 times greater than that of air (0.025 W/m° K) (Holman 2002). By reducing the moisture content, the volume fractions of air are increased and the portion of the pore spaces filled with water is decreased (Ahn et al. 2009). So, the thickness of the water films around the soil particles and the indirect contact area between the soil particles are reduced, which result in decreases in the thermal conductivity (Abu-Hamdeh and Reeder 2000).

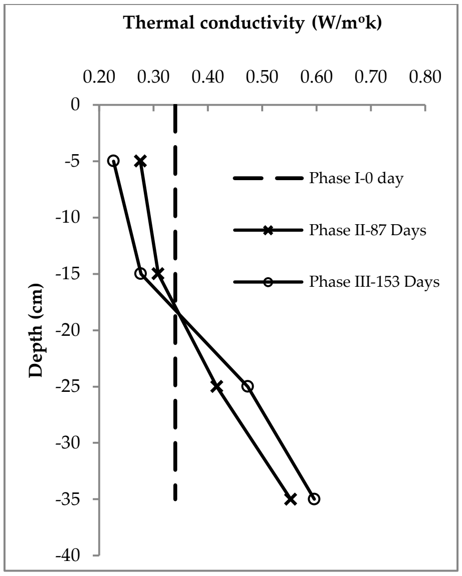


Fig. 4.11. Variation of thermal conductivity of compost biocover medium with depth at different times.

As shown in Fig. 4.9b, by increasing the VWC from the top (6%) to the bottom layers (36%) in Phase III as well as increasing the bulk density from 557.6 kg/m^3 to 887.4 kg/m^3, the thermal conductivity is increased from 0.23 to 0.6 W/m^o K. A similar trend is also observed for Phase II. The results indicated that the effect of the organic content on the thermal conductivity is negligible in comparison to the effect of the moisture content and bulk density. Moreover, by increasing the bulk density of the biocover medium with time and depth (Fig. 4.2b), the contact area between the individual particles increases (Al Nakshabandi and Kohnke 1965). This phenomenon results in the facilitation of heat movement through the medium and an increase in the thermal conductivity.

The efficient and long term operation of field biocovers depends on maintaining a suitable and favourable temperature for the growth of methanotroph bacteria (Chandrakanthi et al. 2005). A thermal conductivity profile (Fig. 4.11) indicates that the compost material has lower thermal conductivity in comparison to that of mineral soils (e.g., 2.9 W/m^o K for silt and clay, 3 W/m^o K for sand stone and 3.8 W/m^o K for dolostone (Côté and Konrad 2005)) which is due to the coarse texture and high amount of air filled space of the compost material (Scheffer and Schachtschabel 1992). This means that the compost material is able to conduct heat at a lower rate (Hettiarachchi 2005) and therefore, provide appropriate temperature insulation (Huber-

Humer 2004). Temperature insulation protects biocovers against unfavorable conditions and guarantees a favorable temperature for the methanotroph bacteria within the biocover which is particularly important in field conditions during winter (Huber-Humer 2004).

4.2.3.5 ChemoBiological properties

4.2.3.5.1 Methane oxidation rate

In this paper, the CH_4 oxidation rate at selected depths is based on CH_4 consumption per Eq. 4.2.

$$\mathrm{CH_4\ oxidation\ rate} = \frac{(C_{CH_4})_{t=0} - (C_{CH_4})_{t=i}}{(C_{CH_4})_{t=0}} \times j_{CH_4} \text{ (Albanna et al. 2007)} \qquad [4.2]$$

In the above equation, the CH_4 oxidation rate is measured in g/m^2 day, $(C_{CH_4})_{t=0}$ is the CH_4 concentration (%v/v) which was fed into the column and assumed to be 100%, $(C_{CH_4})_{t=i}$ is the CH_4 concentration (%v/v) on the ith day, j_{CH_4} is inlet CH_4 flux in g/m^2 day.

The adaptation phase is the time to reach the steady state of CH_4 oxidation in biocovers. In the literature, different adaptation periods (between 5 and 10 days) have been reported for laboratory experiments (Huber-Humer 2004; Wilshusen et al. 2004; Humer and Lechner 2001). The adaptation phase for this study is relatively quick (10 days) which implies the presence of a high microbial mass that acclimatizes quickly (Wilshusen et al. 2004).

The CH_4 oxidation rate of the studied column over a period of 153 days is shown in Fig. 4.12. This figure shows the adaptation phase (10 days) which is followed by the steady state phase. The phase with the high oxidation rate continues for approximately 119 days. In this phase with a high rate of oxidation, the CH_4 oxidation rate reaches a maximum value of 209.7 g/ m^2 day which indicates the suitability of the selected compost as a biocover medium. Moreover, the obtained results of the CH_4 oxidation rate are compared to the estimated CH_4 emissions for a 10 year old bioreactor landfill with an assumed depth of 20 meters. It can be observed that the studied biocover is capable of entirely oxidizing the released CH_4 emissions from this bioreactor landfill (107 g/ m^2 day; Huber-Humer 2004).

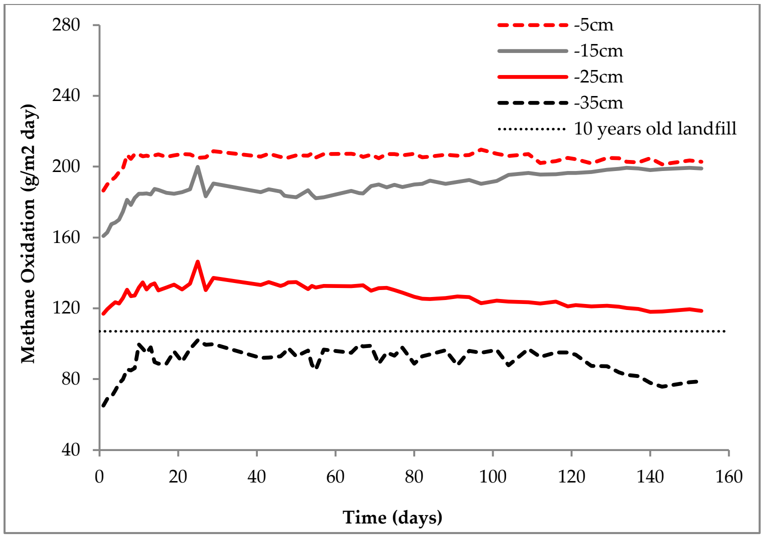


Fig. 4.12. Variation of CH_4 oxidation rate at different depths of compost biocover with time.

After 119 days of the phase with the high rate of oxidation had passed, a decline in the CH_4 oxidation rate was observed at depths of -25 and -35 cm, and the performance of the biocover at the mentioned levels slowly declined until the end of the experiment (153 days). The phase with the reduction in the CH_4 oxidation rate (after the 119th day to the end of the experiment) is a result of EPS formation and therefore this phase is called the "EPS-affected phase" (Wilshusen et al. 2004). It is well known that EPS formation results in the clogging of the pores of the media and hinders CH_4 and O_2 flows within biocovers (Huber-Humer 2004; Sternenfels 2012). The clogging of the pores of the biocover at a depth of -35 cm is also supported by the results of the evolution of the porosity with time and depth as presented in Fig. 4.2c. It can be seen that the lowest porosity value is found at a depth of -35 cm. The competition between methanotroph and heterotroph (which require organic compounds as sources of carbon and energy) microorganisms for available O_2 and nutrients is another factor which contributes to the reduction in the CH_4 oxidation rate (Sternenfels 2012). A similar trend for the CH_4 oxidation rate has also been observed in previous studies (Huber-Humer 2004; Wilshusen et al. 2004; Sternenfels 2012).

4.2.3.5.2 Gas profile

The gas profile is the result of the biochemical reaction, diffusion and advection of gas flow (De Visscher 2001).The gas profile indicates the concentration of O_2, N_2, CH_4 and CO_2 at the selected depths (-5, -15, -25, -35 cm) within the columns. The behaviour and vertical zonation of the microbial community at different depths as well as the suitability of the studied medium for gaseous transport can be evaluated by assessing the gas profiles (Huber-Humer 2004).

The gas profiles for six different selected periods (after 25, 50, and 75, 101, 125 and 150 days of column operation) are shown in Fig. 4.13. Generally, the concentrations of O_2 and N_2 have declined from the top to the bottom of the column while the opposite is true for CH_4 and CO_2.

It can be seen from Fig. 4.13a that the CH_4 concentration becomes less than 20% on the surface layer (-5 cm) at the end of the 25 days of column operation. Also, the O_2 penetration depth is more than 30 cm and the N_2 concentration is almost around its atmospheric concentration in this period of time as well. The explanation for these observations is that O_2 is penetrated along the vertical profile and the CH_4 oxidation process occurs in the presence of adequate O_2.

After 25 days of column operation, O_2 could no longer be found in layers deeper than 25 cm and a high CH_4 oxidation rate during this time period was observed at depths of 25 to 35 cm below the surface. The low O_2 concentrations in layers deeper than 25 cm may be attributed to the fact that O_2 was immediately consumed as it became available.

As time progressed, the CH_4 oxidation layer shifted upwards towards the O_2 source and could be found at a depth of 15 to 25 cm below the surface (after 69 days of column operation). The shifting of the CH_4 oxidation layer has also been reported by Huber-Humer (2004) and Pokhrel (2006) who studied the CH_4 oxidation of compost based biocovers in column experiments. The reason for the shifting CH_4 oxidation layer is due to the accumulation of EPS in the deeper layer (-25 to -35 cm) of the column which prevented the diffusion of O_2 further down (Huber-Humer 2004). It should be noted that the shifting of the active CH_4 oxidation layer did not affect the overall CH_4 oxidation rate and there was still a high oxidation rate after 69 days of column operation. Previous research have reported that the active CH_4 oxidation layer is generally located at a depth of 20 to 30 cm in the soil profile (Scheutz and Kjeldsen 2003; 2004), which is similar to the obtained results in the current research.

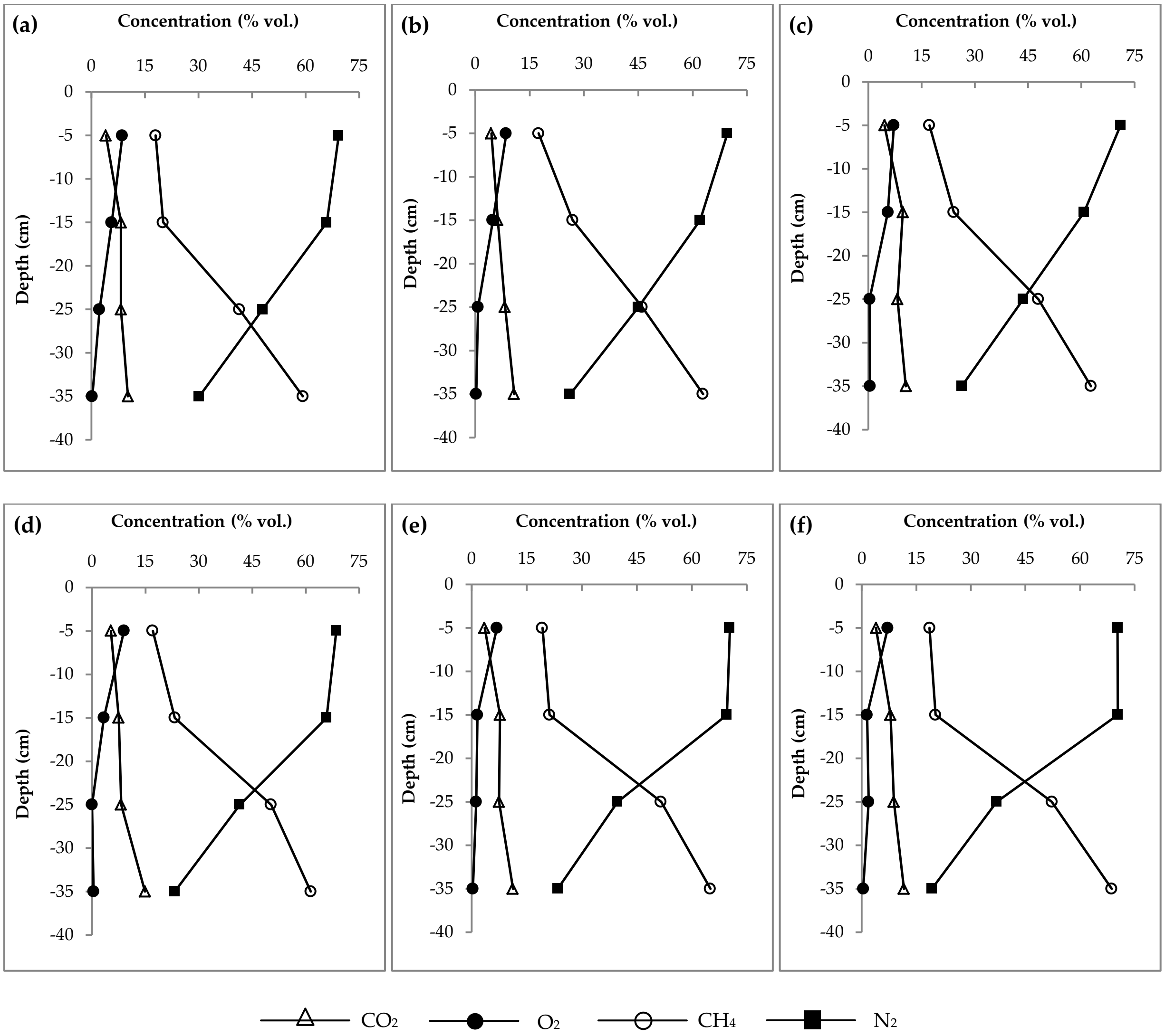


Fig. 4.13. Gas composition of compost biocover during the of column operation ((a) 25th, (b) 50th, (c) 75th, (d) 101st, (e) 125th, and (f) 150th day of column operation).

In contrast to O_2, N_2 is not used for the CH_4 oxidation process. The presence of N_2 in the deepest layer (-35 cm) for an extended period of time can be used as an indicator of air intrusion (Berger et al. 2005) and also implies that the influent CH_4 flux was being diluted (Cabral et al. 2010). The gas profile changed at the end of the experimental period (after 121 days of column operation). The CH_4 profile showed a gradual increase in the surface layer (Figs. 4.13e and f) and the concentration of the downward migrating O_2 is less than 2%. The reduction in the CH_4 oxidation rate can be explained by the unfavourable conditions for methanotrophic activity and

EPS formation which developed a layer with low hydraulic conductivity. This layer restricted the downward mitigation of O_2 and upward mitigation of CH_4

4.2.4 Summary and conclusions

In this research, the evolution of the geotechnical and geoenvironmental properties (T, H, M, and C-B) of a compost biocover and their interactions in two phases of time and different depths are investigated through an experimental laboratory column setup over a period of 153 days and extensive post experiment tests are also conducted. According to the derived results, the following key conclusions can be made.

The average temperature in the column is 28.9°C, which is higher in comparison to an ambient temperature of 24.3°C, and means that this is related to the methanotrophic activity and consequently CH_4 oxidation in the biocover. This temperature increase could maintain a temperature within the biocover high enough to enable the CH_4 oxidation process in field conditions, particularly during winter. The thermal conductivity of the studied compost material is low in comparison to those of mineral soils and progressively increases from the top layer (0.28 and 0.23 W/m°K respectively in Phases II and III) to the bottom layer (0.55 and 0.6 W/m°K respectively in Phases II and III) within the column through increases in the bulk density and VWC. The low thermal conductivity of the compost material provides temperature insulation which could protect the biocover against unfavorable thermal conditions in cold climates.

The biocover medium becomes more compacted due to the pressure of self weight as time progresses, which results in the reduction of the hydraulic conductivity values. The hydraulic conductivities of the bottom layer are 2.4×10^{-7} m/s and 9.34×10^{-8} m/s in Phases II and III respectively, which are lower than the range of the hydraulic conductivity values of traditional landfill covers.

The VWC of a biocover is a key influencing factor for CH_4 oxidation. The low efficiency of the surface layer in CH_4 oxidation especially after 119 days of the column experiment can be attributed to its low VWC (average of 8% in the last 23 days) due to evaporation induced surface desiccation.

The studied biocover materials are relatively compressible. The C_c values are 0.85 and in the range of 0.76 to 0.32 and 0.71 to 0.23 respectively for the three phases. The C_c values and subsequently compressibility of the studied samples generally decrease with depth due to increases in the bulk density. Also, further settlement of the biocover during its life time should be considered in the design process and selection of the initial thickness of the biocover.

The compost material used is capable of removing a CH_4 influent flux of 209.7 g/m^{2}day.

4.2.5 References

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4.3 Behaviour of compost-sand based biocover in column experiments[4]

Afshin Khoshand and Mamadou Fall

Abstract

Natural biological methane (CH_4) oxidation through biocovers is considered an innovative and cost effective method for the mitigation of CH_4 emissions from landfills. In order to enable optimal design, construction, and maintenance of biocovers, a comprehensive evaluation of their geotechnical and geoenvironmental behaviour is essential, including an assessment of their thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) properties. In the current research, a laboratory column study over a period of five months and extensive post experiment tests are conducted to investigate the geotechnical/geoenvironmental behaviour of a compost-sand mixture as a biocover medium. According to the obtained results, the bulk density and organic content of the medium increase with depth and time. The studied specimens exhibit continuous strength gain with an increase in horizontal deformation during direct shear testing. The cohesion (c) and friction angle (φ) of the samples are in the range of 2.7 to 6.1 kPa and 38.3° to 49.5°, respectively. The gas profiles indicate that concentrations of oxygen and nitrogen generally decline from the top to the bottom of the column while the opposite is true for concentrations of CH_4 and carbon dioxide. Over the study period, CH_4 oxidation has been observed at different depths and reaches 178.8 g/m^2 day (which corresponds to 72% of influent CH_4 flux), although optimum CH_4 oxidation almost occurs near the middle layers. Presumably because of unfavourable conditions for methanotrophic activity, low CH_4 oxidation is mostly observed near the surface. Moreover, thermal conductivity increases with depth by increasing the bulk density (0.45 $W/m^{\circ}K$ to 0.58 $W/m^{\circ}K$ and 0.42 $W/m^{\circ}K$ to 0.61 $W/m^{\circ}K$ on the 76th and 150th days, respectively). The findings of the current research can contribute to a better understanding of the behaviour of compost-based biocovers and thus towards the design of more cost-effective and durable biocovers.

Keywords: biocover; compost-sand; THMC; greenhouse gas; climate change.

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[4] Submitted to the Canadian Geotechnical Journal

4.3.1 Introduction

The anaerobic biodegradation of municipal solid waste (MSW) in landfills produces landfill gas (LFG) which mainly consists of methane (CH_4) and carbon dioxide (CO_2) (Shin et al. 2002). The Intergovernmental Panel on Climate Change 2001 and 2007 (IPCC 2001 and 2007) defined CH_4 as a potent greenhouse gas (GHG) with a global warming potential (GWP) 23 to 25 times greater than that of CO_2 in a horizon of 100 years. Landfills are considered to be the fourth largest anthropogenic source of worldwide CH_4 emission (Lu et al. 2011). The current global CH_4 emission from landfills is between 500 and 800 metric tons CO_2 equivalent (Mt $CO_{2\text{-eq}}$) per year (IPCC 2007) and estimated to reach 1500 Mt $CO_{2\text{-eq}}$ per year by 2030 (Bogner et al. 2008).

Different technologies are proposed in the literature to reduce the environmental impact of CH_4 emissions from landfills, such as the application of gas recovery systems and burning CH_4 emissions with high temperature flares (Huber-Humer et al. 2008). These technologies can be economically and technically efficient methods for large and new landfill sites with a high rate of CH_4 production (Haubrichs and Widmann 2006; Huber-Humer et al. 2008). It should be mentioned that even with the application of the mentioned technologies, there is evidence of the escape of a significant amount of CH_4 gas into the atmosphere through the landfill cover layer (Albanna et al. 2007). Therefore, there is a need to take effective steps to develop cost-effective alternative technologies, where implementations of conventional methods are not economically or technically feasible for reducing and controlling CH_4 emissions from landfills.

A promising cost-efficient technology is the oxidation of CH_4 through biological soil covers (which are also referred to as biocovers) by a natural microbial process (Ait-Benichou et al. 2007; Philopoulos et al. 2009). The CH_4 oxidation process in biocovers is mediated by methanotrophic bacteria which use molecular oxygen (O_2) to oxidize CH_4 into CO_2 (Albanna et al. 2007). Biocovers generally consist of a filter substrate for supporting the growth and activity of methanotrophic bacteria, placed above a gas distribution layer for homogenizing LFG fluxes.

Suitable filter material for biocovers should have high porosity, water holding capacity and specific surface area, and appropriate stable nutrient levels in order to enhance bacterial growth and the activity of methanotrophic bacteria (Huber-Humer 2004; Huber-Humer et al. 2009; Philopoulos et al. 2009). Previous laboratory research (Humer and Lechner 1999; Wilshusen et al.

2004) and field studies (Barlaz et al. 2004; Huber-Humer 2004) have demonstrated that stabilized and sanitized compost materials have the aforementioned properties and are therefore promising filter materials for biocovers.

The decomposition of compost material necessitates the replacement of the biocover filter material in order to maintain biocover structure and performance (Pedersen et al. 2011). This could be avoided by mixing compost material with more inert materials, such as sand (Scheutz and Kjeldsen 2003). Also, mixing the compost with sand enhances the geotechnical properties of biocovers, especially under unfavourable conditions (Philopoulos et al. 2009; Scheutz et al. 2009; Powelson et al. 2006).

The performance of biocovers is strongly regulated by various geotechnical and geoenvironmental factors which can be classified as thermal (T), hydraulic (H), mechanical and physical (M), and chemo-biological (C-B) factors. The mechanical behaviour is a critical factor which affects the long term performance and durability of biocovers. The strain due to changes in the stress in biocovers results in settlement, pore water drainage, and crack and fissure development (Bajwa 2012). Continued settlement causes reduction in the porosity of biocovers, which consequently impedes the gas exchange process within the biocovers (Bajwa 2012). Crack development within biocovers results in the development of preferential pathways for CH_4 to escape into the atmosphere and increase the amount of emitted CH_4.

Shear strength is an imperative mechanical parameter since it always plays a vital role in sliding and rotation failures, and subsequently, the physical stability of biocovers (Benson and Othman 1993). The shear strength is the resistance to shear deformation and described in terms of the internal angle of friction (φ) and cohesion (c). Therefore, accurate knowledge about shear strength properties and magnitude, and the rate of the settlement of biocovers with respect to stress level is critically challenging in the evaluation of the long term performance of biocovers.

It has been proven that the CH_4 oxidation process in biocovers is profoundly influenced by thermal properties, including temperature (Bajwa 2012) and thermal conductivity. Methanotrophic bacteria are mainly mesophilic (Hanson and Hanson 1996) and can thrive in moderate temperatures (20°C to 37°C) (Humer and Lechner 1999). The optimum temperature for methanotrophic activity is in the range of 15°C to 35°C (Zeiss 2006). Furthermore, CH_4

oxidation can continue even as low as 4°C and as high as 55°C (Humer and Lechner 2001, Hanson and Hanson 1996) in comparison to the range of optimum temperature for methanotrophic activity. In terms of intrinsic thermal properties, thermal conductivity expresses the rate of heat dissipation (Al Nakshabandia and Kohnke 1964) and can control the temperature (Chandrakanthi et al. 2005) within biocovers. To assess the evolution and distribution of temperature within biocovers, a proper understanding on the thermal conductivity of biocover material is a prerequisite.

The behaviour and performance of biocovers are also affected by hydraulic properties, including moisture content and hydraulic conductivity. Moisture is essential for methanotrophic activity and acts as a transport medium for nutrient supply and metabolite removal (Scheutz et al. 2009). Excessive moisture content hinders gaseous transport processes while insufficient moisture content causes physiological stress to the microorganisms and consequently, inactivation of methanotrophic activity (Huber-Humer 2004, Sternenfels 2012, Humer and Lechner 1999). The hydraulic conductivity of biocovers has a distinct impact on gas transport processes in biocovers (upward advection flux of CH_4 and downward diffusion flux of O_2 into the CH_4 oxidation zone) and consequently, the CH_4 oxidation rate. An appropriate hydraulic conductivity value guarantees efficient gas exchange within biocovers and also prevents water infiltration and leachate generation. Knowledge of the hydraulic behaviour of biocovers is an essential requirement for the accurate design, construction, and maintenance of biocovers.

Prior research has mainly focused on the CH_4 oxidation patterns of biocovers (Humer and Lechner 1999; Kightley et al. 1995; Wilshusen et al. 2004) or the isolated effects of one influencing factor (T, H, M, or C-B) on the performance of biocovers (Hilger et al. 2000; Stein 2000; Huber-Humer 2004). Moreover, there have been no comprehensive recommendations in the literature on compost-sand biocovers with regards to the simultaneous evolution of the main influencing factors (T, H, M, and C-B) and their interaction. There is a need to acquire an appropriate understanding of the geotechnical/geoenvironmental behaviour and interactions between the T, H, M, and C-B properties of biocovers in order to derive criteria that enable optimal design, construction and maintenance of compost-sand biocovers.

The objective of the presented research in this paper is to comprehensively investigate and discuss the simultaneous evolution of the thermal (T) (temperature and thermal conductivity), Hydraulic (H) (hydraulic conductivity, moisture content, and degree of saturation), Mechanical and physical (M) (grain size distribution, shear strength, and consolidation), and ChemoBiological (C-B) (pH, organic content, gas concentration, and CH_4 oxidation rate) factors as the main influencing factors and their interactions in a compost-sand biocover through column experiments and post experiment tests.

4.3.2 Materials and methods

4.3.2.1 Materials

The materials used in this research include compost, sand, and water.

4.3.2.1.1 Compost

The mature and stabilized compost which is recommended in the literature as the biocover medium (Humer and Lechner 1999; Wilshusen et al. 2004; Barlaz et al. 2004; Huber-Humer 2004) was used. The compost was collected from an open windrow operation at the Lafleche landfill site in Moose Creek, Canada.

4.3.2.1.2 Sand

Ottawa sand was used, which was supplied by Unimin Canada Ltd. In order to ensure that methanotrophic bacteria were not present in the sand, the sand was oven dried prior to the experiments. Moreover, the sand used was free of organic content based on the results of the laboratory tests performed in accordance with ASTM D2974.

4.3.2.1.3 Water

Tap water was used to moisten and prepare the biocover medium.

4.3.2.2 Material preparation

The compost samples were transported to a laboratory. Prior to the experiment, the compost material was air-dried at room temperature and sieved through a 9.5 mm mesh in order to remove any plant material or large stones. Then, the compost material was mixed with sand (at a mix ratio of 3:1 (w/w)) and the gravimetric moisture content of the mixture was adjusted to 30%. The moisture content was selected according to recommendations on the optimum moisture content for the growth and activity of methanotrophs in the literature (Humer and Lechner 1999; Huber-Humer 2004; Huber-Humer et al. 2009). The mineralogical composition of the studied compost–sand mixture was determined by X-ray diffraction analyses and the results are summarized in Table 4.4.

Table 4.4. Mineralogical composition of used compost-sand material.

Constituent	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**Na_2O**	**MgO**	**CaO**	**K_2O**	**TiO_2**	**P_2O_5**	**Cr_2O_3**	**MnO**	**V_2O_5**	**LOI[1]**
Content (%)	45.27	6.01	2.1	1.3	1.03	6.44	2.4	0.24	0.99	0.02	0.04	<0.01	33.08

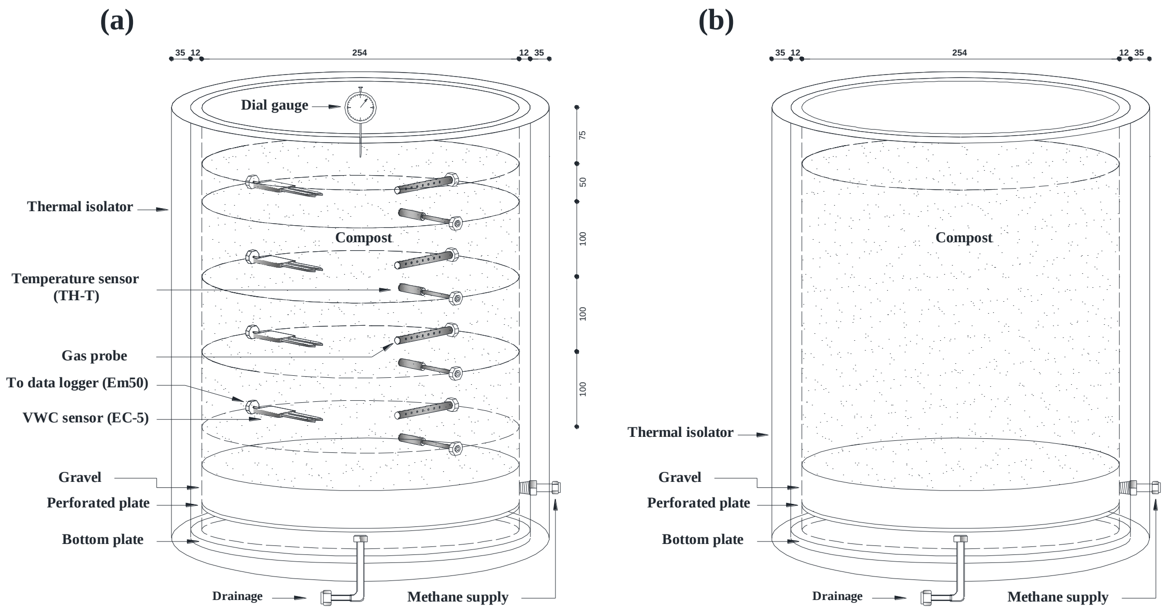
[1] Loss of ignition

4.3.2.3 Column experiment set up

Two columns, Column A for instrumentation and Column B for sampling, were manufactured. To manufacture the columns, two Plexiglas tubes with an inner diameter of 25.4 cm and a height of 60 cm were used as the framework. Each column was packed with a layer of fine and clean gravel as the gas distribution layer in order to supply a homogeneous distribution of CH_4 over the entire area of the biocover. At the middle of the gas distribution layer of each column, an inlet for CH_4 gas was installed and an inlet CH_4 flow (99% purity) of 250 g/m^2 day (equal to 13.21 ml/min) was continuously injected. The mentioned CH_4 inlet was chosen to simulate a mid to high range of landfill CH_4 fluxes (Bogner et al. 1997). The inlet CH_4 flow rate was monitored by a Mass Stream D5111 mass flow controller (M+W Instruments 2011) which was connected to an NI 9219 data acquisition system (National Instruments 2009). To minimize the lateral heat exchange between the biocover material within the column and the surrounding environment, each column was insulated with expansive insulation foam sealant. Also, in order to provide drainage in case of leachate build-up, an outlet was installed at the bottom of both columns. In contrast to previous laboratory column studies with similar setups (e.g. De Visscher et al. 1999; Hilger et al. 2000; Scheutz and Kjeldsen 2003) in which the columns were closed at the top with an impermeable cap, the top of both columns remained open in the current research. This was done to simulate field conditions in which the surface of biocovers is exposed to air.

4.3.2.4 Column instrumentations and monitoring

Four gas sampling ports were placed along the length of Column A at intervals of 10 cm from the first port and penetrated into the center of the column. The sampling ports consist of plastic fittings and tightly sealed butyl-rubber septa which enable gas samples to be taken by using a gastight syringe needle. Moreover, Column A was equipped with various sensors to continuously monitor the evolution of temperature, volumetric water content (VWC), and vertical settlement of the biocover. The temperature was monitored by using four TH-T temperature sensors (Roctest Ltd. 2005) at heights of -5, -15, -25, and -35 cm from the surface of the biocover. Furthermore, the evolution of the VWC for column depth with time was monitored by using calibrated EC-5 dielectric soil moisture sensors (Decagon Devices 2012*a*). The EC-5 dielectric soil moisture sensors were installed at the same level as the TH-T temperature sensors and connected to EM 50 data loggers (Decagon Devices 2012*b*). All of the sensors were horizontally installed through the wall of the column and their wall connections secured with a fabricated brass fitting and butyl rubber O ring to ensure a gastight fit. A dial gauge with a sensitivity of 0.01 mm was installed perpendicular to the surface of the biocover in Column A to monitor the settlement of the filter material over time. Moreover, a temperature and humidity sensor was used to monitor the room temperature and relative humidity during the column operation. Fig. 4.14 presents a schematic diagram of the experimental column set-ups developed in this study.



Note: All dimensions are in millimetres (mm).

Fig. 4.14. Schematic diagram of the developed biocover column set-ups ((a) Column A (monitoring column), (b) Column B (sampling column)).

4.3.2.5 Methods

In addition to the column monitoring as described above, comprehensive laboratory testing was conducted in order to assess the T, H, M, and C-B properties of the compost-sand mixture before beginning the column tests (Phase I), and on the 76th day (Phase II), and 150th day (Phase III) of column testing. For this purpose, Column B on the 76 days (Phase II) and Column A on the 150 days (Phase III) were dismantled in four undisturbed layers (at depths of -5, -15, -25, and -35 cm from the surface) for conducting post experiment analysis and tests. Fig. 4.15 shows a summary of the laboratory experimental testing and monitoring program. The characterization of the T, H, M, and C-B properties of the samples was carried out based on procedures described in the American Society of Testing and Materials (ASTM) standards (ASTM 2010). Each sample was tested in terms of the Atterberg limits, organic content and pH in accordance with ASTM D4318, D2974, and D4972, respectively. A particle size distribution test was conducted in accordance with ASTM D422 for the entire column from Phases I to III.

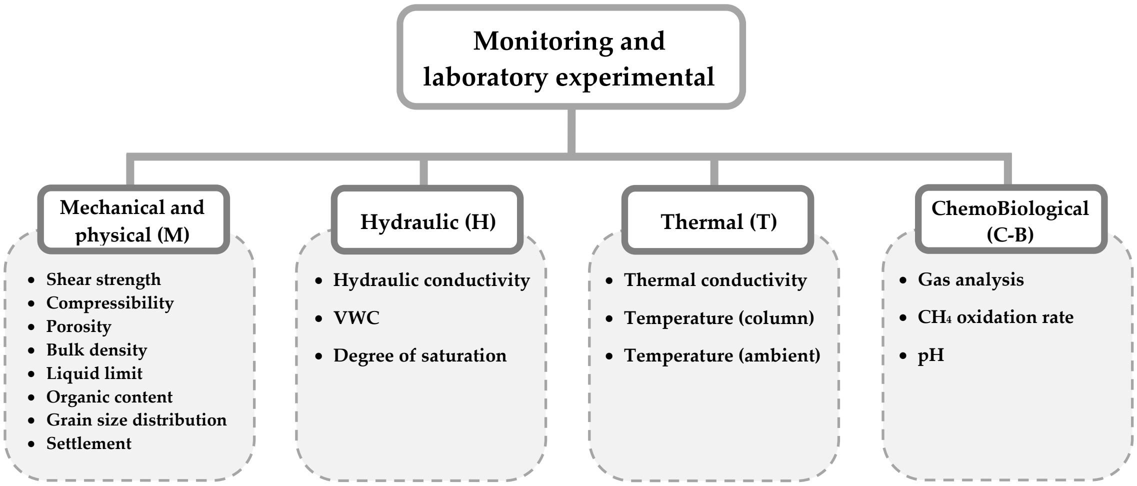


Fig. 4.15. Summary of laboratory experimental testing and monitoring program.

4.3.2.5.1 Determination of hydraulic conductivity

The hydraulic conductivity of the samples was measured by using the constant head technique and fixed wall permeameter system in accordance with ASTM D5084. A Tri-Flex II master control panel with three burette channels, pressure gauges, regulators, and electronic pressure transducers was used in the experiment. Undisturbed cylindrical samples were trimmed by using a thin-walled metal tube with minimal disturbance and placed into the triaxial cell. One sheet of filter paper and a porous stone were placed on both ends of each sample to prevent fine particle segregation during the hydraulic conductivity measurements. The saturation of the samples was accomplished by flushing water under a constant hydraulic gradient and applying back pressure. A low hydraulic gradient of 5 was applied to the samples to avoid anomalies in measurements. The volumes of the inflow and outflow were recorded at predetermined elapsed times and the hydraulic conductivity of the samples was calculated based on Darcy's law. The hydraulic conductivity of each sample was tested at least twice to ensure the repeatability of the measurement and also for quality control.

4.3.2.5.2 Determination of shear strength properties

Prior studies on compost material (e.g., Benson and Othman 1993; Puppala et al. 2006; Bajwa 2012; Ho et al. 2011) have shown that direct shear testing is appropriate for determining the shear strength properties of compost-based biocovers. The consolidated drained direct shear test was used to determine the shear strength parameters of the undisturbed samples in accordance with ASTM D3080. The undisturbed samples were trimmed and placed into the shear box which was filled with tap water for consolidation prior to shearing. Rajesh and Viswanadham (2011) reported that normal stresses in landfill covers are in the range of 10 to 40 kPa, including the self weight of the cover materials. Therefore, the specimens were consolidated at normal stresses of 10, 20 and 40 kPa in order to simulate overburden pressures which are typically expected in landfill covers. After consolidation, the samples were sheared at a constant slow rate (0.0025 mm/min) under the aforementioned normal stress. A slow shearing rate was chosen in order to satisfy the recommended criteria by ASTM D3080 and avoid the generation of excess pore water pressure during shearing. The shearing was continued until the horizontal displacement reached 15% or more of the specimen diameter in the absence of reaching peak strength (Reddy et al. 2011). The shear stress at 15% horizontal deformation versus normal stress was plotted and the c and φ were calculated based on the Mohr-Coulomb failure criteria.

4.3.2.5.3 Determination of compressibility behaviour

Consolidation testing was conducted in accordance with ASTM D2435 in a floating ring oedometer on undisturbed samples in order to determine the compressibility behaviour of the biocover material. The undisturbed circular specimens (with a diameter to thickness ratio of 3:1) were taken from the block sample at different depths (-5, -15, -25, and -35 cm from the surface of the biocover) and placed into the consolidometer ring with minimal disturbance. The specimens were sandwiched between two sheets of filter paper and porous stones to enable two ways vertical drainage and avoid the forcing of fine particles into the pores of the porous stones. The saturation of the specimens was accomplished by soaking them for 24 hours. Once the saturation process was completed, each sample was subjected to pressures up to 80 kPa in the sequence of 5, 10, 20, 40 and 80 kPa and the compressibility of the samples during each loading was continuously monitored for 24 hrs.

4.3.2.5.4 Determination of thermal conductivity

The thermal conductivity of the undisturbed samples was measured by using a portable KD2 thermal properties analyzer (Decagon Devices 2012*c*) and an SH-1 thermal sensor (30 mm in length, 1.28 mm in diameter, and spacing of 6 mm) that uses a dual-needle heat pulse. The KD2 thermal properties analyzer measures thermal conductivity through temperature measurements at intervals of one second during a thirty-second heating period and a thirty-second cooling period (Decagon Devices 2012*c*). To measure the thermal conductivity, the SH-1 thermal sensor was steadily inserted into the undisturbed samples and allowed to equilibrate for at least 15 minutes before the measurement was taken. The default reading time for an SH-1 sensor is two minutes and the relative error for the measurement of thermal conductivity is 10% (Decagon Devices 2012*c*). Moreover, the needles remained parallel to each other during insertion and a minimum of 15 mm of sample surrounded the needles in all directions in order to insure an accurate measurement. Each thermal conductivity measurement test was repeated at least three times to ensure the repeatability and accuracy of the results obtained.

4.3.2.5.3 Determination of gas concentration

Gas samples were taken at regular intervals from the gas sampling ports along Column A by using a gas tight 1 mL syringe over the 150 days of column operation. The gas samples obtained were analyzed for CH_4, O_2, CO_2 and nitrogen (N_2) with a Series 400 isothermal gas chromatograph (GC) instrument (Gow-Mac Instrument 2011), equipped with a thermal conductivity detector (TCD). A Molsieve 13X, 80/100 mesh column was used to quantify O_2 and N_2, while CH_4 and CO_2 were analyzed on a HayeSep Q, 80/100 mesh column. The carrier gas was high purity helium (99.999% He, vol. basis), and the temperature of the column, injector, and detector were maintained at 120 ^{o}C, 130 ^{o}C, and 130^{o}C respectively, during testing.

4.3.3 Results and discussion

4.3.3.1 Evolution of physical properties

Fig. 4.16 presents the grain size distributions of the biocover materials at different times. The grain size distribution curves of the compost-sand samples indicate that the percentage of grains that pass through sieve number 40 (with an opening size of 0.42 mm) is 17.5%, 21.3% and 22.8% in Phases I, II and III, respectively. According to the Unified Soil Classification System (USCS), the compost-sand samples in Phases I (0 days), II (76th day) and III (150th day) are classified as organic well-graded sand (SW). Fig. 4.16 shows that the biocover material becomes finer with time which could be mainly due to the mineralization of the compost material over time (Huber-Humer 2004). The reduction of the particle size of the compost material (as the filter material) with time has also been cited in the literature (Huber-Humer 2004).

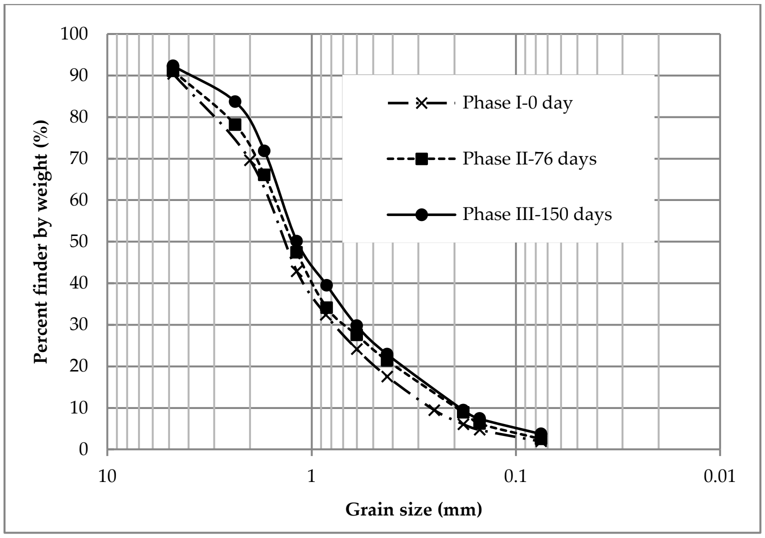


Fig. 4.16. Particle size distribution of compost-sand biocover medium at different times.

The results of the material characterization tests for organic content, bulk density, porosity (n), and Atterberg limits at different times and depths are shown in Fig. 4.17. It can be seen from Fig. 4.17 that the studied compost-sand mixture is a porous material (initial porosity of 77%) with high organic content (initial organic content of 22%). These properties are similar to those which are recommended by Huber-Humer et al. (2009) as properties of suitable filter materials for supporting the growth and activity of methanotrophic bacteria.

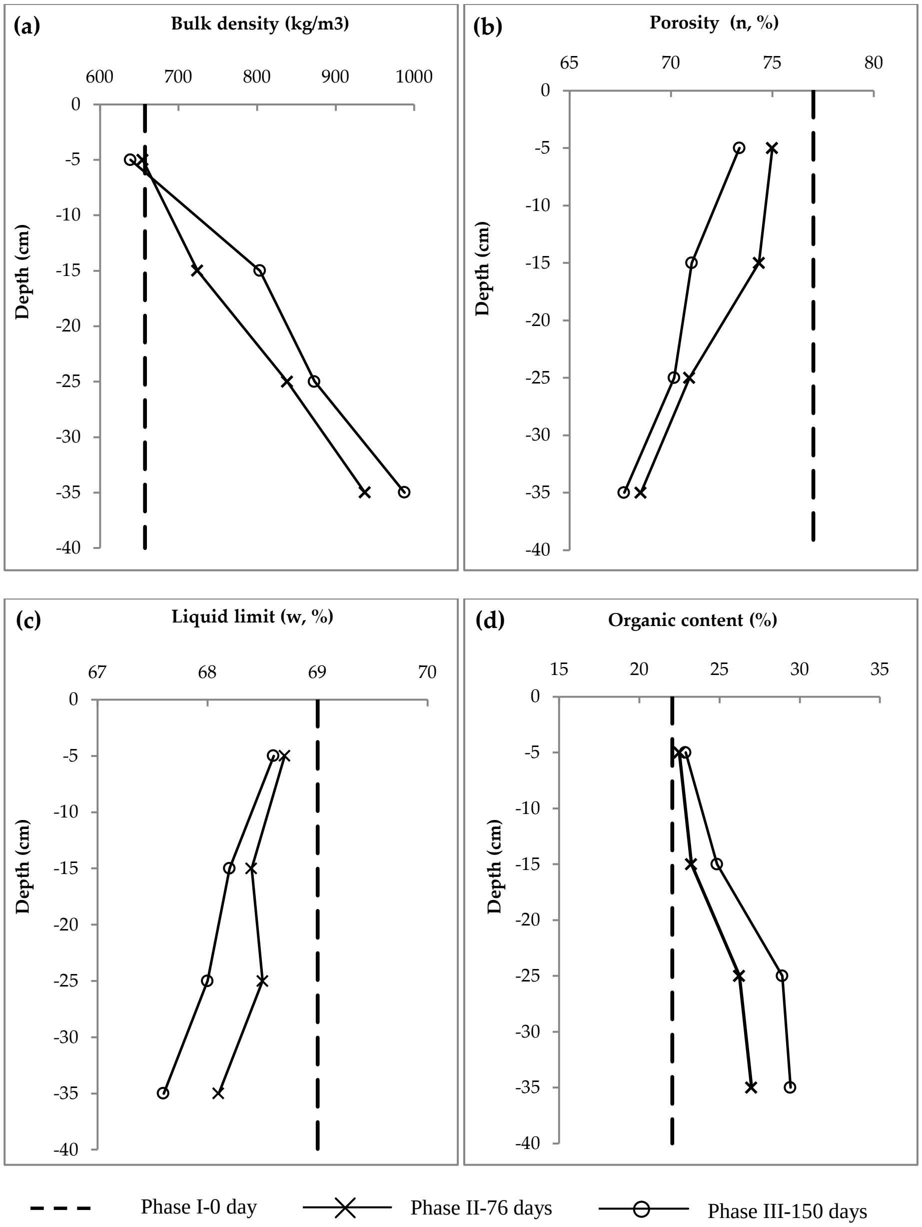


Fig. 4.17. Evolution of bulk density, porosity, LL, and organic content of compost-sand biocover medium with depth at different times.

((a) bulk density, (b) porosity, (c) LL, and (d) organic content).

It can be seen from Fig. 4.17a (bulk density profiles) that the compost-sand medium became compacted, and bulk density values increase with depth. Moreover, the bulk density of the compost-sand medium increases with time and this increase is more significant in Phases I (0 days) to II (76th day) than Phases II (76th day) to III (150th day). The increase in bulk density with time and depth can be attributed to the rearrangement of the orientation of the particles and the degradation of the organic content (Pokhrel 2006). Fig. 4.17b (porosity profiles) shows the reduction of porosity in general with depth and time which is the result of the compaction of the filter material due to settlement. The reduction of porosity could have a negative effect on the gas transport process (upward advection flux of CH_4 and downward diffusion flux of O_2 into the CH_4 oxidation zone) and consequently, the CH_4 oxidation rate over time through the biocover medium (Pokhrel 2006).

As illustrated in Fig. 4.17c (liquid limit profiles), the liquid limit values remain relatively constant with time and depth (varies between 68.1%-68.7 % and 67.6%-68.6 % in Phases II and III, respectively). Similar ranges of high liquid limits for compost materials have also reported by Benson and Othman (1993).

It can be seen from Fig. 4.17d that the organic content of the compost-sand medium is 22% in Phase I, and varies between 22.5%-27% and 22.9%-29.4% in Phases II and III, respectively. The organic content profiles also indicate that the organic content of the compost-sand medium from the surface layer (-5 cm) to the bottom layer (-35 cm) increases from 22.5% to 27% and 22.9% to 29.4% in Phases II and III, respectively. The increase in organic content with time and depth can be related to the formation of exopolymeric substances (EPS) (Pokhrel 2006). Methanotrophic bacteria under certain environmental conditions produce EPS which are long chain organic compounds (Huber-Humer 2004). The formation of EPS was visible within the transparent columns after about 50 days of column operation. EPS formation in the columns can be indicative of the presence of methanotrophic activities (Pokhrel 2006). High organic content at depths with maximum CH_4 oxidation was noted by Kightley et al. (1995) and Wilshusen et al. (2004) in soil and compost columns. Therefore, the organic content profile can be a surrogate for determining the primary zone of CH_4 degradation (Pokhrel 2006).

4.3.3.2 Evolution of mechanical properties

4.3.3.2.1 Evolution of shear strength properties

Figs. 4.18 and 4.19 show the relationships between shear stress and horizontal displacement of the biocover material at different depths and phases. The stress-strain curves of the specimens do not show a definite yield point, and continuous strength gain with increasing horizontal deformation can be observed for all of the samples.

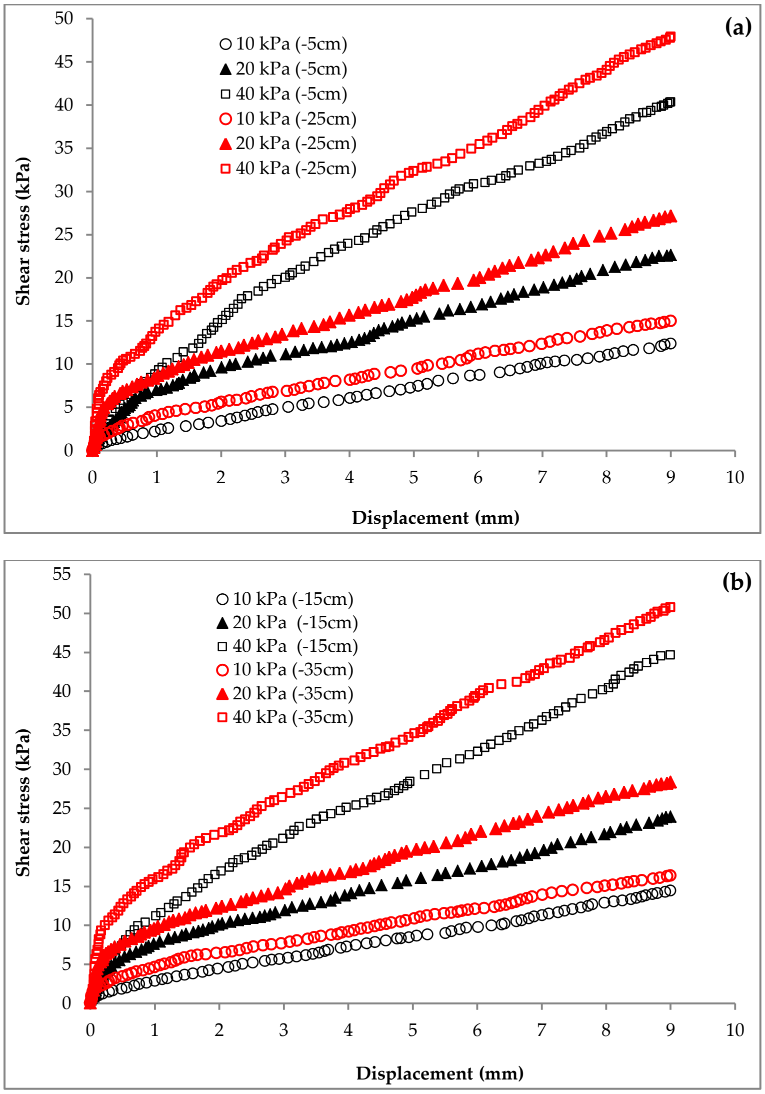


Fig. 4.18. Results of direct shear tests on compost-sand biocover samples at different depths in Phase II (76th day)

((a) -5 cm and -25 cm, (b) -15 cm and -35 cm).

Also, it can be seen that the failure envelopes are slightly nonlinear at higher normal stresses (40 kPa), but close to a straight line in lower normal stresses (10 and 20 kPa).

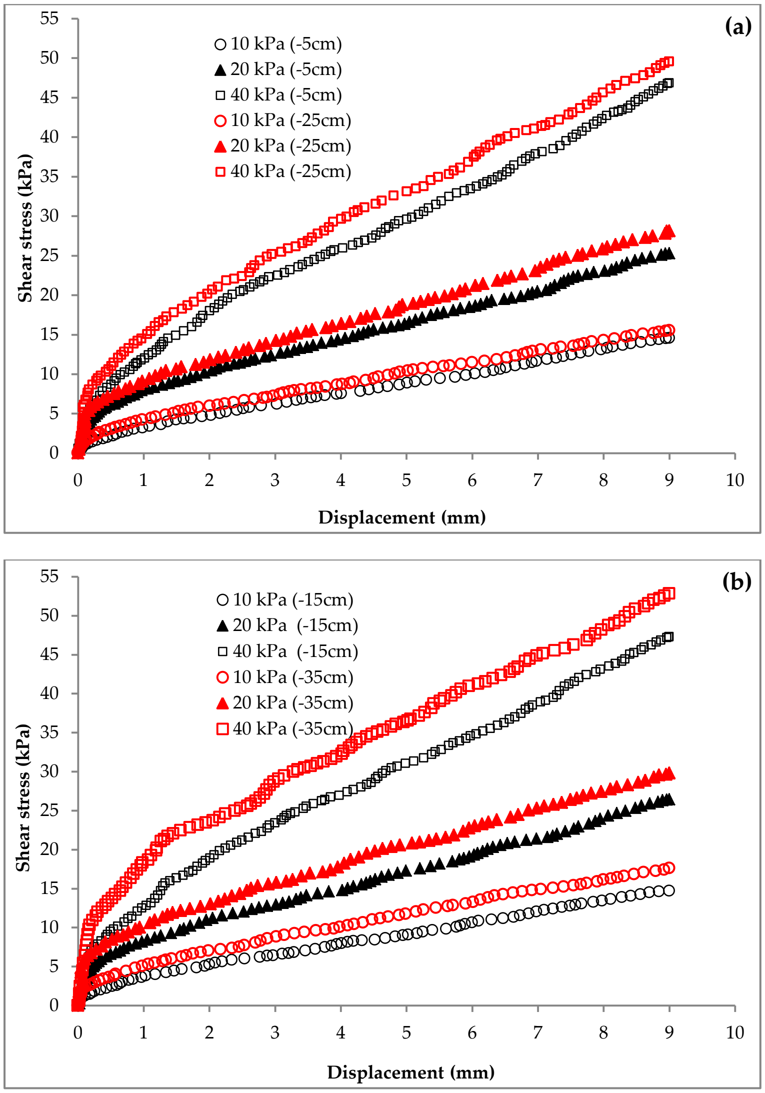


Fig. 4.19. Results of direct shear tests on compost-sand biocover samples at different depths in Phase III (150th day)

((a) -5 cm and -25 cm, (b) -15 cm and -35 cm).

As shown in Figs. 4.18 and 4.19, the difference between the ultimate strengths decreases with time because of the decreasing rate of compaction as time passes. The difference between the ultimate strengths in Phase I and that of the sample at a depth of -35 cm in Phase III is 35%

under a normal stress of 40 kPa, while it is 4% between Phases II and III under the same normal stress. It can be clearly observed from Fig. 4.17a that the biocover material changes from a loose to a dense condition because of the rearrangement and deformation of compost particles with depth and over time (Pokhrel 2006). In denser conditions, compost-sand particles are in close interaction with each other and mobilize consistent frictional resistance for relatively larger shear displacement (Bajwa 2012). So, at the same normal stress, the ultimate strength of stress-strain curves increases with increasing depth and time.

The shear strength of the studied samples was analyzed by using the Mohr-Coulomb theory. The shear strength parameters (c and φ) of the samples at different depths and the three phases are shown in Table 4.5. As shown in Table 4.5, the studied materials are frictional in nature (φ varies between 38.3° and 49.5°) and the φ increases with depth and time. This trend is associated with the compaction of the biocover medium because of settlement with depth (Fig. 4.21) which results in larger interlocks between the particles and subsequently increases the φ (Mouzai and Bouhadef 2011).

Table 4.5. Shear strength parameters of the biocover medium at different depths and times.

Sample	Depth (cm)	Cohesion, c (kPa)	Angle of friction, φ (°)
Phase I	All depths[1]	2.7	38.3
Phase II	-5	3.5	42.8
	-15	4.1	45.3
	-25	4.6	47.4
	-35	4.7	48.8
Phase III	-5	3.8	47
	-15	4.3	47.2
	-25	4.8	48.4
	-35	6.1	49.5

[1] Includes depths at -5, -15, -25, and -35 cm.

It can be seen from Table 4.5 that the cohesion (c) of the studied materials in Phase I is 2.7 kPa and it increases with increasing organic content from the top to the bottom of the columns in Phases II and III. Nimmo (2004) and Annabiabc et al. (2007) found that organic materials exert forces through surface tension or electrical charges, and increase the cohesion through the binding of soil particles.

In field conditions, internal seepage erosion can cause lower shear strength which can consequently result in the shear failure of the biocover; therefore, the c and φ values obtained in the laboratory should be reduced by 15-25% as recommended in the literature (Bagchi, 1990). Since the laboratory obtained φ of the used material under drained conditions that ranged between 38.3° and 49.5°, the application of the cited safety factor indicates that the materials under study have enough strength to resist shear failures on slopes less than about 30°.

4.3.3.2.2 Evolution of compressibility properties

The values of the coefficient of consolidation (C_v) at selected depths and times under different loading conditions are shown in Table 4.6. It should be mentioned that the square root time (Taylor's) method was used to calculate the C_v values.

Table 4.6. Coefficient of consolidation at different depths and times.

Load	Depth (cm)	Cv (m^2/year)		
		Phase I (0 days)	Phase II (76th day)	Phase III (150th day)
5	-5	1.98	2.07	2.18
	-15		2.10	2.22
	-25		2.12	2.26
	-35		2.16	2.31
10	-5	1.85	1.88	2.04
	-15		1.93	2.07
	-25		1.99	2.10
	-35		2.03	2.14
20	-5	1.73	1.69	1.88
	-15		1.74	1.92
	-25		1.76	1.96
	-35		1.81	1.99
40	-5	1.60	1.57	1.71
	-15		1.60	1.76
	-25		1.63	1.78
	-35		1.65	1.8
80	-5	1.35	1.44	1.55
	-15		1.47	1.6
	-25		1.5	1.64
	-35		1.53	1.68

Based on the theory of consolidation, the C_v value decreases with increasing consolidation pressure (Leonards and Girault 1961). It can be seen from Table 4.6 that there is a general trend of the reduction of the C_v values of samples with increasing consolidation pressure.

The compressibility behaviour of organic soils is significantly controlled by the organic content (Mesri and Ajlouni 2007). It can be observed that by increasing the organic content with depth and time (Fig. 4.17d), the value of C_v, which ranged from 1.35 m^2/year to 1.98 m^2/year before beginning the column operation (Phase I), increased to a range of 1.44 m^2/year to 2.16 m^2/year in Phase II, and reached the maximum range of 1.55 m^2/year to 2.20 m^2/year at the end of the column operation (Phase III). The variation of the C_v values with the organic content of organic soils has also been cited in the literature (Islam et al. 2006). The increase in the values of C_v from Phases I to III (1.35 m^2/year to 1.98 m^2/year versus 1.55 m^2/year to 2.20 m^2/year) is more significant than that of Phases II to III at the same depth. This difference is attributed to more change in the organic content from Phases I to III in comparison to Phases II to III as shown in Fig. 4.17d.

The consolidation curves of the samples at different depths (-5, -15, -25 and -35 cm), and in phases I and II are illustrated in Fig. 4.20.

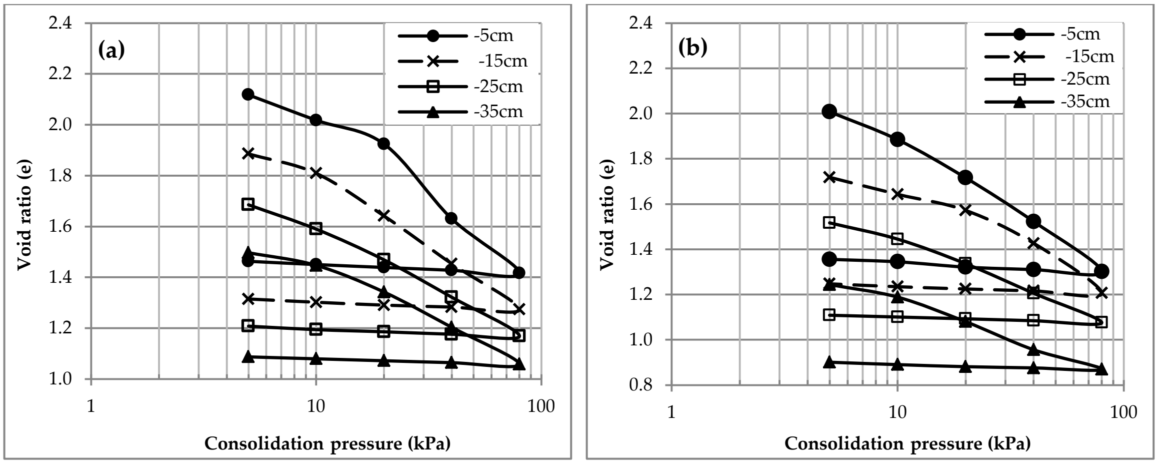


Fig. 4.20. Consolidation curves of compost-sand biocover medium at different depths and phases ((a) Phase II (76th day), and (b) Phase III (150th day)).

The compost-sand material is fairly compressible with reductions in the void ratios (*e*) with increasing consolidation pressure (σ). Also, it is clear from Fig. 4.20 that the void ratio of the samples decreases with depth. This is caused by the fact that the biocover material becomes more compacted with depth (as shown in Fig. 4.17a) which results in lower void ratios. The compressibility of the samples was quantified in terms of the compression index (C_c) and the recompression index (C_r), which are the slopes of the consolidation curves (Fig. 4.20) for the loading and unloading stages during the consolidation test, respectively. Table 4.7 summarizes the C_c and C_r values of the samples at different depths and times. The consolidation behaviour and associated settlement can be expressed by the C_c value, such that a higher value results in increased settlement. Besides the organic content, the compressibility of organic soils is also controlled by the dry bulk density (Mesri and Ajlouni 2007).

Table 4.7. Compression and recompression indexes at different depths and times.

Sample	**Depth (cm)**	C_c	C_r
Phase I	All depths[1]	0.64	0.054
	-5	0.54	0.039
	-15	0.50	0.035
	-25	0.40	0.032
Phase II	-35	0.25	0.025
	-5	0.58	0.045
	-15	0.48	0.034
	-25	0.34	0.027
Phase III	-35	0.21	0.024

[1] Includes depths at -5, -15, -25, and -35 cm.

It is clear from Table 4.7 that the value of C_c in Phase I is 0.64, which is greater than the value of C_c in Phases II (0.25 to 0.54) and III (0.21 to 0.58) at all depths. This difference is associated with the lower bulk density and organic content of the biocover material in Phase I (505.6 kg/m^3 and 22%, respectively) in comparison to those in Phases II and III at all depths (Figs. 4.17a and d). Also, the value of C_c generally decreases with an increase in the bulk density with depth in Phases II and III. Furthermore, the C_r value which reflects the swelling potential of the materials is in the range of 0.025 to 0.039 and 0.024 to 0.045 for Phases II and III, respectively. The recompression index generally decreases as depth increases due to compaction.

Besides the consolidation behaviour, the vertical settlement of the biocover medium was studied during the 150 days of column operation and the results are presented in Fig. 4.21. It can be observed from Fig. 4.21 that the settlement curve has a steep slope and the biocover settled 12 mm in the first 22 days of the column operation (with a settlement rate of 0.55 mm /day). After 22 days, settlement with lower increments followed, up to the 51st day, and eventually maintains a straight line with time for the rest of the 150 days of the column operation. This behaviour can be related to the rearrangement of the compost particles which is due to the decrease in pressure due to self weight over time. The results obtained are comparable with those reported in the literature (Huber-Humer 2004; Bajwa 2012). It should be mentioned that settlement did not affect the efficiency of the CH_4 oxidation in the current study (Fig. 4.27). However, in determining the minimum thickness of biocovers, particularly when a minimum thickness is required by regulatory agencies, it should be taken into consideration that a reduction in the thickness of biocovers will be induced by settlement.

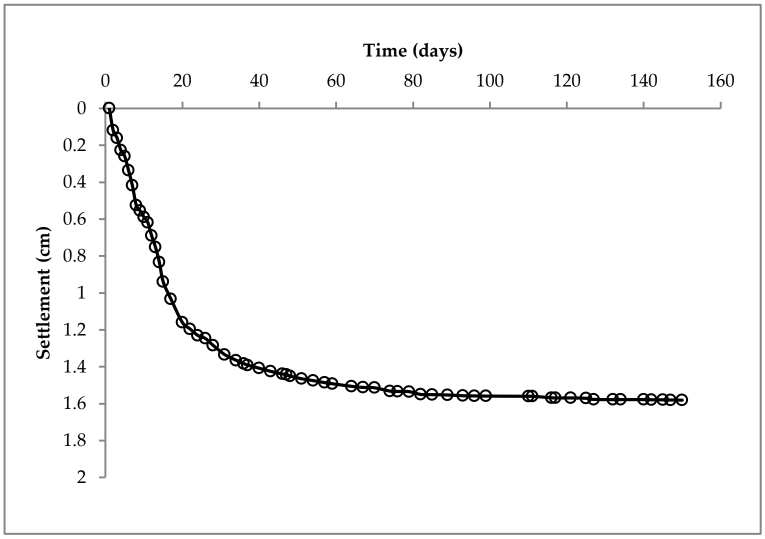


Fig. 4.21. Vertical settlement of compost-sand biocover medium over 150 days.

4.3.3.3 Evolution of hydraulic properties

4.3.3.3.1 Evolution of saturated hydraulic conductivity

Fig. 4.22 illustrates how the hydraulic conductivity of the studied specimens varies with depth in the different phases. The hydraulic conductivity value is 3.32×10^{-4} m/s in Phase I and varies in a range of 2.15×10^{-4} m/s to 8.4×10^{-6} m/s in Phase II and 1.21×10^{-4} m/s to 9.87×10^{-7} m/s in Phase III. The general trend is that the hydraulic conductivity decreases with depth and time. It can be seen that the hydraulic conductivity of the biocover medium significantly declines from 3.32×10^{-4} m/s in Phase I to a range of 2.15×10^{-4} m/s to 8.4×10^{-6} m/s in Phase II.

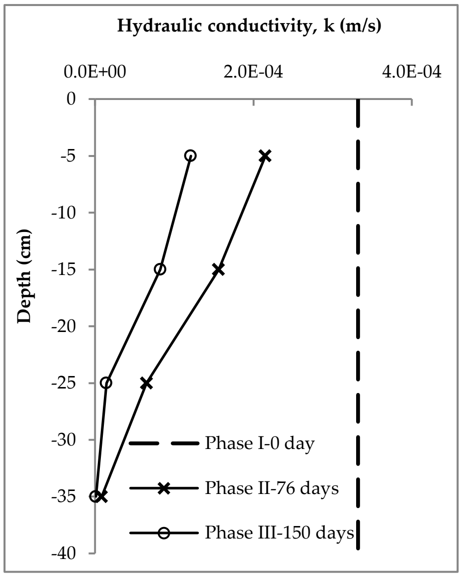


Fig. 4.22. Evolution of hydraulic conductivity of compost-sand biocover medium with depth at different times.

Moreover, the hydraulic conductivity decreases from the top to the bottom layer by at least two orders of magnitude in both the second and third phases. Two possible reasons could account for the reduction of the saturated hydraulic conductivity with depth and time. First, hydraulic conductivity is strongly controlled by the physical and structural arrangements of constituent particles (Edil, 2003), the void ratio, and the size and shape of the flow channels (Mesri and Ajlouni 2007). The compost particles are porous, and have high void ratios (Fig. 4.17b) which caused high initial hydraulic conductivity at the beginning of the operation of the columns. As time passed, the biocover medium changed from a loose to dense condition (Fig. 4.17a) because of the overburden pressure due to self weight and particle size reduction (Fig. 4.16) induced by the mineralization of the compost material over time (Huber-Humer 2004). These phenomena resulted in a reduction of coarse pores and porosity (Fig. 4.17b), destruction of pore continuity (Dec et al. 2008) and an eventual decrease in hydraulic conductivity (Huat et al. 2011; Ankeny et al. 1990; Fuentes et al. 2004; Horn and Smucker 2005). Secondly, another factor that contributed to the decrease in saturated hydraulic conductivity with depth and time is the increase in the organic content with depth over time (Fig. 4.17d). The formation and accumulation of EPS (visible after about 50 days of column operation), which are chains of organic compounds (Huber-Humer 2004) due to methanotrophic activities, clog the pores of the biocover substrate and impede the flow of water. Also, the produced organic substrates are able to retain water and hinder the flow of water, and thereby reduce hydraulic conductivity (Nemes et al. 2005).

A simultaneous analysis of the hydraulic conductivity results (Fig. 4.22) and the CH_4 oxidation capacity of the studied biocover (Fig. 4.27) implied that a reduction in hydraulic conductivity does not result in significant reduction in the CH_4 oxidation capacity of the biocover. This means that the studied biocover with permeability values as low as those presented in Fig. 4.22 was able to oxidize CH_4 at an acceptable rate. In addition, the low hydraulic conductivities of the studied biocover reduced water infiltration into the biocover. Water infiltration not only contributes to leachate generation, but can also increase the degree of saturation (S_r) of the biocover medium to a value of more than 85%. It is well known that when the S_r approaches 85%, the air phase in the pores of the biocover medium becomes occluded (Brooks and Corey 1966; Nagaraj et al. 2006), which leads to a considerable reduction in gas migration and thereby inefficiency of the biocover.

4.3.3.3.2 Evolution of degree of saturation

The water saturation degree (S_r) can influence gas transport processes through the medium as well as the geotechnical stability of biocovers (Bajwa 2012). A high S_r causes the discontinuity of air filled voids (Nagaraj et al. 2006). This condition causes the aqueous diffusion of CH_4 and O_2 as dissolved species through the biocover medium, which is much slower (10^{-4} folds less rapid) than gaseous diffusion. Therefore, CH_4 oxidation rate is reduced as a result of a slow gas exchange process and gas occlusion (Cabral et al. 2010*a*).

Variation in the S_r of the biocover medium with depth in the different phases is presented in Fig. 4.23. As shown in Fig. 4.23, the S_r declines at the surface layer (-5 cm) over time (20%, 14% and 7% in Phases I, II and III, respectively). This trend can be associated with evaporation induced surface desiccation of the surface layer with time. Moreover, the S_r increases with depth in both the second and third phases. This increase is more significant in Phase III. This behaviour could be attributed to increasing moisture content due to downward moisture movement (as shown in Fig. 4.24), more methanotrophic activity in the bottom layer, and porosity reduction of the filter material with depth over time.

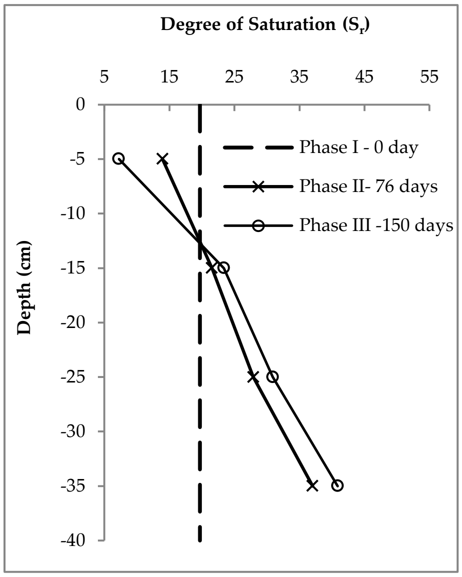


Fig. 4.23. Evolution of degree of saturation of compost-sand biocover medium with depth at different times.

A high S_r at the bottom layer of biocovers has also been reported in the literature (Bajwa 2012 and Cabral et al. 2010*b*). It should be mentioned that the S_r during the column operation was less than 85%. As explained before, an S_r of 85% is the threshold, beyond which, air becomes occluded in soil (Brooks and Corey 1966; Nagaraj et al. 2006), gas exchange processes become slow (Nicholson et al. 1989; Yanful 1993; Aachib et al. 2004; and Cabral et al. 2004) and there is a consequent reduction in the CH_4 oxidation rate (Cabral et al. 2010b).

4.3.3.3.3 Evolution of moisture content

Fig. 4.24 shows the evolution of the VWC within the biocover with depth and time. It can be seen that the original VWC throughout the depth of the biocover was 20%. The surface layer (-5 cm) dried out over time and experienced a loss of around 14% in moisture content after 150 days of column operation. The drying out of the surface layer with time is attributed to evaporation induced surface desiccation (Stein and Hettiaratchi 2001; Stein 2000). A low VWC of the surface layer of the biocover material may have contributed to the lack of methanotrophic activity at those depths which can affect the CH_4 oxidation rate (Wilshusen et al. 2004).

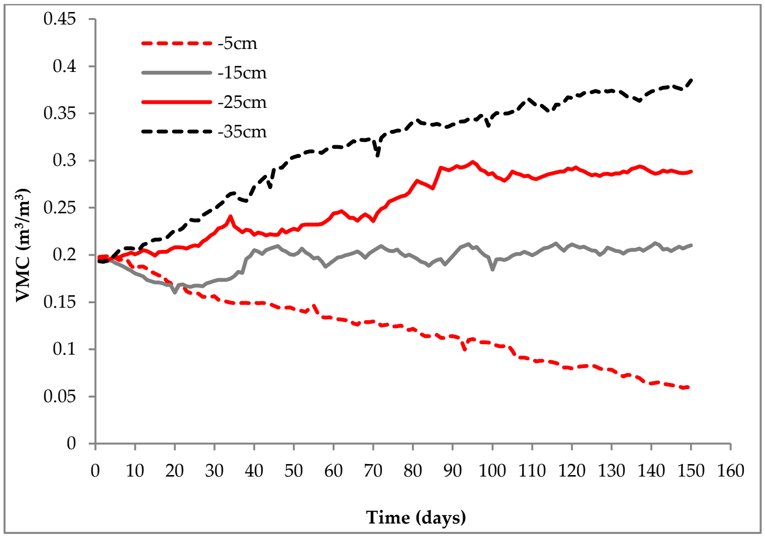


Fig. 4.24. Evolutions of VWC at different depths of compost-sand biocover medium with time.

In contrast to the surface layer, the VWC continuously increased at the bottom layer with time and reached 33.2% and 38.5% respectively in Phases II and III, which are significantly higher than the initial value of 20% in Phase I. The high VWC value at the bottom layer is the result of the downward migration of moisture (Stein 2000; Bajwa 2012) and the production of water during the CH_4 oxidation process (Pedersen 2010) which indicates relatively high methanotrophic activity in this zone (Stein 2000).

4.3.3.4 Evolution of thermal properties

4.3.3.4.1 Evolution of temperature

The variation in temperature at selected depths of the studied biocover over 150 days is shown in Fig. 4.25. The average initial temperature throughout the depth of the biocover is 21.7°C. The temperature consistently increased in the first week and reached a maximum value of 35.9°C on the 7th day at the surface layer (-5 cm) where availability of O_2 was not a limiting factor. This behaviour in the first week of the column operation could be the result of the aerobic degradation of available carbon sources in the compost (Sternenfels 2012). Bajwa (2012) also reported a similar trend in compost based biocovers.

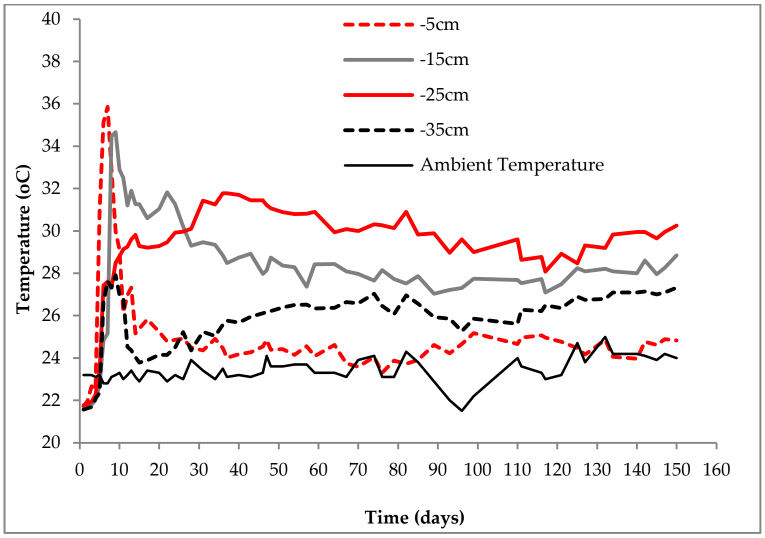


Fig. 4.25. Evolutions of temperature at different depths of compost-sand biocover with time.

It can be clearly seen from Fig. 4.25 that the average temperature in the column is 27.1°C which is significantly higher than the ambient temperature of 23.4°C. This difference becomes more pronounced over time and reaches a value of over 6°C at a depth of -25 cm after 150 days of column operation. A similar difference between ambient and column temperatures has been also quoted by Pedersen (2010) and Berger et al. (2005). The CH_4 oxidation process is an exothermic process which releases 780 kJ per mol of oxidized CH_4 (Scheutz et al. 2009). The heat generated by methanotrophic activity is the cause of the difference between the ambient and column temperatures (Huber-Humer 2004).

Furthermore, the variation of the temperature at different levels within the biocover can be investigated to obtain further information on the CH_4 oxidation process and vertical zonation of microbial activity inside the column. Development of a high temperature zone between the depths of -15 and -25 cm of the studied biocover (as shown in Fig. 4.25) indicates intense microbial activity at the mentioned layer and subsequently higher CH_4 oxidation capacity. The CH_4 oxidation capacity (Fig. 4.27) is consistent with the mentioned observation and the high CH_4 oxidation rate zone was localized in the middle layer. It should be noted that the average temperatures at depths of -15 and -25 cm during the column operation were respectively 28.3 and 29.2°C. These temperatures are generally higher than the average temperature at the bottom (-35 cm) and surface (-5 cm) layers (25.7°C and 25.2°C, respectively). This difference is attributed to more methanotrophic activity in the middle layers. Pedersen (2010) also reported an increase in the temperature in the layer of the biocover with accumulated visible water vapour and orange colored biofilm (active oxidation layer).

The temperature within the biocover and therefore the CH_4 oxidation capacity of the biocover is affected by the atmospheric temperature (Dever et al. 2010). In field conditions during the winter, the CH_4 oxidation process may slow down, particularly when the atmospheric temperature falls below 10°C (Dever et al. 2010). The results presented here suggest that the exothermic process of the methanotrophic activity could maintain the temperature within the biocover high enough to enable the CH_4 oxidation process even in a cold climate (Humer and Lechner 2001). Unlike a cold climate, the temperature increase in a warm climate due to the exothermic process of methanotrophic activity can result in increasing evaporation, drying out the upper layers of the biocover, and consequently reducing the CH_4 oxidation rate (Dever et al. 2010). Indeed, at temperatures higher than 40°C, the CH_4 oxidation process severely slows down and no oxidation takes place at a temperature of 50°C (Zeiss 2006). Therefore, temperature within biocovers should be considered as a factor that may be detrimental to their performance.

4.3.3.4.2 Evolution of thermal conductivity

The evolution of thermal conductivity within the biocover in the Phases I, II and III and different depths is illustrated in Fig. 4.26. It can be seen that the minimum thermal conductivity

(0.42 W/m° K) is achieved at the surface layer (-5 cm) at the end of the column operation where the VWC was minimal (Fig. 4.24). As illustrated in Fig. 4.26, the thermal conductivity increases from the top to the bottom of the column with increasing VWC (Fig. 4.24) and decreasing porosity (Fig. 4.17b) and reaches a maximum value of 0.61 W/m° K after 150 days. The thermal conductivity of water (0.59 W/m° K) is more than 20 times greater than that of air (0.025 W/m° K) (Holman 2002). By increasing the moisture content, the volume fractions of air are decreased and the portion of the pore spaces filled with water is increased (Ahn et al. 2009). Therefore, water films around the soil particles are completed and indirect contact areas between particles are increased by increasing the moisture content which results in an increase in thermal conductivity (Abu-Hamdeh and Reeder 2000). Chandrakanthi et al. (2005) also reported an increase in thermal conductivity due to increasing moisture content in soils.

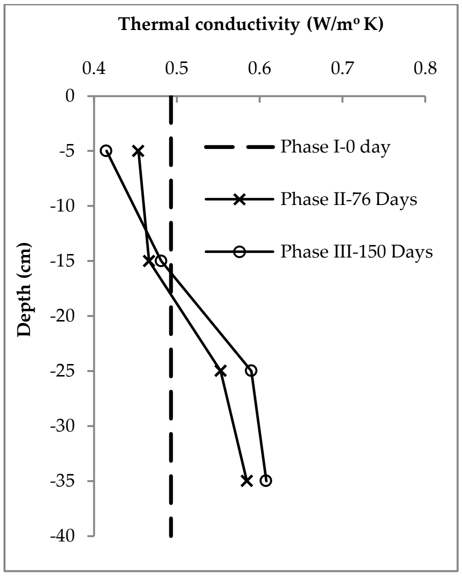


Fig. 4.26. Evolutions of thermal conductivity of compost-sand biocover with depth at different times.

Moreover, the degree of interparticle surface contact, which is determined by particle packing efficiency, has an important role in controlling the thermal conductivity in soils (Hall and Allinson 2009). As the porosity of biocover material decreases due to compaction induced by settling (Fig. 4.17b), the contact between individual particles becomes more intimate which results in facilitating heat movement through the filter material and an increase in thermal conductivity.

It is well known that thermal conductivity decreases with increasing organic content (Abu-Hamdeh and Reeder 2000). However, Fig. 4.17d shows an increase in the organic content from the surface to the bottom of the biocover; thermal conductivity increases with depth (from 0.45 W/m° K to 0.58 W/m° K and 0.42 W/m° K to 0.61 W/m° K in Phases II and III, respectively). The increasing thermal conductivity with depth is simultaneous with increasing VWC (from 12.5% to 33.2% and 5.8% to 38.5% in Phases II and III, respectively) and decreasing porosity (from 75% to 68.5% and 73.4% to 67.7% in Phases II and III, respectively) with depth. The results indicate that the effect of the organic content on thermal conductivity is insignificant in comparison to the effects of the moisture content and bulk density.

The efficient operation of field biocovers depends on maintaining a temperature which is suitable for the growth of methanotrophic bacteria (Chandrakanthi et al. 2005). As shown in Fig. 4.26, the compost-sand mixture used in this experiment has lower thermal conductivity than mineral soils (e.g., 2.9 W/m° K for silt and clay, 3 W/m° K for sandstone and 3.8 W/m° K for dolostone (Côté and Konrad 2005). This is attributed to the coarse texture and relatively high amount of air-filled space of the compost-sand mixture (Scheffer and Schachtschabel 1989). This means that the studied compost-sand mixture conducts heat at a lower rate (Hettiarachchi 2005) and thereby provides better temperature insulation (Huber-Humer 2004). Temperature insulation guarantees the proper temperature for methanotrophic bacteria within the biocover which is especially important during winter in field conditions (Huber-Humer 2004).

4.3.3.5 Evolution of chemobiological properties

4.3.3.5.1 Methane oxidation rate

In this paper, the CH_4 oxidation rate at selected depths is calculated based on CH_4 consumption. The following equation was used to calculate the CH_4 oxidation rate:

$$\mathrm{CH_4\ oxidation\ rate} = \frac{(C_{CH_4})_{t=0} - (C_{CH_4})_{t=i}}{(C_{CH_4})_{t=0}} \times J_{in,CH_4} \text{ (Albanna et al. 2007)} \qquad [4.3]$$

where the CH_4 oxidation rate is in g/m^2 day, $(C_{CH_4})_{t=0}$ is the CH_4 concentration (%v/v) which was fed into the column and assumed to be 100%, $(C_{CH_4})_{t=i}$ is the CH_4 concentration (%v/v) at day ith, and J_{in,CH_4} is the influent CH_4 flux which is 250 g/m^2 day in this study.

The CH_4 oxidation rates at selected depths over the 150 days of column operation are shown in Fig. 4.27. This figure shows an adaptation phase of 16 days which is the time necessary to reach the steady state of CH_4 oxidation in biocovers. It can be seen that the adaptation phase is followed by a steady state which continues until the end of the experiment.

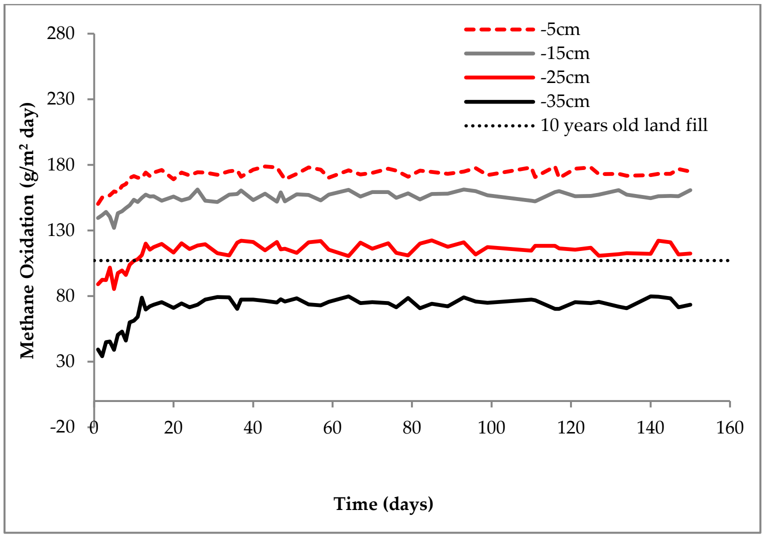


Fig. 4.27. Evolutions of CH_4 oxidation rate at different depths of compost-sand biocover with time.

Different adaptation periods have been quoted in the literature for laboratory experiments (Huber-Humer 2004; Wilshusen et al. 2004; Humer and Lechner 2001). Philopoulos et al. (2009) and De Visscher et al. (1999) also reported long lag phases towards reaching high CH_4 oxidation rates in mineral materials. In some studies, the steady state gradually occurred over two or three weeks (Wilshusen et al. 2004; Hilger et al. 2000)) for wood chip compost and soils, respectively, while the development of the steady state occurred after a few days of column operation in other studies (Wilshusen et al. 2004 and De Visscher and Van Cleemput 2003)) for leaf compost and soils, respectively. The CH_4 oxidation rate reached a maximum value of 178.8 g/m^2 day (which corresponds to a 72% efficiency in CH_4 oxidation) in the steady state oxidation phase. Furthermore, the CH_4 oxidation rates obtained in the current study were compared to the estimated CH_4 emission for a 10 year-old bioreactor landfill with an assumed depth of 20 metres (Huber-Humer 2004). It can clearly be seen from Fig. 4.27 that the compost-sand material used in this study is able to entirely remove 107 g/m^2 day of CH_4 which is the estimated CH_4 emission from the 10 year-old bioreactor landfill.

Some previous studies have reported a decline in the CH_4 oxidation rate after a steady state of CH_4 oxidation as a result of EPS formation (Wilshusen et al. 2004; Huber-Humer 2004; Hilger et al. 2000). EPS formation can cause clogging of the pores of the media and hindering of the CH_4 and O_2 flow within the biocover (Huber-Humer 2004; Sternenfels 2012). It should be noted that this phenomenon only occurs in fresh and fine textured compost materials or natural soil (Huber-Humer 2004). It is believed that EPS formation cannot cause bioclogging and reduction in CH_4 oxidation in mature and well textured compost with high porosity (Pedersen 2010). In the current research, the organic content profile in Fig. 4.17d indicates EPS formation throughout the depth of the column while there is no significant change in the CH_4 oxidation, see Fig. 4.27, as a result of EPS formation and clogging of the pores. It can be concluded that the studied compost-sand mixture is coarse enough to counteract the clogging effect of EPS formation and enable the gas exchange process without any significant obstructions. Recent studies published in the literature have also reported no reduction in CH_4 oxidation rate in coarse biocover material as a result of EPS formation (Haubrichs and Widmann 2006; Gebert et al. 2006; Hilger et al. 2000; Pedersen 2010).

4.3.3.5.2 Gas profile

The gas profile is the result of biochemical reactions, and diffusion and advection of gas flow (De Visscher 2001). The gas profile indicates the concentrations of O_2, N_2, CH_4 and CO_2, and reveals the behaviour and vertical zonation of the microbial community at different depths (Huber-Humer 2004). Fig. 4.28 illustrates the gas composition profiles along the height of the column on Days 5, 31, 59, 89, 121 and 150 of the column operation. It can be seen that the concentration of CO_2 gradually decreases with column height, while the concentration of CH_4

sharply decreases. Also, the concentration of O_2 steadily decreases from the top to the bottom of the column because of air diffusion from the surface of the biocover (Perdikea et al. 2008).

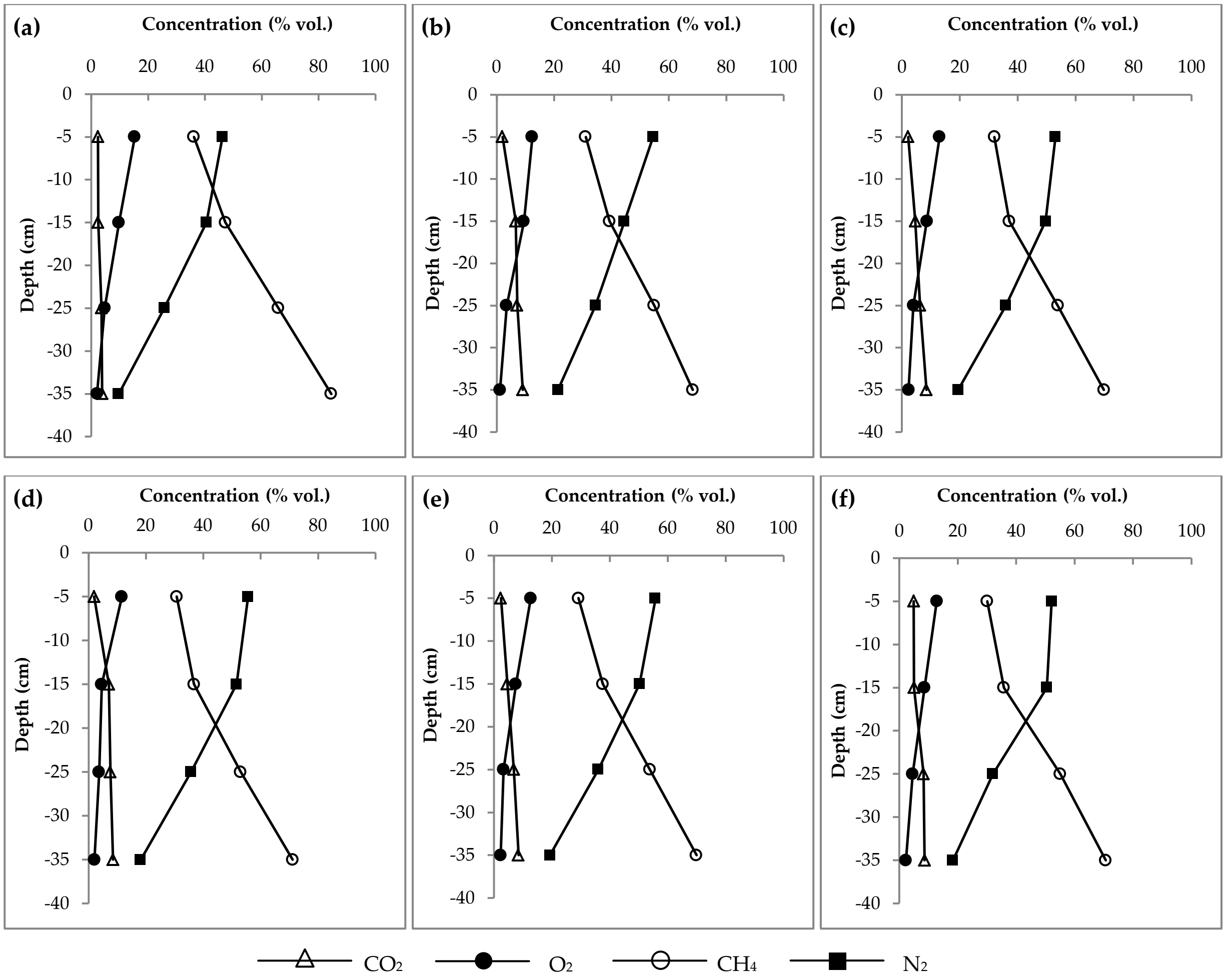


Fig. 4.28. Gas concentration of compost-sand biocover during the of column operation ((a) 5th, (b) 31st, (c) 59th, (d) 89th, (e) 121st, (f) 150th day of column operation).

Significant changes in the gas concentration profiles were clearly observed from the 5th to the 31st day of the column operation. On the 5th day (Fig. 4.28a), the biocover material was still going through the adaptation phase and therefore the concentration of CH_4 was relatively high along the height of the column. This indicates that CH_4 was not completely oxidized. On the 31st day of the column operation (Fig. 4.28b), the depth of O_2 penetration reached 30 cm and concentration of CH_4 decreased from 68% at a depth of -35 cm to 32% at a depth of -5 cm in the biocover. These observations indicate that O_2 penetrates along the vertical profile and the CH_4 oxidation process occurs in the presence of enough O_2.

During the steady state phase of CH_4 oxidation (Day 31 to the end of the column experiment), the N_2 profiles were relatively similar throughout the height of the column. It could be seen that N_2 easily penetrated into the depth of the column and reached a depth of -35 cm of the column through diffusion against the upward CH_4 flow. N_2 is neither produced nor consumed in the CH_4 oxidation process; therefore, the presence of N_2 at a deep layer (-35 cm) for an extended period of time can be used as an indicator of air intrusion (Berger et al. 2005) and this also implies that the influent CH_4 flux was being diluted (Cabral et al. 2010*b*).

It should be mentioned that during the steady state phase of CH_4 oxidation, O_2 penetrated at a considerably lower concentration and less deeply into the biocover material in comparison with N_2, which implies that O_2 is immediately consumed in the oxidation process as it becomes available (Cabral et al. 2010*b*). The gas concentration profiles in Fig. 4.28 show that the zone where there is high CH_4 oxidation capacity, in which the main part of the oxidation process has taken place, developed in the middle layers. Moreover, the production of CO_2 is directly proportional to the oxidation of CH_4 (Perdikea et al. 2008) and therefore the concentration of CO_2 at different depths can be indication of methanotrophic activity. However, it should be noted that part of the CO_2 production is accumulated in the biofilm which is produced during CH_4 oxidation and so leaves the gas phase (Delhoménie et al. 2002; Jorio et al. 1998). Also, the diffusion coefficient of CO_2 in air is less than that of CH_4 in air (1.61×10^{-5} m^2/s versus 2.21×10^{-5} m^2/s at 22 °C) (De Visscher et al. 1999). Therefore, it is difficult and less accurate to assess the exact influence of the CH_4 oxidation reaction on the concentration of CO_2.

4.3.3.5.2 Evolution of pH

The evolution of pH at different depths and time is shown in Fig. 4.29. The pH values vary in a narrow range of 6.7 to 6.6 and 6.8 to 6.6 in Phases II and III, respectively. It can be seen from Fig. 4.29 that there is a slight tendency for the pH to change from basic to acidic. This is related to the decreasing concentration of ammonia during the column operation (Einola 2010). It should be noted that pH is neutral and no significant change in pH values with depth was observed.

Einola (2010) also reported a similar trend of pH variation with depth and time. A simultaneous analysis of the pH profile (Fig. 4.29) and CH_4 oxidation rate (Fig. 4.27) indicated that the pH of the biocover medium is not a limiting factor in this research. Previous studies have also reported the growth and activity of methanotrophs in the observed pH range (Hütsch et al. 1994; Bender and Conrad 1995).

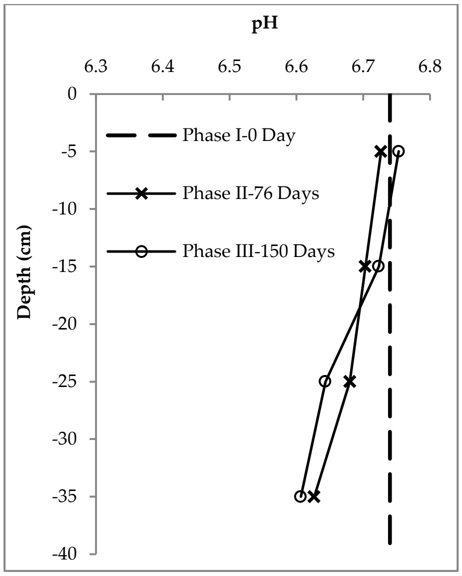


Fig. 4.29. Evolution of pH of compost-sand biocover medium with depth at different times.

4.3.4 Summary and conclusions

The laboratory monitoring of an instrumented column experiment over a period of five months as well as an extensive post-experiment analysis and tests have been conducted to investigate the simultaneous evolution of the thermal, hydraulic, mechanical and chemo-biological properties of a compost-sand biocover with time and depth. The following key conclusions can be made from the data presented.

The moisture content appears to be an imperative factor which affects the CH_4 oxidation rate. The low efficiency of CH_4 degradation mostly near the surface layer of the biocover studied can be associated with the low VWC of the surface layer (an average of 14% in the last three months of the column operation) and drying of the biocover material.

The hydraulic conductivity of the compost-sand mixture is 3.32×10^{-4} m/s in Phase I which is reduced by two to three orders of magnitude with time and depth, and reaches 8.4×10^{-6} m/s and $9.87\ \times10^{-7}$ m/s at a depth of -35 cm in Phases II and III respectively because of compaction. However, no significant changes in the CH_4 oxidation capacity of the biocover studied is observed due to the reduction of the hydraulic conductivity with time and depth.

The average temperature in the column is 27.1°C which is 3.7°C more than the average ambient temperature (23.4°C). This difference is correlated to the heat generated by methanotrophic activity. Furthermore, there is a general trend towards an increase in thermal conductivity with depth through increasing bulk density and VWC. The low thermal conductivity of the compost-sand mixture provides temperature insulation that could protect biocovers against unfavorable thermal conditions in a cold climate.

The C_c values are 0.64 and in the range of 0.25 to 0.54 and 0.21 to 0.58 in Phases I, II and III, respectively. The C_c values and subsequently compressibility of the studied samples generally decreases with depth due to the increase of the dry bulk density.

The bulk density and organic content of the medium increase with depth and time while there is the opposite trend for porosity. The observed changes do not affect the CH_4 oxidation rate and the compost-sand mixture under study removes up to 72% (178.8 g/m^2 day) of influent CH_4 flux.

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4.4 Behaviour of peat biocover in column experiments[5]

Afshin Khoshand and Mamadou Fall

Abstract

This paper presents the results of laboratory column experiments as well as comprehensive post experiments on a peat biocover over a period of 156 days which are performed to investigate the thermal (T), hydraulic (H), mechanical (M), and chemo-biological (C-B) properties of the peat biocover in two dimensions of depth and time. The obtained results indicate that the CH_4 oxidation capacity reaches 150.6 g/m^2 day (corresponding to 60% of the influent CH_4 flux) over a period of 99 days. The CH_4 oxidation rate gradually declines to 130.2 g/m^2 day over the following 57 days presumably due to a lack of favourable conditions for methanotrophic activity. The post experiment analysis reveals that the biocover medium consistently compacts with depth and time which results in increasing bulk density. The average temperature within the columns (27.5°C) is 3°C more than the average ambient temperature (24.5°C) due to the generated heat during the CH_4 oxidation process. The thermal conductivity varies in a range of 0.2 to 0.53 $W/m^{o}K$ and increases with depth with increasing bulk density. The direct shear tests show that the studied samples have high frictional resistance with friction angle and cohesion in a range of 30.7^{o} to 41.3^{o} and 6.3 kPa to 12.3 kPa and, respectively. The hydraulic conductivity varies in a range of 8.47×10^{-4} m/s to 6.87×10^{-6} m/s and decreases with depth and time. On the basis of consolidation testing, the studied samples are compressible in nature and the compression index (C_c) values range from 0.41 m^2/year to 1.27 m^2/year, which generally decrease with depth in each column due to the increase in bulk density.

Keywords: biocover, peat, geotechnical properties, methane oxidation.

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[5] Submitted to the International Journal of Greenhouse Gas Control

4.4.1 Introduction

Methane (CH_4) is an imperative greenhouse gas with 23 to 25 fold global warming potential (GWP) in comparison to carbon dioxide (CO_2) over a 100 year horizon (IPCC 2001 and 2007). The global atmospheric concentration of CH_4 has risen more than 200% (from 715 to 1774 ppb) over a period of 255 years between 1750 and 2005 (IPCC 2007). CH_4 is released into the atmosphere by both natural and anthropogenic sources (Albanna et al. 2007), but it is now estimated that approximately 70% of the global CH_4 emissions have anthropogenic sources (IPCC 2001). Currently, landfills are among the largest anthropogenic sources of CH_4 and contribute to 10-20% of worldwide anthropogenic emissions of CH_4 (IPCC 2001). In landfills, CH_4 is produced as a result of the biodegradation of the organic fraction of disposed waste via a complex series of biological reactions under anaerobic conditions (Scheutz and Kjeldsen 2003). Based on the amount of biodegradable waste disposed and degradation conditions in the landfill, CH_4 production and emission can continue for several decades even after landfill closure (Hilger and Humer 2003). Therefore, there is a need to take effective and urgent steps for controlling and minimizing uncontrolled CH_4 emissions from landfills (Stern et al. 2007).

Landfill gas (LFG) collection and treatment systems, and the burning of CH_4 emission with high temperature flares, are common technologies for controlling and reducing the environmental impacts of CH_4 emissions from landfills (Huber-Humer et al. 2008). It should be noted that the mentioned technologies are mostly economically and technically applicable in large and new landfill sites with a high level of LFG production (Haubrichs and Widmann 2006, Huber-Humer et al. 2008). Furthermore, escaping large amounts of CH_4 gas into the atmosphere as fugitive emissions have been reported even at sites which are equipped with the mentioned technologies (Albanna et al. 2007).

One of the most innovative, promising and cost effective methods for the mitigation of CH_4 emission from landfills is exploiting the natural process of microbial CH_4 oxidation through a reactive biological cover soil which is referred to as biocovers (Ait-Benichou et al. 2007, Philopoulos et al. 2009). The CH_4 emission is oxidized in biocovers by a group of ubiquitous aerobic soil bacteria called methanotrophs at the interface of the aerobic and anaerobic zones

(Chanton et al. 2009). The biological CH_4 oxidation reaction through biocovers is similar to chemical reactions except that it is catalyzed by enzymes and biomass is produced (Chanton et al. 2009) as shown by Eq. 4.4 (Van Dijken 1975):

$$38.25\ CH_4 + 3\ NH_3 + 63.75\ O_2 \rightarrow 3\ C_4H_8O_2N + 26.25\ CO_2 + 69\ H_2O + \text{Heat} \qquad [4.4]$$

Biocovers are generally made up of a gas distribution layer with high gas permeability to homogenize LFG fluxes and an overlying filter substrate to support the growth and activity of methanotroph bacteria. Peat materials are potentially promising filter substrates, in part because they have high porosity, water holding capacity and specific surface area, and appropriate stable nutrient levels which enhance bacterial growth and the activity of methanotroph bacteria (Einola 2010, Stein and Hettiaratchi 2001, Streese and Stegmann 2003).

The performance of biocovers is affected by the numerous properties of the chosen material as the filter substrate as well as the surrounding environmental conditions (Einola 2010, Huber-Humer 2004). The key influencing factors can be classified as thermal (T) (temperature and thermal conductivity), hydraulic (H) (hydraulic conductivity, moisture content, and degree of saturation), mechanical (M) (grain size distribution, shear strength, and consolidation), and chemo-biological (C-B) (pH, organic content, gas concentration and composition) factors.

Various research has been conducted with different designs and substrates to understand the behaviour of biocovers (e.g., Einola 2010, Streese and Stegmann 2003, Huber-Humer 2004, Albanna et al. 2007). However, these studies have mostly investigated the CH_4 oxidation patterns of biocovers (Humer and Lechner 1999, Kightley et al. 1995, Wilshusen et al. 2004) or the isolated effects of one influencing factor (T, H, M, C-B) on the performance of biocovers (Hilger et al. 2000, Stein 2000, Huber-Humer 2004). To the best of the knowledge of the author, no such attempts have been made in the peer reviewed literature that investigate the behaviour of peat biocovers with respect to the simultaneous evolution of the key influencing factors (T, H, M, and C-B) and their interactions. It seems logical that there is a need to acquire a sufficient understanding of the behaviour and interactions between the T, H, M, and C-B properties of peat biocovers in order to derive the criteria that enable optimal design, construction and maintenance of peat biocovers.

The objective of the current paper is to study and discuss the simultaneous evolution of the key influencing factors (T, H, M, and C-B) and their interactions in a peat biocover by conducting column experiments as well as performing post experiment tests and analysis.

4.4.2 Materials

Laboratory investigations were conducted on peat materials which were used as the filter substrate. The peat materials used in this study are taken from the Moose Creek Bog in Moose Creek, Canada. The X-ray diffraction method was used to determine the mineralogical composition of the studied peat materials and the results are presented in Table 4.8.

Table 4.8. Mineralogical composition of biocover medium.

Constituent	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	MgO	CaO	K_2O	TiO_2	P_2O_5	Cr_2O_3	MnO	V_2O_5	LOI[1]
Percentage (%)	11.7	2.49	1.04	0.62	0.85	5.13	0.7	0.09	0.3	<0.01	0.03	<0.01	76.1

[1]Loss of ignition

The peat materials were air-dried at room temperature in the laboratory prior to the experiments. Plant materials and large stones were removed by sieving peat materials through a 9.5 mm mesh. Water was added to the peat material to bring the gravimetric moisture content to 40%. The mentioned moisture content has been recommended by prior studies that investigated the optimum moisture content of different filter substrates with regards to their CH_4 oxidation potential (Humer and Lechner 1999, Huber-Humer 2004, Huber-Humer et al. 2009).

4.4.3 Experimental program

In order to achieve the objective of the current research, an extensive experimental program which included a laboratory column study (monitoring program) over 156 days as well as post analysis and tests were conducted on samples. In Fig. 4.30, a summary of the conducted experimental program is presented.

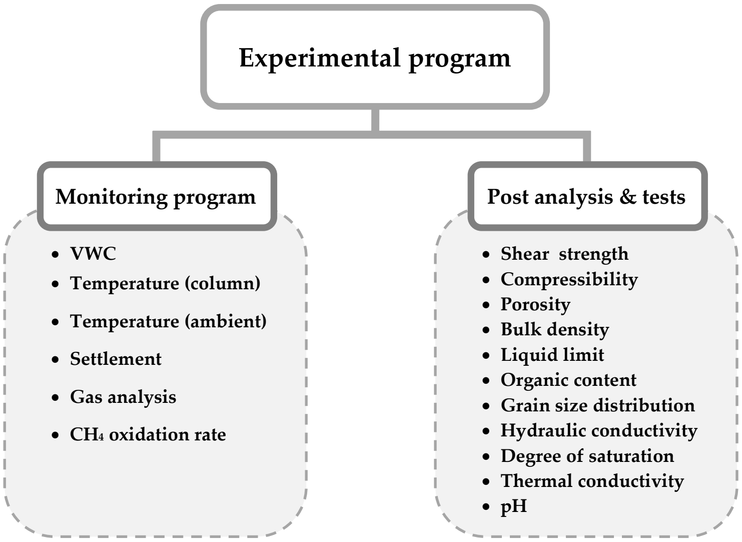


Fig. 4.30. Summary of the laboratory experimental program.

4.4.3.1 Monitoring program

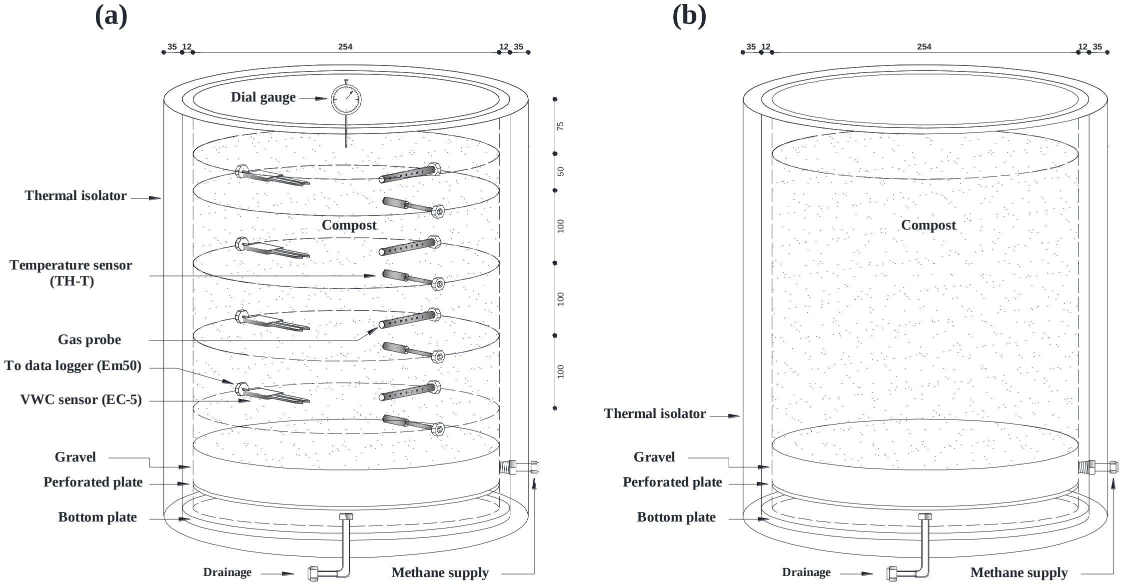
4.4.3.1.1 Column experiment set up

Since the column experiments represent an advanced step towards the evaluation of the behaviour of biocovers under continuous flow conditions (Perdikea et al. 2008), two columns (A and B) including one instrumented column (A) and one column (B) for sampling were developed and then manufactured with Plexiglas tubes (inner diameter of 25.4 cm and height of 60 cm). A perforated aluminum plate was placed above the drain at the bottom of each column to support the filter substrate. To provide a homogeneous and uniform distribution of CH_4 over the entire area of the biocover, each column was packed with a layer of fine and clean gravel as the gas distribution layer. The inlet CH_4 flow (99% purity) of 250 g/m^{2}day (equal to 13.21 ml/min) was introduced into the middle of the gas distribution layer. The gas flow was monitored by a Mass Stream D5111 mass flow controller (M+W Instruments 2011) which was connected to an NI 9219 data acquisition system (National Instruments 2009). The inlet CH_4 flow rate was selected as a typical mid to high CH_4 flux rate in landfills (Kightley and Nedwell 1994). The columns were thermally shielded from the outside environment by using expansive insulation foam to minimize lateral heat exchange between the peat material in the column and the surrounding atmosphere due to thermal gradients.

4.4.3.1.2 Column instrumentations and monitoring

A schematic representation of the columns and developed instrumentation is shown in Fig. 4.31. The probes for the measurement of the gas concentration, volumetric water content (VWC), and temperature were installed along Column A at depths of -5, -15, -25, and -35 cm from the surface of the biocover. The gas sampling ports were penetrated into the middle of the column cross-section. Each gas sampling port consisted of plastic fitting and a tightly sealed butyl-rubber septa which enable the taking of gas samples via a gastight syringe needle.

Measurement of the VWC and temperature based on the depth of the column with time was performed by using calibrated EC-5 dielectric soil moisture sensors (Decagon Devices 2012a) and TH-T temperature sensors (Roctest Ltd. 2005), respectively. The temperature (TH-T) and VWC (EC-5) probes were connected to EM 50 data loggers (Decagon Devices 2012*b*). All of the sensors were horizontally installed through the wall of the column and their wall connections were equipped with a fabricated brass fitting and butyl rubber O ring which ensured complete sealing. The settlement of the biocover was continuously monitored by using a dial gauge with a sensitivity of 0.01 mm which was installed perpendicular to the surface of the biocover in Column A. All of the column experiments were carried out at the laboratory temperature of about 22°C. As shown in Fig. 4.31, the developed column experimental set up simulates the landfill biocover environment with an upward flow of CH_4 gas injected into the bottom of each column while the surface of the biocover was exposed to air.



Note: All of the dimensions are in millimetres (mm).

Fig. 4.31. Schematic diagram of the developed biocover column set-ups ((a) Column A (monitoring column), (b) Column B (sampling column)).

4.4.3.2 Post analysis and tests

4.4.3.2.1 Material characterization tests

Prior to the start of the column operation (Phase I), comprehensive laboratory testing was performed to determine the T, H, M, and C-B properties of the used peat material. Respectively, after 82 days (Phase II) and 156 days (Phase III) of column operation, Columns B and A were dismantled into four undisturbed layers (at depths of -5, -15, -25, and -35 cm from the surface) for conducting post experiment analysis and tests.

All the experiments were conducted at room temperature and based on standard procedures established by the American Society of Testing and Materials (ASTM) standards for soils (ASTM 2010). In Table 4.9, the standard procedures used for the measurement of the Atterberg limits, organic content, pH, particle size distribution, and density are presented.

Table 4.9. Standard procedures used to test basic properties of biocover medium.

Property	Method	Comment
Atterberg limit	ASTM D4318	Includes liquid limit (LL) and plastic limit (PL)
Organic content	ASTM D 2974	
pH	ASTM D 4972	Determined for dissolved samples in water
Particle size distribution	ASTM D 422	Determined for the entire column at each phase
Density	ASTM D 2937	

The particle size distribution of the peat medium at different times is illustrated in Fig. 4.32. According to the Unified Soil Classification System (USCS) and gradation test results, the peat samples included 21.2%, 24.9% and 29% fine sand size in Phases I, II and III, respectively.

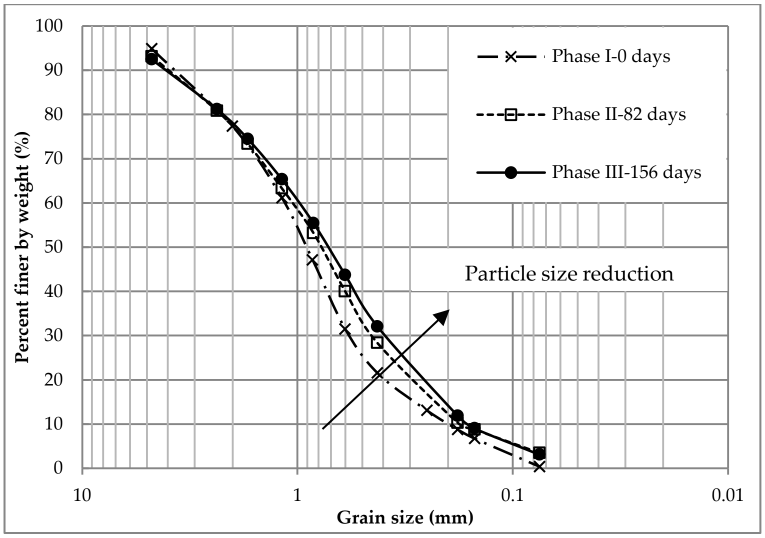


Fig. 4.32. Grain size distribution curves of peat biocover medium at different times.

Moreover, the peat specimens in Phases I (0 days), II (82nd day) and III (156th day) were classified respectively, as organic well-graded sand (SW), organic well-graded sand (SW), and organic poor-graded sand (SP) based on the USCS. The particle size distributions showed that the samples became slightly finer with time which can be due to the mineralization of the peat material over time.

4.4.3.2.2 Saturated hydraulic conductivity

To measure constant head saturated hydraulic conductivity, a flexible wall (triaxial) permeameter was used in accordance with ASTM standard procedure D5084. The constant head test was performed by using a TRI-FLEX II standard panel which was equipped with pressure gauges, regulators, electronic pressure transducers and graduated pipettes. The undisturbed cylindrical specimens were trimmed from thin-walled metal tubes and then placed into a triaxial cell with minimal disturbance. Generally, the hydraulic conductivity of porous materials decreases when increasing number of occupied pore spaces of the materials are filled with air (Ng and Lo 2007). Thus, de-aired water was used for permeation and back pressuring purposes throughout all of the tests. There is the possibility of the presence of trace amounts of sharp foreign objects in the peat materials, thereby the membranes used were carefully inspected to avoid leaks and flaws before the testing was carried out. The samples were subjected to an initial confining pressure and then saturated by flushing water under a constant hydraulic gradient (the saturation of each sample was also checked through post experiment tests). High hydraulic gradients result in clogging macrovoids and affect the hydraulic conductivity (Daniel 1984). Therefore, once a sample was saturated, the hydraulic conductivity test was performed at a low and constant hydraulic gradient of 5 to prevent anomalies during measurement. The flow measurement (volume of inflow and outflow) was taken at a predetermined elapsed time and Darcy's law was used to calculate the hydraulic conductivity in accordance with the following equation:

$$\mathrm{k} = -\frac{\mathrm{QL}}{\mathrm{Aht}} \qquad [4.5]$$

where k is the hydraulic conductivity in m/s, Q is the quantity of flow for a given time interval in m^3, L is the length of the sample in m, A is a cross sectional area of the sample, h is the average head loss across the sample in m, and t is an interval of time.

It should be mentioned that each hydraulic conductivity test was repeated at least twice and the average value was considered as the saturated hydraulic conductivity of the sample.

4.4.3.2.3 Consolidated drained shear strength

Several studies have revealed that the simple direct shear test is applicable to determine the consolidated drained shear strength properties of peat materials (e.g., Mesri and Ajlouni 2007, Ulusay et al. 2010, Edil and Dhowian 1981). Therefore, the shear strength parameters of undisturbed peat samples at different depths (-5, -15, -25, and -35 cm from the surface of the biocover) and times (Phases I- 0th day, II-87th day, III-153rd day) were obtained from consolidated drained direct shear tests by following ASTM procedure D3080. The undisturbed samples were extruded into the shear box, and kept submerged in water for saturation. Each sample was subjected to three vertical normal stresses of 10, 20, and 40 kPa which are in the range of induced normal stresses in landfills in field conditions (Rajesh and Viswanadham 2011). After consolidation, the specimens were sheared at a displacement rate of 0.0025 mm/min. All of the tests were strain controlled and conducted at a constant normal stress. Shear force and horizontal displacements were measured by using a load cell and an LVDT, respectively. The total and effective shear strength parameters (cohesion (c) and friction angle (φ)) were calculated based on Mohr–Coulomb failure criteria.

4.4.3.2.4 Compressibility

One dimensional consolidation tests were carried out in a floating ring oedometer on undisturbed samples per ASTM D2435. A sample extruder was used to obtain undisturbed circular specimens with minimal disturbance. The samples were placed into a circular oedometer ring (with diameter to thickness ratio of 3:1) and each sample was subjected to a series of constant vertical loads. The sample were allowed to consolidate for 24 hours for each load before applying the next load. The variation of strain with time for each constant vertical load was continuously monitored. In the current study, the loading sequence of 5, 10, 20, 40 and 80 kPa is selected in order to represent the field situation. It should be noted that the load increment ratio was constant to avoid the build up of internal resistance to loads (Ng and Lo 2007). After the loading step, the samples were gradually unloaded and the swelling of the samples was recorded.

4.4.3.2.5 Thermal conductivity

Thermal conductivity testing was conducted under isothermal conditions by using a portable KD2 thermal properties analyzer (Decagon Devices 2012*c*) and dual stainless-steel needle SH-1 thermal sensor (30 mm long, 1.28 mm in diameter, and 6 mm in spacing). The KD2 thermal properties analyzer employs the transient line source (TLS) method and measures thermal conductivity by measuring the temperature at intervals of one second during a thirty second heating period which was followed with thirty seconds of cooling (Decagon Devices 2012*c*). The testing procedure included slowly and steadily inserting of dual stainless-steel needle SH-1 probes into the undisturbed samples. A reading was taken after thermal equilibrate took place after 15 minutes. The probes were to remain parallel to each other during insertion and a minimum of 15 mm of the sample surrounded the probe in all directions. The default reading time for the SH-1 probe is 2 minutes and thermal conductivity was measured with a relative error of 10% (Decagon Devices 2012*c*). Each test was repeated two times and the average value was reported as the thermal conductivity of the sample.

4.4.3.2.6 Gas Analysis

Gas analysis testing was carried out by constantly taking gas samples from the sampling ports along Column A by using a gas tight 1 mL syringe over 156 days of column operation. The apparatus used to measure the concentrations of CH_4, CO_2, O_2, and nitrogen (N_2) was a Series 400 isothermal gas chromatograph (GC) (Gow-Mac Instrument 2011), equipped with a thermal conductivity detector (TCD) and two stainless steel columns. O_2 and N_2 were quantified on a Molsieve 13X, 80/100 mesh column and CH_4 and CO_2 on a HayeSep Q, 80/100 mesh column. The carrier gas was high purity helium (99.999% He, vol. basis) and the detection settings included a column temperature of 120°C, and injector and detector temperatures of 130ºC.

4.4.4 Results

4.4.4.1 Basic properties

Fig. 4.33 illustrates the variation in the material properties, including pH, bulk density, porosity (n), Atterberg limit, and organic content with time and depth. The studied medium was porous with large air space volume (initial porosity of 83.7.4%), contained high organic content (initial organic content of 69.73%), and had a neutral pH (initial pH of 6.7). These properties are similar to the recommended chemical and physical properties in the literature for suitable filter materials of biocovers (Huber-Humer et al. 2009).

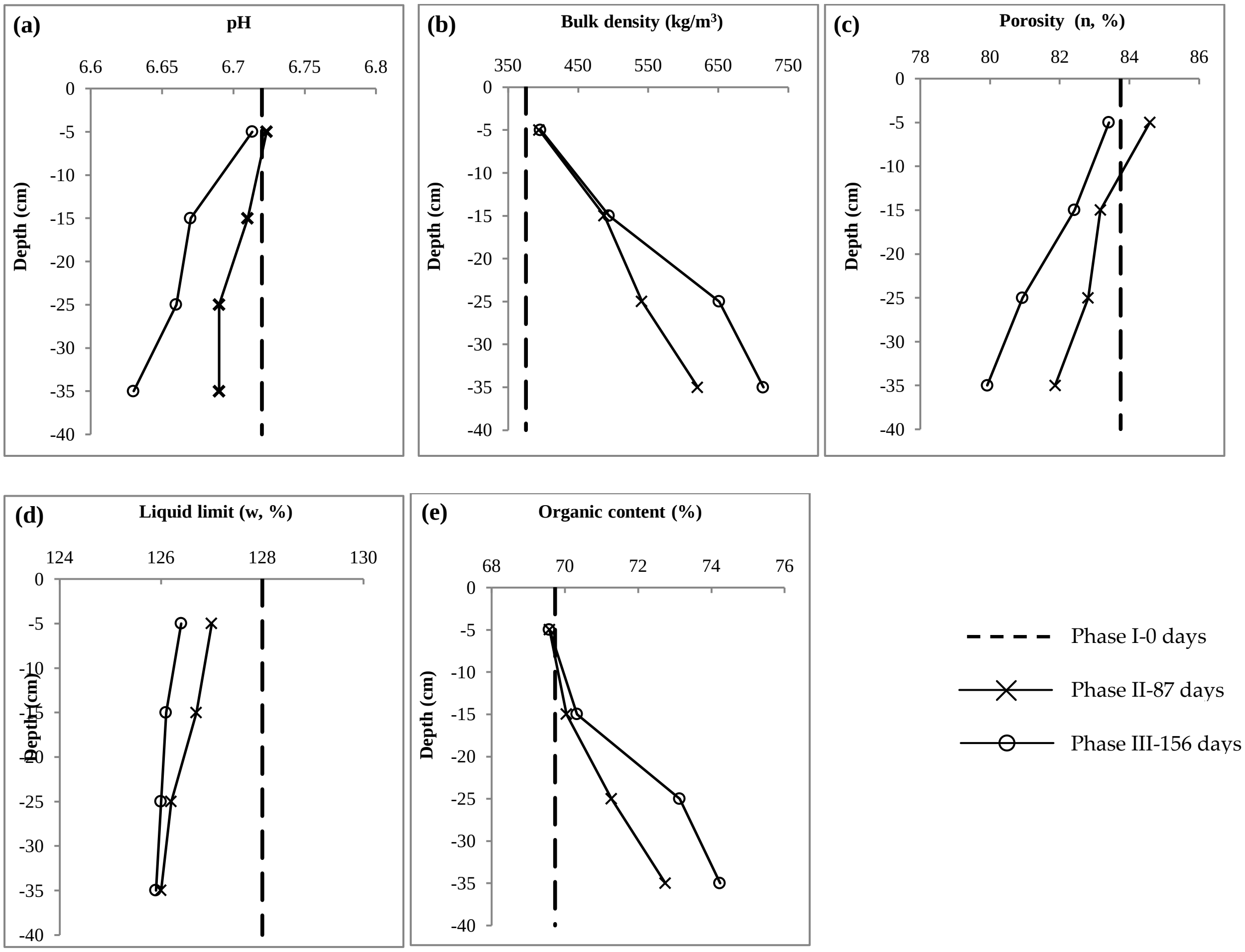


Fig. 4.33. Variation of pH, bulk density, porosity, LL, and organic content of peat biocover medium with depth at different times.

((a) bulk density, (b) porosity, (c) LL, and (d) organic content).

Fig. 4.33a (pH profiles) shows that the pH values remain relatively constant and only varies in a narrow range of 6.6 to 6.7. The bulk density profiles in Fig. 4.33b show that the bulk density of the biocover increases and the peat becomes compacted with depth and time. Furthermore, the peat medium becomes compacted and the bulk density values increase with time. It should be noted that the increase in bulk density is more significant from Phases I (0 days) to II (82nd day) than from Phases II (82nd day) to III (156th day) which implies that the time dependent increase of the bulk density is damped over time. As shown in Fig 4.33c (porosity profiles), there is a general trend in the reduction of the porosity with depth and time because of the compaction of the filter material due to settlement (Fig. 4.35). It can be seen from the liquid limit profiles in Fig. 4.33d that the liquid limit of the peat ranges between 125.9% and 128% and there is no significant difference between the liquid limit values at the start of the experiments and post experiment. The obtained high ranges of the liquid limits for the peat materials are consistent with those reported in the literature (Deboucha and Hashim 2009). The organic content profiles in Fig. 4.33e indicate a slight increase of the organic content of the peat medium from 69.6% – 72.7% in Phase II (82nd day) to 69.6% – 74.3% in Phase III (156th day) throughout the depth of the column. An increase in organic content with time is associated with the formation of exopolymeric substances (EPS) (Pokhrel 2006). After approximately 60 days, EPS zones were observed throughout the transparent columns.

4.4.4.2 Mechanical properties

4.4.4.2.1 Compressibility characteristics

The value of the coefficient of consolidation (C_v) at different depths, times and under the studied normal stress conditions is shown in Table 4.10. Sing et al. (2008*a*, *b*) compared the square root time (Taylor) and log time (Casagrande) methods for determination of the C_v values and found compression curves of peat materials fit better to the theoretical square root time curve. Therefore, C_v is calculated based on the square root time (Taylor) method in the current research. It can be seen from Table 4.10 that the C_v values generally decrease with increases in the consolidation pressure. Terzaghi et al. (1996) also observed a continuous reduction of the C_v with increasing consolidation pressure in peat materials. As presented in Table 4.10, the value of C_v which ranges from 3.65 to 5.09 m²/year before beginning the column operation (Phase I) increases to a range of 3.72 to 5.29 m²/year and 3.95 to 5.38 m²/year in Phases II and III, respectively with increase in the organic content with depth and time (Fig. 4.33e).

Table 4.10. Coefficient of consolidation of biocover medium at different times and depths.

Load	Depth (cm)	C_v (m²/year)		
		Phase I (0 days)	Phase II (82nd day)	Phase III (156th day)
5	-5	5.09	5.14	5.20
	-15		5.18	5.25
	-25		5.24	5.31
	-35		5.29	5.38
10	-5	4.71	4.88	4.93
	-15		4.81	5.01
	-25		4.89	5.13
	-35		4.98	5.11
20	-5	4.43	4.62	4.69
	-15		4.72	4.77
	-25		4.81	4.84
	-35		4.88	4.93
40	-5	4.05	4.25	4.46
	-15		4.32	4.63
	-25		4.44	4.60
	-35		4.52	4.69
80	-5	3.65	3.72	3.95
	-15		3.85	4.01
	-25		3.92	4.11
	-35		4.01	4.21

It is obvious that an increase in the C_v values from Phases I to III is more considerable than that from Phases II to III at the same depth. The mentioned difference can be associated to less change in the organic content from Phases II to III in comparison to that from Phases I to III as shown in Fig. 4.33e.

The variation void ratio (e) versus logarithm of the consolidation pressure (σ) of the samples at different depths and times is shown in Fig. 4.34. It can be seen that the studied materials are compressible with significant reductions in void ratio with increasing consolidation pressure. Moreover, at the same normal stress, the void ratio of the samples decreases with depth.

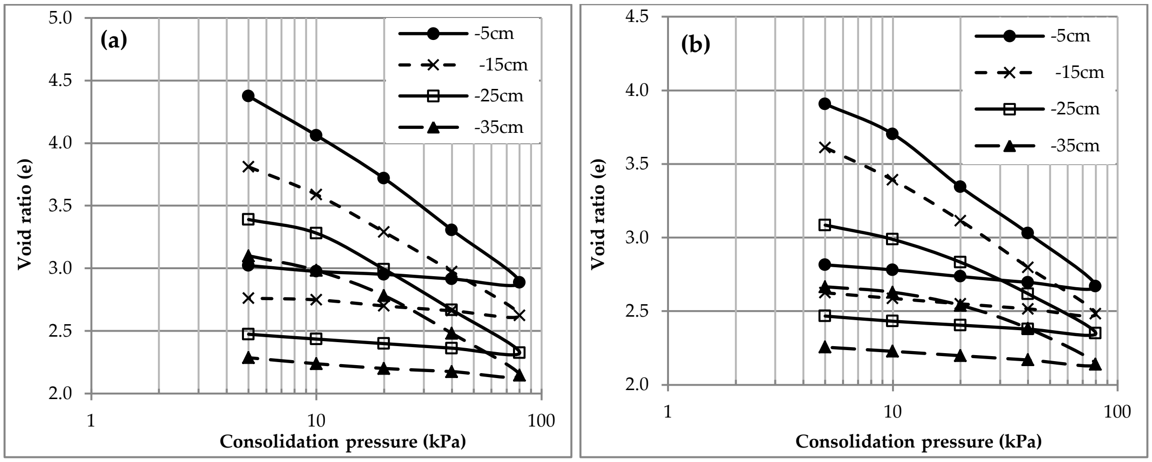


Fig. 4.34. Consolidation curves of peat biocover medium at different depths and times ((a) Phase II (82nd day), and (b) Phase III (156th day)).

Table 4.11 is a summary of the values of the compression index (C_c) and recompression index (C_r) of the samples which are the slope of the consolidation curves (Fig. 4.34) for the loading and unloading stages during consolidation testing, respectively. Compressibility and associated settlement of the biocover medium can be explored by analyzing the consolidation parameters including the C_c and C_r values. Materials with a high C_c value generally experience higher settlement.

It can be seen from Table 4.11 that the C_c value of the biocover medium at the end of the column operation (Phase III) is in the range of 1.120 to 0.409 which is significantly less than the value of C_c in Phases I and II which is 1.271 and varies in a range of 1.254 to 0.834, respectively. Also, the C_r value which reflects the swelling potential of the materials generally decreases with depth from 0.128 in Phase I (0 days) to a range of 0.107 to 0.090 and 0.109 to 0.095 respectively in Phases II and III.

In addition to the consolidation behaviour, the vertical settlement of the biocover medium was monitored during the period of the column operation and the obtained results are presented in Fig. 4.35. The settlement curve has a steep slope in the first 28 days of the column operation and the biocover settled 17 mm with a settlement rate of 0.6 mm/day in the mentioned period. From the 28th to the 85th day, settlement followed with lower increments (0.15 mm/day) and finally maintained a relatively straight line with time until the end of the experiment. The findings of the current research are consistent with those of Huber-Humer (2004) and Bajwa (2012).

Table 4.11. Compression and recompression indexes of the biocover medium at different depths and times.

Sample	Depth (cm)	C_c	C_r
Phase I	All depths[1]	1.271	0.128
Phase II	-5	1.254	0.107
	-15	1.022	0.123
	-25	1.017	0.119
	-35	0.834	0.090
Phase III	-5	1.120	0.109
	-15	0.987	0.113
	-25	0.614	0.092
	-35	0.409	0.095

[1] Includes -5, -15, -25, and -35 cm.

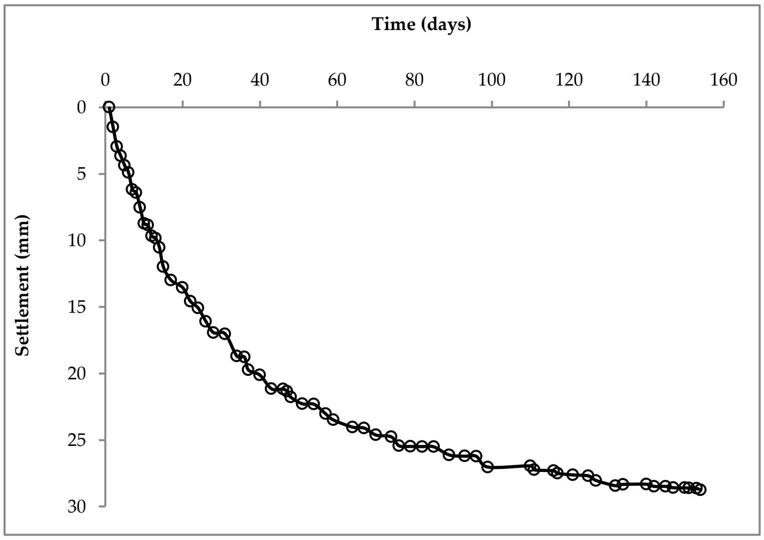


Fig. 4.35. Vertical settlement of peat biocover medium over 156 days.

4.4.4.2.2 Consolidated drained shear strength properties

Figs. 4.36 and 4.37 show the stress-strain curves under normal stresses of 10, 20 and 40 kPa for the studied material at different depths and times (Phases II-82nd day and III-156th day).

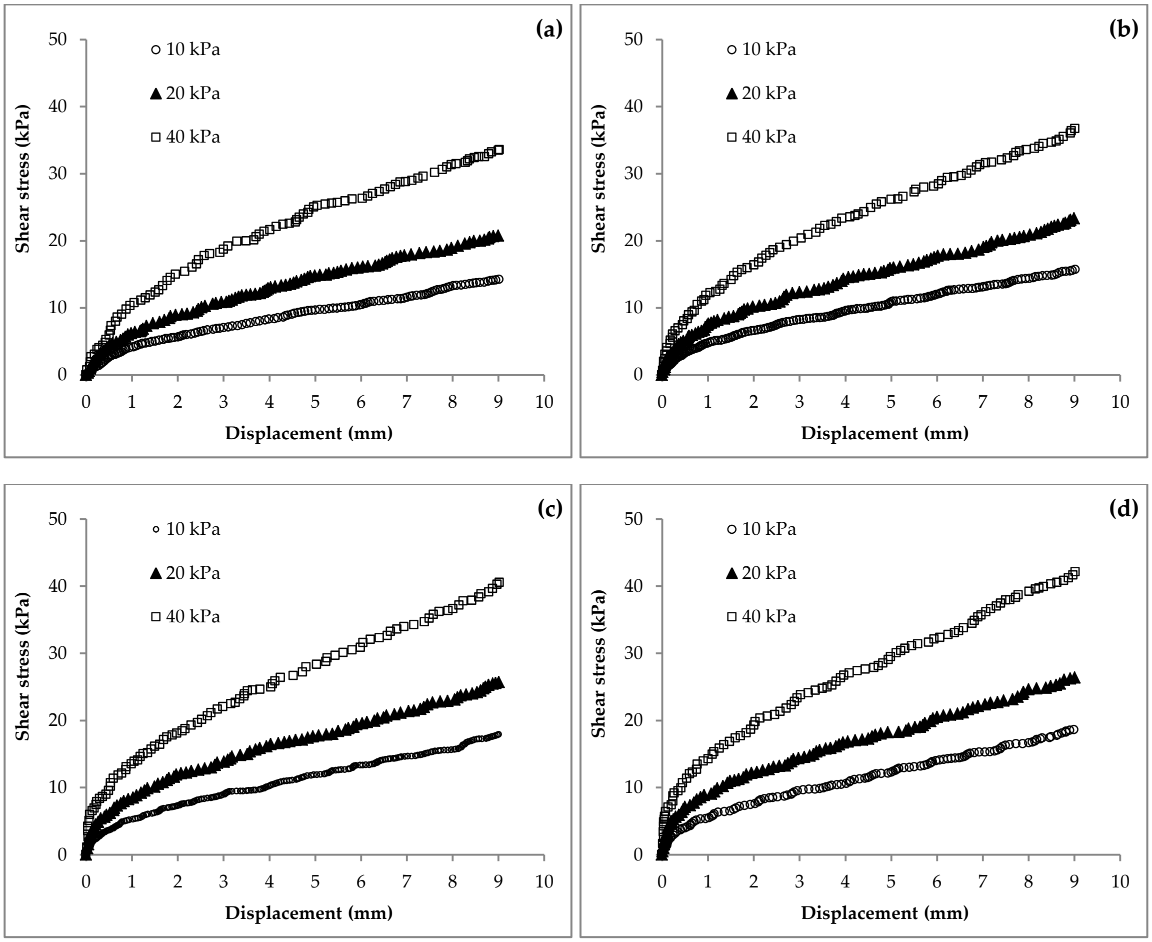


Fig. 4.36. Results of direct shear tests on peat biocover medium samples at different depths in Phase II (82nd day)

((a) -5 cm; (b) -15 cm; (c) -25 cm; (d) -35 cm).

The stress-strain curves in Figs. 4.36 and 4.37 indicate that at the same depth and normal stress, the ultimate strength increases with time which can be associated with increasing compaction as time passed. The mentioned difference is more pronounced with depth. At a depth of -35 cm and under a normal stress of 40 kPa, the difference between the ultimate strength of the samples in Phases II and III is 11% while it is 5% at a depth of -5 cm.

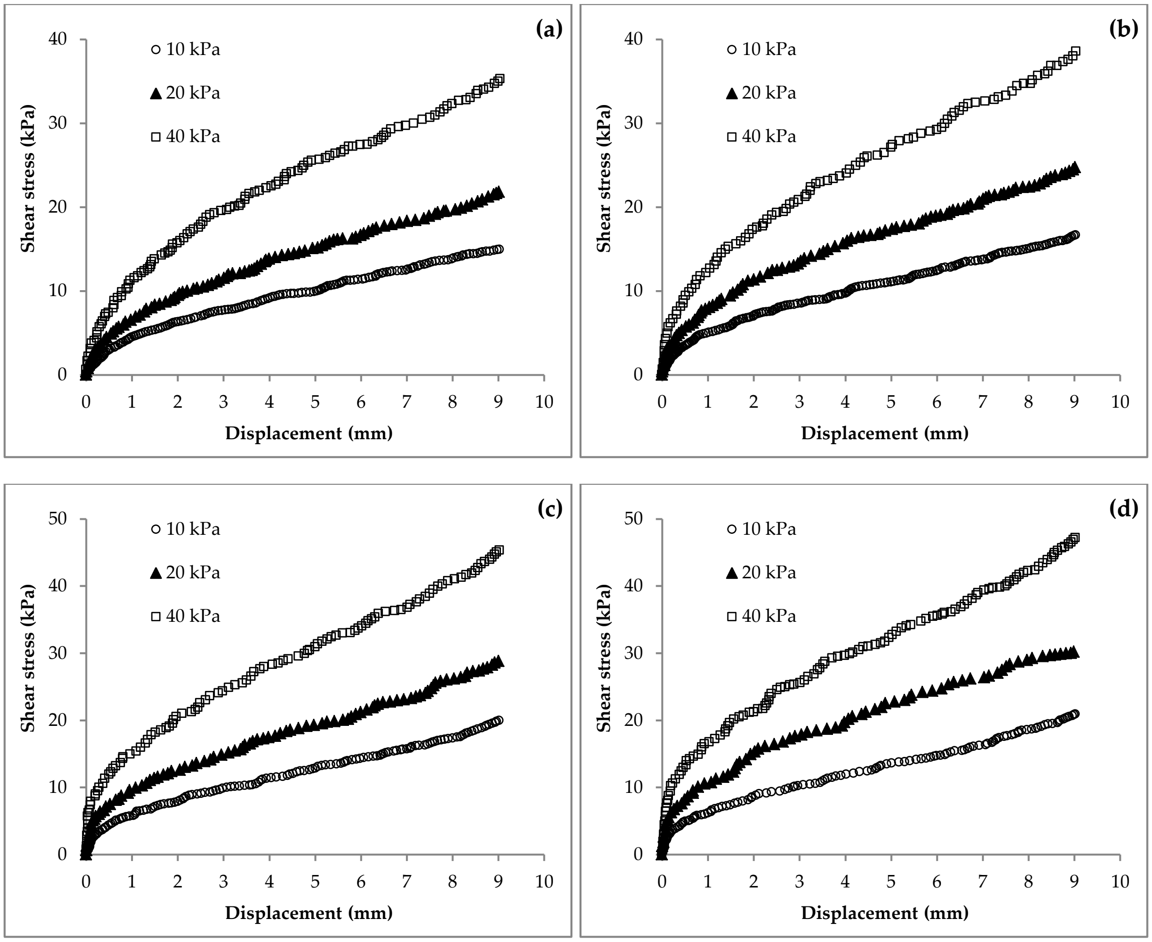


Fig. 4.37. Results of direct shear tests on peat biocover medium samples at different depths in Phase III (156th day)

((a) -5 cm; (b) -15 cm ; (c) -25 cm; (d) -35 cm).

It can be seen from Figs. 4.36 and 4.37 that no definite peak strength can be observed with increasing horizontal deformation. In the absence of reaching peak strength, the Mohr-Coulomb failure envelopes were established based on shear strength at 15% of strain. As show in Fig. 4.38, the Mohr-Coulomb shear strength envelopes for the studied samples are well characterized by approximate linear relationships for the studied normal stresses (10 to 40 kPa).

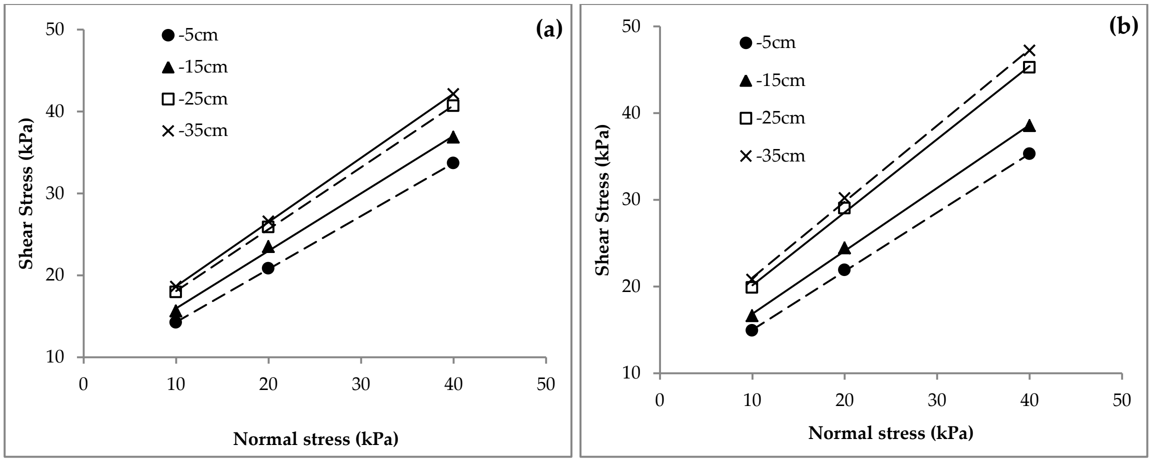


Fig. 4.38. Linear Mohr-Coulomb approximation of peat biocover medium samples at different depths and times

((a) Phase II (82nd day), and (b) Phase III (156th day)).

The cohesion and friction angle of the specimens at different depths and times (Phase I-0 days, II-82nd day and III-156th day) are listed in Table 4.12. It can be seen that the behavior of the peats is frictional with high friction angles (friction angle varies between 30.7° and 41.3°) and relatively small cohesions (cohesion varies between 6.3 and 12.3 kPa). The obtained results are consistent with the findings of Ulusay et al. (2010) and Mesri and Ajlouni (2007) for different types of peat materials.

Table 4.12. Shear strength parameters of the biocover medium at different depths and times.

Sample	Depth (cm)	Cohesion, c (kPa)	Angle of friction, φ (°)
Phase I	All depths[1]	6.3	30.7
Phase II	-5	7.8	32.9
	-15	8.9	35
	-25	10.5	37.1
	-35	10.8	38.1
Phase III	-5	8.2	34.1
	-15	9.6	36
	-25	11.7	40.1
	-35	12.3	41.3

[1] Includes -5, -15, -25, and -35 cm.

The cohesion of the studied material varies with depth and time. The cohesion of the studied material in Phase I (0 days) is 6.3 kPa and increases with increasing organic content from the top to the bottom of the columns and reaches a maximum value of 12.3 kPa at a depth of -35 cm in Phase III (156th day).

4.4.4.3 Hydraulic properties

4.4.4.3.1 Saturated hydraulic conductivity

Fig. 4.39 shows how the saturated hydraulic conductivity of the biocover varies with depth at different times. It can be clearly observed that the hydraulic conductivity of the biocover medium is strongly influenced by time. There is a general trend of hydraulic conductivity reduction with time such that the hydraulic conductivity of the biocover medium experiences significant declines from 8.47×10^{-4} m/s in Phase I (0 days) to a range of 6.01×10^{-4} m/s to 9.99×10^{-6} m/s and 3.21×10^{-4} m/s to 6.87×10^{-6} m/s in Phases II (82nd day) and III (156th day), respectively.

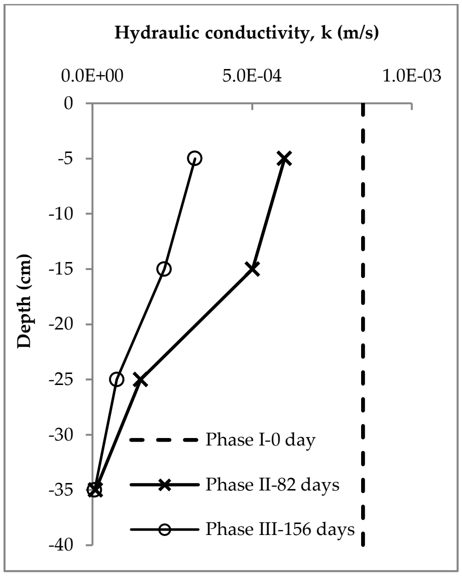


Fig. 4.39. Variation of hydraulic conductivity of peat biocover medium with depth at different times.

Fig. 4.39 indicates that the hydraulic conductivity of the biocover medium is also a function of the depth of the biocover. The hydraulic conductivity at the bottom layer (9.99×10^{-6} m/s and 6.87

$\times 10^{-6}$ m/s in Phases II (82nd day) and III (156th day), respectively) is two orders of magnitude less than that at the surface layer (6.01×10^{-4} m/s and 3.21 $\times10^{-4}$ m/s in Phases II (82nd day) and III (156th day), respectively). This decrease in hydraulic conductivity with depth is attributed to the increase in the bulk density of the samples with depth (as shown in Fig. 4.33b).

4.4.4.3.2 Degree of saturation and moisture content evolution

The degree of saturation (S_r) expresses the relative pore volume available for gas exchange processes within biocovers (Bajwa 2012). Fig. 4.40 illustrates the variations in the degree of saturation of the biocover medium with depth and time. It can be seen that the S_r gradually increases with depth and reaches the maximum value of 27% and 34% in Phases II (82nd day) and III (156th day), respectively. The increase of the S_r with depth is attributed to the simultaneous reduction of the porosity of the medium with depth (as show in Fig. 4.33c) and increase in the moisture content due to downward moisture movement and more methanothrophic activity in the bottom layer. Bajwa (2012) and Cabral et al. (2010*b*) also found a high degree of saturation in the bottom layer of their studied biocovers.

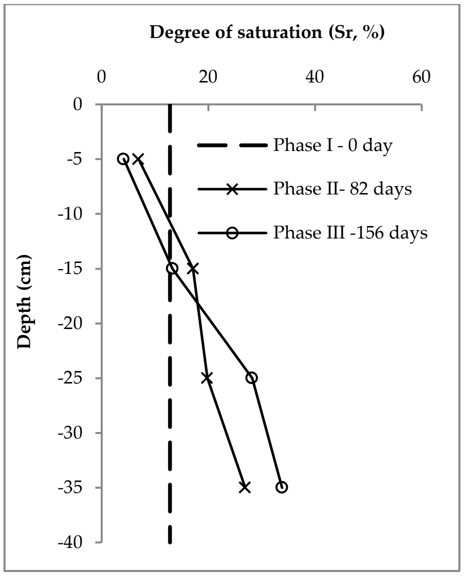


Fig. 4.40. Variation of degree of saturation of peat biocover medium with depth at different times.

Furthermore, it can be seen that the S_r in the surface layer (-5 cm) significantly decreases over time (12.8%, 6.9% and 4.1% respectively in Phases I (0 days), II (82nd day), and III (156th day)) because of surface desiccation due to evaporation over time. Variation of the volumetric water content (VWC) with time at different depths of the biocover is illustrated in Fig. 4.41.

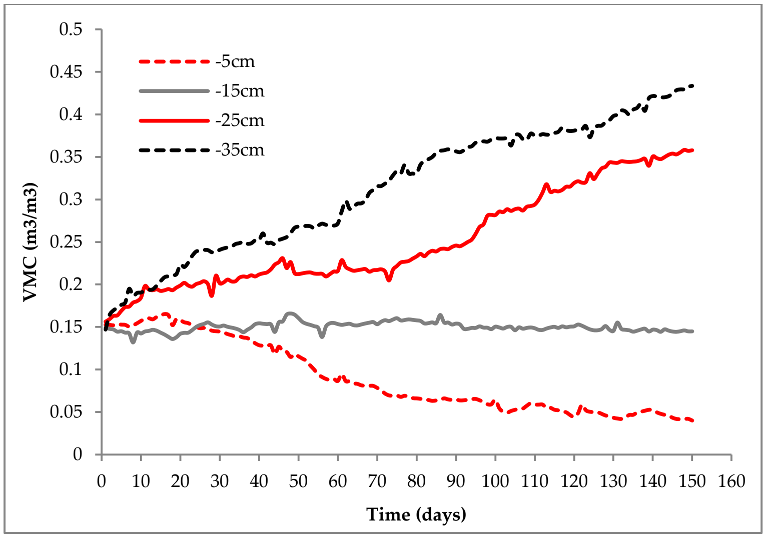


Fig. 4.41. Variation of VWC at different depths of peat biocover medium with time.

The initial VWC throughout the depth of the biocover was 15% which consistently dropped in the top layer (-5 cm) with time and experienced a loss of approximately 12% of the moisture content over 156 days. The VWC at a depth of -15 cm did not exhibit any significant changes and was relatively constant (with an average of 15%) during the 156 days of column operation.

At a depth of -25 cm, the VWC also followed a similar trend and increased to a value of 23% and 34% in Phases II (82nd day) and III (156th day), respectively. As shown in Fig. 4.41, the VWC in the bottom layer (-35 cm) continuously increases over time and reaches 34.5% and 44% in Phases II (82nd day) and III (156th day), respectively. It can be seen that the changes in the VWC with time is more significant at a depth of -35 cm in comparison to the rest of the column.

4.4.4.4 Thermal properties

4.4.4.4.1 Temperature

Fig. 4.42 shows the variation of temperature at different depths (-5,-15,-25, and -35 cm) of the biocover over the 156 days of the column operation.

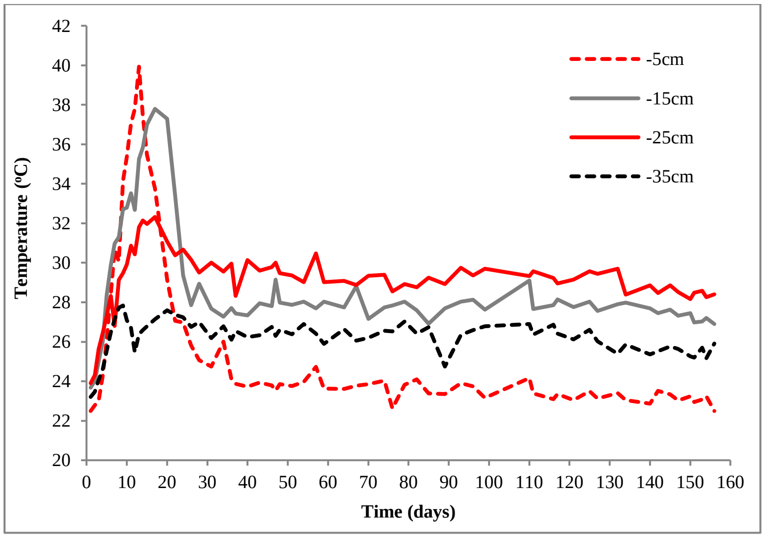


Fig. 4.42. Variations in temperature at different depths of peat biocover medium with time.

The average initial temperature throughout the depth of the biocover was 23.3°C which is close to the ambient temperature on the first day of the column operation (23°C). It can be seen from Fig. 4.42 that the temperature at all depths consistently increases from the initial value and reaches a maximum value of 39.9°C, 37.8°C, 32.3°C, and 27.8°C at depths of -5 cm, -15 cm, -25 cm, and -35 cm, respectively during the first 20 days of column operation. It should be noted that the mentioned increase in temperature is more significant at the top layers (-5 and -15 cm) where availability of O_2 was not a limiting factor.

After the mentioned period, the temperature profile in Fig. 4.42 does not show any significant changes and the temperature is relatively constant at all depths with an average of 24.2°C, 28.1°C, 29.5°C, and 26.5°C at depths of -5 cm, -15 cm, -25 cm, and -35 cm, respectively until the 110th day of column operation. It can be clearly observed from Fig. 4.42 that the temperature at depths of -15 cm and -25 cm is relatively higher than that at depths of -5 cm and -35 cm during the 156 days of column operation. A period of steady-state temperature followed with declines in the temperature until the end of the experiment. In the period of temperature decline, the average temperature is approximately 1°C less than that of the steady-state period at all depths.

It should be mentioned that the average temperature throughout the depth of the column was 27.5°C over the 156 days of column operation while the average ambient temperature was 24.5°C in the same period. Pedersen (2010) and Berger et al. (2005) also reported higher temperatures within biocovers in comparison to the ambient temperature.

4.4.4.4.2 Thermal conductivity

Fig. 4.43 shows the thermal conductivity profile over time. The thermal conductivities of the samples are in the range of 0.24 to 0.46 W/m° K and 0.2 to 0.53 W/m° K in Phases II (82nd day) and III (156th day), respectively. The obtained results are consistent with those in Dissanayaka et al. (2012) for peaty soils.

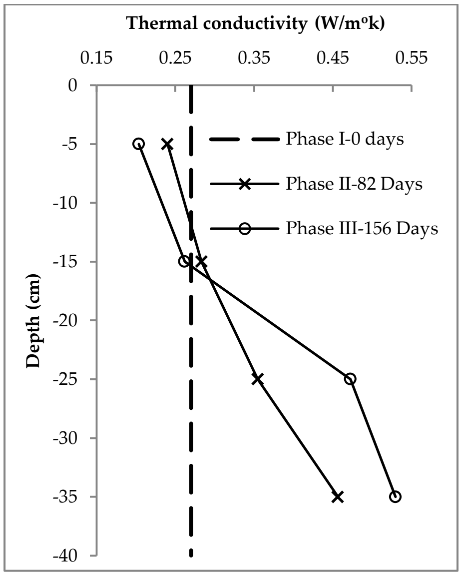


Fig. 4.43. Variations of thermal conductivity of peat biocover medium with depth at different times.

It can be seen that in both the second and third phases, the thermal conductivity increases from the top (0.24 and 0.2 W W/m° K in Phases II and III, respectively) to the bottom layer (0.46 and 0.53 W/m° K in Phases II and III, respectively) with a simultaneous increase in the VWC (Fig. 4.41) and bulk density (Fig. 4.33b). The rate of increase in the thermal conductivity from a depth of -5 to -15 cm is 1.2 W/m²°K in Phase III, which is 0.6 W/m²° K less than that at a depth of -15 to -35 cm.

It can be seen from the thermal conductivity profile in Fig. 4.43 that the change in thermal conductivity is also time dependent. At the surface layer (-5 cm), the thermal conductivity decreases with time and from an initial value of 0.27 W/m° K, reaches the minimum value of 0.2 W/m° K at the end of the column operation. In contrast to the surface layer, the thermal conductivity at depths of -25 and -35 cm is clearly increased to 0.47 and 0.57 W/m° K in Phase III, respectively.

4.4.4.5 Chemo-biological properties

4.4.4.5.1 Methane oxidation rate

The rate of CH_4 oxidation is defined as $\frac{C_{out}}{C_{in}} \times J_{in,CH_4}$ (Albanna et al. 2007), where C_{in} is the inlet concentration of CH_4 (%v/v) which is 100%, C_{out} is the difference between C_{in} and the measured concentration of CH_4 (%v/v), and J_{in,CH_4} is CH_4 load during the experiments (250 g/m²day).

Fig. 4.44 shows the CH_4 oxidation rate at selected depths (-5, 15, -25, and -35 cm) over the time of examination (156 days). It can be seen that the CH_4 oxidation rate at all depths increases during the first 22 days of the column operation. This period is the time necessary for reaching the steady state of CH_4 oxidation in biocovers and referred to as the adaptation phase. Development of a steady state of CH_4 oxidation gradually occurred over two or three weeks in some of the studies, for instance, Wilshusen et al. (2004) and Hilger et al. (2000) for wood chip compost and soils, respectively, while the adaptation phase took a few days in other research work, for example, Wilshusen et al. (2004) and De Visscher and Van Cleemput (2003) for leaf compost and soils, respectively. After the adaptation phase, the biocover evolved to a steady state phase which continued for approximately 99 days of the column operation. During the steady state period, the CH_4 oxidation efficiency reached a peak value of 60% (which corresponds to 150.6 g/m^2 day).

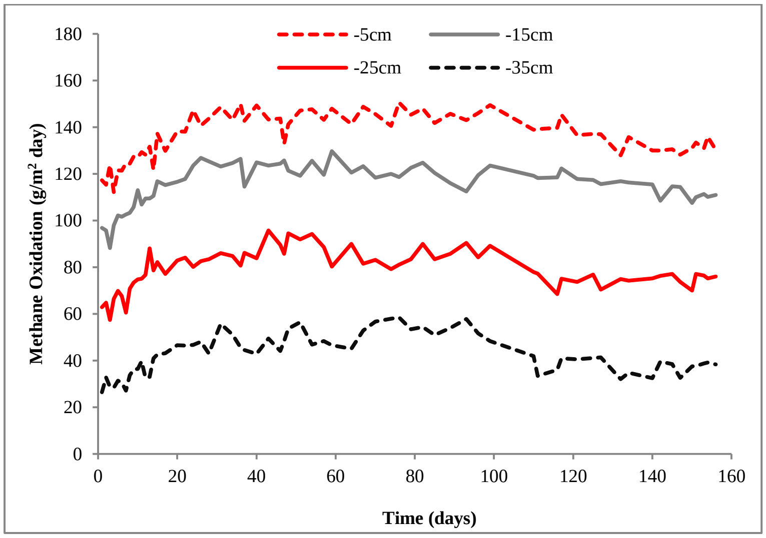


Fig. 4.44. Variation of CH_4 oxidation rate at different depths of peat biocover medium with time.

Thereafter, the CH_4 oxidation rate started to gradually decline until the end of the experiment. It should be noted that the mentioned decline is more significant at depths of -5 and -15 cm. The average CH_4 oxidation efficiency during the decline period was 45% at a depth of -15 cm which is approximately 4% less than that of the steady state period at the same depth.

4.4.4.5.2 Gas profile

The gas composition profiles for several selected days are shown in Fig. 4.45. The gas profile is a function of biochemical reactions, diffusion and advection of gas flow within biocovers (De Visscher 2001). It can be seen from Fig. 4.45 that in contrast with the concentrations of CH_4 and CO_2, the concentrations of O_2 and N_2 gradually decline with depth at all times.

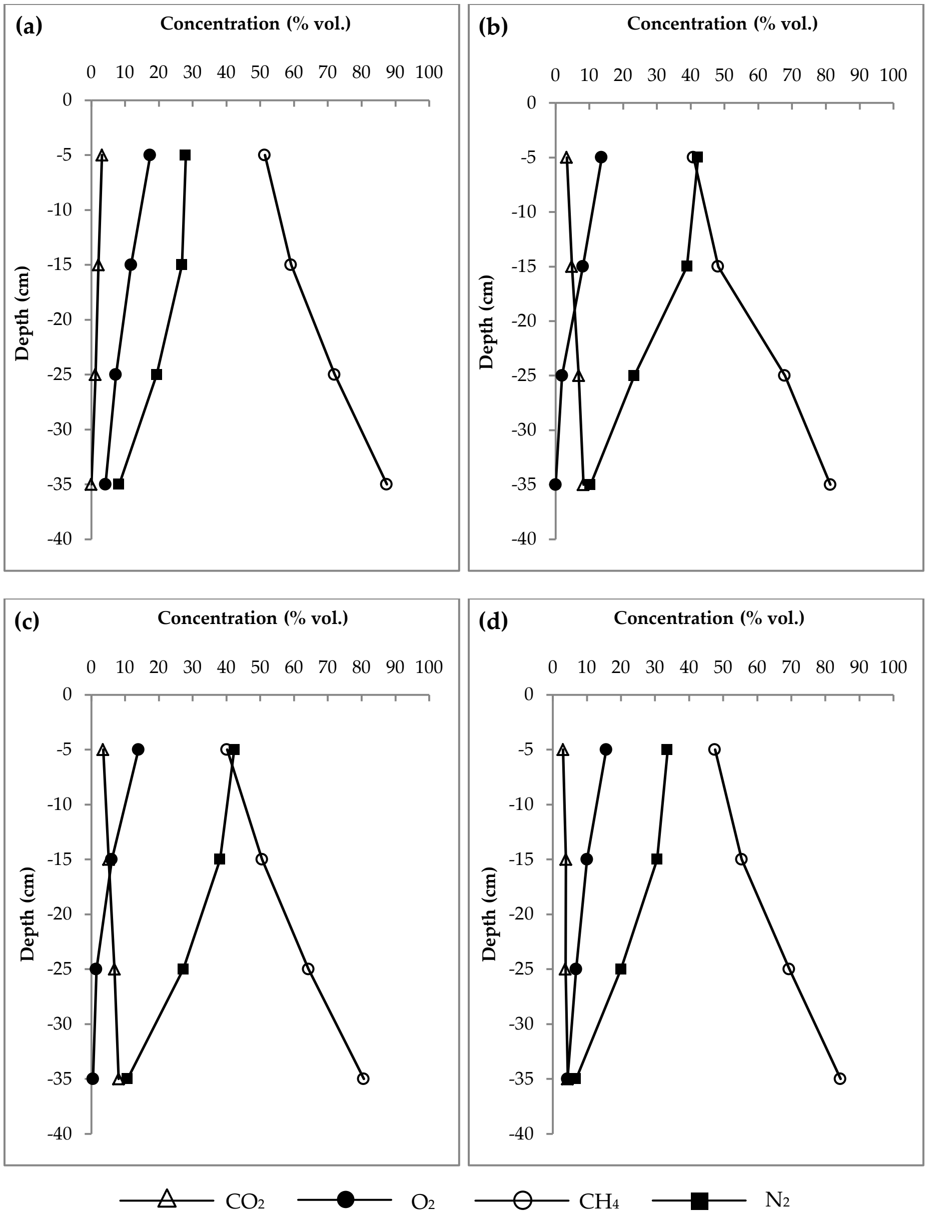


Fig. 4.45. Gas concentrations of peat biocover during the column operation ((a): 5th, (b): 59th, (c): 59th, (d): 99th, (e): 153rd day of column operation).

The gas profile of the 5th day per Fig. 4.45a shows that there is a relatively high CH_4 concentration throughout the depth of the column. The gas profile looks remarkably different at the steady state phase (between the 22nd and 99th day) in comparison to the adaptation phase. Evidently, the gas composition profiles during the steady state phase per Figs. 4.45b and c are similar. As shown in Figs. 4.45b and c, the average CH_4 concentration throughout the depth of the column on the 59th and 99th days is respectively 9% and 10% less than that on the 5th day.

In contrast to the gas profiles observed on the 59th and 99th day, the depth of the penetration of O_2 reached -35 cm on the 153rd day. Concurrently, the CH_4 concentration showed a gradual increase at the surface layer.

4.4.5 Discussions

4.4.5.1 Basic properties

Generally, the behaviour of the studied peat biocover is examined as a function of depth and time. The increase in the bulk density with time and depth is associated with the rearrangement of the orientation of the particles and degradation of the organic content (Pokhrel 2006). The compaction of the filter material due to settlement causes a reduction in the porosity of the biocover medium with depth and time which influences the gas exchange process and can have a negative effect on the CH_4 oxidation rate (Pokhrel 2006). The EPS are long chains of organic compounds which are produced under certain environmental conditions by methanotroph bacteria (Huber-Humer, 2004). Since the formation of EPS in the columns can imply activity and growth of methanotroph bacteria (Pokhrel 2006), the organic content profile can be used as a surrogate to determine the main zones of CH_4 oxidation (Pokhrel 2006). Kightley et al. (1995) and Wilhsuesen et al. (2004) also found higher organic contents at depths where maximum CH_4 oxidation was obtained.

In contrast to bulk density, porosity, and organic content, the pH and liquid limit of the studied peat biocover were relatively constant. A concurrent analysis of the pH profile (Fig. 4.33b) and CH_4 oxidation rate (Fig. 4.44) revealed that the pH is not a limiting factor in the CH_4 oxidation process in the current study.

4.4.5.2 Mechanical properties

4.4.5.2.1 Compressibility characteristics

Strains due to sudden changes in the stress in biocovers during construction and maintenance activities can result in settlement and drainage of pore water. Extensive settlement is undesirable from a maintenance point of view, since it may lead to crack and fissure development and consequently affect the physical stability of biocovers. Furthermore, settlement has significant effects on the porosity of the biocover material and influences the gas exchange process within biocovers, and thereby the rate of CH_4 oxidation (Bajwa 2012). It has been found that the consolidation behaviour of organic soils is influenced by the organic content (Mesri and Ajlouni 2007). In the current study, the value of C_v increases with depth as the organic content is increased. The variation of C_v with organic content in organic soils was also observed by Islam et al. (2006). Besides the organic content, the compressibility of the peat materials is also influenced by bulk density (Mesri and Ajlouni 2007) and compaction. Compaction and increasing bulk density of the studied peat biocover medium with depth and time (Fig. 4.33b) caused lower void ratios and reduction of C_c and C_r values (Table 4.11). The settlement of the biocover medium is the result of the rearrangement of the compost particles due to the decrease in the pressure as a result of self weight over time. A comparison of the settlement curve (Fig. 4.35) and CH_4 oxidation rate (Fig. 4.44) indicated that settlement of the biocover medium does not influence the rate of CH_4 oxidation. It should be noted that in the determination of the minimum thickness of the biocover and especially when a minimum thickness is required by regulatory agencies, reduction of the thickness of the biocover induced by extensive settlement should be taken into account.

4.4.5.2.2 Consolidated drained shear strength properties

As shown in Figs. 4.36 and 4.37, the ultimate strength of the samples increases with depth and time at the same normal stress. This is caused by the fact that the biocover medium changes from a loose to dense condition with depth and time (Fig. 4.33b) mainly due to the rearrangement and deformation of peat particles. The peat particles have closer interaction with each other and can mobilize consistent frictional resistance for relatively larger shear displacement in denser conditions (Bajwa 2012).

In the current research, the cohesion and angle of the internal friction of the samples are a function of depth and time (Table 4.12). The internal friction angle is increased with depth and time, which can be attributed to an increase in the interlocking between the peat particles due to the compaction of the biocover medium with time and depth (Mouzai and Bouhadef 2011). Moreover, the cohesion of the samples increases as the organic content increases from the top to the bottom of the columns (Fig. 4.33e). The organic matters exert forces through surface tension or electrical charges, and increase the cohesion through the binding of the soil particles (Nimmo 2004, Annabiabc et al. 2007).

It should be mentioned that internal seepage erosion in field conditions can result in lower shear strength than that obtained from laboratory experiments. Therefore, it is recommended that a safety factor of 15–25% be applied to the obtained laboratory values of cohesion and angle of friction (Bagchi 1990). Since the obtained laboratory friction angle of the studied material under drained conditions is in the range of 30.7° to 41.3°, by considering the mentioned safety factor, the studied materials have enough strength to resist shear failures on slopes less than about 20°.

4.4.5.3 Hydraulic properties

4.4.5.3.1 Saturated hydraulic conductivity

The gas exchange processes affect the CH_4 oxidation rate since downward O_2 diffusion from the atmosphere and upward CH_4 advection from landfills into the CH_4 oxidation zone are essential for CH_4 oxidation. The gas exchange processes are significantly influenced by the hydraulic conductivity of the porous media (Pedersen 2010) in a way that higher hydraulic conductivity results in better gas exchange through the biocover, thus promoting the CH_4 oxidation rate. Conversely, biocovers must have low hydraulic conductivity to minimize rainfall infiltration, which contributes to leachate production, biocover saturation and subsequently reduction of the CH_4 oxidation rate (Pokhrel 2006; Scheutz et al. 2009), so a proper hydraulic conductivity value of the biocover material can support an optimal CH_4 oxidation rate and also control water intrusion through the biocover.

The physical and structural arrangements of constituent particles (Edil 2003), void ratio, and size and shape of flow channels (Mesri and Ajlouni 2007) are the key parameters that affect the hydraulic conductivity of porous material. The relatively high initial hydraulic conductivity of the studied biocover material in Phase I is the result of the high initial porosity of the material (83.7%). The studied biocover material changed from a loose to dense condition (Fig. 4.33b) due to overburden pressure and became finer (Fig. 4.32). This phenomenon causes the reduction of coarse pores and porosity (Fig. 4.33c), destruction of pore continuity (Dec et al. 2008) and consequently, the reduction of hydraulic conductivity (Huat et al. 2011, Ankeny et al. 1990, Fuentes et al. 2004, Horn and Smucker 2005).

It should be mentioned that biocovers should be able to minimize water infiltration. Water infiltration contributes to leachate generation and consequently biocover saturation. Biocover saturation hinders the gas exchange process and thereby decreases the efficiency of biocovers. The saturated hydraulic conductivity of traditional landfill covers is usually in the range of 10^{-6} to 10^{-7} m/s (Ng and Lo 2007). It can be seen that the laboratory saturated hydraulic conductivity of the studied biocover at the bottom layer is in the same range as that of traditional soil covers. Therefore, the relatively impermeable nature of the studied biocover makes it suitable as a landfill cover in terms of controlling and preventing excessive percolation and water infiltration.

Moreover, the derived results from the saturated hydraulic conductivity tests (Fig. 4.39) and gas analysis (Fig. 4.44) indicated that the reduction in hydraulic conductivity does not significantly affect the rate of CH_4 oxidation.

4.4.5.3.2 Degree of saturation

A high degree of saturation causes the aqueous diffusion of CH_4 and O_2 through biocovers which is much slower (10^{-4} folds less rapid) than gaseous diffusion. So, the CH_4 oxidation rate is reduced at high degrees of saturation as a result of the discontinuity of air filled voids (Nagaraj et al. 2006), slow gas exchange process, and gas occlusion (Cabral et al. 2010*a*).

As shown in Fig. 4.40, the S_r values are always less than 85% which is a favourable S_r for gas exchange processes. At an S_r more than 85%, air becomes occluded in the soil matrix (Brooks and Corey 1966, Nagaraj et al. 2006), the gas exchange processes become quite low (Nicholson et al. 1989, Yanful 1993, Aachib et al. 2004, Cabral et al. 2004) and thereby the CH_4 oxidation rate is reduced (Cabral et al. 2010*b*).

4.4.5.3.3 Moisture content

Moisture is essential for methanotrophic activity which acts as a transport medium for the nutrient supply and also metabolite removal (Scheutz et al. 2009). The growth of microorganisms is affected by physiological stress under low moisture contents which lead to the inactivation of methanotrophic microorganisms and subsequently reduction of CH_4 oxidation rate (Huber-Humer 2004; Sternenfels 2012; Humer and Lechner 1999).

In the current research, the surface layer dried out over time (Fig. 4.41). The drying out of the top layer over time due to evaporation induces surface desiccation (Stein and Hettiaratchi 2001, Stein 2000) which results in the lack of methanotrophic activity within those depths and affect the CH_4 oxidation rate (Wilshusen et al. 2004). Unlike the top layer, the VWC at the bottom layer was 29% higher than the initial value which can be explained by the downward movement of moisture (Stein 2000, Bajwa 2012) and also water production during the CH_4 oxidation process (Pedersen 2010).

4.4.5.4 Thermal properties

4.4.5.4.1 Temperature

Temperature has an imperative impact on methanotrophic activity and subsequently CH_4 oxidation rate (Scheutz et al. 2009). The temperature that supports the maximum methanotrophic activity is referred to as the optimum temperature for CH_4 oxidation. Different ranges of temperatures have been given in the literature as the optimum moisture content for

CH_4 oxidation process. Dunfield et al. (1993) and Mor et al. (2006) found that maximum methanotrophic activity occurs at temperatures between 20°C to 25°C, while Börjesson and Svensson (1997) reported a range of 25°C to 35°C as the optimum temperature for CH_4 oxidation. Methanotrophic bacteria are still active at a temperature of 4°C as well as 55°C (Humer and Lechner 2001; Hanson and Hanson 1996) and the CH_4 oxidation process can occur at those temperatures at a lower rate than in the optimum temperature range. So, proper knowledge on the evaluation of the temperature within a biocover is essential in order to promote a high rate of CH_4 oxidation.

The increase in temperature within the first 20 days of column operation can be associated with the aerobic degradation of available carbon sources in peat materials. Bajwa (2012) also found a similar trend in compost biocovers which have properties that are comparable to those of peat. It should be noted that the CH_4 oxidation process is an exothermic process and 780 kJ per mol of oxidized CH_4 is released (Scheutz et al. 2009). The heat generated by methanotrophic activity during the CH_4 oxidation process is the origin of the higher temperature of the column in comparison to an ambient temperature (Huber-Humer 2004).

The development of temperature at different depths within biocovers can be investigated to provide further information on the vertical zonation of microbial activity and consequently the CH_4 oxidation process inside biocovers. The average temperature of the middle layers (28.5°C and 29.2°C at depths of -15 and -25 cm, respectively) was 2.9°C higher than those of the bottom (-35 cm) and surface (-5 cm) layers, which were 26.2°C and 25.7°C, respectively. The development of a high temperature zone at the mentioned depths implies intense microbial activity in the specified layer and consequently higher rate of CH_4 oxidation.

The temperature within biocovers is also affected by the atmospheric temperature aside from methanotrophic activities (Dever et al. 2010). During the winter in field conditions when the temperature generally drops below 10°C, the CH_4 oxidation process may slow down. The development of a high temperature zone inside the studied biocover can counteract against the negative effect of atmospheric temperature and prevent the reduction of the CH_4 oxidation rate in cold climates.

4.4.5.4.2 Thermal conductivity

It is well known that thermal conductivity depends on the organic content, texture, and moisture content of the material (Hettiarachchi 2005). An increase in the thermal conductivity with depth in the current research (Fig. 4.43) is attributed to two possible reasons. First, the thermal conductivity of water (0.59 W/m°K) is more than 20 times greater than that of air (0.025 W/m°K) (Holman 2002). An increase in the moisture content (Fig. 4.41) results in a reduction of the volume fractions of air, increasing the portion of pore spaces filled with water, completing water films around the soil particles, increasing indirect contact areas between particles, and consequently increasing the thermal conductivity (Abu-Hamdeh and Reeder 2000). Kujala et al. (2008) reported similar trends for peat materials, namely, increases in the moisture content result in increases in the thermal conductivity. Secondly, the amount of interparticle surface contact has an imperative effect on the thermal conductivity of soils (Hall and Allinson 2009). Since the bulk density of filter material increases with depth over time (Fig. 4.33b), the contact between individual particles becomes more intimate which facilitates heat movement through the filter material and increases thermal conductivity.

Generally, the thermal conductivity decreases with increasing organic content of soil (Abu-Hamdeh and Reeder 2000). It should be noted that in the current research, both organic content (Fig. 4.33e) and thermal conductivity increase with depth (Fig. 4.43). When the opposite was observed during this study, this meant that the effect of the organic content on thermal conductivity is negligible in comparison to that of moisture content and bulk density.

The thermal conductivity of the biocover medium controls heat transport and the thermal environment for the CH_4 oxidation process within biocovers. The thermal conductivity of the studied peat biocover is in range of 0.2 to 0.53 W/m° K, which is significantly lower than that of mineral soils (e.g., 2.9 W/m° K for silt and clay, 3 W/m° K for sand stone and 3.8 W/m° K for dolostone (Côté and Konrad 2005)). The low thermal conductivity of the peat biocover means that the heat flux within the biocover is hindered (Hettiarachchi 2005) and subsequently this results in temperature insulation (Huber-Humer 2004). The temperature insulation could guarantee a suitable temperature for the growth and activity of methanotroph bacteria within biocovers, which is particularly important in cold climates (Huber-Humer 2004).

4.4.5.5 Chemo-biological properties

4.4.5.5.1 Methane oxidation rate

Fig. 4.44 shows that the studied biocover medium experienced three different phases, including adaptation, steady state, and decline. Two possible reasons could account for the reduction in the CH_4 oxidation rate during the phase of decline. First, the organic content profile (Fig. 4.33e) indicated EPS formation throughout the depth of the column. The formation of EPS causes bioclogging of the pores, hinders the gas exchange process, and consequently, reduces the CH_4 oxidation rate (Huber-Humer 2004, Sternenfels 2012). Secondly, the VWC constantly decreased during the column operation at depths between -5 and -15 cm (Fig. 4.41). Decreases in the moisture content can cause inactivation of methanotrophic activity and subsequently reduction of the CH_4 oxidation rate (Dobbie and Smith 1996). Several studies have also reported declinse in CH_4 oxidation rate due to EPS formation (Wilshusen et al. 2004, Huber-Humer 2004) and drying out of the biocover medium (Boeckx et al. 1996, Cai and Yen 1999).

It should be noted, as shown in Fig. 4.33c, that the studied biocover material is porous enough (particularly at depths of -5 and -15 cm) which can slightly reduce the clogging effect from EPS formation. Therefore, the effect of drying out of the biocover medium on the reduction of CH_4 oxidation rate is more pronounced than that of the effect of EPS formation.

4.4.5.5.2 Gas profile

The gas profile provides the result of diffusion and advection of gas flow and biochemical reactions (De Visscher, 2001).

The biocover went through the adaptation phase in the first 22 days of column operation and the CH_4 was not completely oxidized. Therefore, a relatively high CH_4 concentration can be observed throughout the depth of the column, as shown in Fig. 4.45a.

During the steady state phase, the depth of the O_2 penetration was limited to a depth of -25 cm. This indicates that the O_2 was instantly consumed in the CH_4 oxidation process as soon as it became available (Cabral et al. 2010*b*). Moreover, the concentrations O_2 and CH_4 at a depth of -25 cm suggest development of a region of high activity.

It can be clearly observed from the gas profiles in Fig. 4.45 that N_2 easily penetrates into the depth of the column because of the air diffusion from the top. It should be noted that N_2 is neither produced nor consumed in the CH_4 oxidation process; thereby the presence of relatively high concentrations of N_2 throughout the depth of the column is an indication of air intrusion (Berger et al. 2005).

During the phase of decline, relatively high concentrations of O_2 and N_2 throughout the depth of the biocover imply that the restriction in the downward mitigation of O_2 and upward mitigation of CH_4 due to bioclogging was not a limiting factor in the CH_4 oxidation process. Therefore, reduction in the CH_4 oxidation rate can be correlated to unfavoured conditions (low VWC) for methanotrophic activity (Boeckx et al. 1996, Cai and Yen 1999).

4.4.6 Conclusion and remarks

On the basis of the derived results, it can be concluded that peat biocovers are characterized as having high compressibility and a frictional nature. The value of C_c is 0.64 in Phase I (0 days) and varies in the range of 0.25 to 0.54 and 0.21 to 0.58 in Phases II (82nd day) and III (156th day), respectively. Decreases in the C_c values and subsequently compressibility of the studied samples are observed with increasing depth. The internal angle friction varies from 30.7° to 41.3° and the cohesion ranges from 6.3 to 12.3 kPa. The increase in the friction angle is correlated to the increase of interlocking between the peat particles due to the compaction of the peat biocover with time and depth. The hydraulic conductivity of the peat biocover varies in a range of 8.47×10^{-4} m/s to 6.87×10^{-6} m/s and decreases with depth as a result of confinement due to overburden pressure. The thermal conductivity of the studied peat material is relatively low in comparison to that of mineral soils and varies in a range of 0.2 and 0.53 W/m°K. Peat biocovers can be protected against unfavorable thermal conditions because of temperature insulation due to the low thermal conductivity of peat materials. The increase in thermal conductivity with depth is attributed to the simultaneous increase in moisture and bulk density with depth. The gas analysis experiments reveal that an acceptable rate of microbial CH_4 oxidation (average of 145 g/m^2 day) is achieved during steady state (22nd to 99th day). The observed changes in the porosity, organic content and hydraulic conductivity do not significantly affect the CH_4 oxidation rate. This indicates that the methanotrophic activity population is limited by low VWC, particularly in the top layers. The VWC of the surface layer consistently declines with time and reaches a value of 4.4% due to evaporation induced surface desiccation.

4.4.7 References

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5 Summary and comparative analysis of behaviour of compost and peat based biocovers

5.1 Introduction

This study aims to investigate the geotechnical and geoenvionmental properties (T, H, M, and C-B) of peat and compost based biocovers, their time-dependent evolution as well as their interactions in order to provide valuable information for the design, operation, and monitoring of biocovers.

In the foregoing chapters, the geotechnical and geoenvionmental properties of compost, compost-sand (3:1) and peat based biocovers have been investigated and separately discussed. This chapter provides a comparative analysis of the geotechnical and geoenvironmental properties of all the studied biocover materials based on the derived results from both laboratory tests and column experiments. This comparative analysis enables the ranking of the studied cover materials with regards to their performance as biocovers.

5.2 Mechanical and physical properties

The material characteristics of biocovers have a strong effect on their performance. In Table 5.1, the value of the moisture content, water holding capacity, organic content, and pH of the studied biocover materials are compared to the corresponding recommended values in the literature. It should be noted that in Table 5.1, the initial moisture contents of the studied biocover materials are compared to the recommended moisture content value. In order to avoid incompatibility between the measured moisture content and recommended values for practical application purposes, the biocover material should be air-dried and thereafter moistened to reach the desired moisture content. The derived results indicate that all of the studied compost and peat based materials have a pH value in the recommended range. Moreover, the water holding capacities of all the samples except for the compost- sand mixture with mix ratio of 1:3 (w/w) are in the desired range.

Table 5.1 Summary of comparison of basic parameters of the studied materials and recommended values in the literature.

Parameter	Compost	Compost – Sand			Peat	Peat – Sand		
		3:1 (w/w)	1:1 (w/w)	(1:3 w/w)		3:1 (w/w)	1:1 (w/w)	(1:3 w/w)
Moisture content (%) [1]	×	×	✓	×	×	×	×	×
Organic content (%) [2]	✓	✓	×	×	✓	✓	✓	✓
pH [3]	✓	✓	✓	✓	✓	✓	✓	✓
Water holding capacity (%) [4]	✓	✓	✓	×	✓	✓	✓	✓

Note: ✓ means the measured parameter is in the recommended range and × means that it is not; [1]The recommended moisture content is in the range of 30% to 50% (Huber-Humer et al. 2009); [2]The recommended organic content is more than 15% (Huber-Humer et al. 2009); [3]The recommended pH value is in the range of 6.5 to 8.5 (Huber-Humer et al. 2009; Hütsch et al. 1994; Bender and Conrad 1995); [4]The recommended water holding capacity is in the range of 50%to 130% (Huber-Humer et al. 2009).

Figs. 5.1, 5.2 and 5.3 show a comparison between the grain size distributions of all of the studied biocover materials in the current research. The CH_4 oxidation capacity is affected by the texture and grain size distribution of the biocover medium (Huber-Humer 2004). The fraction of the soil with a particle size less than 2 mm is classified as fine grained cover soil and the fraction with a particle size greater than 2 mm is referred to as the skeleton structure or structure that forms the fraction (Figueroa 1993).The pure compost and pure peat samples show quite similar grain size distribution curves with a relatively high amount of fine fraction. It can be seen from Figs. 5.1, 5.2 and 5.3 that increasing the sand content generally results in promoting the fraction of soil particles with a particle size greater than 2 mm (or structure forming fraction).

Among the biocover materials, which were tested in the column experiments, the compost-sand material with mix ratio of 3:1 can be regarded as the best structured material. As compost-sand (3:1) has the highest fraction of particle size greater than 2 mm (32%) in comparison to the pure compost (30%) and pure peat (23%) samples. However, the grain size distribution generally becomes finer as time passes, compost-sand (3:1) medium experienced the least changes in grain size distribution as opposed to the pure compost and pure peat materials.

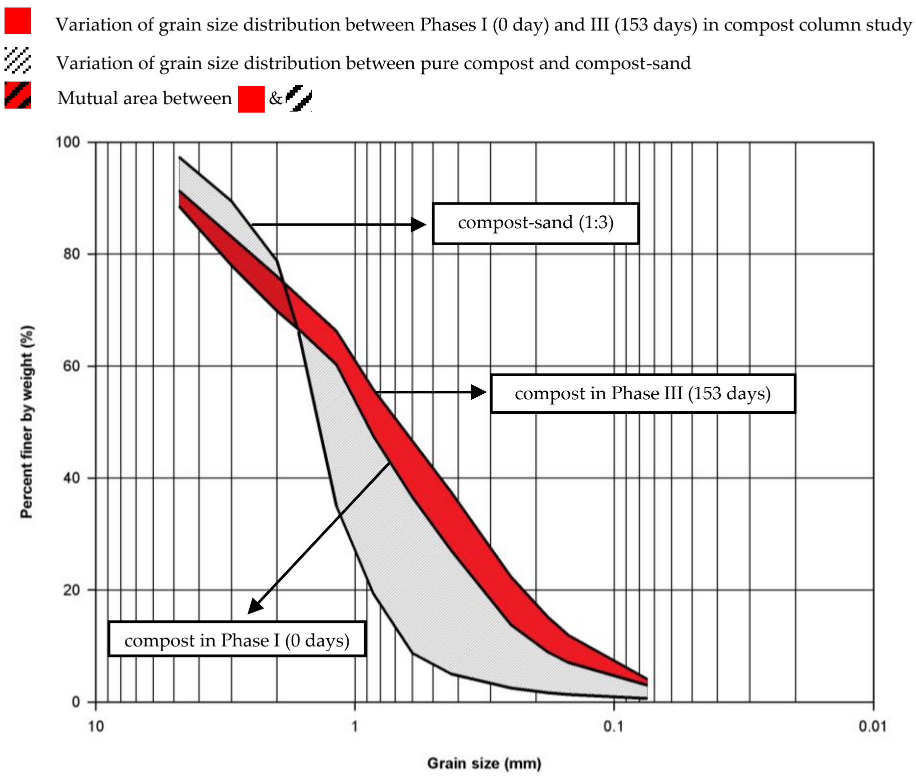

Fig. 5.1. Grain size distribution of compost (before and after column test) and compost-sand (1:3).

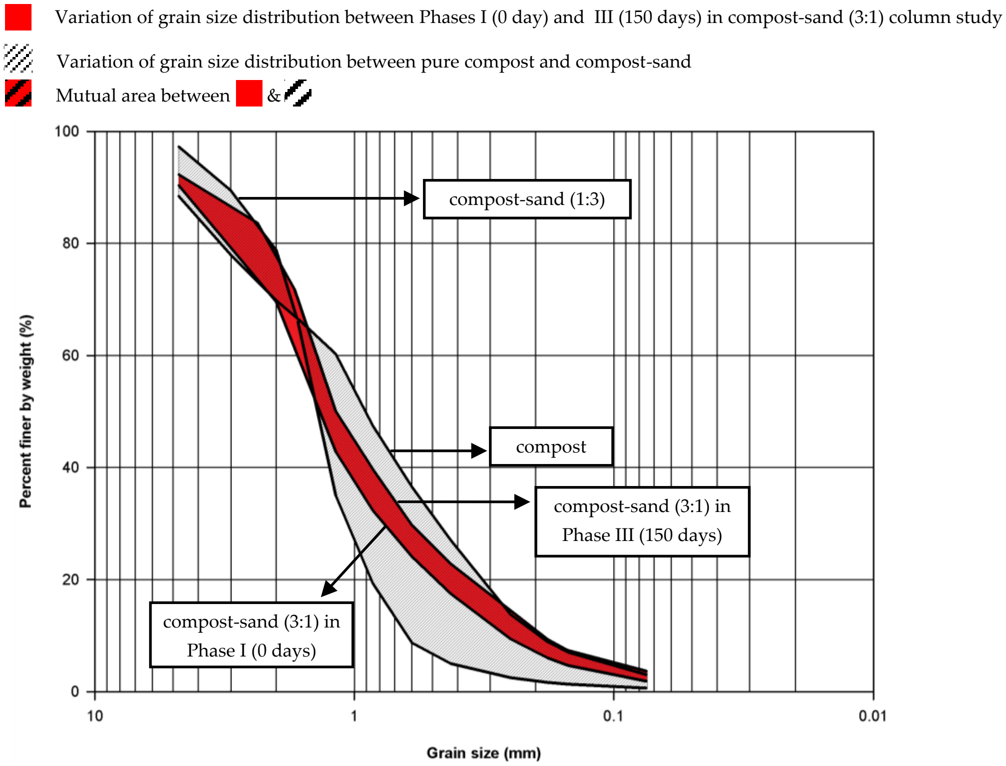

Fig. 5.2. Grain size distribution of compost-sand (3:1) (before and after column test), compost, and compost- sand (1:3).

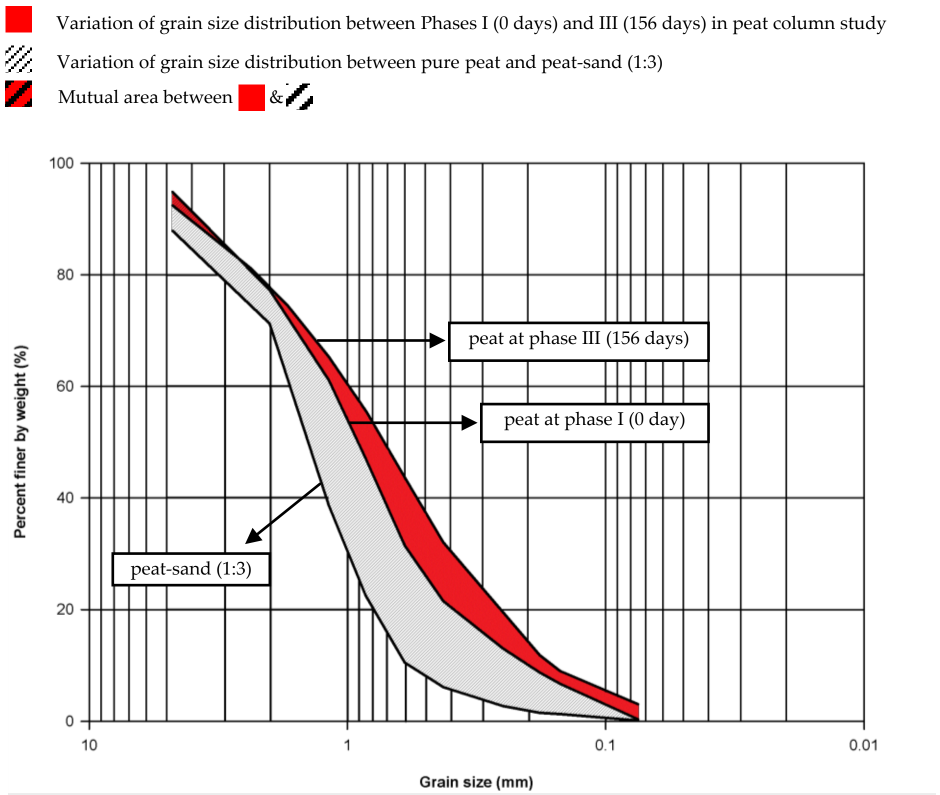

Fig. 5.3. Grain size distribution of peat (before and after column test) and peat-sand (1:3).

The comparison between the results of the compaction tests on compost, compost-sand mixtures (with mix ratio of 3:1, 1:1, and 1:3 (w/w)), peat, and peat-sand mixtures (with mix ratio of 3:1, 1:1, and 1:3 (w/w)) is shown in Fig. 5.4. The compaction generally enhances the mechanical behaviour and minimises the natural settlement of the biocover medium (Dever et al. 2010). On the other hand, the compaction has a negative effect on the gas exchange process within the biocover (Gebert et al. 2011).

It can be seen from Fig. 5.4 that the maximum dry density of samples has increased with sand content, while there is the opposite trend for optimum moisture content. Relatively high maximum dry density of compost-sand and peat sand mixtures in comparison to pure compost and peat is attributed to higher specific gravity of sand (2.65) than that of compost (2.05) and peat (1.65) materials.

As illustrated in Figs. 5.1and 5.3, pure compost and peat materials have a high amount of fine particles and therefore undergo significant compaction, while the samples with sand content are less compactable. Based on the derived results, it can be concluded that mixtures of compost or peat with sand (more inert material) are less compactable than pure compost and peat and consequently will be less susceptible to excessive settlement in field conditions.

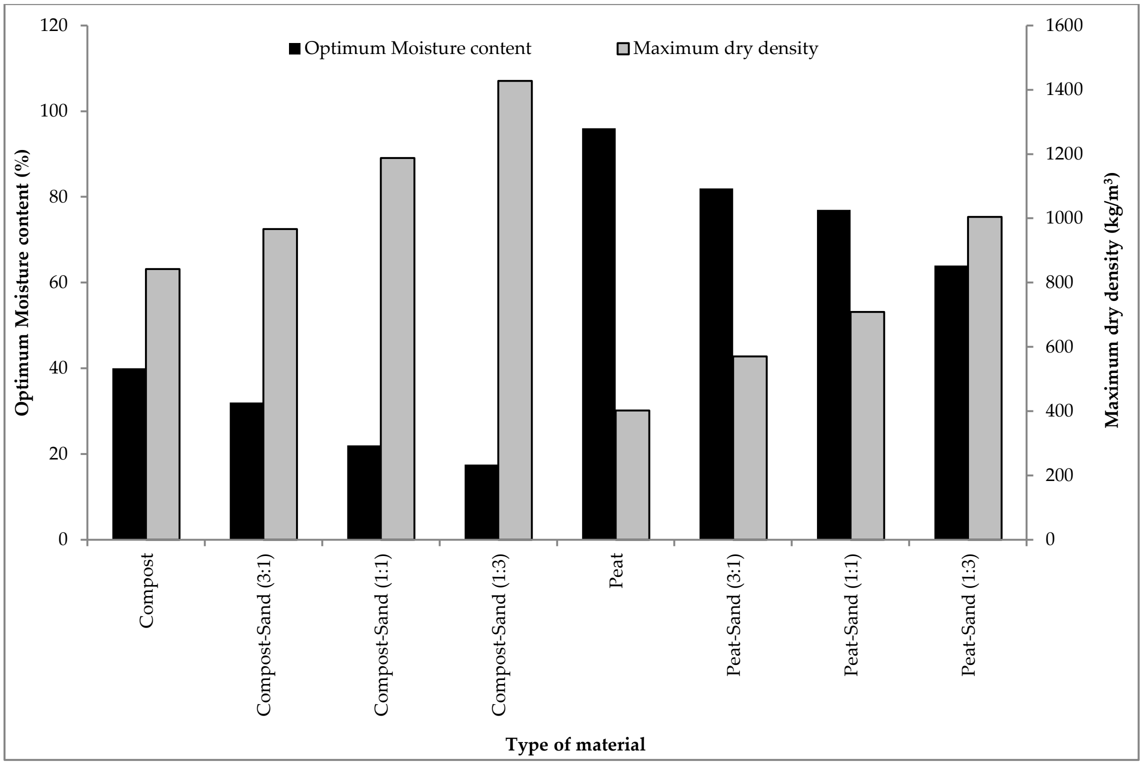

Fig. 5.4. Optimum moisture content and maximum dry density of studied biocover materials.

Figs. 5.5 and 5.6 show a comparison between the shear strength parameters (friction angle and cohesion) of the studied biocover materials in the column experiments. The studied materials are frictional in nature with relatively low cohesion. It can be clearly observed from Fig. 5.5 that the friction angle increases with depth and time which is attributed to the compaction of the biocover medium with depth and time. Furthermore, compost-sand (3:1) has the highest range of friction angle among the studied samples. This is caused by the fact that sand content enhances the interlocking mechanism of the aggregates which is the principally responsible mechanism for the variation of the friction angle.

It should be noted that the shear strength of biocover material in field conditions may be lower than laboratory shear strength due to internal seepage erosion or presence of a weak zone in field conditions. Therefore, in the procedure on the design of biocovers, the consideration of a safety factor of 1.15-1.25 on shear strength properties obtained in the laboratory tests is recommended (Bagchi, 1990). It should be mentioned that by applying the mentioned safety factor, the studied compost, compost-sand (3:1), and peat biocovers are theoretically stable on slopes less than 25°, 30°, and 20°, respectively. Moreover, a sloped biocover made of compost-sand (3:1) will show higher mechanical stability than one made of pure compost or peat material.

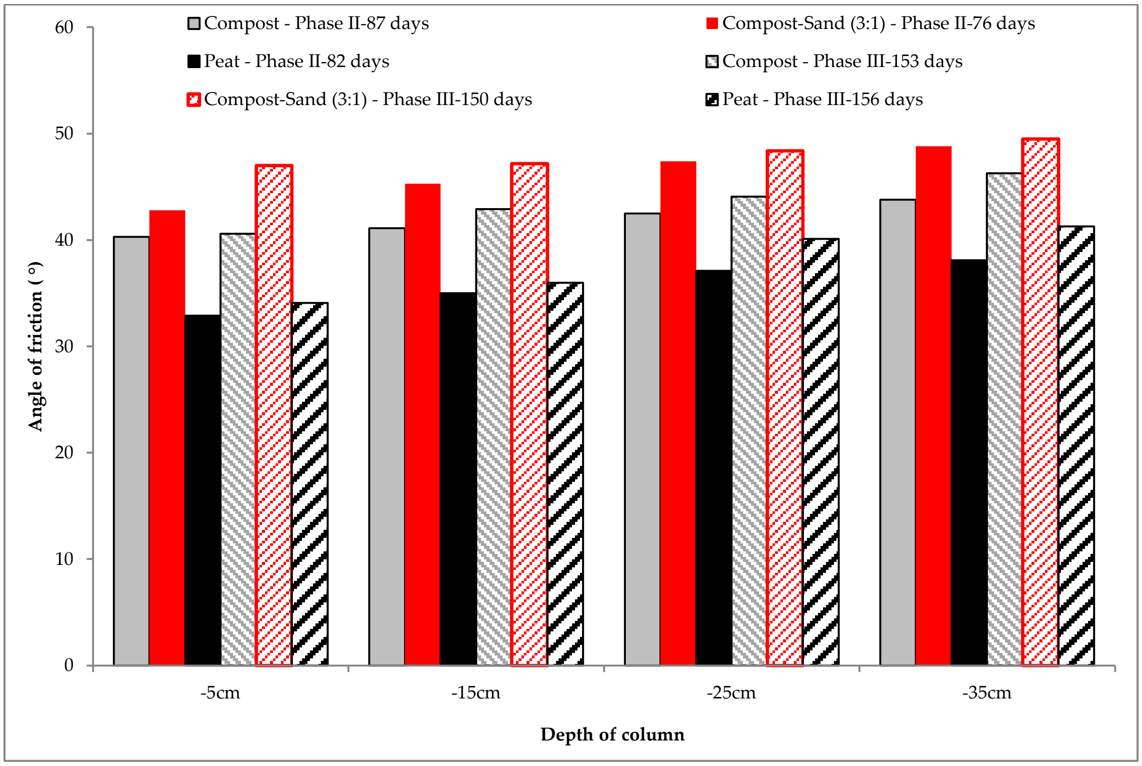

Fig. 5.5. Friction angle of studied biocover materials in the column experiments.

Cohesion is also a function of depth and time. It can be seen from Fig. 5.5 that the cohesion of all the studied biocover materials increases at each specific depth with time. This behaviour is correlated to the increase of the organic content of the studied biocover medium with depth. The organic materials exert forces through surface tension or electrical charges, and increase cohesion through the binding of soil particles. As shown in Fig. 5.5, the highest cohesion values among all of the materials belong to the peat material. This can be explained by the higher organic content of the peat material in comparison to that of compost and compost-sand (3:1).

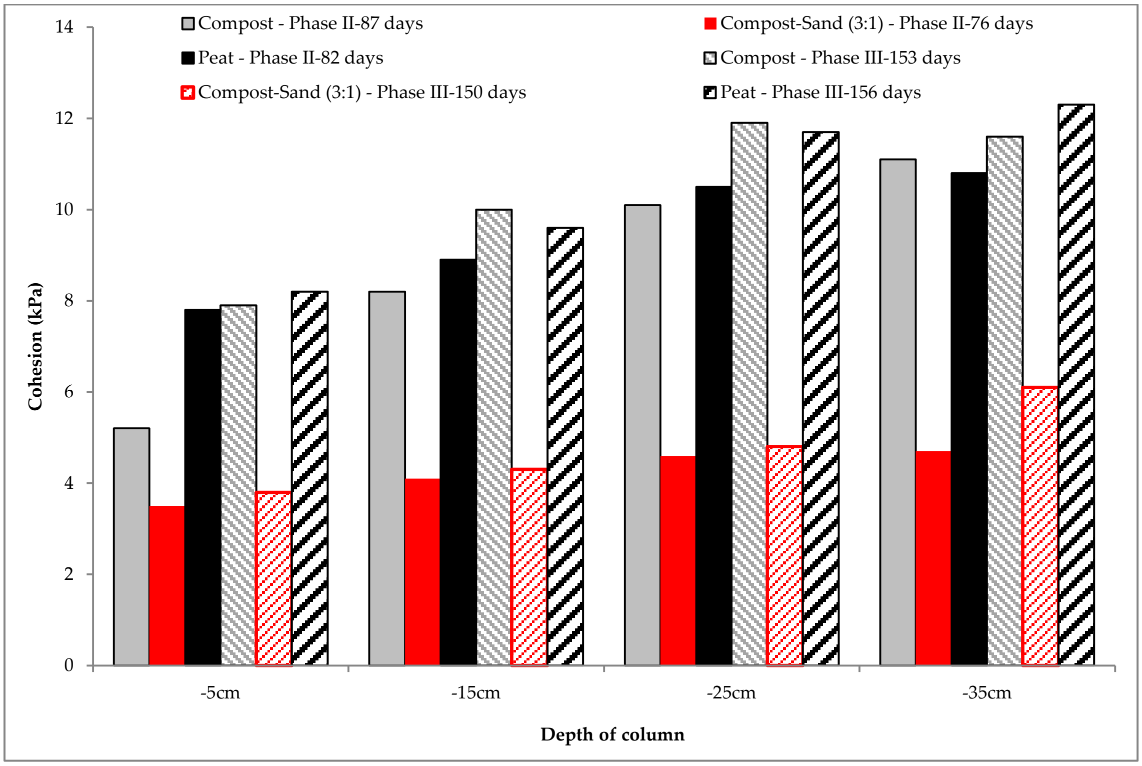

Fig. 5.6. Cohesion of studied biocover materials in the column experiments.

Fig. 5.7 is a comparison of the C_c values (which reflect the compressibility of the materials) of all the studied specimens in the column experiments. It is clear that the peat samples have the highest values of C_c and consequently experienced the highest settlement (Fig. 5.8) among all the studied materials. Unlike the peat samples, compost-sand (3:1) has the lowest values of C_c and subsequently experienced the smallest amount of settlement, see Fig. 5.8, in the current research. The consolidation behaviour of the studied samples is also strongly influenced by the organic content and bulk density of the samples. There is a general trend of reduction in the C_c values with increasing bulk density such that samples at the bottom layer have the lowest C_c values in comparison to those in the upper layers. Moreover, as shown in Fig. 5.8, the rate of settlement of the studied biocover medium is time dependent and decreases with time. This behaviour can be due to the rearrangement of the particles as a result of to the pressure of the self weight which is reduced over time.

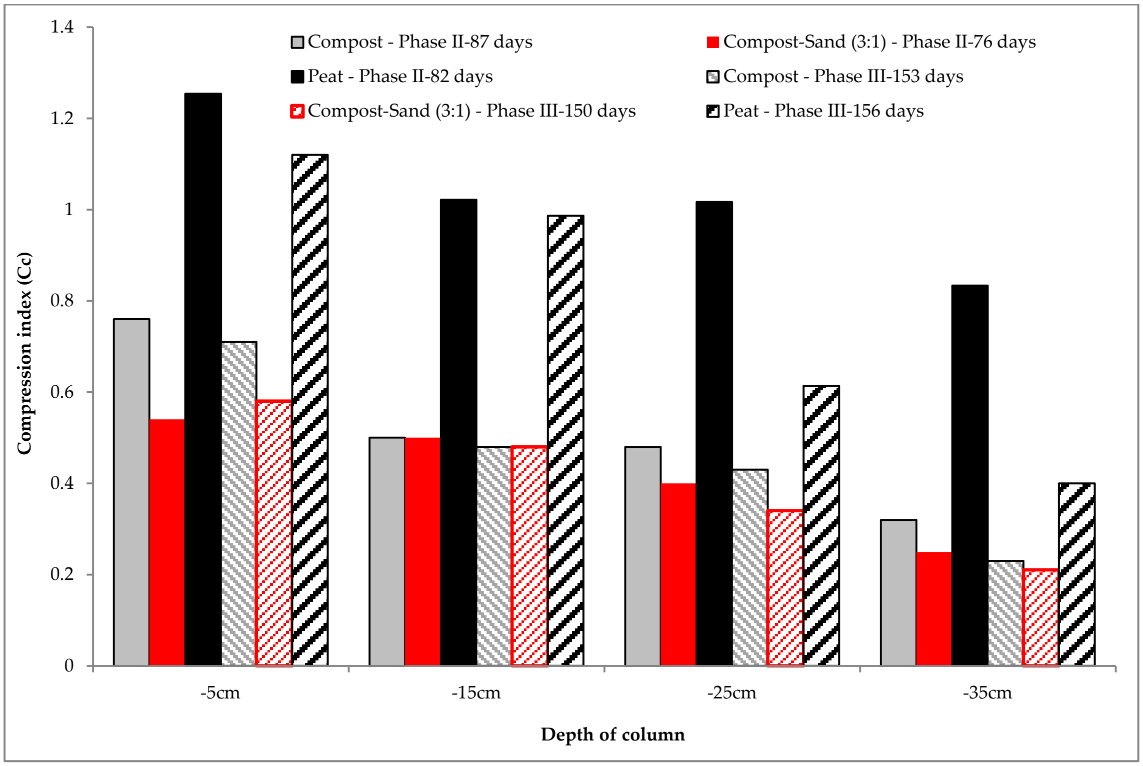

Fig. 5.7. Compression index of studied biocover materials in the column experiments.

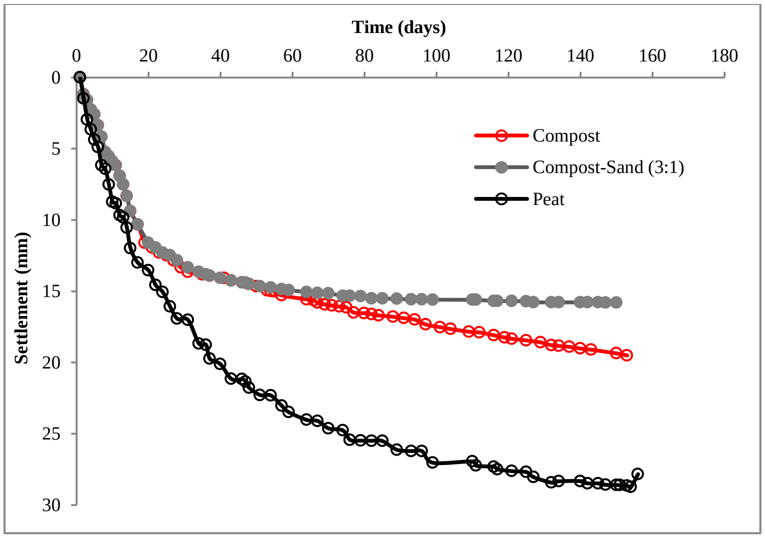

Fig. 5.8. Settlement of studied biocovers in the column experiments.

5.3 Hydraulic properties

Hydraulic conductivity is one of the imperative hydraulic parameters which affect the gas exchange processes within biocovers and control water infiltration.

In the current research, the lowest hydraulic conductivity is achieved at optimum moisture content and maximum dry density. The compost and peat materials have lower hydraulic conductivities than the compost-sand and peat-sand mixtures. This is mainly caused by the fact that increasing the sand content of the specimens causes larger void ratios, pores and straight flow channels through the samples, which result in higher hydraulic conductivities.

Fig. 5.9 compares the hydraulic conductivity of the studied biocovers in the column experiments. It can be seen that the hydraulic conductivity is a function of depth and time during the column operation. It is clear from Fig. 5.9 that the hydraulic conductivity significantly drops with time and depth in all of the studied biocover materials. This trend is related to the compaction of the biocover with time and depth. The bioclogging due to the formation of EPS also contributes to the reduction of the hydraulic conductivity of the biocover particularly in the compost biocover. It should be noted that the reduction of hydraulic conductivity with depth and time in compost-sand (3:1) and peat did not significantly affect the rate of CH_4 oxidation in the mentioned biocovers.

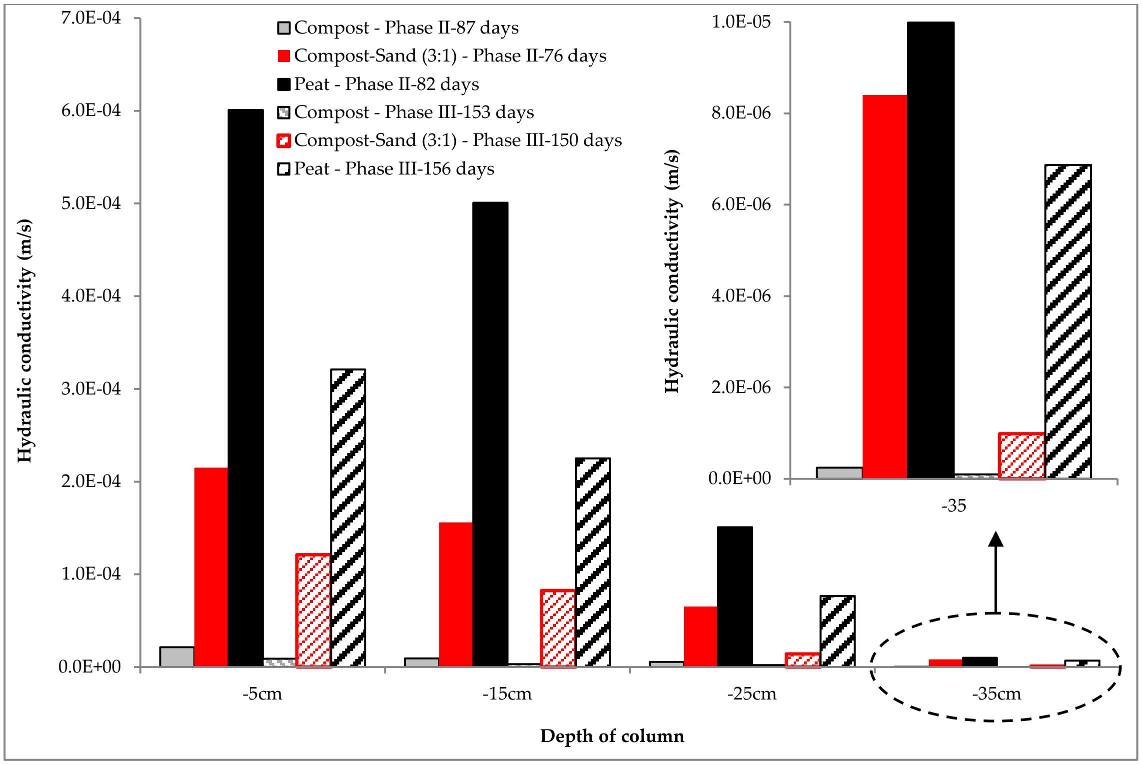

Fig. 5.9. Hydraulic conductivity of the studied biocover materials in the column experiments.

Degree of saturation is another hydraulic parameter which affects the gas exchange process within biocovers. The obtained results from the column experiments indicated that the degree of saturation at the surface layer of all the studied biocovers declines over time. This behaviour is attributed to the evaporation induced surface desiccation of the surface layer over time. In contrast to the surface layer, the degree of saturation consistently increased with time at the bottom layer and reached maximum values of 37.7%, 40.9%, and 33.8% in the compost, compost-sand (3:1), and peat biocovers, respectively. The increase in degree of saturation in the bottom layer with time of the studied biocovers can be explained by the simultaneous increase in moisture content (due to downward moisture movement and methanotrophic activity) and also reduction in the porosity of the studied biocover media with time. It can be seen that the degree of saturation during the operation of all the studied biocover media was always less than 85%. At degrees of saturation more than 85%, gas exchange processes become slow (Nicholson et al. 1989; Yanful 1993; Aachib et al. 2004; and Cabral et al. 2004) and consequently the CH_4 oxidation rate decreases (Cabral et al. 2010*b*). It can be concluded that the increase in the degree of saturation in all of the studied biocovers does not affect the rate of CH_4 oxidation.

Moisture is essential for methanotrophic activity since the growth of methanotrophs is strongly bounded to moisture availability. Fig. 5.10 shows a comparison between the evolution of the VWC in the compost, compost-sand (3:1), and peat biocovers during the column experiment. It can be clearly seen that the surface layer of all of the studied biocovers dried out over time. Drying out of the surface layer is caused by evaporation induced surface desiccation. The minimum VWC for the compost, compost-sand (3:1), and peat biocovers is 7%, 6%, and 3%, respectively. A low VWC has a negative effect on methanotrophic activity and consequently the CH_4 oxidation rate (Wilshusen et al. 2004). In the current research, the negative effect of low VWC on the CH_4 oxidation rate is more significant in the peat biocover among the studied biocovers.

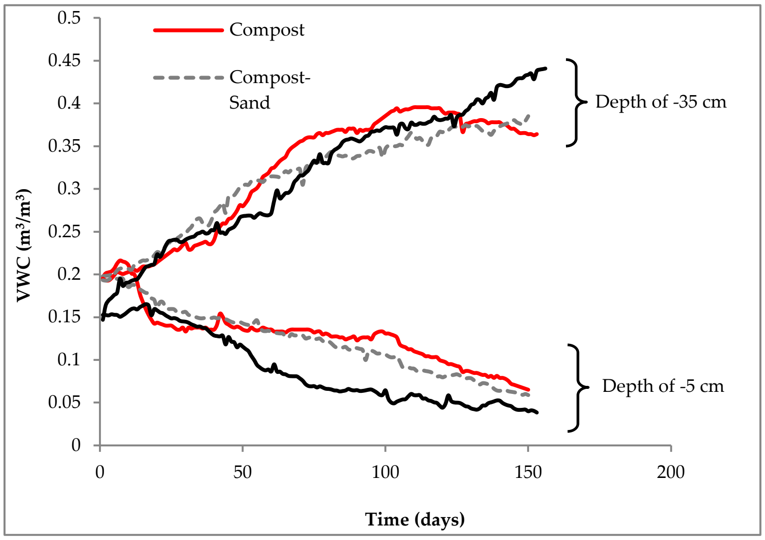

Fig. 5.10. Evolution of VWC at depth of -5 cm of studied biocover media with time in the column experiments.

5.4 Thermal properties

It has been proven that the CH_4 oxidation process in biocovers is profoundly influenced by the temperature. Fig. 5.11 shows variations of temperature within the studied biocover media and the average ambient temperature during the column experiments. The temperature profile can be a surrogate in determining the main zone of CH_4 oxidation. The development of the highest temperature zone at a depth of -25 cm of all of the studied biocovers indicates intense microbial activity there and subsequently high CH_4 oxidation capacity. It is clear from Fig. 5.11 that the compost biocover has the highest steady temperature during the column operation among the studied biocovers. The observed behaviour implies higher methanotrophic activity in the compost biocover as opposed to the compost-sand (3:1) and peat biocovers. It should be mentioned that the temperature within the studied biocovers during the column operation was generally higher than the average ambient temperature. The CH_4 oxidation process is an exothermic process (Scheutz et al. 2009) and generated heat by methanotrophic activity is the reason for the difference between the ambient and column temperatures (Huber-Humer 2004).

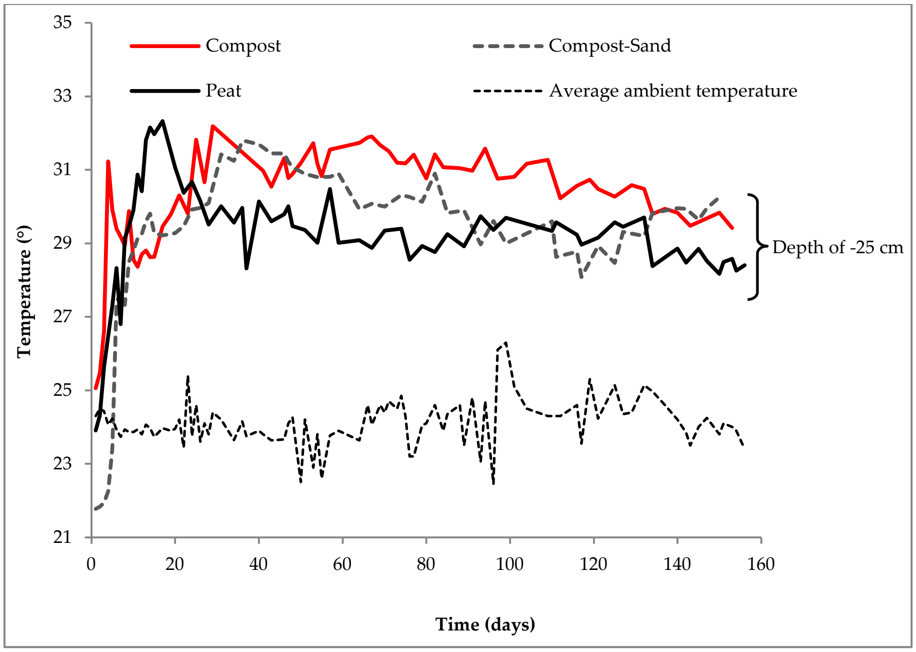

Fig. 5.11. Evolution of temperature at depth of -25 cm of studied biocover media with time in the column experiments.

Thermal conductivity expresses the rate of dissipation of the heat flux and controls the thermal performance of biocovers in various climatic and thermal loading conditions. The derived results indicated that the thermal conductivity of compost and peat based materials is affected by the bulk density and moisture content. Generally, the thermal conductivity of the studied biocover materials increased with increasing moisture content and bulk density. Increasing moisture content results in completion of water films around the soil particles, increasing the indirect contact area between the soil particles, and subsequently increasing thermal conductivity. Increasing the bulk density due to compaction causes more intimate direct contact between individual particles which results in facilitating heat movement and increasing thermal conductivity.

The evolutions of the thermal conductivity of the studied biocover materials during the column operation are compared in Fig. 5.12. It can be seen from Fig. 5.12 that there is a general trend of increasing thermal conductivity with depth. This behaviour can be explained by increasing VWC and decreasing porosity with depth which facilitate heat movement through the biocover and an increase in thermal conductivity. It is well known that thermal conductivity is also affected by organic content. The obtained results indicated that the effect of organic content on thermal conductivity is less pronounced in the studied biocovers, particularly in the bottom layers. Generally, the thermal conductivity of mineral soils is higher than that of organic soils. In the current research, among all of the studied biocovers, compost-sand (3:1) exhibited the highest range of thermal conductivity during the column operation while the peat biocover medium had the lowest range. This means that the compost-sand (1:3) material conducts heat at the highest rate among the other studied biocover materials and thereby provides lower temperature insulation (Huber-Humer 2004). The efficient and long term operation of biocovers depends on maintaining a suitable and favourable temperature for the growth of methanotroph bacteria (Chandrakanthi et al., 2005). In contrast to compost-sand (1:3), the peat material conducts heat at the lowest rate among the other studied biocover materials and therefore provides better temperature insulation. Proper temperature insulation protects biocovers against unfavorable conditions and guarantees a favorable temperature for methanotroph bacteria within biocovers, which is particularly important in field conditions during cold seasons (Huber-Humer, 2004).

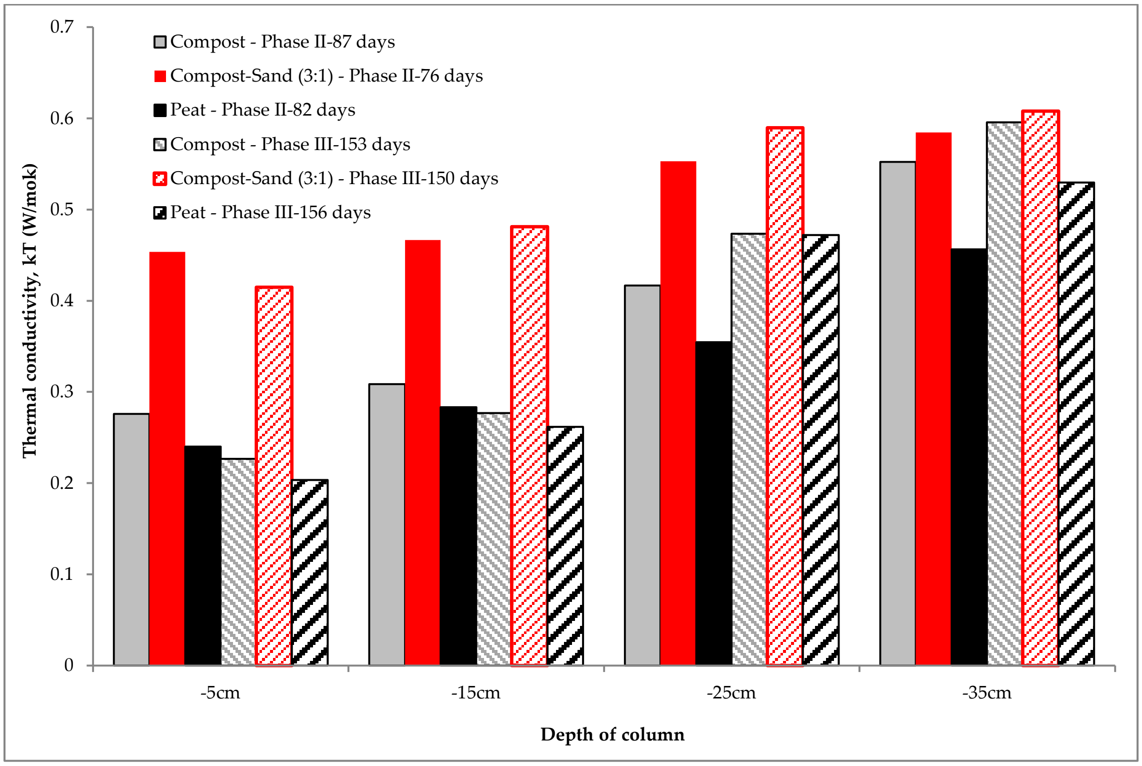

Fig. 5.12. Thermal conductivity of studied biocover materials in the column experiments.

5.5 Chemo-biological properties

A comparison of the CH_4 oxidation rates of the studied biocovers is shown in Fig. 5.13. The obtained results indicate that the studied compost and peat biocovers experience three different phases, including adaptation, steady state, and decline while no significant decline in the CH_4 oxidation rate of the compost-sand (3:1) biocover was observed during the column operation.

The decline in the CH_4 oxidation rate of the compost biocover is the result of EPS formation. The EPS formation results in clogging of the pores, hindering the CH_4 and O_2 flows within the biocover, and consequently reducing the CH_4 oxidation rate. The constant reduction of VWC with time (particularly in the top layers) was more pronounced in the peat biocover than the compost and compost-sand (3:1) biocovers. The reduction in the VWC in the peat biocover caused inactivation of the methanotrophs and subsequently reduction of the CH_4 oxidation rate. As shown in Fig. 5.13, the compost biocover with a CH_4 oxidation rate of 209.7 g/m^2 day (which corresponds to an 84% efficiency in CH_4 oxidation) has the highest rate of CH_4 oxidation. However, the CH_4 oxidation efficiency of the compost-sand (3:1) biocover is 14% less than that of the studied compost biocover, but the performance of the compost-sand (3:1) biocover was steady and no significant decline in the CH_4 oxidation rate occurred during the period of its operation.

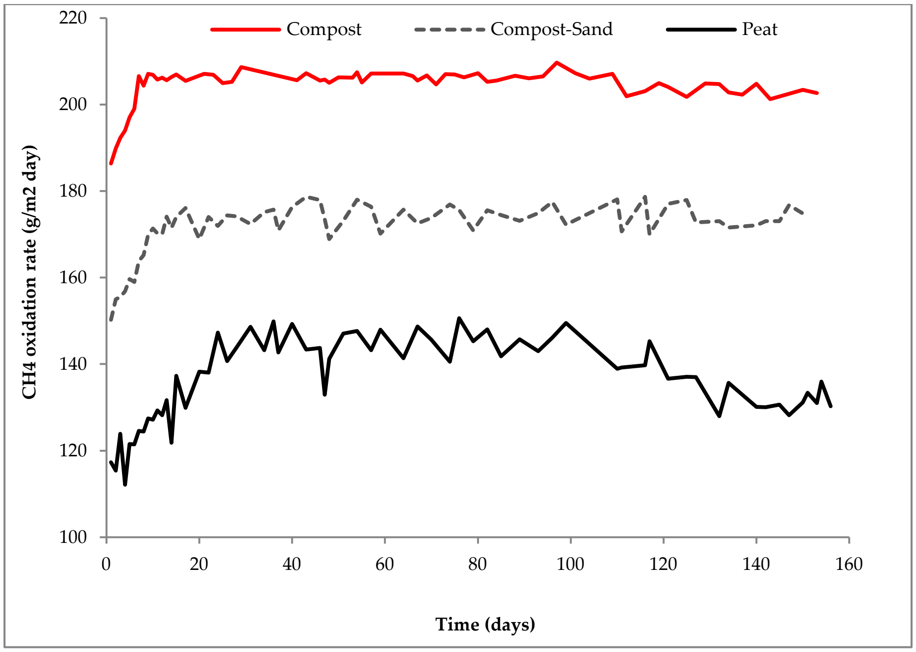

Fig. 5.13. Evolutions of CH_4 oxidation at depth of -5 cm of studied biocovers with time.

5.6 Summary and conclusion

In this chapter, the geotechnical and geoenvironmental properties of all the studied biocover materials are comparatively analysed. In Table 5.2, the main T, H, M, and C-B properties of the studied biocover materials in the column experiments are ranked according to the comparative analysis undertaken in this chapter.

From the viewpoint of the mechanical behaviour of biocovers, the increasing of the sand content of the biocover medium generally results in higher angles of friction and less compressibility (and consequently less settlement) of biocovers, which are desired mechanical properties for biocovers. As indicated in Table 5.2, compost-sand (3:1) has the highest range of angle of friction and experiences the smallest amount of settlement among the studied biocover materials in the column experiments.

From the viewpoint of the thermal behaviour of biocovers, the increasing of the sand content of the biocover medium generally leads to a higher range of thermal conductivity. As indicated in Table 5.2, the peat biocover has the lowest range of thermal conductivity among all of the studied biocover materials in the column experiments. This means that pure compost and peat materials used as biocover materials can provide better thermal insulation, which protects biocovers against unfavourable thermal conditions, particularly during cold seasons and in cold regions.

From the viewpoint of the hydraulic behaviour of biocovers, the increasing of the sand content of the biocover medium generally causes a higher range of hydraulic conductivity and promotes the gas exchange process within biocovers. On the other hand, a higher range of hydraulic conductivity could cause water infiltration, saturation of the biocover and subsequently a drastic reduction in the CH_4 oxidation capacity of the biocover. As indicated in Table 5.2, the compost biocover has the lowest range of hydraulic conductivity among all of the studied biocover materials in the column experiments.

From the viewpoint of the chemo-biological behaviour of biocovers, as indicated in Table 5.2, the compost biocover has the highest and peat biocover the lowest rate of CH_4 oxidation among the studied biocovers. The CH_4 oxidation process in the compost-sand (3:1) biocover is steadier than that in the compost and peat biocovers over time and no significant decline in the CH_4 oxidation rate was observed during the operation period of the compost-sand (3:1) biocover.

Table 5.2. Ranking of T, H, M, and C-B properties of studied biocover materials in the column experiments.

Rank	Thermal property		Hydraulic property			Mechanical property			Chemo-biological property		
	Thermal insulation[1,3]	Temperature[2]	Hydraulic conductivity[3]	S_r[4]	WHC[5,2]	Settlement[3]	Angle of friction[2]	Cohesion[2]	CH_4 Oxidation[2]	Steady CH_4 Oxidation[2]	pH
First	Peat	Compost	Compost	All three materials[4]	Peat	C-S (3:1)[6]	C-S (3:1)[6]	Peat	Compost	C-S (3:1)[6]	All three materials[4]
Second	Compost	C-S (3:1)[6]	C-S (3:1)[6]		Compost	Compost	Compost	Compost	C-S (3:1)	Compost	
Third	C-S (3:1)[6]	Peat	Peat		C-S (3:1)[6]	Peat	Peat	C-S (3:1)[6]	Peat	Peat	

[1] Lower thermal conductivity provides better thermal insulation; [2] Higher values are desirable; [3] Lower values are desirable; [4] Degree of saturation; [5] Water holding capacity; [6] Compost-sand mixture with mix ratio of 3:1 (w/w)

5.7 References

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6 Conclusions and recommendations

The current research comprises the following two main parts.

1. Geotechnical properties of compost and peat based biocovers.

2. Evolution of the T, H, M, and C-B properties of compost and peat based biocovers in column experiments.

This chapter addresses the key conclusions from the research conducted on these two items and also provides recommendations for future studies.

6.1 Conclusions

The following key conclusions can be drawn from the derived results.

1. The pure compost and pure peat samples have similar grain size distributions with a relatively high amount of fine fraction. The increasing of the sand content generally results in coarser grain size distributions. In the column experiments, the grain size distribution of the studied biocovers became finer over time due to mineralization and degradation of organic matter. Among the studied biocover materials, the compost-sand (3:1) biocover can be regarded as the best structured biocover and experiences smaller changes in grain size distribution than the pure compost and pure peat based biocovers.

2. Evolutions of the material characteristics have a significant effect on the performance of the biocovers. The derived results indicate that the pH and LL of the studied biocovers are relatively constant. The bulk density and organic content of the studied biocovers increase with depth and time while there is the opposite trend for porosity. The increase of organic content and reduction of porosity with depth and time are more pronounced in the compost and peat biocovers, respectively.

3. Cracking and formation of fissures which have a negative impact on the performance of biocovers can be prevented with proper compaction. The compaction characteristics of the compost and peat based biocovers have been investigated and the obtained results indicate that

the maximum dry density in the compost-sand and peat-sand mixtures is obtained in a mix ratio of 1:3 (w/w) (respectively 1428.5 and 1004 kg/m^3). There is a general trend in the increase of the maximum dry density of the studied materials with increasing sand content of the biocover materials due to higher specific gravity of the sand in comparison with that of compost and peat.

4. Settlement of the CH_4 oxidizing biocover medium, besides physical failure risk, can also result in the reduction of CH_4 oxidation efficiency due to negative effects on the gas exchange process. The derived results indicate that the studied materials are compressible with considerable reductions in the void ratio with increasing consolidation pressure. The pure compost and peat materials generally consist of more deformable particles than the compost-sand and peat-sand mixtures; therefore, they are more compressible than the compost-sand and peat-sand mixtures. The compressibility of the biocover materials is a function of the consolidation pressure, initial moisture and organic content, and bulk density. In the column experiments, the C_c values, which reflect that the compressibility of the materials decreases with depth due to compaction of the biocover induced by the pressure of self weight. The obtained results show that the peat biocover experiences the highest amount of settlement and the compost-sand (3:1) biocover experiences the smallest amount of settlement among the studied biocovers.

5. The assessment of the physical (mechanical) stability of biocovers is based on shear strength parameters, including cohesion and angle of friction. The studied materials are frictional in nature with relatively low cohesion. The high internal friction angles of the studied biocovers are attributed to the presence of fibres that act as reinforcement. The friction angle is influenced by moisture and sand content. Increases in moisture content cause the formation of thicker water films around the biocover particles and the particles become more and more slippery and thereby the angle of friction is decreased. The frictional forces between the sand and compost particles are greater than those forces between the compost particles. In the column experiments, the friction angle and cohesion of all the studied biocovers increased with depth and time. The increase in friction angle and cohesion with depth and time is the result of the

compaction of the biocover medium and increasing organic content with depth and time, respectively.

6. There is a general pattern of decreasing hydraulic conductivity with increasing moisture content of the samples up to OMC and minimum hydraulic conductivities are achieved at OMC for the studied samples. Increases in the sand content result in larger void ratios, pores, and straight flow channels which cause higher hydraulic conductivities. The column experiments results indicate that the hydraulic conductivity of the studied biocovers is significantly reduced with depth and time, which is related to the compaction of the biocovers with depth over time. The bioclogging due to the formation of EPS is also another factor that contributes to the reduction of the hydraulic conductivity of the studied biocovers over time.

7. The VWC of biocovers is a key influencing factor on CH_4 oxidation since the growth and activity of methanotrophs are strongly bounded to moisture availability. The surface layer of all the studied biocovers dries out over time, which is related to evaporation induced surface desiccation. Unlike the surface layer, the VWC consistently increases in the bottom layer of all the studied biocovers due to downward moisture movement and methanotrophic activity. In the current research, low VWC is a limiting factor on CH_4 oxidation rate. The negative effect of low VWC on the CH_4 oxidation rate is more significant in the peat biocover among all of the studied biocovers.

8. The temperature is another imperative parameter that strongly affects the CH_4 oxidation process in biocovers. The increase in temperature in the first weeks of column operation is related to the aerobic degradation of the available carbon sources. The CH_4 oxidation process is an exothermic process and heat is generated by methanotroph bacteria during the oxidation process. The variations in the temperature within the studied biocovers result in the development of the highest temperature zone at a depth of -25 cm for all of the studied biocovers, which implies intense methanotrophic activity and consequently high CH_4 oxidation rate at this depth. A significant temperature difference is also observed between the ambient and column temperatures, which is due to methanotrophic activity.

9. The thermal conductivity of biocover material is considered as one of decisive thermal factors, which can control the suitability of the thermal conditions for methanotrophic activity. The results demonstrate that the thermal conductivity is a function of bulk density and moisture content, but thermal conductivity is more sensitive to variation in the moisture content than bulk density. In the column experiments, the thermal conductivity of all the studied biocovers increased with increasing moisture content and bulk density with depth and time. In the current study, the compost-sand (3:1) and peat biocovers show respectively the highest and the lowest range of thermal conductivity during the column operation among all of the studied biocovers. This means that peat material conducts heat at the lowest rate among all of the studied biocover materials and therefore provides better temperature insulation. The efficient and long term operation of biocovers depends on maintaining a suitable and favourable temperature for the growth of methanotroph bacteria. Proper temperature insulation protects biocovers against unfavorable conditions, and guarantees a favorable temperature for methanotroph bacteria within biocovers, which is particularly important in field conditions during cold seasons or in cold regions.

10. The studied compost, compost-sand (3:1), and peat biocovers are able to oxidize 84%, 72%, and 60% of influent CH_4 flux respectively. The studied compost and peat biocovers underwent the phases of adaptation, steady state, and decline during the column operation. However, the compost biocover had the highest efficiency in CH_4 oxidation, the performance of the compost-sand (3:1) biocover was steadier over time and no significant decline in CH_4 oxidation rate occurred during the period of operation.

6.2 Recommendations

Biocovers are a simple and innovative technological means for reducing CH_4 emissions from landfills. Although much information and data have been obtained in this research, some questions and uncertainties still remain. The following section summarizes the primary research deficiencies that are related to CH_4 oxidizing biocovers.

1. Generally, the passive venting of LFG through biocovers is considered as one of the significant approaches for reducing the environmental impacts of landfill emissions. In each case study, both CH_4 oxidation capacity and the geotechnical behaviour of locally available materials as alternative biocover materials should be investigated for the cost-effective and optimal field scale application of biocover technology.

2. The geotechnical properties of the compost and peat based biocovers change over time due to biodegradation processes during the CH_4 oxidation process. Subsequent long term laboratory and field investigations are needed to study the long term effect of the biodegradation of biocover materials on the geotechnical behaviour of biocovers.

3. The anaerobic phase of landfill life span with high rate of CH_4 production is estimated to be about 20 to 30 years, while experience with operating biocovers is limited to about five years. The long term CH_4 oxidation potential of biocovers should be studied under field and laboratory conditions in order to determine the suitability of the materials used during the landfill CH_4 production period.

4. There is a complex relationship among the T, H, M, and C-B factors in biocovers. The development of sound theoretical constitutive models to couple the T, H, M, C-B factors is still required to accurately assess the performance of biocovers during their life time.

5. The development of a comprehensive numerical model is required in order to predict the evolution of the T, H, M, and C-B processes during CH_4 oxidation process in different conditions.

6. The moisture content of a biocover medium (which has an impressive effect on the performance of biocovers) is strongly influenced by rainfall and evaporation in field conditions. The effect of rainfall and evaporation on biocover performance should be comprehensively studied through both laboratory and field investigations in order to enable the optimal design, maintenance, and construction of biocovers.

7. Environmental stresses, including freezing and thawing cycles, and wet and drying cycles, not only affect the CH_4 oxidation capacity, but also influence the geotechnical behaviour of biocovers. Therefore, the effect of environmental stresses on the performance of biocovers is another issue which should be addressed in future studies.

8. The bioclogging of biocovers due to microbial growth or formation of EPS can hinder the gas flow within biocovers and consequently affect their performance. A proper understanding of bioclogging in biocovers is essential in order to enable the efficient and long term performance of biocovers.

9. A proper knowledge of behaviour of biocovers in unsaturated condition is crucial for design, construction, and maintanence any type of biocover. A comprehensive research on application of unsaturated soil mechanics in evaluating geotechnical behaviour of biocovers will be valuable.

Appendix A

Selected pictures of conducted laboratory column experiments are presented in Appendix A.

Fig. A.1. Perforated pipe as a part of gas distribution layer.

Fig. A.2. PVC fitting and septa for sealing gas sampling ports through the wall of column.

Fig. A.3. Perforated pipe as a part of gas sampling port.

Fig. A.4. 5TM sensor for measurement of VWC.

Fig. A.5. TH-T sensor for measurement of temperature.

Fig. A.6. Brass fitting for sealing sensor contentions through the wall of column.

Fig. A.7. Cardboard tube as a part of insulation layer.

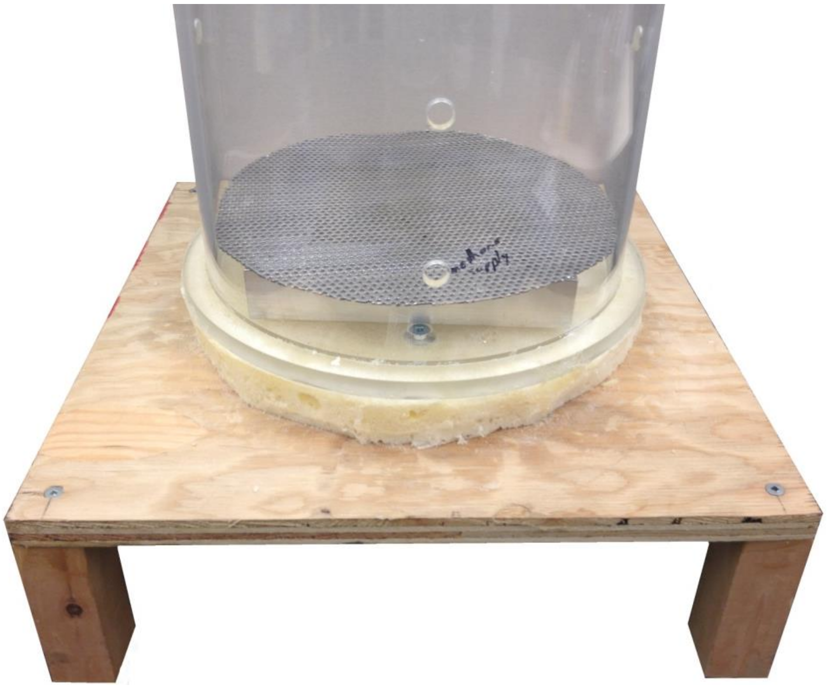

Fig. A.8. Front view of column base and drainage layer.

Fig. A.9. Front view of column base, drainage layer, and gas distribution layer.

Fig. A.10. Front view of column base, drainage layer, gas distribution layer, sensors, and gas sampling ports.

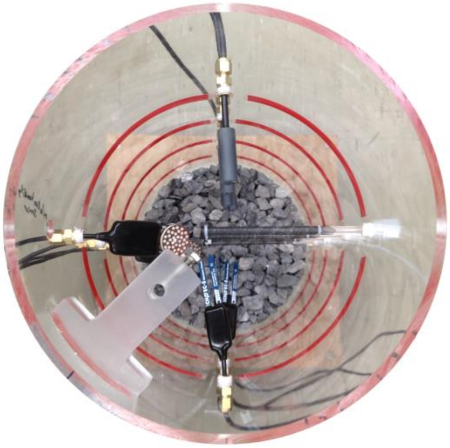

Fig. A.11. Top view of gas distribution layer, sensors, and gas sampling ports.

Fig. A.12. Front view of final column set-up.

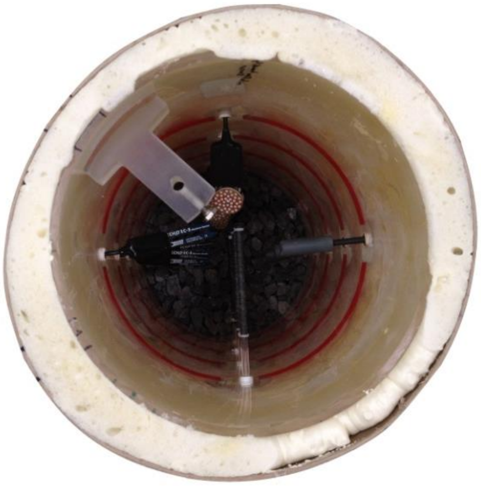

Fig. A.13. Top view of final column set-up.