

Geotechnical and Geo-Environmental Behaviour of Landfill Biocover under Freeze-Thaw Condition

By

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To my Parents

Abstract

Landfill biocovers have been proven as a green and efficient technology to mitigate landfill methane emissions. Thermal, hydraulic, mechanical and bio-chemical (THMBC) factors regulate biocover behaviour. The aim of the current study is to evaluate the geotechnical and geo-environmental response or performance of compost based biocovers under freeze-thaw conditions. A comprehensive experimental program, including tests on samples as well as biocover column experiments, has been conducted. The results demonstrate that the thermal properties (thermal conductivity and thermal diffusivity) of the biocovers change due to the FTCs. Moreover, the outcomes of the column experiments demonstrate that biocover performance remains at an acceptable level even after experiencing two FTCs despite that most of the THMBC parameters in the biocover have changed due to the impacts of the FTCs and methane injection. The findings presented in this thesis will contribute to a better understanding and design of compost biocovers in cold regions.

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Chapter 1

Introduction

This chapter will provide a brief introduction to the current thesis including problem description and novelty of the research followed by the research objectives and expectations. This will be followed by thesis organization and references.

1.1 Problem Statement

Methane (CH₄) gas owns the 2nd place in contribution towards global warming after carbon dioxide (CO₂) (Scheutz et al. 2009). Landfills are considered as one of the major sources of anthropogenic CH₄ emission, and account for up to 15% of the global CH₄ sources (Chalvatzaki and Lazaridis, 2010). The global warming potential of CH₄ is about 25 times that of CO₂ (Scheutz et al. 2009). Minimizing the CH₄ emission from landfills can be an effectual solution to tackle the greenhouse impact. An innovative approach to mitigate CH₄ emission from landfills is to apply a biotic cover at the top of the landfills (Cabral et al., 2010). Compost based landfill biocovers have been confirmed to be an economically efficient approach to mitigate CH₄ emission (Humer and Lechner, 1999, Lu et al., 2011 and Roncato and Cabral, 2012). However, many aspects of the practical application of compost as landfill biocovers have not been investigated and/or are not understood. One of these aspects is the performance of compost biocovers in cold regions, particularly the response of compost biocovers to freeze-thaw cycles (FTCs). Cold and freeze-thaw climatic conditions are common in Canada. To date, however, there is no study that addresses the response of compost biocovers to FTCs, or the performance

of compost biocovers in freezing and thawing climatic conditions. Therefore, the present research is conducted to investigate the performance of compost biocovers subjected to freeze-thaw conditions.

1.2 Research Objectives

The objectives of the present research are to investigate the effect of FTCs on:

- (i) the heat transfer ability or thermal properties of compost biocovers (thermal factor: T) by conducting experimental studies, and
- (ii) the simultaneous evolution of the thermal (T), hydraulic (H), mechanical (M) and bio-chemical (B-C) (e.g. CH₄ oxidation capacity) properties and behaviour of compost biocovers by conducting column experiments.

1.3 Research Approach and Methodology

The following methods and approach are used to address the aforementioned objectives.

Several compost biocover samples are prepared at different compaction degrees and corresponding water contents to assess the thermal property changes under FTCs. In considering the aim of this study, the thermal properties (thermal conductivity and thermal diffusivity) of small samples of compost biocover are evaluated prior and after undergoing numerous FTCs. Finally, by using the experimental data, an empirical formula that predicts the thermal conductivity of a compost biocover subjected to FTCs is proposed and then validated.

To evaluate the effect of FTCs on the thermal, hydraulic, mechanical and bio-chemical (e.g. CH₄ oxidation capacity) properties and behaviour of a compost biocover, column

experiments, in which the biocover is subjected to FTCs and then CH₄ injection, are conducted. Throughout the periods of CH₄ injection, numerous parameters, such as CH₄ oxidation, volumetric water content, temperature and settlement, are monitored. After each cycle of CH₄ injection, small samples from a depth profile of the columns are tested with regard to their mechanical (e.g., shear strength and consolidation), hydraulic (e.g., degree of saturation), thermal (e.g., thermal conductivity) and bio-chemical (e.g., organic content) properties.

1.4 Thesis Organization

The flow chart presented in Figure 1 shows the organization of the present thesis and the relationships between the different work steps of the investigations carried out. In **Chapter 1**, the problem statement, description, research objectives and approach are provided. In **Chapter 2**, the theoretical and technical background information that is useful toward a better understanding of the present thesis is summarized. Compost biocover technology is explained and a brief review on relevant current knowledge about biocovers is provided. In **Chapter 3**, the results of an experimental study on the thermal properties (thermal conductivity and thermal diffusivity) of a compost biocover subjected to FTCs is presented and discussed. **Chapter 4** deals with the results of the column experiments. The results provide a wide range of information about the effect of FTCs on the THMBC properties of compost biocovers as well as the performance of biocovers in freeze-thaw conditions. Finally, **Chapter 5** will provide a summary and conclusion of this study. Moreover, suggestions for future studies will be proposed.

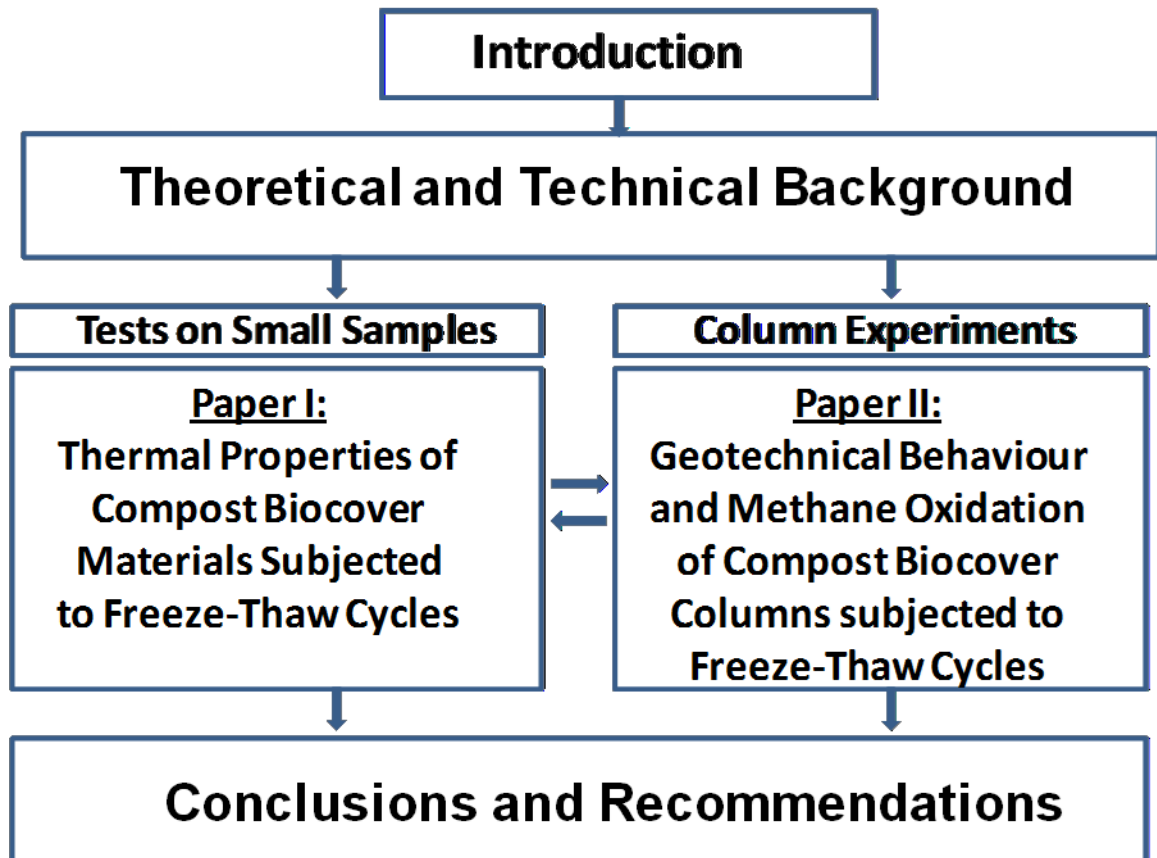


Figure 1-1 Organization and approaches of the thesis

1.5 References

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Chapter 2

Theoretical and Technical Background

2.1 Global Warming

The earth's atmosphere mainly consists of nitrogen and oxygen. However, a small portion (1%) accounts for the total gases that contribute to global warming. Solar energy is transferred to earth through radiation mechanism (USEPA, 2013). A part of solar energy is absorbed by the earth and the rest is reflected to the atmosphere again (USEPA, 2013). Due to the existence of several gases such as water vapor (H₂O), carbon dioxide (CO₂), and methane (CH₄) in the atmosphere, a part of the emitted heat remains in the atmosphere (USEPA, 2013). This mechanism is usually called "heat blanket" impact (Hogan et al., 1991). Heat blanket impact could be resonance due to high concentrations of greenhouse gases (GHGs) in atmosphere (Hogan et al., 1991). As far as we know, certain concentration levels of the GHGs are required to maintain our planet temperature suitable to live and also to be suitable for many species to survive on the planet. However, following the industrial revolution in previous centuries their concentrations started to increase in the atmosphere (Etheridge et al., 1998). For instance, the average concentration of CH₄ witnesses an increase from the range of 1732 parts per billion (ppb) to almost 1774 ppb in the course from early 90s up to 2005 (IPCC, 2007a). This increase in concentration values of the GHG gases lead to an increase in the average global temperature. This is mostly called the global warming (IPCC, 2007b). The gases that have contributed towards the global warming, named greenhouse gases (GHGs), can be categorized into two groups; first, long-lived greenhouse gases (LLGHGs) and secondly

short-lived gases (IPCC, 2007a). The former group remains in the atmosphere for an extensive period of time even in the course of decades. However, the latter group is normally oxidized through a natural process in the atmosphere in a shorter time (IPCC, 2007a).

The climate change (global warming) phenomenon leads to a diverse alteration in the weather and also in ecological behaviour (IPCC, 2007b). For a long period of time, the main scope of scientific studies towards main reason of global warming was on the CO₂ sources (Khalil et al., 1996). However, now the importance of CH₄ as one of the most contributor to global warming is more evident (Pedersen, 2010) due to the higher potential of CH₄ in absorbing the infra-red energy (Scheutz et al., 2009) that is almost 25 times higher than CO₂ (Scheutz et al., 2009, Lu et al., 2011). According to the literature the involvement of methane gas into global warming has been estimated in the range from 15% (Lu et al., 2011) to 18% (Forster et al. 2007).

2.2. Landfills and Methane Production

Waste industries are responsible for around 18% of the globally human-caused methane production (Bogner et al., 2007) of which landfills have a greater share (Bogner et al., 2007). Landfilling is a common way of disposing the waste due to its lower cost and simplicity in comparison to other applicable ways of handling the waste and tackling its associated problems (Barrett and Lawler, 1995). Currently, most of the governmental policies have been directed towards a greener environment, these strict rules increase the total cost of construction and operation on landfills (Bogner et al., 2007).

After the placement of waste into the landfill and landfill closure the process of gas production starts (Bogner et al., 2007, Perdikea et al., 2008). The process would start even before the accomplishment of landfills and installing the final cover (Perdikea et al., 2008). The reason is that the biodegradation of the waste material commences right after waste placement into the landfill (Huber-Humer et al., 2008a). The gases produced throughout waste biodegradation in landfill are called landfill gas (LFG) (Scheutz et al., 2009). LFGs are produced either under aerobic or anaerobic circumstances in the landfill (William, 2005). Several factors are important for the amount of generated LFGs; amongst them age of the waste, organic matter of the waste, environmental circumstances and volume of the waste are more remarkable (Scheutz et al., 2009). Besides, the compaction degree of the waste and the geometry of the landfill can also be considered as dominant factors (Pedersen, 2010). The geometry of the landfill could contribute to high concentration of LFG emissions (Kjeldsen, 1996). While a high degree of compaction of waste can contribute to more lateral LFG emission (Kjeldsen, 1996). Basically, the LFGs rate of production varies throughout the time (Williams, 2005). It seems when anaerobic methanogenic phase occurred in landfill, the landfill emission consists of 55% methane (CH₄) gas and 44% carbon dioxide (CO₂) and 1% of H₂ (Hrad, 2010).

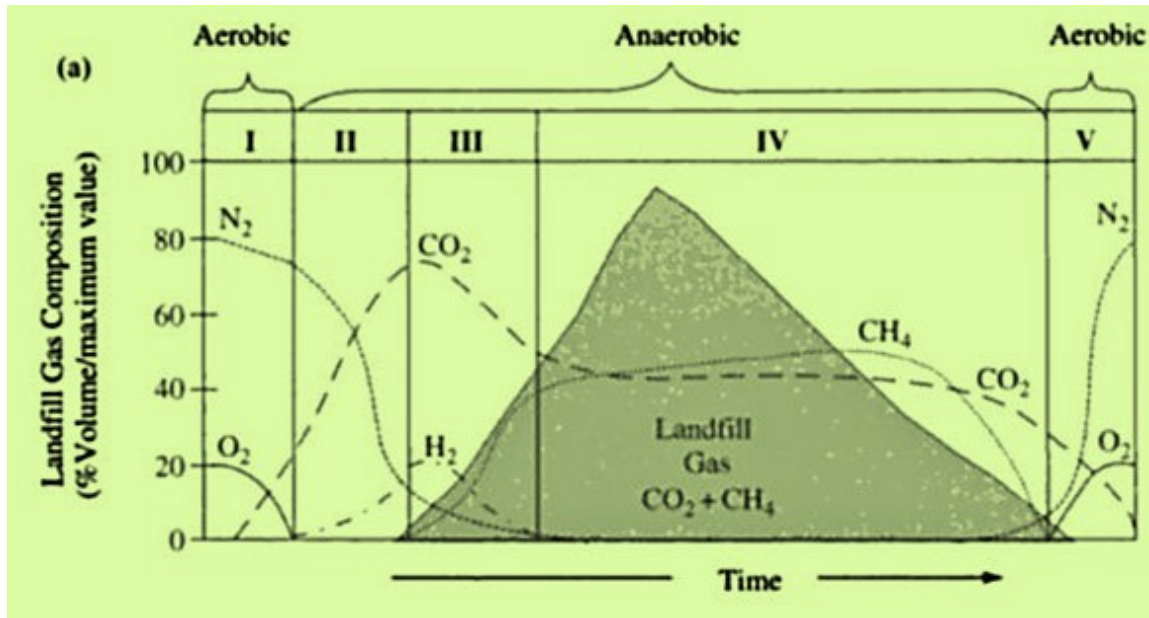


Figure 2-1 Landfill gas composition versus time (Williams, 2005)

Landfills rank second in anthropogenic CH₄ production in the US and Europe with roughly 34% and 30% LFG production, respectively (Perdikea et al., 2008). The value for Canada is around 21% (Perdikea et al., 2008). Moreover, in developing countries that are experiencing economic and population growth, the rate of CH₄ production from landfills is increasing (Barker et al., 2007). Based on a study by Bogner et al. (2007), the rate of anthropogenic CH₄ production by landfills will significantly increase from now to 2050.

2.3. CH₄ Management at Landfills

There are several ways to address waste GHG reduction, including preventing waste generation at the source (post-consumer recycling), applying LFG recovery systems to decrease CH₄ emissions from landfills, composting the organic portion of waste as much as possible to prevent GHG generation and finally, thermal processing, such as incineration and so forth (Bogner et al., 2007). Some of the aforementioned methods apply well and have led to effective results, such as a 20% decrease in LFG emissions in

Europe which could have only come into fruition due to the wide utilization of flaring and recovery systems, and also reduction in the volume of organic waste that was previously buried in landfills (Bogner et al., 2007).

Here, more considerations will be discussed. First, LFG emissions could continuously occur even for a long period of time (e.g. a century). Secondly, as can be seen in Figure 2-2, LFGs are not produced at a constant rate over time; the trend follows a pattern to reach a peak followed by a gradual reduction (Huber-Humer et al., 2008a). Nowadays, it is common to gather the LFG and transfer it to appropriate facilities (e.g. electrical boilers) to generate electricity (Bogner et al., 2007). Most of the power generators are in the range of 30 kWe to 50 MWe, while the capacity of most landfills to generate electricity can be categorized in the range of 1-15 MWe (Bogner et al., 2007). Even if landfills have the potential to efficiently generate power, there are still some difficulties that are commonly found in such systems, such as clogging or damaging of pipes or extraction systems (Bogner et al., 2007).

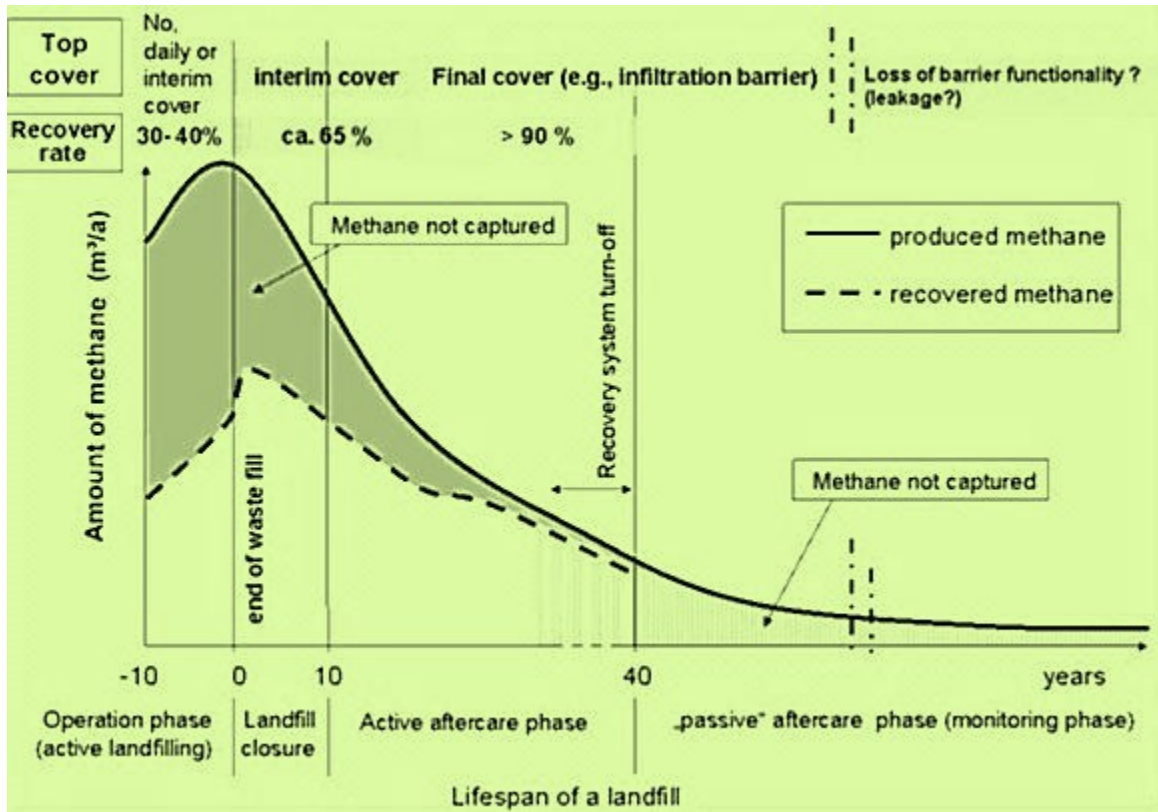


Figure 2-2 Methane generation and recovery versus time in landfill service life
(Huber-Humer et al., 2008a)

The installing of horizontal pipes along with vertical wells is known as an appropriate way to extract and transfer LFG emissions (Bogner et al., 2007). Today, in many countries, this method is considered as a mandatory step for the mitigation of LFG emission from landfills (Ait-Benichou et al., 2009). If the gas recovery systems are designed and constructed well, it will have the ability to prevent even 97% of the LFG that goes into the atmosphere (Spokas et al., 2006). Such a system is built in France (Spokas et al., 2006). Unfortunately, in landfills that are small or medium in size, the applying of the same technology and approach with the costs of maintenance do not seem to be economical (Mor et. al., 2006). These costs are usually high for LFG extraction systems in landfills (Wang et al., 2011). Another problem with gas recovery systems such

as flaring systems is the very low rate of efficiency. This problem results because the average length of their practical performance is about 20% of their initial life time design (Oonk and Boom, 1995). When considering these two facts, it seems that emissions from landfills are inevitable during their life span (Ait-Benichou et al., 2009). Therefore, scientists have started to search for alternative approaches that will lead to the reduction of LFGs.

With regards to the large number of trials and studies, it is already known that a group of bacteria can oxidize CH₄ (Pederson, 2010). The by-products of this bio-chemical reaction are heat, water and CO₂ (Pederson, 2010). Numerous studies have been carried out on this new biocover technology in terms of its development. Amongst them are Kettunen et al. (2006), Stern et al. (2007) and Einola et al. (2008). This new technology is mostly called the biocover system. Basically, a biocover system is a new generation of biofilters that have been confirmed as an effective tool to refine chemical compound emission (ammonia or hydrogen sulfide) (Chandrakanthi et al, 2005, He et al., 2011). Also, biocover technology is recognized as a promising technology to tackle CH₄ emission, even at the rate of 100% CH₄ removal (Roncato and Cabral, 2012). Another benefit of applying biocovers as the final cover on landfills is their ability to oxidize a group of non-CH₄ organics (NMOCs), such as vinyl chloride, dichloromethane and chloromethane (Scheutz et al., 2003). These chemical compounds are found in LFG emissions and considered hazardous to human health as well as the environment (Scheutz et al. 2003).

A survey on biocover technology, the concept of biocover performance and various types of bio-reactive covers are discussed in the next section.

2.4. Biocover Technology

Biocovers have the ability to oxidize CH_4 gas through a bio-reactive layer that is laid on the top of the landfill and therefore causes reduction of CH_4 emission from the landfill (Hilger & Humer, 2003, Pedersen, 2010). Biocovers are usually made of two major components. A bottom layer is responsible for the appropriate distribution of CH_4 gas and provides the conditions for gas transfer to take place from the landfill to the biocover without issues (Pedersen, 2010). This bottom layer is mostly made of coarse materials (e.g. gravel). The second main component is the upper layer that provides a suitable environment for methanotroph bacteria to grow and then oxidize the CH_4 gas (Pedersen, 2010). This layer is located on the top of the bottom layer as can be seen in Figure 2-3 (Hilger and Humer, 2003, Scheutz et al., 2009). Figure 2-3 is a schematic of the biocover concept.

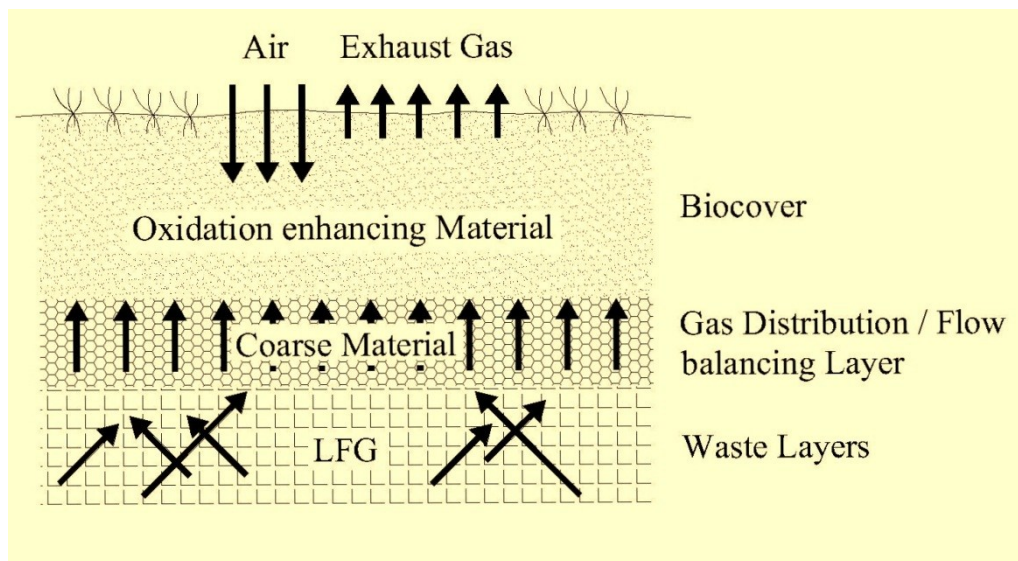


Figure 2-3 Schematic shape of the concept of biocover (Reproduced from Huber-Humer et al., 2008a)

2.4.1. Methanotrophs Bacteria and Methane Oxidation Reaction

Methanotrophic bacteria can be categorized under a larger group of bacteria named methylotrophs (Scheutz et al., 2009). This group of bacteria is recognized for their ability to convert CH₄ into energy, CO₂ and water (Scheutz et al., 2009). Methanotrophs are also divided into two groups based on their characteristics in which the first group (Type I) constitute Methylococcus, Methylobacterium, Methylobacter and Methylomonas, and the second group (Type II) encompass Methylosinus and Methylocystis (Scheutz et al., 2009). Two major differences make them distinguishable for scientists. The first difference is that Type I bacteria cannot handle nitrogen while the reverse is true for Type II bacteria. The second difference is that the latter group can compete with other microorganisms and outcompete them even in circumstances with low O₂ and nutrients and high CH₄ while the former group is unable to do so (Hanson and Hanson, 1996, Scheutz et al., 2009). This could be the reason that most experiments tend to be conducted on biocover media enriched with highly organic materials, such as compost or its mixtures (Huber-Humer et al. 2009, Roncato and Cabral, 2012). In the presence of O₂, CH₄ is converted into CO₂, water and energy (Scheutz et al., 2009). The reaction terms can be seen in chemical equilibrium 1.



Methane oxidation can only take place if sufficient concentration of O₂ and CH₄ are available. The CH₄ penetrates from the landfill (LFG emission) into the biocover while the O₂ source is the atmosphere (Scheutz et al., 2009). High achievements of methane removal occur where vertical profiles of both O₂ and CH₄ concentrations coincide on each other (Pedersen, 2010).

2.4.2. Other Methane Oxidation Techniques in Landfill using Biological active layer

2.4.2.1. Biowindows

In many applications, the biowindow technique is the optimal design for landfills. The technique is prevalent in cases where there is an absence of gas extraction systems, or in landfills which have very low LFG emissions, so there is really no need to cover the entire surface with a biocover (Scheutz et al., 2011). In addition, another application could be in landfills which already have conventional covers, such as clay liners (Scheutz et al., 2011). In these applications, the utilizing of biowindows could be an alternative design option. Similar to biocovers, they are also made of two components: the bottom layer that transfers gas from the landfill to the bio medium of the cover, and the upper layer that contains bacteria for CH_4 oxidation (Scheutz et al., 2011). The first biowindow was constructed in the Fakse landfill in Denmark (Scheutz et al., 2011). Figure 2-4 shows a schematic of a biowindow.

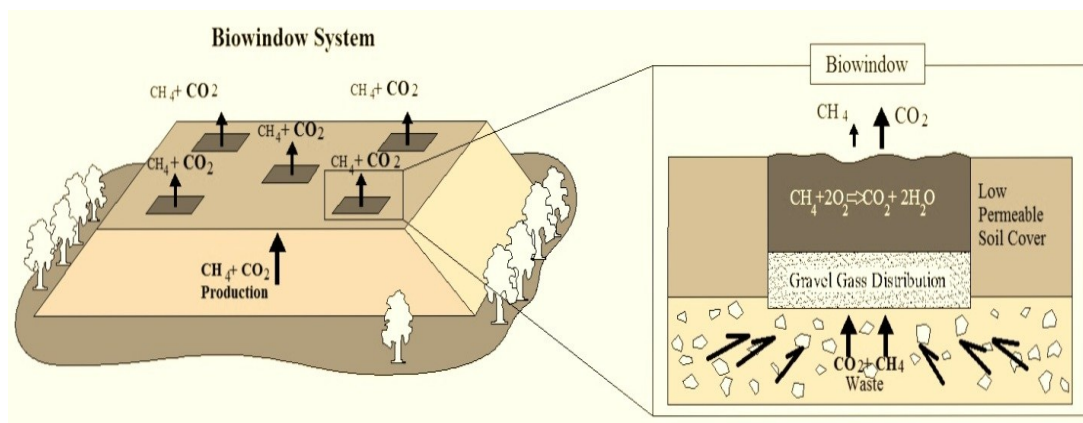


Figure 2-4 Schematic shape of biowindows (Reproduced from Scheutz et al., 2011)

2.4.2.2. Biofilters

Adaptability to various situations (e.g. landfill situations) could be considered as a merit for biofilters. Biofilters need active or passive facilities to transfer gas from landfills to the bio-reactive layer (Huber- Humer et al., 2008a). A Canadian experiment in this regard is a study by Zeiss (2006). The technology that was applied in the aforementioned study, called MethOx, utilizes vertical wells to extract heat from inside landfills and tries to maintain the temperature of the MethOx bed in a narrow range of suitable temperatures for CH₄ oxidation. An average CH₄ oxidation ratio of 89% was observed when measurements took place from August 2001 to February 2005; during which, the landfill cover experienced seasonal temperature changes. The results showed the establishment of the idea of MethOx in Canadian weather environments. Moreover, Straka et al. (1999) achieved an average removal of 90% in their organic biofilter. Figure 2-5 shows a schematic of the biofilter concept.

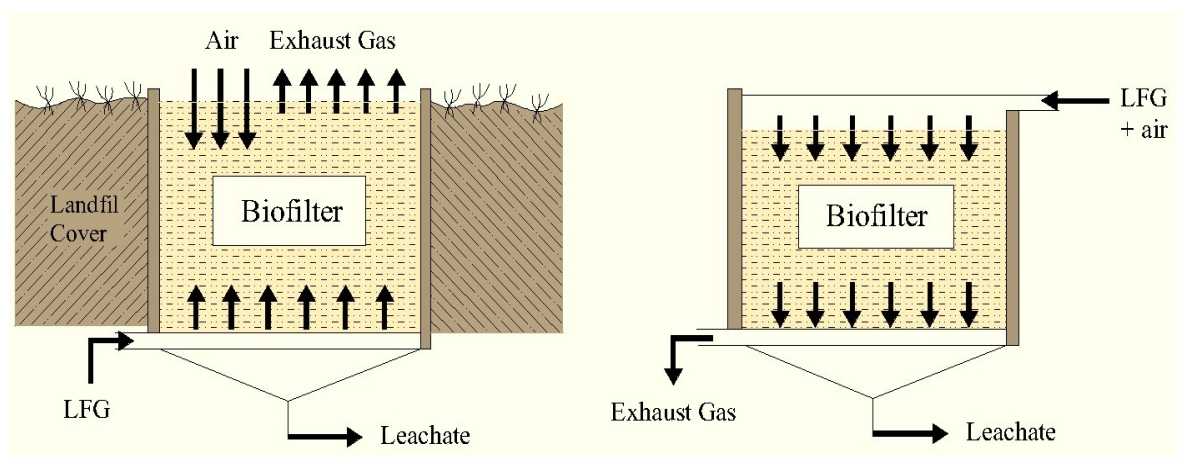


Figure 2-5 Schematic shape of biofilter concept (Left: Up-flow mode, Right: Down flow mode)(Reproduced from Huber- Humer et al., 2008a)

2.4.2.3. Biotarps

All the concepts that have been discussed are based on the fact that they can only be applicable as the final cover or built on the final cover of landfills. However, it is known that the process of LFG generation and emission starts from the moment that waste is deposited into landfills (Huber- Humer et al., 2008a). It might take years or even a decade until a landfill is closed. Therefore, LFGs can be emitted during this period of time. To avoid emissions from these open cells, a new technique that uses biotarps is utilized (Huber- Humer et al., 2008a). Biotarps with a thickness between 30- 45 cm can allow methanotroph bacteria to remove CH₄ (Huber- Humer et al., 2008a). The only concern is the stability of these biotarps (Huber- Humer et al., 2008a). Figure 2-6 shows a schematic of a biotarp.

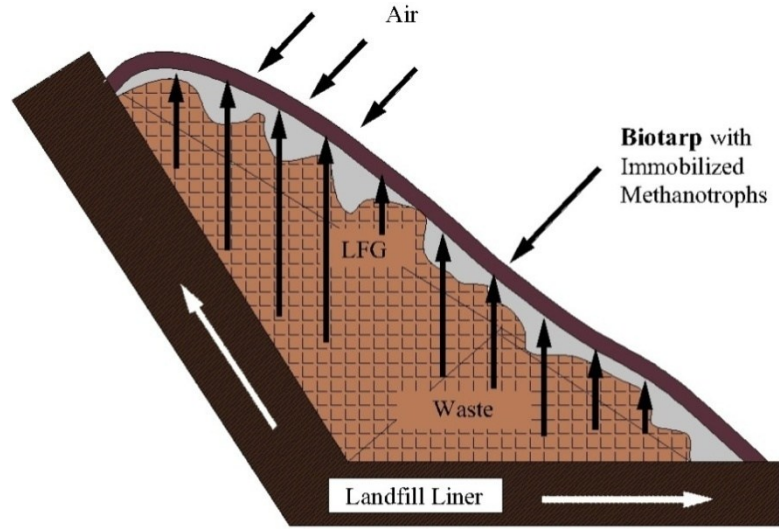


Figure 2-6 Schematic shape of biotarps (Reproduced from Huber- Humer et al., 2008a)

2.5. Factors that can affect the methane oxidation in Biocover

2.5.1 Thermal factors

Temperature has a profound impact on the behavior of microbial communities and their capacity to oxidize CH_4 (Scheutz et al., 2009). Several studies in the literature have demonstrated the dependency of the CH_4 oxidation of methanotroph bacteria on temperature variations (Borjesson and Svensson, 1997; Visvanathan et al., 1999; Börjesson et al., 2004; Einola et al., 2007). The optimum temperature for CH_4 oxidation has been mentioned by Zeiss (2006) as 15-35°C. At a temperature level as high as 50°C, Zeiss (2006) mentioned that no CH_4 oxidation can technically occur. Similar results were reported by Scheutz & Kjeldsen (2004). However, in a review by Scheutz et al. (2009), they concluded that the optimum temperature of CH_4 oxidation in bio-reactive covers is

25–35°C. It is worth mentioning that in some other studies (e.g. Mor et al., 2006), the optimum temperature for CH₄ oxidation was found to be 40°C. Even though the suggested optimum ranges of temperature are narrow, several studies have shown that CH₄ oxidation can continue in temperatures as low as approximately 1–2°C (Scheutz & Kjeldsen, 2004; Einola et al. 2007).

It is known that as a result of the biodegradation of organic wastes, heat is generated in landfills (National Research Council of The National Academies, 2007). In addition, the oxidation process itself produces some heat in biocovers (Scheutz et al. 2009). These two factors can lead to rise in the temperature of the covers, up to even higher than 50°C in the summer, which means no bacterial activities and therefore no oxidation in the biocovers (Zeiss, 2006). Furthermore, the temperature rise in turn leads to higher evaporation rates in the covers (Maurice and Lagerkvist, 2003), and causes positional changes in the degree of saturation in the soil over the cover profile (Moghbel and Fall, 2011). The changes in temperatures are greater in the surface layers of biocovers that are exposed to environmental conditions (Ait-Benichou et al., 2009). Thus, effectiveness of the thickness of the covers for the oxidation of CH₄ gas is reduced, thus indicating a lower efficiency of the covers (Moghbel and Fall, 2011). Hence, for either the design of biocovers or maintenance of existing highly efficient biocovers, it is critical to predict and control temperature changes in the biocover profile during their service life (Chandrankanthi et al., 2005).

In order to predict temperature changes along the depth, the profile of the biocover mass and heat transfer analysis are essential items (Chandrankanthi et al., 2005). The primary parameters that take part in the heat transfer analysis are thermal conductivity and

thermal diffusivity. Furthermore, it has been found by several researchers that the thermal properties of soil material are resultant of a number of parameters, such as density, type of mineral material available, water content, soil structure, salt concentration and the percentage of organic material available (Abu-Hamdeh and Reeder, 2000, Singh and Devid, 2000, Côté and Konrad, 2005). In landfills that experience long and cold winters, the landfill cover experiences long cold periods so that its temperature falls under 0°C or the cover might remain under permafrost (Henry, 2007; Phillips and Newlands, 2011). It is also known that many of geotechnical properties of the soil material could change under regular freezing and thawing processes that occur in cold regions during winter to spring (Qi et al., 2006; Phillips and Nowlands, 2011); therefore it might change or impact the soil thermal properties as well (Farouki, 1981).

To the best of the author's knowledge, there is no study in the literature that addresses the impact of FTCs on the thermal properties of compost biocover material.

2.5.2. Hydraulic factors

Moisture content has one of the greatest impacts on biocover's performance (Scheutz et al., 2009). Moisture is not only a prerequisite element for bio-reactions and microbial activities due to its ability to transfer nutrients into the biocover medium, but also has the responsibility of eliminating bio-chemical reaction residuals (Scheutz et al., 2009). The importance of water content for the CH₄ oxidation capacity of compost biocovers is mentioned or proven in several studies, such as Yuan (2006), Pokhrel, (2006), and Albanna and Fernandes (2009). In a study by Whalen et al. (1990), it was mentioned that the lack of sufficient water content has an impact on CH₄ removal in the cover material. It

is mentioned by Huber- Humer (2009) that the mixture of biocover material with 30% up to 50% gravimetric water content could lead to high performance of biocover. As previously discussed by Scheutz et al. (2009), the CH₄ and O₂ supply to the oxidation zone and existence of adequate nutrients are the key factors that pertain to biocover behaviour and efficiency. Water content affects all of those factors; therefore, it impacts the optimal environment for methanotrophs and gas fluxes from both the atmosphere and landfill on biocovers (Scheutz et al., 2009). The gas exchange of the biocover material becomes impacted by the hydraulic conductivity of the biocover media (Pokhrel, 2006).

Another key parameter is the degree of saturation. The degree of saturation may have impacts on both gas transfer and stability analysis in biocovers (Bajwa, 2012). It is known that CH₄ access to the oxidation zone is mostly provided by advective mechanisms (Pederson, 2010). Oxygen penetration is mostly supported by diffusion mechanisms (Pederson, 2010). Moreover, the capability of the material used for the purpose of gas transport is a key factor that affects the penetration of both O₂ and CH₄ gases into the covers (Pederson, 2010). It has been demonstrated by Ait-Benichou et al. (2009) that the depth of CH₄ oxidation is affected by the saturation degree of the biocover. If the water exceeds the threshold of a high degree of saturation equal to 85%, the gases should first solve in the water phase (Cabral et al., 2004, Scheutz et al., 2009). The rate of gas diffusion in the liquid phase is roughly 10000 times lower than that in the gas phase (Cabral et al., 2004, Scheutz et al., 2009), and eventually, affects the biocover performance and leads to a significant decrease in CH₄ oxidation (Scheutz et al., 2009). On the other hand, very low amounts of water in the biocover medium leads to microbial stress and consequently reduces CH₄ oxidation, too (Scheutz et al., 2009).

In landfills located in cold regions, biocovers will experience FTCs. FTCs can impact numerous geotechnical properties of soil (Qi et al., 2006). To elaborate, Chamberlain and Gow (1979) demonstrated that FTCs cause great increases in the hydraulic conductivity of soil material. Similar trends in results were obtained by other researchers, such as Kim and Daniel (1992) who reported a maximum of a sixfold increase of the hydraulic conductivity in soil material. Moreover, research has been done by Zimmie and LaPlante, (1990) who proved a one to two order of magnitude increase in the hydraulic conductivity. Several mechanisms might be attributed to increases in the hydraulic conductivity. First, it may be attributed to the soil particle movement phenomenon that is confirmed to take place under FTC conditions (Chamberlain and Gow, 1979; Viklander and Eigenbrod, 2000). Secondly, it could be explained by the formation of free voids after the thawing process has ensued (Chamberlain et al., 1990).

To the best of the knowledge of the author, the hydraulic conductivity of compost biocover material which is subjected to CH_4 oxidation and FTCs has not yet been addressed in the literature. Furthermore, how FTCs will affect other hydraulic factors or parameters of compost biocovers (degree of saturation, moisture content, gas transport) is still not well known.

2.5.3. Biological and Chemical factors

The existence of high concentrations of NH_4^+ prevents CH_4 oxidation from occurring at suitable levels (Scheutz et al., 2009). One of the studies that has proven this fact was conducted by Boeckx & Van Cleemput (1996). They found a linear reduction correlation between the initial NH_4^+ and CH_4 removal. This inhibition in CH_4 oxidation reaction might be attributed to two phenomena. First, ammonium could compete with CH_4 for O_2

and outcompete CH₄ in the oxidation process (Bodelier and Laanbroek, 2004). Secondly, the processing products are nitrite and hydroxylamine which could be toxic for CH₄ oxidizing bacteria (Bodelier and Laanbroek, 2004).

Commonly, CH₄ oxidation reaches a peak and then gradually decreases (Scheutz et al., 2009). This behaviour is attributed to the formation of exopolymeric substances (EPS) in bio-reactive material exposed to CH₄ flux (Molins et al., 2008). EPS function as an anchorage that links bacteria to the soil surface (Scheutz et al., 2009). This has been well discussed by several researchers, such as Hilger et al. (2000) and Wilshusen et al. (2004) followed by a brief conclusion by Scheutz et al. (2009) in that the mechanisms associated with this phenomenon are first the cloggings of the free pore space by the formation of EPS, and secondly, the reduction of gas diffusion into the biocover medium. Hilger et al. (2000) discovered that EPS limit oxygen diffusion into the biocover medium. However, there is no such issue observed for LFG penetration into the biocover. Up to the present, the mechanisms associated with EPS formation are not well understood (Scheutz et al., 2009).

Another key influencing factor is the pH of biocovers. Based on previous studies, Scheutz et al. (2009) concluded that the pH values for the performance of biocovers should be in the range of 5.5 to 8.5. Figueroa (1993) also mentioned the same range for appropriate pH values.

The organic content of biocovers is correlated with the rate of CH₄ removal in biocovers (Hrad, 2010). Higher organic contents lead to larger amount of CH₄ removed in biocovers (Hrad, 2010). Albanna et al. (2007) found that the addition of nutrients to the biocover medium at appropriate water contents could lead to a considerable surge in CH₄

oxidation. To justify the greater amount of CH₄ removed obtained in the study by Börjesson et al. (1998) to values obtained by Börjesson et al. (2004), the amount of organic content was mentioned as a contributing factor.

As discussed in previous sections, appropriate concentrations of CH₄ and O₂ are correlated to microbial (methanotroph) activity (Ait-Benichou et al., 2009). Jones and Nedwell (1993) stated that the greatest amount of CH₄ oxidized is achieved at a depth profile where the CH₄ and O₂ concentration profiles overlap each other. Therefore, the formation of this narrow layer needs to satisfy many criteria (Scheutz et al., 2009). Numerous parameters affect the location of the oxidation zone in biocovers, such as the water content, temperature and adequate concentration of CH₄ from both landfills and O₂ from the atmosphere (Hrad, 2010). Due to the diversity of the circumstances in materials utilized as the biocover medium, various results were reported by researchers for the depth of the oxidation zone for biocover depth profiles. Even Huber-Humer (2004) found that the CH₄ oxidation zone can move upwards if higher concentrations of CH₄ gas is injected into the biocover. This is because higher gas flux from inside a landfill limits the amount of O₂ from penetrating into the biocover (Abichou et al., 2004). Overall, the oxidation zone has been reported to be located at a very shallow level, the very first 15 cm of the biocover (Urmann et al., 2007) to deeper parts of the cover at roughly 30 cm in depth (Humer and Lechner, 1999) and to even greater depths. However, Hrad (2010) concluded from the literature that the oxidation zone is commonly situated at a depth between 30 to 40 cm and the maximum amount of CH₄ removal occurs at a depth below 20 cm.

In cold environments, where biocovers undergo FTCs, it is crucial whether methanotroph bacteria can survive under the aforementioned circumstances and perform well again in the spring season after the thawing process is completed. Some studies (e.g. Walker et al., 2006) conclude that microorganisms can adapt to the circumstances of long winters in order to survive in such an environment. However, it cannot be denied that FTCs have some impacts on the microbial behaviour as well as the biological behaviour (Sulkava and Huhta, 2003). Feng et al. (2007) mentioned that FTCs can alter the degradation pattern of the organic portion of the soil. Another issue that occurs during the freezing-thawing process is the conversion of the volume of water to ice. Continuous freezing leads to the formation of more ice lenses which means less presence of unfrozen water in the pores (Wagner et al., 2003). Water is a key parameter for microbial activity; therefore, it might affect microbial behaviour or even the survival of bacteria in cold environments (Wagner et al., 2003). An additional issue lies with the given concentration of salts in the soil due to the lack of unfrozen water, and the concentration of salt will increase in unfrozen water, which might affect the biological behavior throughout the soil (Wagner et al., 2003).

Some studies (e.g. Feng et al., 2007) have concluded that FTCs can improve microbial mineralization and activity which usually lead to a CO₂ flush. On the other hand, Männistö et al. (2009) concluded from their experimental tests that FTCs have little impact on the soil microbial community. Their team also mentioned that the current knowledge about the group of bacteria that can survive after FTCs or those that can remain active is not adequate. Panikov (1997) mentioned that psychrophilic bacteria constitute the main members of the soil microbial community in cold regions. Also, a

study by Berestovskaya et al. (2002) proved that the methanotrophic community can gradually adapt themselves to circumstances that are prevalent in the arctic tundra soil. Besides that, methanotroph bacteria are detected even in sediments of lakes located in the Antarctica (68° S 78° E) (Bowman et al., 1997).

The literature review presented above clearly shows that the impact of FTCs on the biological and chemical factors of biocovers is still not well understood. Many questions remained unanswered. For example: How will FTCs affect the evolution of the organic contents of biocovers?

2.5.4. Mechanical and Geometric factors

2.5.4.1. Thickness of Biocover

As discussed, climatic conditions affect biocover properties, especially the upper layers. This might be due to a reason provided by Pokhrel (2006), who noted that the thickness of biocovers is of paramount importance when biocover performance is a concern. A thickness value of 1.2 m was suggested by Huber-Humer et al. (2008b) as the biocover medium is supported by at least a 0.5 m gas distribution layer. Their concern in defining a minimum thickness of the gas distribution layer can be attributed to the clogging of the top part due to finer particle movement from the biocover medium to the gas distribution layer (Huber-Humer et al., 2008b). A thicker oxidation layer, and higher CH₄ oxidation capacity will be obtained (Einola, 2010). However, greater thickness of biocovers might cause severe increases in construction costs. A study by Albanna (2009) determined that a bio-reactive layer with only 5 cm more in thickness can increase the CH₄ oxidation capacity due to the escalation of the CH₄ retention time and also provision of a more suitable environment for bacteria. A thin biocover with a thickness of 30 cm made from

compost and other organic materials was tested by Perdikis et al. (2008) in order to measure its capability for CH₄ oxidation. A CH₄ removal rate of 100% was achieved in their experiment.

It can be concluded that the determination of the optimum thickness of biocovers has been shrouded in controversy and depends on various conditions. Climatic conditions seem to be the most important.

2.5.4.2. Shear Strength Properties

One of the main issues in landfill design is slope stability. In any geotechnical structure, stability should be checked during the design process (Benson and Othman 1993, Bajwa, 2012). Stability was also taken into consideration in the design of the MethOx technology by Zeiss (2006). Several trials and reviews were carried out on organic soils to quantify their shear strength parameters (Benson and Othman, 1993, Puppala et al., 2006, Kazemian et al., 2011, Bajwa and Fall, 2011, Bajwa, 2012). Their methods and results proved that direct shear testing is an appropriate way of measuring the shear strength parameters of compost material. From classical soil mechanics, such as the notes of Mitchell (1976), it is known that high friction angles for fiber soils (e.g. compost) are expected. Bajwa and Fall (2011) reported an average friction angle of approximately 43° for compacted compost material. Moreover, Benson and Othman (1993) reached a friction angle value of 61° for organic soil (Figure 2-7).

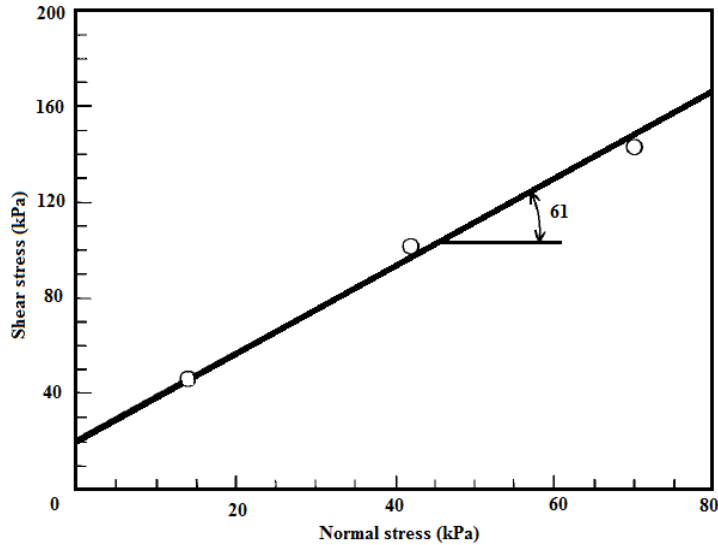


Figure 2-7 Strength envelope of compost material by Benson and Othman (1993)

These high friction angles are well described by Benson and Othman (1993) in that the existence of organic fibers functions as reinforcement through the soil material. It is worth noting that compost samples compacted at optimum reveal the highest shear resistance (Bajwa and Fall, 2011).

For landfills located in cold regions where the issues are long winters and low temperatures, the impact of FTCs on the shear parameters of the biocover material should be considered throughout the biocover design process. From the literature, it is known that FTCs can alter shear strength parameters. On the one hand, studies such as Graham and Au (1985) and Leroueil et al. (1991) mentioned that shear strength is reduced under FTCs. On the other hand, some studies, such as Alkire and Morrison (1982), proved an increase in undrained shear strength under FTC. Most of the shear strength alteration occurred during the initial FTCs (Yong et al., 1985).

Numerous studies had been conducted to determine the impact of FTCs on the shear strength of soil material. However, to the best of the knowledge of the author, there is no study in the literature that considers the impact of FTCs on compost biocover material subjected to CH₄ injection. Therefore, further studies on the discussed parameters are valuable to establish a better understanding of the shear behaviour of compost biocover material under the combined impacts of CH₄ injection and FTCs.

2.5.4.3. Consolidation and Settlement

To evaluate the performance of biocovers, a better understanding of their consolidation and settlement behaviours could be the key factors. Gas permeability and porosity are recognized as important parameters in the performance of biocovers (Pedersen, 2010). Moreover, the settlement behaviour of biocovers under operation has been linked to O₂ penetration into biocovers (Bajwa, 2012). This might be attributed to the fact that due to the settlement or consolidation of the biocover material, the bulk density will increase. Increases in bulk density lead to decreases in porosity and consequently might affect the gas permeability of the biocover medium. This might decrease the CH₄ and O₂ penetration into biocovers, thereby resulting in a smaller CH₄ oxidation zone in biocovers, which eventually affects biocover performance. The aforementioned reasons explain the importance of any factors that can lead to a decrease in porosity. Such behaviours could be settlement and consolidation behaviour of biocovers.

To review the characteristics of compost biocovers with regard to consolidation behaviour, a relevant study was conducted by Bajwa (2012). Bajwa performed several tests at various compaction degrees, and determined that increases in water content under compacted conditions lead to a surge of compressibility in the compost. Other results

obtained by Bajwa (2012) include the swelling of compost during the unloading process. Higher swelling values were observed for samples with higher initial water contents. Due to increments in loads, compacted compost with initial higher water contents tends to decrease in void ratio faster than those with lower water contents (Bajwa and Fall, 2011). Finally, he concluded that under an 80 kPa load and at 79% water content, the minimum value of 0.15 (e) was obtained which means that there is almost not enough free space for gas penetration and movement in the biocovers. This might decrease the performance of biocovers. Therefore, he came up with the recommendation of applying lower water content to satisfy the purpose of gas transfer in biocovers. In the opinion of the author, the above is true, but only valid for compacted compost biocover material. As discussed earlier, compost biocovers should not be compacted too much especially with heavy equipment. Hence, a study should be carried out to evaluate the behaviour of compost material compacted under its own self-weight.

The literature review presented above depicts the importance of considering consolidation and settlement behaviour of biocovers. However, the combined impacts of FTCs and CH_4 migration that take place in real biocovers located in cold regions on the settlement and consolidation behaviour of the biocover medium is still not well understood. Until now, no study has been performed to address this issue.

2.6. Coupled Process in Compost Biocover

It is known that methanotroph bacteria have their best performance in a specific range of temperatures (Yuan, 2006; Pokhrel, 2006). Also, heat is a by-product of aerobic CH_4 oxidation reactions (Scheutz et al., 2009); therefore, there is a source of heat inside biocovers during CH_4 oxidation. During the summer, due to climatic conditions (e.g. sun

radiation and high air temperature), there is a heat source at the top of the landfill biocover. Moreover, due to the biodegradation of waste material inside the landfill, heat is generated. This could be said to be the third source of heat in biocovers that regulates heat transfer at the bottom of biocovers. These three sources of heat (a thermal factor: T) individually or in combination might increase the temperature of the biocovers along with their profile (Zeiss, 2006; Chandrakanthi et al., 2005). This might lead to the evaporation of available water content (a hydraulic factor: H) in biocovers (Maurice and Lagerkvist, 2003, Visvanathan et al., 1999), and therefore cause changes in the degree of saturation in biocovers (a hydraulic factor: H) (Maurice and Lagerkvist, 2003). It is well established by researchers that severe decreases in the degree of saturation lead to microbial stress in biocovers (Scheutz et al., 2009) (Biological factor: B) and hence a decrease in biocover performance, i.e. CH₄ oxidation by the bacteria (Bio-Chemical term: B-C) (Del Grosso et al., 2000; Dobbie and Smith; 1996, Scheutz et al., 2009). It is also well known that temperature can have significant effects on the deformation of the porous media as well as on the pore water pressure, fluid flow and stress within the pore media. On the other hand, due to the CH₄ oxidation reaction (B-C), water is generated as a by-product (Maurice and Lagerkvist, 2003; Scheutz et al., 2009). Increases in water content lead to increases in the degree of saturation along the effective zone of biocover profiles (Cabral et al. 2004) (H) and consequently, sharp decreases in gas transfer through biocover profiles (H) (Cabral et al. 2004). The aforementioned decrease in gas transfer might result because of the decrease in CH₄ and O₂ gas concentrations in biocovers (B-C), and finally, the reduction of biocover performance (B-C) (Scheutz et al., 2009). An increase in water

content will also affect the effective stress and heat transfer within the porous media (compost).

This above example and explanation indicate that for a better understanding of the behaviour of biocovers, the “coupled processes” that occur within biocovers should be taken into account and well understood. Through biocovers, heat transfer (T), stress/deformation/settlement (M), gas/fluid flow (H) and bio-chemical reactions (B-C) phenomena occur simultaneously and affect each other at the same time (Bajwa, 2012) as schematically described in Figure 2.8. Thus, biocover behaviour cannot be understood and explained well unless the mentioned interacting factors or coupled processes are understood. In a nutshell, it would be logical to say that biocover behaviour can be described well in terms of coupled thermo hydraulic mechanical bio-chemical behaviour (THMBC). To date, there is no study in the literature that covers all of these aspects at the same time. Moreover, there is no study that addresses the evolution of the THMBC factors in compost biocovers. Therefore, a study on the THMBC processes in biocovers under FTCs could be an effective step towards better understanding of the behaviour of biocovers in cold regions. This will also be helpful if the cost effective design of biocovers are an issue.

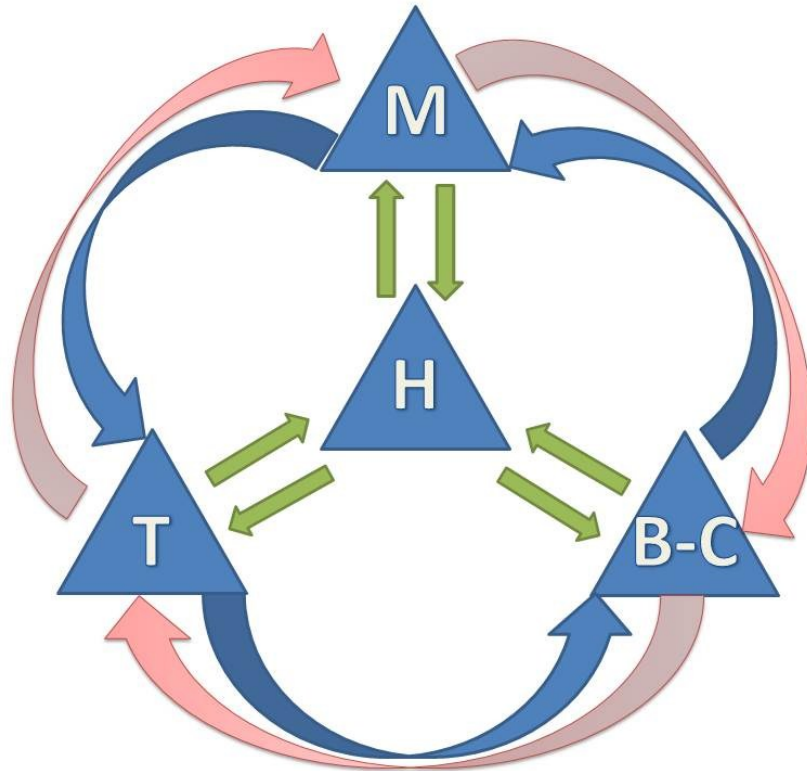


Figure 2-8 Basic THMBC map relations and mechanism (Reproduced Based on the general concept of Jing and Feng, 2003)

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Chapter 3

Thermal Properties of Compost Biocover Subjected to Freeze-Thaw Cycles

Abstract

In this article, the key heat transfer parameters, thermal conductivity and thermal diffusivity of biocover material made of compost, subjected to freeze-thaw cycles (FTCs) for a wide range of water content, is investigated by means of the transient method. The samples are kept at -12°C to freeze and at room temperature (23°C) to thaw. The results obtained show that FTCs have an impact on the thermal properties of compost biocovers. However, approximately more than 70% of the total thermal conductivity changes occur in the first two FTCs. Moreover, it has been found that a linear relation between thermal conductivity and degree of saturation is valid even under FTCs. Furthermore, it is found that variation in the thermal properties is due to the combined effect of three factors: volume change, grain size distribution and crack formation. Finally, an empirical equation has been developed to predict the thermal conductivity changes versus FTCs.

3.1. Introduction

Among greenhouse gases (GHGs), carbon dioxide (CO₂) and methane (CH₄) gases are widely recognized due to their potential to adsorb high levels of infra-red (IR) light (Scheutz et al., 2009; Pedersen, 2010). Meanwhile, due to the higher long term IR absorption of CH₄ gas and the time (GWP₁₀₀) that it remains in the environment 25 times greater than that of CO₂ and considered more unpleasant (Scheutz et al., 2009; Lu et al., 2011). CH₄ gas is assessed to contribute to 15% of the global warming phenomenon (Lu et al., 2011). Landfills account for 10% of all anthropogenic CH₄ emissions (Stein and Hettiaratchi, 2001). Recent studies show that the CH₄ gas production of waste industries are considered to be the second highest source of anthropogenic CH₄ emission in Europe and the US (Scheutz et al. 2011). To elaborate, landfills produce 21%, 30% and 34% of all anthropogenic CH₄ emissions in Canada, Europe and the US, respectively (Perdikea et al., 2008).

Numerous investigations and trials have been conducted in order to develop current technologies that are founded based on the idea of biotic treatment of landfill gases (LFGs) and to prevent uncollected LFGs from escaping into the atmosphere (Zeiss, 2006; Stern et al., 2007; Huber-Humer et al., 2008; Perdikea et al., 2008; Scheutz et al., 2011; Roncato and Cabral, 2012). These uncollected gases might be either the gases that the gas collection system in the landfill site could not collect or the emissions from old or small/medium landfills which do not have any collection systems at all or in which installing a gas collection system is not economical (Scheutz et al., 2009; Wang et al., 2011). The main focus of the aforementioned studies has been on biocovers. Biocovers are an advanced type of biofilter that have been tested for the refining or elimination of

hydrogen sulphates and ammonia (Chung et al., 2001; 2005) or only hydrogen sulphates (He et al., 2011). The CH₄ oxidation process in biocovers is carried out by methanotrophic microorganisms commonly called methanotrophs (Scheutz et al., 2009). Significant factors that affect the microbial behavior of methanotrophs include temperature and water content (Scheutz et al., 2009). It has been proven that variations in temperature are a dominant factor that influences the efficiency of methanotrophs in the oxidation process (Borjesson and Svensson, 1997). The ideal temperature range for bacterial growth is 15-35°C; at temperatures higher than 40°C, their oxidation ability severely decreases, and at 50°C, practically no oxidation takes place (Zeiss, 2006). On the other hand, it can be found from studies by Trotsenko and Khmelenina (2005), Zeiss (2006) and Einola, et al. (2007) that at temperatures below 10°C, bacterial activity is reduced, and in some cases, the biocovers contain certain enzymes where minimal activity of bacteria can be seen even at a temperature as low as approximately 1°C.

It is known that as a result of the biodegradation of organic wastes, heat is generated in landfills (National Research Council of The National Academies, 2007). In addition, the oxidation process itself produces some heat in biocovers (Scheutz et al., 2009). These two factors could lead to an increase in the temperature of covers to more than 50°C in the summer, which means no bacterial activities and therefore no oxidation in the biocovers (Zeiss, 2006). Furthermore, the temperature increase in turn leads to a higher evaporation rate in the covers (Maurice and Lagerkvist, 2003) and causes positional changes in the degree of saturation of the soil over the cover profile (Moghbel and Fall, 2011). The above mentioned changes due to the temperature are more significant in the surface layers of biocovers, which are exposed to environmental conditions (Ait-Benichou et al.,

2009). Thus, the thickness of a cover affects its effectiveness, as the oxidation of CH₄ gas is reduced, and this means lower efficiency of the cover (Moghbel and Fall, 2011). Hence, whether it is to design a biocover or maintain an existing highly efficient biocover, it is critical to be able to predict and control the temperature changes in the profile of the biocover during its service life (Chandrakanthi et al., 2005).

Biocover behavior is more crucial for landfills located in cold regions. In these localities, temperatures are lower than 0°C for long periods of time throughout the year (Phillips and Newlands, 2011; Henry, 2007) and the cover remains under permafrost for a long time (Rykaart and Hockley, 2009). Soil thermal properties are resultant of several parameters, including density, type of mineral material available, water content, soil structure, salt concentration and the percentage of organic material available in the porous material, all of which are significant (Abu-Hamdeh and Reeder, 2000; Singh and Devid, 2000; Côté and Konrad, 2005). Due to regular changes that take place in the aforementioned geotechnical properties (e.g. soil structure and porosity) under FTCs in the soil material (Qi et al., 2006) and the subsequent changes in thermal properties of the soil material (Farouki, 1981), the thermal properties of compost biocovers might be impacted as well.

To predict the temperature profile through biocovers in order to assess the associated microbial activities and therefore biocover performance, studies on mass and heat transfer are mandatory (Chandrakanthi et al., 2005), thus the thermal conductivity and thermal diffusivity of the biocover material are prerequisite elements (Chandrakanthi et al., 2005). Thermal conductivity and thermal diffusivity are two main parameters that have been used in heat transfer analysis (Hanson et al., 2000). Among the studies which have investigated the thermal properties of organic soils, most of them have focused on the

thermal conductivity of peat, and thermal conductivity of compost material is seldom mentioned. One of the few cases is a study by Chandrakanthi et al. (2005) who conducted a survey on the relationship between the degree of saturation and the thermal conductivity of compost. As previously pointed out, the thermal properties of the compost biocover material of biocovers that are located in cold regions are susceptible to changes under FTCs. However, there is no study in the literature that has addressed the thermal properties of compost biocovers under FTCs. Therefore, the current research aims are to first, investigate the impact of FTCs on the thermal conductivity and thermal diffusivity of compost biocovers, and secondly, to develop an empirical formula that can predict the thermal conductivity of biocovers subjected to FTCs.

3.2. Materials

The materials used are compost and water.

3.2.1. Compost Material

The compost material was collected from the Moose Creek landfill compost facility in Ontario, which is operated by Lafleche Environmental Inc. The specific gravity of the compost was determined to be 2008 in accordance with ASTM D854. The Atterberg limits were determined in accordance with ASTM D4318-10. The results revealed that the liquid limit (LL) of the compost materials is roughly 75%. A similar result was reported by Bajwa and Fall (2011) and Bajwa (2012), which was about 88% for the LL. The plastic limit determination method could not be followed due to the nature of the compost material. The reason could be the small pieces of wood which were in the

compost biocover material. They made it impossible to conduct the plastic limit test. The organic content measurement of the compost biocover material was determined in accordance with ASTM D2974-07a to be equal to 22%. The grain size distribution test was conducted on the compost material in accordance with ASTM D6913 - 04(2009). The result is illustrated in Figure 3-1.

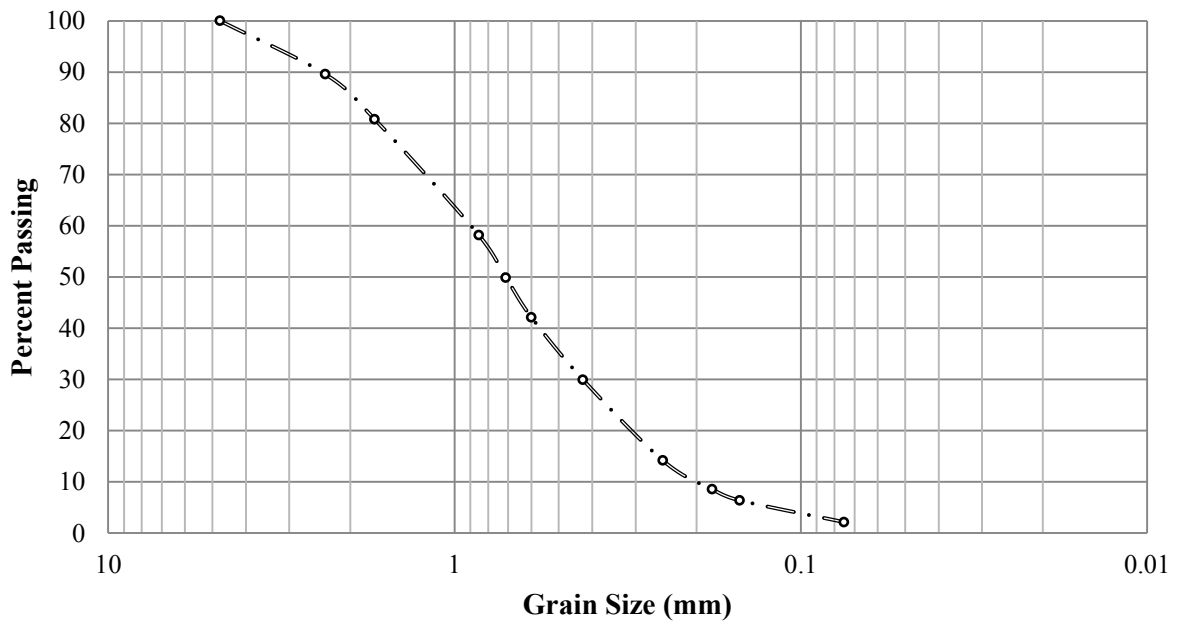


Figure 3-1 Grain size distribution of the compost biocover

3.2.2. Water

Distilled water used to mix with compost for the purpose of this study.

3.3. Experimental Methods

3.3.1. Sample Preparation and Experimental Procedure

The wet compost with an initial water content of 73% was first dried for approximately four days in an oven. The oven temperature was kept at 70°C, based on the suggestion of Moo-Young and Zimmie (1996), to prevent evaporation of the organic substances. The

dried material was left in a sealed plastic bag container for two weeks to reach thermal equilibrium. To prepare the samples, sufficient gravimetric water content was added and then mixed well with the dry compost. The samples were then kept in sealed and closed bags for a few days for the purpose of homogenous water distribution.

The mixture was then compacted to desirable dry densities by following a compaction procedure (see Section 3.2). Then, each sample was submitted to FTCs. After each FTC, the thermal conductivity and diffusivity of the compost biocover material were determined. Moreover, the volume change of the material was measured before and after each FTC by using a dial gauge. Finally, after completing all nine FTCs, the grain size distribution of the compost material was determined per ASTM D6913 - 04(2009).

3.3.2. Compaction Test

Proctor tests on samples before they were subjected to FTCs were performed in accordance with ASTM D698-07. The compaction tests were performed from the dry side of the compaction curve to the wet side. To conduct testing on the thermal properties of the compost material in a wide range of water contents, six water contents, including 22%, 32%, 42%, 55%, 65% and 72%, were chosen. Three trials were conducted for each of the water contents to assure the repeatability of the tests. Figure 3-2 shows the compaction curve of the compost material before being subjected to FTCs. The water contents are plotted against the dry densities. The optimum moisture content (OMC) of the compost material was found to be equal to 42% with a corresponding maximum dry unit weight of 8.74 kN/m³.

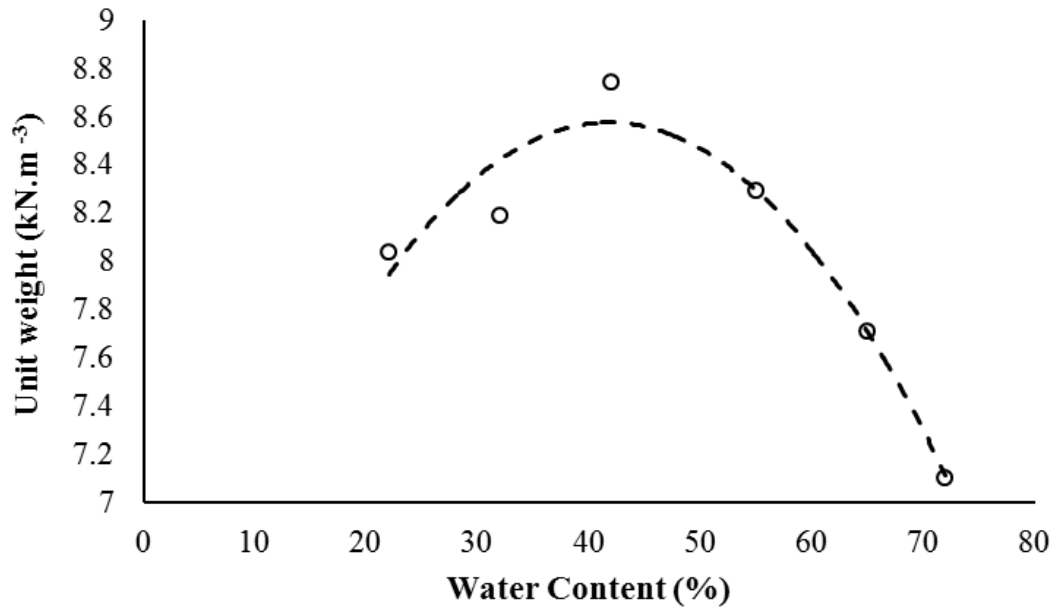


Figure 3-2 Compaction curve of the compost biocover

3.3.3. Freeze-Thaw Cycles (FTC)

To investigate the impact of freeze-thaw conditions on the thermal properties of compost biocovers, the samples were exposed to FTCs. The temperature -12°C and room temperature (23°C) were selected as the freezing and thawing temperatures, respectively. The aforementioned freezing temperature was chosen based on the statistical climate data of Ontario, Canada (Environment Canada, 2011). Also, other researchers (e.g., Konrad and Samson, 2000) applied the same temperature to study the effect of FTCs on the geotechnical properties of soils. To control the deviation of temperature throughout the freezing period in the freezer, a temperature controller with an accuracy of $\pm 1^{\circ}\text{C}$ was utilized. In the current study, nine FTCs were considered. To choose the number of FTCs in the experiment, two facts were taken into consideration. First, Henry (2007) mentioned that most of the studies that have investigated the impact of FTCs on soil behaviour have not exceeded 5 FTCs. Moreover, it is known that the

number of FTCs that would impact soil particle's stability is between 3 to 9 (Oztas and Fayetorbay, 2003; Hanson, 2007).

The ASTM D 6035-96 was followed during the freeze-thaw stress application. The required time for each specimen to accomplish freezing or undergo the thawing process and meet the threshold temperatures at known rates of temperature alterations was obtained by providing a control sample. This sample has the same geometry, water content and bulk density as the ones to be tested in the experiment. By inserting the sensor needles into the center of the specimen, the required time for each of the processes were obtained (Celestin and Fall, 2008). The average time needed for the samples to freeze from 23°C to -12°C was about 12 hours (Figure 3-3). Moreover, for the samples to thaw and revert back to room temperature, a period of 220 minutes (3.6 hours; Figure 3-3) was needed. However, throughout the experiment, the specimens were kept for one complete day in the freezer for each FTC in order for a uniform methodology (Celestin and Fall, 2008). Figure 3-3 illustrates the temperature evolution with time.

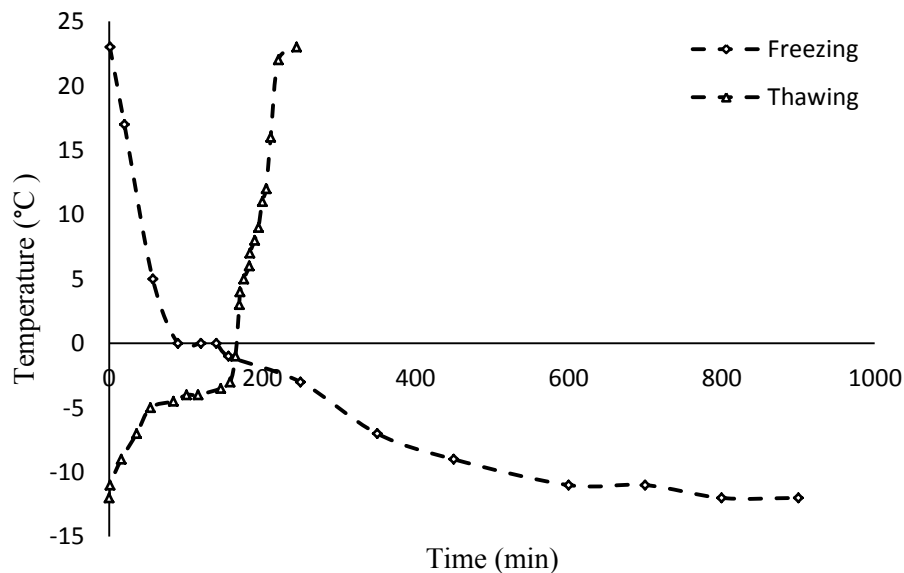


Figure 3-3 Freezing and thawing processes

3.3.4. Monitoring of the sample heave/ settlement

To monitor the height change of the samples versus FTC, a dial gauge was installed on the top of the samples. The accuracy of the measurement was 0.01 cm. Each measurement was repeated for at least five points on the surface of the sample with double duplication. The value that was reported is the average of the aforementioned readings. By using the obtained values of height changes versus FTC and the assumption that no significant lateral changes occurred throughout the experiment, the volume changes of the samples were calculated.

3.3.5. Thermal Properties Measurement

The thermal conductivity and diffusivity of the compost biocover were determined via Sh1 probes of a KD2 device. Both needles of the Sh1 probes were carefully inserted into the compost material and then the KD2 device started to record. Approximately 3 minutes was needed to carry out each reading. The aforementioned device utilizes the transient heat transfer method for the measurement of the thermal properties of porous material. The precision of the measurements is about 5% (KD2 Pro Operator's Manual, 2006). For the purpose of reliability and regeneration of the results, each test was repeated for a minimum of three times.

3.4. Experimental Results and Discussions

3.4.1. Thermal conductivity

3.4.1.1. Evolution of the Thermal Conductivity with the Compaction degree

In Figure 3-4, the coupled impact of dry density and water content on the thermal conductivity of compost biocover is presented. It can be seen that as the water content

increases from the dry side to the optimum water content, there is a sharp rise in the thermal conductivity. Beyond the OMC, an increase in water content only leads to a mild increase in the thermal conductivity. The reason for this behaviour is the fact that when the compost has the lowest water content on the dry side of the compaction curve, water films have a thickness only equal to a few water molecules (Nakshabandi and Kohnke, 1965). These thin water films are not able to connect solid particles and make a continuous environment nor fill the voids between particles (Nakshabandi and Kohnke, 1965; Becker et al., 1992). In this case, any increase in water content contributes to the formation of more and thicker water films and consequently, increasing contact area between compost particles (Abu-hamdeh and Reeder, 2000; Becker et al., 1992). This would form a more uniform and continuous environment with less air voids. Air voids mostly perform as an isolator (air is a poor conductor) through heat transfer in material (Chandrakanthi et al., 2005) due to the lower thermal conductivity of air in comparison to water and solid particles (Coté and Konrad, 2005). In a nutshell, the mentioned increment in the contact area of the soil particles and formation of a uniform heat transfer environment contribute to better heat transfer (Becker et al., 1992). This phenomenon leads to a rapid increase in the thermal conductivity of compost biocovers before OMC. This behaviour was seen in samples up to 55% water content; however, beyond that, only a slight increase in thermal conductivity was observed. This could be attributed to the fact that after 55% water content, the water molecules already occupied the free voids between the compost particles and the addition of water to the compost leads to small changes in the degree of saturation and therefore slightly increases the thermal conductivity (Fricke et al., 1997).

Moreover, another compaction induced influencing factor of thermal conductivity is bulk density (Nakshabandi and Kohnke, 1965; Hanson, 2000). As the compaction degree increases, so does the bulk density. A higher bulk density leads to increment in the contact area of the compost particles and therefore an increase in the soil thermal conductivity (Nakshabandi and Kohnke, 1965).

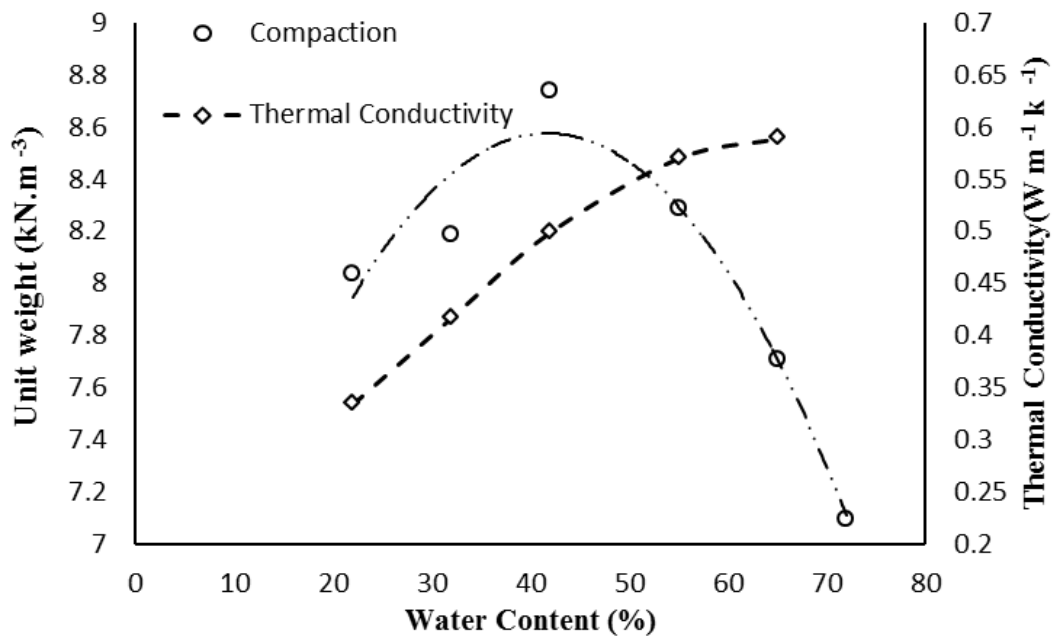


Figure 3-4 Coupled Impact of Water Content and Dry Density on Thermal Conductivity

3.4.1.2. Effect of Freeze-thaw Cycles on the Thermal Conductivity

The Figure 3-5 depicts the thermal conductivity of compost biocover samples with five different water contents plotted against a number of FTCs. Under room temperature, thermal conductivities of 0.334, 0.417, 0.499, 0.570 and 0.589 $W.(m^{-1}.K^{-1})$ were measured for water contents of 22%, 32%, 42%, 55% and 65%, respectively. Then, the

general trend of the thermal conductivity decreases while the compost samples experience FTCs. In addition, a significant drop in the thermal conductivity of the compost material in the first two cycles is evident. In the FTCs that followed, the trend gradually decreases or is almost constant. After the first two FTCs, thermal conductivity values of 0.292, 0.352, 0.428, 0.473 and 0.514 $W.(m^{-1}.K^{-1})$ were obtained for the aforementioned water contents respectively. The combined effect of the following, which will be discussed in Section 3.4, is responsible for this behaviour: (i) FTC induced volume change, (ii) FTC induced reduction in the grain size of the compost biocover; and (iii) crack formation under freeze-thaw conditions.

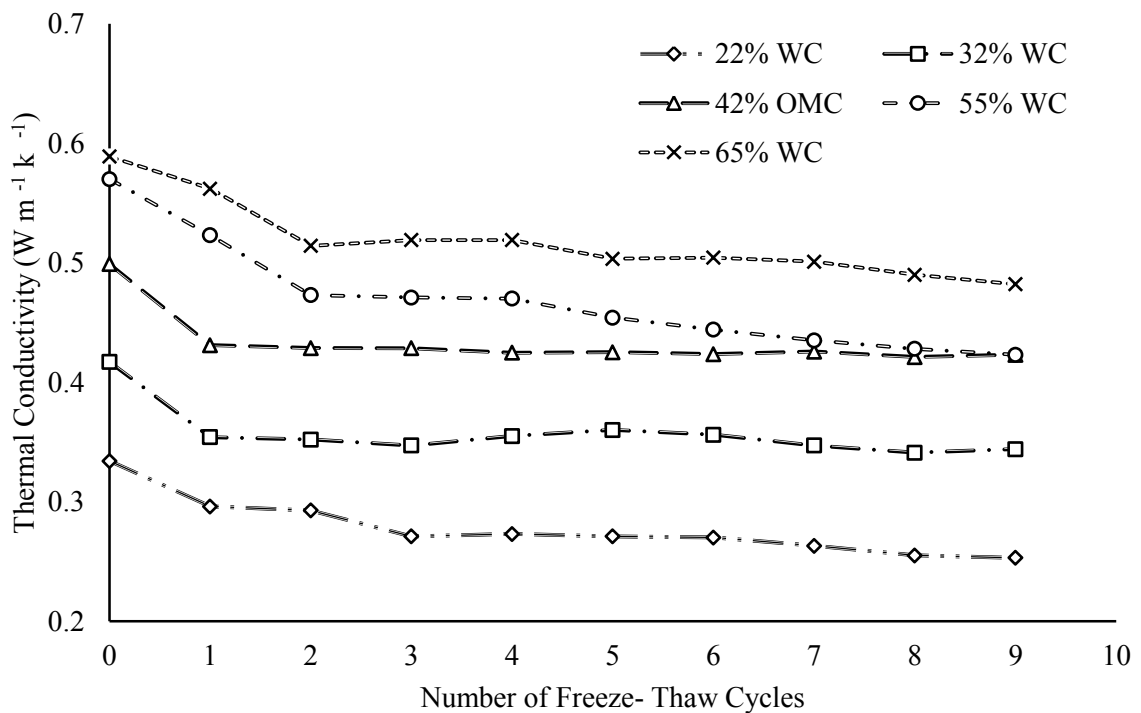


Figure 3-5 Thermal conductivity versus number of FTC

In Figure 3-6, the blue columns represent the total changes in the thermal conductivity of the samples after experiencing nine complete FTCs. As it can be seen, for the samples

with water contents of 22%, 32%, 42% (OMC), 55% and 65%, the thermal conductivity declines by 24.0%, 17.5%, 15.0%, 25.7% and 18.1 % after experiencing nine complete FTCs. These data suggest that the samples on the wet and dry side of the compaction curve show similar changes in thermal conductivity after nine FTCs. The lowest changes in thermal conductivity occur in samples with OMC (42% WC) and the highest dry density. Moreover, Figure 3-6 shows that the first two FTCs have greater influence on the thermal conductivity changes under freeze-thaw circumstances. The red columns, which represent the contribution of the first two FTCs for the total changes in thermal conductivity, show that their contribution to the total changes in the thermal conductivity for samples with water contents of 22%, 32%, 42%, 55% and 65% are approximately 51%, 89%, 92.5 %, 66% and 70%, respectively. Consequently, this demonstrates that the contribution of the remaining FTCs are 49%, 11% ,7.5%, 34% and 30% for samples with water contents of 22%, 32%, 42%, 55% and 65%, respectively. This is in total agreement with the outcome presented in Figure 3-5 which depicts that the initial FTCs have higher impacts than the remaining FTCs in terms of thermal conductivity changes.

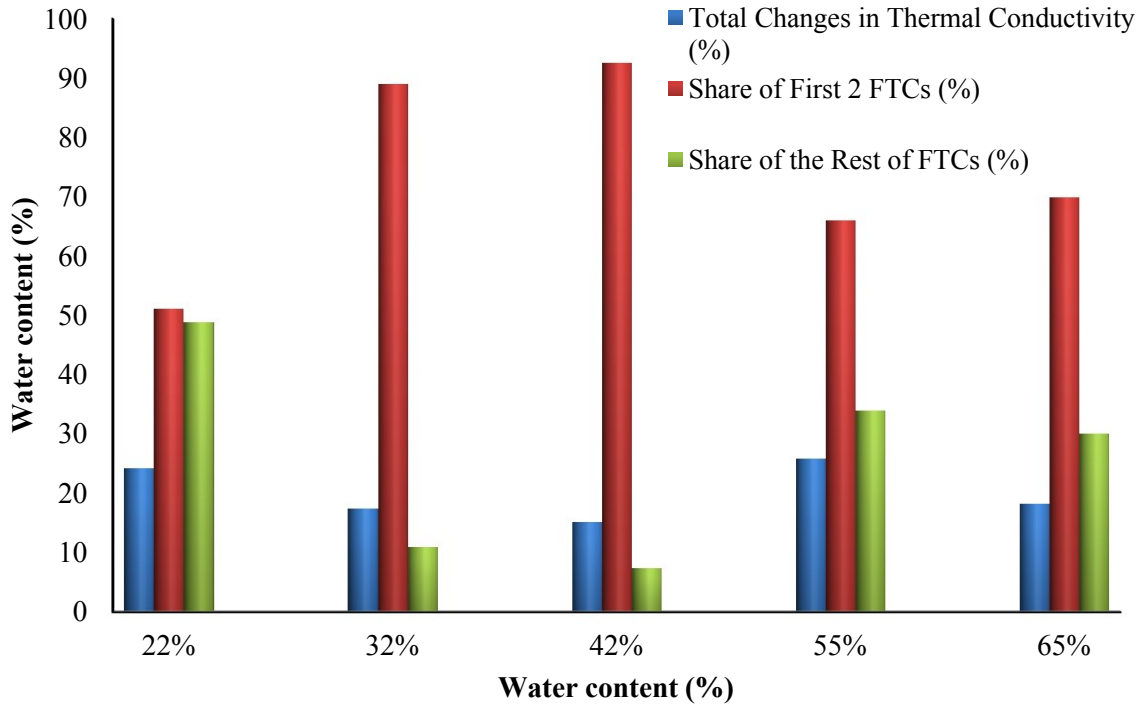


Figure 3-6 Contribution of early FTCs on thermal conductivity changes in comparison to both remaining FTC and all the FTC

3.4.1.3. Thermal Conductivity and Saturation Degree under FTC

Figure 3-7 shows the thermal conductivity of the compost biocover subjected to several FTCs versus the degree of saturation. Since the initial density of each sample prior to subjection to FTCs is known and a one dimensional volume change was also measured after undergoing each FTC, the degree of saturation can be easily calculated after each FTC. Furthermore, Equation (1) as suggested by Chandrakanthi et al. (2005), was used to describe the relationship between the water saturation degree of the compost and its thermal conductivity was used to predict the thermal conductivity of the samples subjected to FTC:

$$K = a + c\theta \quad [\text{Eqn.1}]$$

where K is the thermal conductivity, ϕ is the degree of saturation, and a and c are free parameters.

Figure 3-7 shows that as the degree of saturation of the compost biocover increases, so does the thermal conductivity. This is because as the degree of saturation increases, less air will be present in the compost, thereby increasing the thermal conductivity as previously explained. Moreover, from Figure 3-7, it can be noticed that Equation (1) can also predict relatively well the thermal conductivity of the compost in the first four FTCs. The equation for prediction accuracy is provided in Table 1. However, from Table 1, it can be observed that after four FTCs, the R^2 is lower than 0.9. In other words, thermal conductivity cannot be only explained by the degree of saturation and thus, there should be other additional factors or mechanisms responsible for the changes. Hence, it can be concluded that Equation (1) cannot be used to predict relatively well the thermal conductivity of compost subjected to more than four FTCs.

Table 3-1 Accuracy (R^2) of experimental results calculated using linear formula provided by Chandrakanthi et al. (2005) prior to FTC and after each FTCs

| Number of FTCs | R^2 |
|----------------|-------|
| 0 | 0.93 |
| 1 | 0.967 |
| 2 | 0.914 |
| 3 | 0.903 |
| 4 | 0.912 |
| 5 | 0.876 |
| 6 | 0.86 |
| 7 | 0.831 |
| 8 | 0.823 |
| 9 | 0.797 |

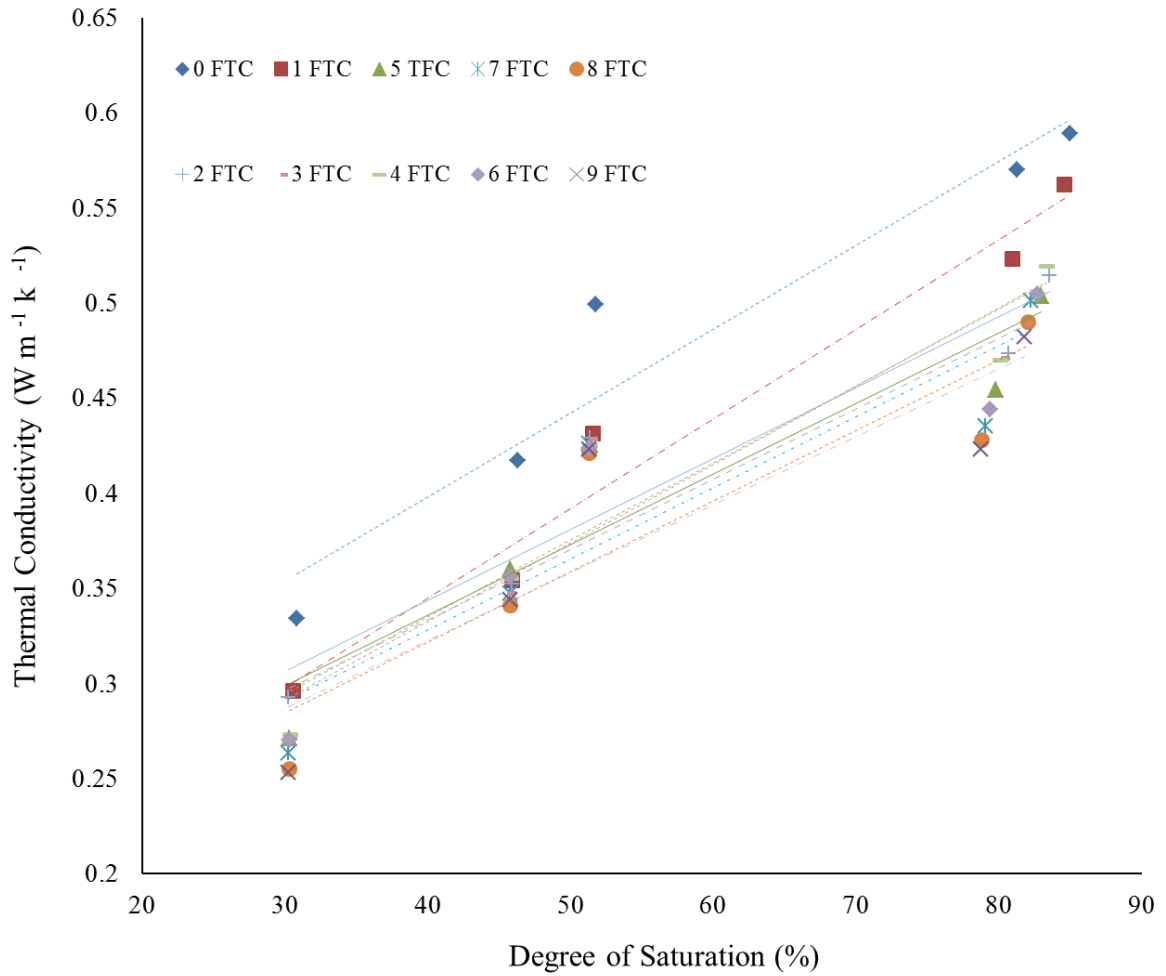


Figure 3-7 Relation of Thermal conductivity and degree of saturation under freeze-thaw condition

3.4.1.4. Mechanisms responsible of FTC induced Changes of Thermal Conductivity of Compost Biocover

The combined effects of the mechanisms described below are responsible of the changes in thermal conductivity induced by FTC.

3.4.1.4.1. Volume Change of Compost Biocover under FTC

Figure 3-8 shows the volume change behaviour of the compost biocover versus FTC found in the present study. Heave and settlement in the soil specimens affect the degree of saturation of the samples. The total volume of the samples increases with an increase in the number of FTCs; this means that with an increase in the total number of FTCs, generally, the soil bulk volume and porosity increase while its bulk density decreases, thus leading to a lower degree of saturation in the compost biocover (Singh and Devid, 2000). This reduction in soil bulk density has also been observed by Unger (1991) in agricultural soils during winter and described in terms of the impacts of FTCs on the soil structure.

Moreover, the dependence of volume change on the number of FTCs is more pronounced in the initial FTC than the FTCs that follow. The final volume change of the compost biocover for the specimens with water contents of 22%, 32%, 42% 55% and 65% are 1.04%, 0.66%, 0.55%, 1.88% and 2.40%, respectively after exposure to 9 complete FTCs. In the compost samples with lower water contents than OMC, the first two or three FTCs contribute to the maximum volume change. Not surprisingly, similar to Figure 3-5, the share of the first two FTCs on the volume change of the compost biocover are approximately about 52%, 89% and 96% for the samples with a water content of 22%, 32% and 42%, respectively. The overall trend of the volume change of the samples increases to the maximum value at the 2nd or 3rd cycle, and after that, the samples roughly show an overall constant trend in data. In addition, the minimum variation of volume change occurs in samples with OMC (42%). Therefore, it can be concluded that environmental conditions (e.g. ambient temperatures in cold regions) might have the

lowest effect on volume change and thermal properties (thermal conductivity) of compost biocover materials which are compacted at maximum dry density and corresponding OMC.

When the water content in the samples is higher than the OMC, the trend of the volume change follows a different pattern. Due to a higher degree of saturation, water fills more of the pores in comparison to the samples located on the dry side of the compaction curve. During the freezing process, the water in the voids starts to freeze. More ice lens formation and less free space in the voids lead to higher volume changes in higher degrees of saturation. Hence, this leads to more variation in the structure and location of the soil particles (Viklander, 1998b) compared with the compost biocover samples that have a lower degree of saturation. Moreover, the soil structure changes weaken the bonding at soil particle contact (Qi et. al, 2006; Henry, 2007), and decreases the compost or soil thermal conductivity (Becker et al., 1992). This can be explained by considering the void ratio; a smooth increase in the void ratio will confine heat transfer throughout the porous material (per a current study of compost biocovers) (Singh and Devid, 2000). In cases of low degrees of saturation (22% and 32% water contents), throughout the formation of the ice lenses, the volume of the available water in the pores increases; however, due to the availability of more free volume (air voids), the total increase in the volume of water stops when the available air voids found in the pores after the initial cycles are pushed out. This leads to a smaller total volume change in the sample. The highest volume changes observed at the highest degree of saturation could be attributed to the above reason. Moreover, this pressure from the ice lenses to the compost particles not only may change the structure of the compost and location of the particles, but also affect

the grain size of the compost biocover due to the pressure applied onto the particles through the heaving process and/or thermal loading. This issue will be addressed in the following section.

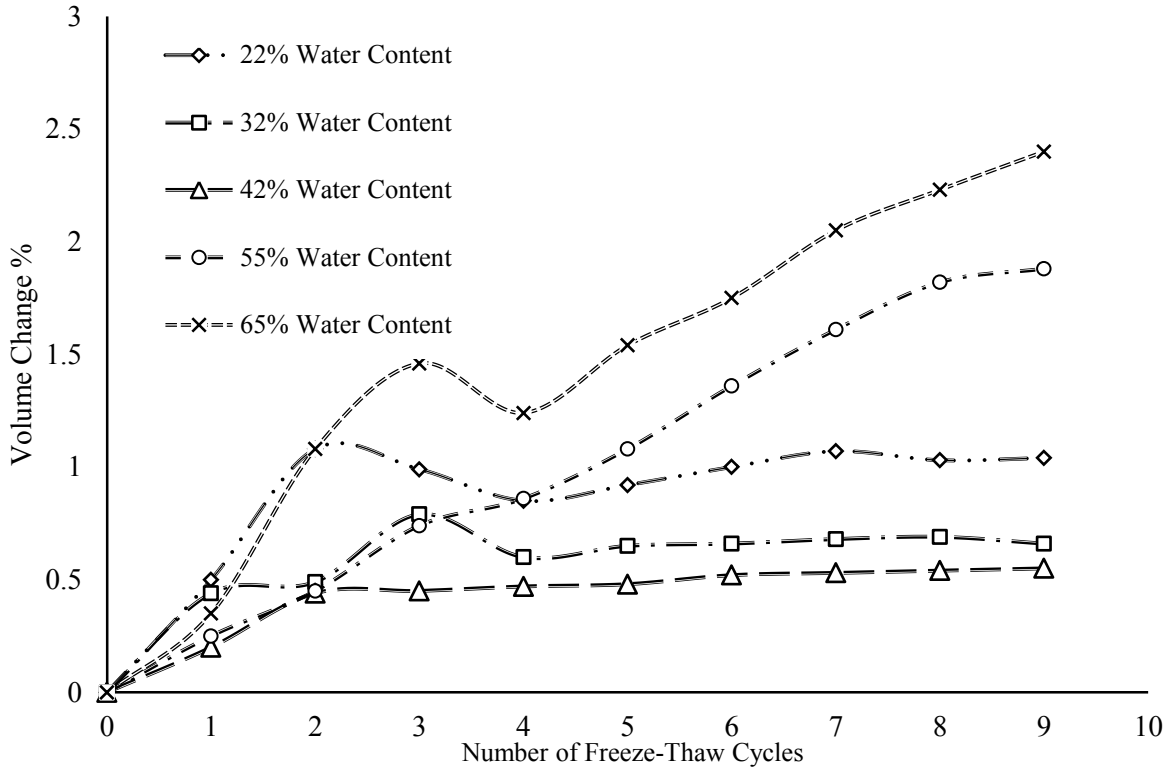


Figure 3-8 Volume change versus FTC

3.4.1.4.2. Grain Size of Compost Biocover under FTC

Figure 3-9 presents the grain size of the compost biocover after 0 and 9 FTCs, respectively. It can be observed that after experiencing a total of 9 FTCs, the average size of the compost particles decreases. The reduction of the grain size of the compost is considered as a second contributor to thermal conductivity decrease under FTCs. This can be attributed to the fact that compost material contains many organic particles (e.g. wood chips) which have the potential of breaking and changing into smaller particles. It is known that the effect of FTCs on macro-aggregates is greater than on micro-aggregates

(Six et al., 2004). That could be the reason that bigger particles (fibrous organics) break down into finer particles and the average of the grain size of the compost biocover becomes finer. Also, thermal conductivity had been correlated to the grain size distribution of soil (Nakshabandi and Kohnke, 1965). Even though the effect of soil particle size on the thermal properties of the soil material is less than the impact of the water content, it cannot be neglected (Nakshabandi and Kohnke, 1965). Due to the existence of a “structural skeleton” in fibrous organic material, they have a higher thermal conductivity in comparison to that which originate in sedimentary organic soils (Hanson et al., 2000). Through FTCs and associated aggregate abruption, these structural skeleton in fibrous organic material might be destroyed. Hence, finer particles cause lower thermal conductivity of soil (Nakshabandi and Kohnke, 1965; Abu-hamdeh and Reeder, 2000).

As the number of FTCs increase, the particle size decreases. This means that for the same porosity, more particles are needed when the soil has finer particles (Abu-hamdeh and Reeder, 2000). This can be attributed to resistance in heat transfer which leads to a reduction in the thermal conductivity of a compost biocover under FTCs. The rapid reduction in the first two or three FTCs can be mostly explained by the first factor, which is volume change. However, the gradual reduction of thermal conductivity in the cycles that followed can be attributed to the grain size.

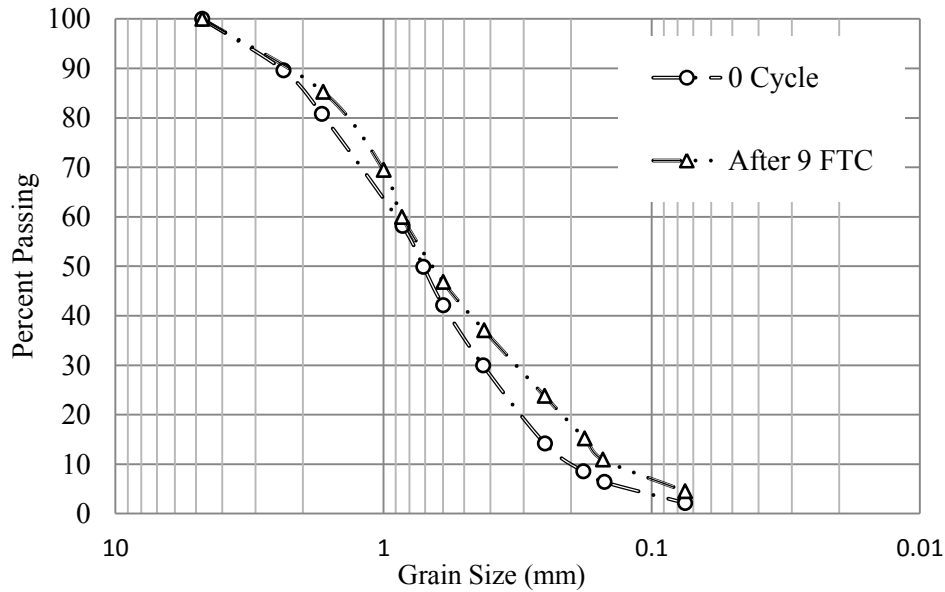


Figure 3-9 Grain Size Distribution versus FTC

3.4.1.4.3. Surface Crack Formation

The third influential factor is crack formation or surface geometry change at the surface of the compost cover material. From the experiment, it was observed that (Figure 3-10) in rare cases, cracks (surface change) visible to the naked eye formed on the top of the compost material samples along the organic fibers. However, very narrow cracks were more common. Similar observations were made in previous studies on soils subjected to FTCs. For example, studies by Chamberlain and Gow (1979), Viklander (1998a) and Konrad and Samson (2000) discussed that latitudinal or longitudinal cracks or both form in freeze-thaw conditions in soil material. This behavior could be attributed to the formation of ice lenses through the soil matrix which leads to the separation of the soil layers or crack formation (Viklander, 1998a).

The observed cracks in the compost could create gaps or voids between the compost particles. These gaps will behave as an isolator in the heat transfer process, thereby reducing the thermal conductivity of the compost material.



Figure 3-10 Surface change along with organic fibers at the surface of the material

3.4.1.5. Empirical analysis of the alteration of thermal conductivity of compost biocover under FTC

To explain the quantitative impact of FTCs in the current research, a normalized approach to thermal conductivity is chosen. First, all the experimental data obtained were categorized into two groups. An empirical formula was proposed based on the first group of data. Then, the second group of data was used for the purpose of validating the proposed equation. The first group of data comprised the results of the thermal conductivity of the samples with water contents of 22%, 42% and 65% after experiencing several FTCs, while the second group of data comprised the thermal conductivity of the compost biocover samples with water contents of 32% and 55%, respectively, as well as thermal conductivity data from the column experiments presented in the following chapter.

In this part of the study, to capture the effect of FTCs on the thermal conductivity, thermal conductivity is defined as follows:

$$f(T_N) = f(0) \times f_{Effect\ of\ FTC}(N) \quad [2]$$

where $f(T_N)$ is the thermal conductivity of the compost biocover at FTC number N , $f(0)$ is the thermal conductivity of the compost biocover at 0 cycle, $f_{Effect\ of\ FTC}(N)$ is the coefficient that takes into account the impact of FTCs at cycle number N , and N is the number of FTCs that the sample will experience. As previously mentioned, $f(0)$ could be any thermal conductivity prediction model which is able to model the thermal conductivity of the compost material. In this paper, the second term of Equation (2), which is defined to consider the impact of FTCs on thermal conductivity, will be studied and discussed.

To capture the quantitative impact of FTCs on the thermal conductivity of the compost biocover, the normalized thermal conductivity (N.T.C) of the compost material of the first group of data was utilized. The N.T.C. at each FTC was calculated as the thermal conductivity of the sample in the aforementioned FTC divided by the thermal conductivity of the sample with the same water content prior to undergoing an FTC. In Figure 3-11, the N.T.C. of the compost biocover material is shown. The vertical axis is the N.T.C. The horizontal axis shows the number of FTCs that the specimens have undergone. The blue line is one of the best fitting curves to the first group of data.

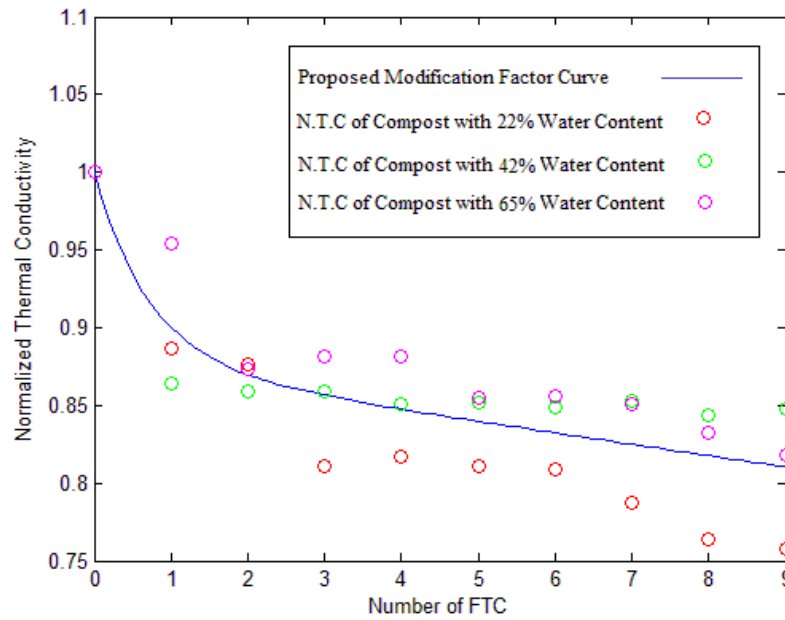


Figure 3-11 Normalized thermal conductivity vs. FTC

The equation for the fitting curve is calculated as Eq. 3:

$$f_{Effect\ of\ FTC}(N) = a \times e^{b \times N} + c \times e^{d \times N} \quad [3]$$

whereas a , b , c and d are fitting parameters and N is the number of freeze-thaw cycles.

The quantitative values for a , b , c and d are calculated as follows:

$$a = 0.1225$$

$$b = -1.397$$

$$c = 0.8776$$

$$d = -0.008848$$

In Figure 3-12, the proposed empirical equation is plotted in blue color. A deviation of plus and minus 9% is presented via two red lines at the top and bottom of the corresponding equation line. Also, to demonstrate the precision of the proposed coefficient (Equation 3), the normalized values of the second group of data are plotted in

Figure 3-12. As can be concluded, the trend of the behaviour of the compost biocover (measured data) agrees well with the proposed empirical equation. The average deviation is approximately 7% in all of the cycles with a maximum deviation of roughly 9% in only the 9th cycle.

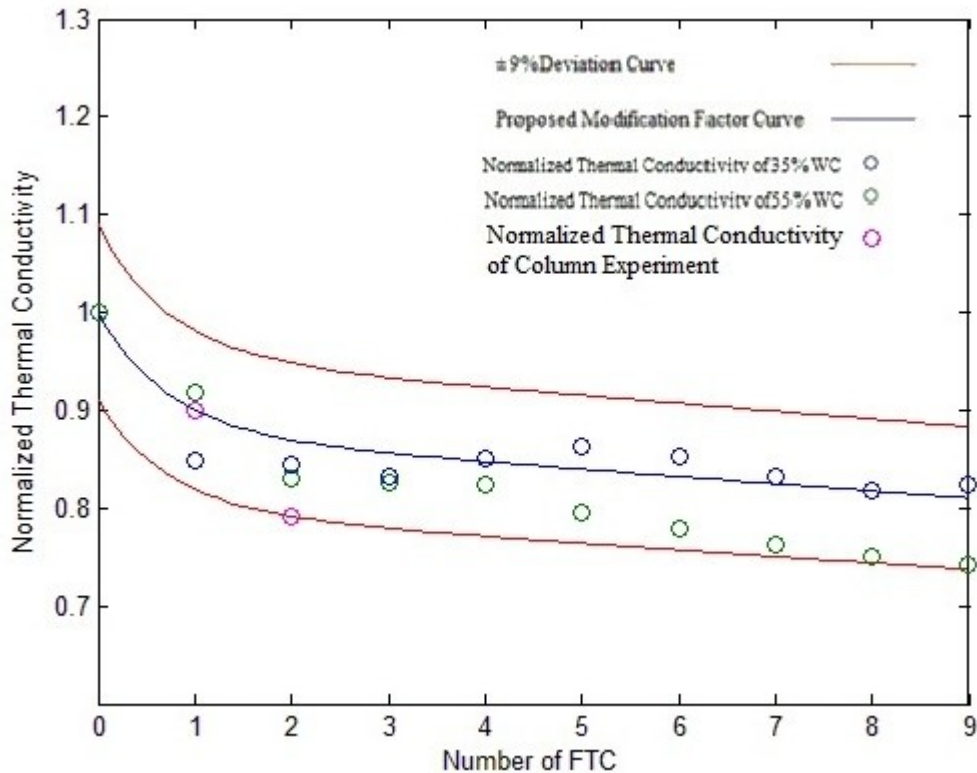


Figure 3-12 Validation of coefficient of impact of FTC on thermal conductivity of compost biocover

3.4.2. Thermal Diffusivity of Compost Biocover under FTC

Figure 3-13 plots the thermal diffusivity of the compost biocover against the number of FTCs. However, the variation in the thermal diffusivity does not follow the exact pattern that was previously seen in the thermal conductivity. There is a general decreasing trend of the thermal diffusivity as the number of FTCs increase. This behavior can be interpreted based on the factors previously explained. The aforementioned factors cause

increases in the porosity and therefore a greater portion of air volume in the porous material, which consequently affects the thermal diffusivity. Not surprisingly, the overall trend of the thermal diffusivity behavior of a material is mostly consistent with the thermal conductivity of the material (Nakshabandi and Kohnke, 1965) and can be explained by similar physical mechanisms (Ochsner et al., 2001). As such, it was pointed out by Nakshabandi and Kohnke (1965) that in the same material with a constant water content, a lower thermal diffusivity can be obtained by a finer texture soil. As shown in Figure 3-13, the maximum thermal diffusivity occurs at OMC. At OMC, the biocover material has maximum dry density and the lowest porosity; thus thermal diffusivity is at a maximum. Moreover, the change in the thermal diffusivity for the sample at OMC is roughly 37%; however, more than 50% of the change took place in the first two FTCs. It is not a coincidence that this behaviour is similar to the volume change of the compost material under FTCs, in which most of the heave occurred in the first 2 cycles.

Also, from the literature (Ochsner et al., 2001), it has been indicated that porosity and portion of air volume are the most important parameters for the thermal diffusivity of soil. This also helps to interpret the higher values of thermal diffusivity for samples with a water content of 55% and 65% in comparison to those with 22% and 32%. Besides that, maximum variation occurred in the samples with the same water content. Greater volume changes in the aforementioned samples with high water content (See Section 4.1.4.1) led to higher increments in porosity and consequently, significant decreases in the thermal diffusivity.

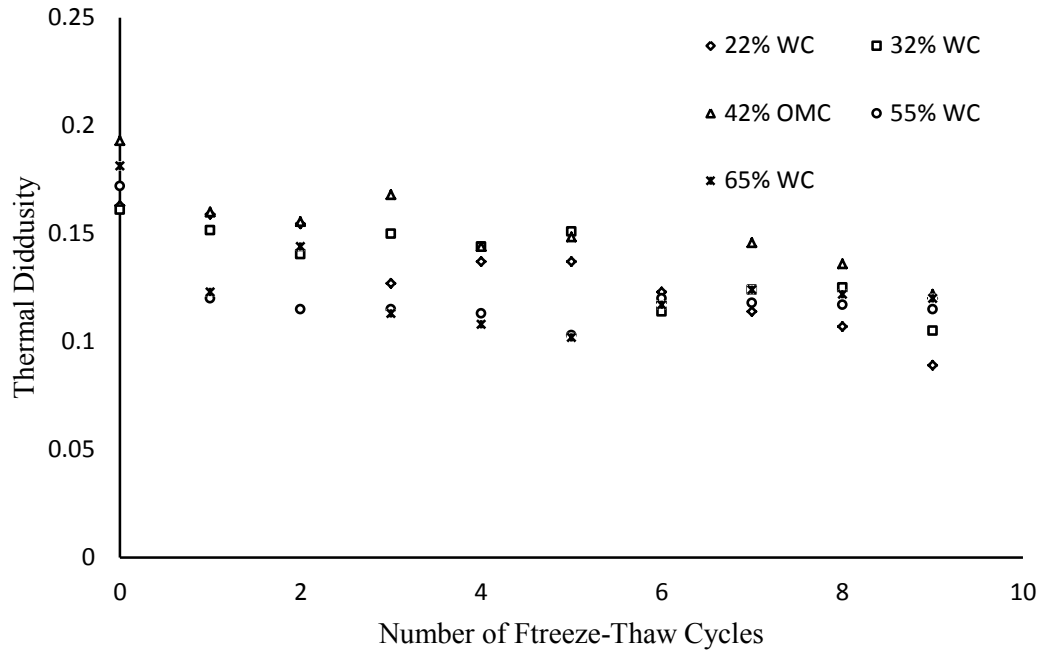


Figure 3-13 Thermal diffusivity vs. number of FTCs of compost biocover

3.5. Conclusion

The thermal properties of compost biocover material are measured prior and after undergoing FTCs. Prior to undergoing FTC, the water content and bulk density are recognized as effective parameters for the thermal conductivity of the compost biocover. Also, a linear relationship between the thermal conductivity of the compost biocover and degree of saturation under FTC has proven in the current study. Besides that, the impact of FTCs on the changes in the thermal properties of the biocover material is evident. It is found that the first two FTCs have the highest effect on the changes in the thermal properties of the landfill compost biocover. Also, it can be understood that the variation in the thermal conductivity and thermal diffusivity of the biocover which had been subjected to FTCs can be explained in terms of the volume change of the specimens, grain size and crack formation (surface changes) of the samples. The empirical predictive

equation that has been proposed in the present study can be utilized for heat transfer analyses of landfill biocovers located in cold regions. Also, based on the results of the variation in the thermal diffusivity of the compost material, it can be concluded that when the compost biocover material undergoes FTCs, this leads to a longer time for heat transfer through the biocover. Hence, based on the results of the current study, the overall thermal diffusivity of compost biocovers decreases as they experience more winters. Consequently, it will take more time for biocovers to be able to react to thermal gradients. This would be desirable for biocovers in the summer, when there are different sources of heat and increase of temperature to over 50°C.

Acknowledgement

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Chapter 4

Geotechnical Behaviour and Methane Oxidation Capacity of Compost Biocover Columns Subjected to Freeze-thaw Cycles

Abstract

In the present paper, the effects of freeze-thaw cycles (FTCs) on the geotechnical (thermal, hydraulic, mechanical) properties and the methane oxidation capacity (biochemical factors) of compost based biocovers are investigated by column experiments. In the utilizing of column experiments, three columns are developed, manufactured, prepared and treated by a period of methane injection (0 FTC), after 1 FTC and 2 FTCs, in three respective stages. One column is instrumented with various sensors to monitor the evolution of temperature, volumetric water content, settlement and gas content at four different depths for one of the columns (i.e. -5, -15, -25, -35 cm). In addition, extensive laboratory testing is carried out on the biocover samples with regards to their thermal, hydraulic, and mechanical and physical properties. Methane gas is injected into all of the columns.

The results show freeze-thaw induced changes in a number of the THMBC properties of the biocover. As for mechanical factors, the settlement rate and the average grain size of the compost surface decrease throughout the stages while the shear strength increases. Hydraulic conductivity decreases except in the top layer after applying the FTC. The average temperature is recorded to be above the ambient temperature in all of the layers and stages. Moreover, in the lower layers of the columns (-30 to -40 cm), small yellow or white materials can be observed which are related with the formation of exopolymeric

substances (EPS) during the FTCs. This can be interpreted as a decrease in the overall performance of the biocover compost.

Overall, the performance of the biocover decreases by less than 20% under a series of FTCs despite considerable changes to the geotechnical and geo-environmental properties of the biocover. This suggests that the studied biocover solution can be utilized for mitigating the emission of landfill gases in freeze-thaw conditions.

4.1. Introduction

Global warming and its negative impacts on the planet have raised concerns about the effect of human activities in its acceleration. A major consequence of the activities that accounts for climate change is the release of greenhouse gases (GHGs), such as carbon dioxide (CO₂) and methane (CH₄). These gases have excessive capability of absorbing radiated infra-red, which prevents the planet from cooling down. Amongst them, CH₄ has been the subject of exclusive research as its contribution to global warming is around 25 times greater than that of CO₂ (IPCC, 2007). According to the IPCC (2001), the average concentration of CH₄ in the Earth's surface has sharply increased by 1.5 times higher during the last 250 years (compared to a 30% increase in CO₂ for the same period of time). While CH₄ contributes to 15% of all global warming (Lu et al., 2011), its impact will be even more substantial in the future (Themelis and Ulloa, 2007). One of the major CH₄ production sources is by waste sector landfills (Bogner et al., 2007). They are recognized as the fourth top anthropogenic source of CH₄ emission into the atmosphere (Lu et al., 2011). Perdikea and Hettiaratchi (2008) mentioned that 21% of the annual anthropogenic CH₄ emission in Canada and 39% in Beijing, China (BMCCAE, 2012) may be attributed to landfills. Recent studies show that CH₄ gas production from the

waste industries are considered as the second highest source of anthropogenic CH₄ emission in Europe and the US (Scheutz et al. 2011). Furthermore, landfills produce 30% and 34% of all anthropogenic CH₄ emissions in Europe and the US, respectively (Perdikea et al., 2008).

Gas collection systems are requisite in many countries (Ait-Benichou et al., 2009) in order to prevent or decrease the amount of LFG emissions into the atmosphere. However, these systems are not financially efficient (Ait-Benichou et al., 2009; Mor et al., 2006; Streese and Stegmann, 2003) in landfills that are small in size, old in age or located in cold regions (Zeiss, 2006), where the rate of LFG emissions is not sufficient for utilizing burning or energy recovery systems (Huber-Humer and Lechner, 2009). Moreover, as uncontrolled dumps or landfills with (temporary) inactive gas collection systems are also potential sources of LFG (Ait-Benichou et al., 2009), both fugitive and residual emissions may exist during the life time of a landfill (Roncato and Cabral, 2012). However, a green solution for preventing LFG escape is the utilization of biocovers. Biocovers are a type of landfill top cover which enhances the environmental circumstances for methanotroph bacteria which consume (i.e. oxidize) CH₄ during its escape from landfills (Huber-Humer, 2009). Several studies have demonstrated biocovers to be a promising technology for mitigating CH₄ emission from landfills (e.g. Roncato and Cabral, 2012; Chi et al., 2012; Zeiss, 2006). In order to provide the appropriate environmental circumstances for the mentioned bacteria, the biocover material should possess properties such as sufficient porosity, organic content and capacity to hold water (Kettunen et al., 2006). The presence of these properties have been observed in compost material and supported by field (e.g. Bogner et al., 2005; Azam, 2007) and laboratory studies (e.g. Yuan, 2006). Overall,

literature suggests that compost can be a suitable option for the biotic remediation of CH₄.

Numerous parameters affect the aerobic reaction in biocovers, behaviour of methanotroph bacteria and consequent performance of biocovers. Amongst them, geotechnical and biochemical factors are significant as explained below. The geotechnical factors include thermal (T) (e.g., temperature, thermal properties) (e.g., Borjesson and Svensson, 1997; Trotsenko and Khmelenina, 2005; Zeiss, 2006; Einola, et al., 2007), hydraulic (H) (e.g., degree of saturation, gas permeability, gas flow and diffusivity, water content, and water flow) (e.g., Dobbie and Smith, 1996; Christophersen et al., 2000), mechanical (M) (e.g., settlement and compaction behaviour, crack formation, strength) factors or properties.

Temperature factor pertains to the three heat sources that are by-products of aerobic CH₄ oxidation reaction (Scheutz et al., 2009) within biocovers, the outside environmental conditions (e.g. solar radiation and air temperature, winter temperatures) above landfill biocovers, and the biodegradation of waste material in the landfill beneath (Moghbel and Fall, 2012). Methanotroph bacteria need an optimum range of temperature for their best performance (Scheutz et al., 2009).

Existence of moisture (water content) is crucial for bio-reactions and microbial activities due to its ability to transfer nutrients to the biocover medium and eliminate bio-chemical reaction residuals (Scheutz et al., 2009). In addition, highly saturated biocovers slow down the transfer of gases within the biocovers and lower their efficiency. Nevertheless, these hydraulic factors are themselves influenced by thermal factors since higher temperatures may lead to the evaporation of water and reduce the degree of saturation

(Maurice and Lagerkvist, 2003). Variation in the degree of saturation affects biocover properties which are necessary for the bacteria to optimally perform.

Termed as biological and chemical (B-C) factors, the properties include several factors, such as the amount of necessary substances for the bacteria (e.g. O₂), and those harmful to their performance (e.g. NH₄⁺). Sharp reductions in the degree of saturation cause microbial stress in biocovers (Scheutz et al., 2009) and leads to a decrease in the performance of biocovers (Del Grosso et al., 2000; Dobbie and Smith, 1996).

The biological-chemical factors affect the mechanical (M) properties of biocovers by gradually changing their texture. This leads to biocover settlement (Huber-Humer et al., 2008) which reduces the pore air volume in the biocovers and consequently, their permeability against gases, or in other words, hydraulic factors (Bajwa and Fall, 2011).

As mentioned, the above factors affect each other recursively. The relationship between two factors is so that the initiation and progress of each directly affects and is affected by the other at the same time, thus forming a process termed as a *coupled process* (Jing and Feng, 2003). As for biocovers, the five factors (T, H, M, B-C) act within a series of coupled processes. Through biocovers, heat transfer (T), stress/deformation/settlement (M), gas/fluid flow (H) and bio-chemical reactions (B-C) occur and affect each other simultaneously. Thus, biocover behaviour cannot be understood unless the interactions of these interconnected geotechnical and geo-environmental parameters are examined. Accordingly, biocover behaviour can be described well in terms of the coupled thermal, hydraulic, mechanical, and biological and chemical (THMBC) behavior.

While the study of THMBC is a complex process due to its coupled nature, it will be more challenging when the studied landfills are located in cold regions. In such localities,

biocovers remain covered under snow or frozen for a long period of time (Rykaart and Hockley, 2009). Furthermore, biocovers will be subjected to freeze-thaw cycles. FTCs may alter many of the biocover soil properties, including thermal (Moghbel and Fall, 2012), hydraulic (Chamberlain and Gow, 1979; Zimmie and LaPlante, 1990) and mechanical properties (Qi et al., 2006), and microbial and bio-chemical behaviours (Sulkava and Huhta, 2003; Feng et al., 2007). Therefore, a comprehensive understanding of the evolution of the geotechnical (THM) and bio-chemical behaviour or properties (B-C) of biocovers under freeze-thaw conditions is necessary in order to design cost-effective biocover in cold regions.

There are a few studies that have investigated the performance of biocovers in cold regions (Borjesson and Svensson, 1997; Philopoulos et al., 2008). In many of them, only the CH₄ oxidation capacity of biocovers (bio-chemical behaviour) and primary performance properties (temperature and water content profile) as assets, were studied (Borjesson and Svensson, 1997; Zeiss, 2006). However, there is no study in the literature that addresses the effect of freeze-thaw cycles on the geotechnical response, the evolution of the THMC factors and the methane oxidation capacity of biocover. Therefore, the aim of the current study is to investigate the coupled evolution of the performance properties of compost biocovers (geotechnical, THMBC, methane oxidation), when subjected to FTCs. To achieve the aims of the current study, column experiments have been carried out.

4.2. Experimental Programs and Procedure

4.2.1 Materials

The materials used are compost, water and methane gas.

4.2.1.1. Compost

The compost material was collected from the composting facilities of the Moose Creek landfill located in Ontario (Canada) and operated by Lafleche Environmental Inc. The compost biocover material was absolutely odorless which shows the maturity of the material (Perdikea and Hettiaratchi, 2008).

The specific gravity of the compost biocover particles was determined in accordance with American Standard Testing Method (ASTM) D854 to be equal to 2008. The Atterberg limits were specified by following the procedure in ASTM D4318- 10. The liquid limit (LL) of the compost biocover material was determined to be 75%. Due to the nature of the compost material, the plastic limit (PL) of the compost biocover could not be determined. The existence of small wood particles in the compost biocover material might be the cause of the aforementioned problem. The organic content of the compost biocover material was determined to be equal to 26% according to ASTM D2974-07a. Moreover, the grain size distribution of the compost which is presented in Figure 4-1 was obtained by following the procedure in ASTM D6913 – 04 (2009). In addition, the pH of the original compost was determined to be 6.8 in accordance with ASTM D 4972 (2007).

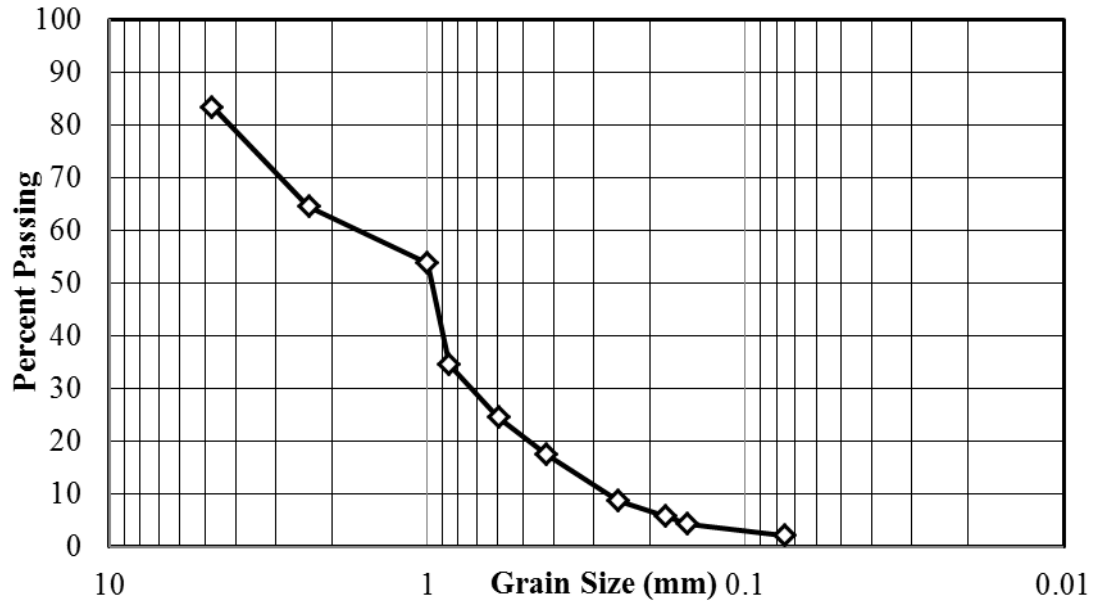


Figure 4-1 Grain size distribution of the compost material

In order to explore the portion of the minerals available in the compost, X-ray diffraction test was performed. The results displayed in Table 1 show that the main compost mineral available is quartz with an average of 24% in the samples. Other significant portions of minerals present are albite, calcite, orthoclase and muscovite, with a weight percentage of 17.2, 14.2, 11.8 and 7.8%, respectively.

Table 4-1 Summary of Semi- quantitative X-Ray diffraction analysis (material compositions)

| Mineral | Average Weight Percentage |
|--------------|---------------------------|
| Quartz | 24.0 |
| Albite | 17.2 |
| Calcite | 14.2 |
| Orthoclase | 11.8 |
| Muscovite | 7.8 |
| Chlorapatite | 4.3 |
| Hedenbergite | 3.7 |
| Phlogopite | 3.3 |
| Pyrophyllite | 3.1 |
| Biotite | 2.3 |
| Ankerite | 2.1 |
| Lizardite | 1.8 |
| Dawsonite | 1.5 |
| Magnetite | 1.2 |
| Pyrite | 1 |
| Total | 99.9 |

4.2.1.2. Water and methane gas

In order to mix the compost, distilled water was used for the purpose of the study. CH₄ gas with a purity of 99%, grade IV, from Linde Ltd., was used. A bottle of CH₄ was connected to each of the columns and injected at a rate of 250 g m⁻² day⁻¹.

4.2.2. Compost sample preparation

To prepare the mixture for the column experiments, mature compost was mixed well with distilled water. A gravimetric water content of 30% was selected for the purpose of the

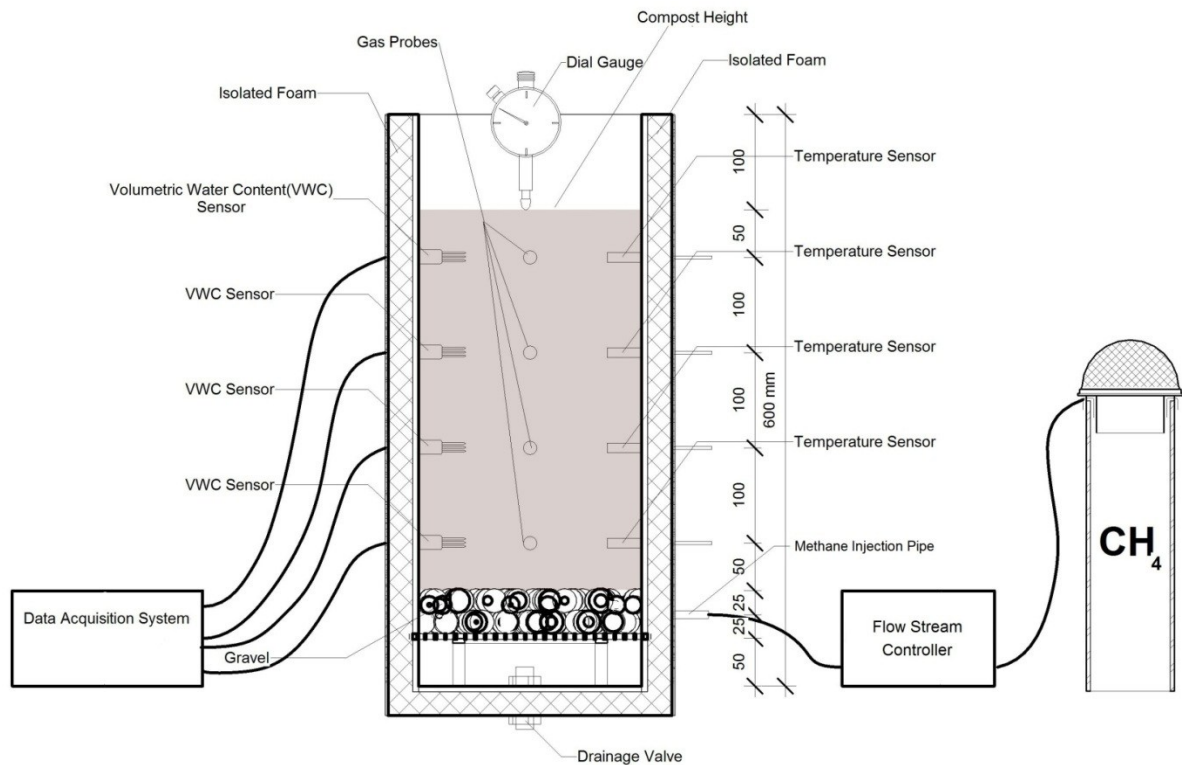
study, based on the recommendation in Huber-Humer et al. (2009), who suggested gravimetric water content between 30% to 50% and also recommendations provided by Huber-Humer (2004) in that the OMC should comprise a high concentration of CH₄ in biocovers. The aforementioned water content is commonly 25-50% of the actual water content of the material (Huber-Humer, 2004).

4.2.3. Developed column experimental set up

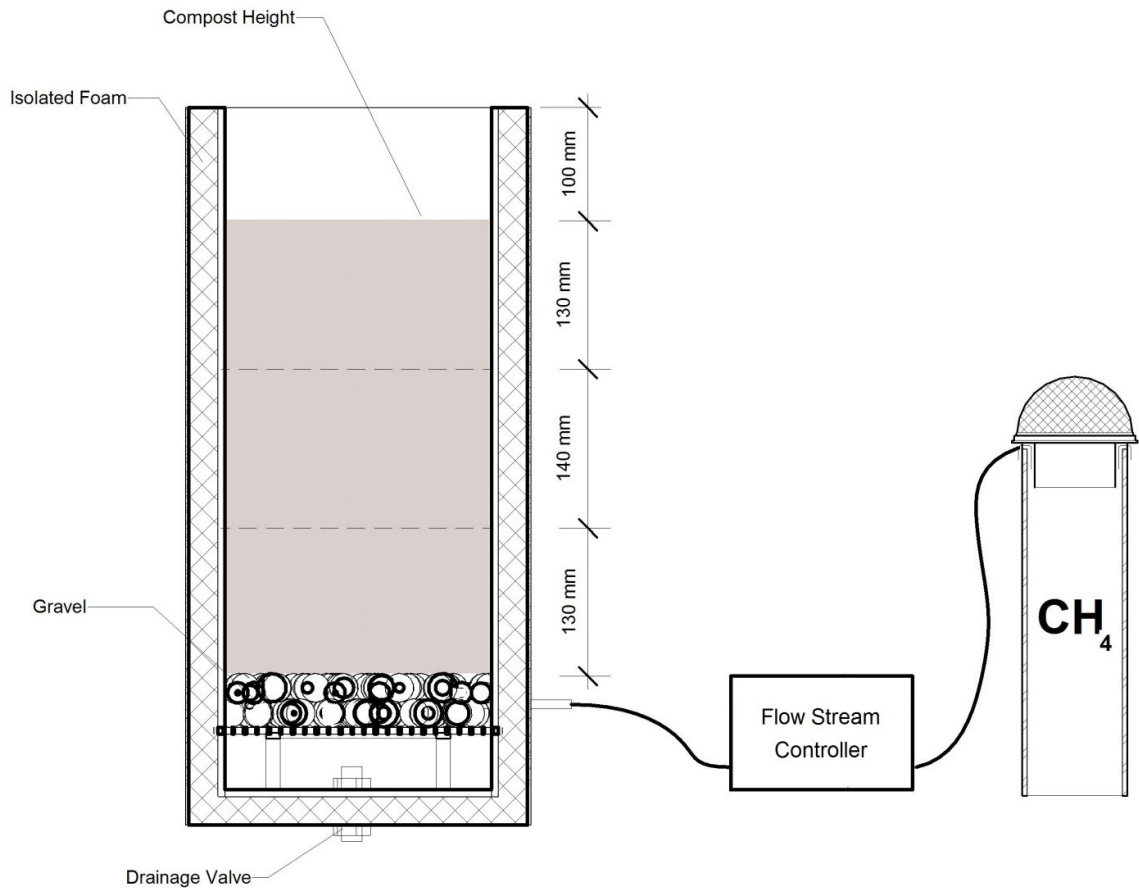
In order to investigate the response of compost biocovers to FTCs, three columns were developed and then manufactured (one instrumented column for monitoring; two column not instrumented for sampling test specimen). The schematic of the experimental set-up of the columns developed is presented in Figure 4-2. Plexiglass tubes with internal and external diameters of 25.4 and 26 cm respectively were utilized to build the columns. The height of each column from the base upwards was 60 cm. Each plexiglass column was inserted into a cardboard tube with an internal diameter of 30.4 cm. The gap between the plexiglass and the cardboard tube was filled with expansive insulation foam with a thermal resistance (k-factor thermal resistance) of 0.033 W/m C (Abdul-Hussain, 2011). This provides the opportunity to simulate one-dimensional freezing-thawing in landfill biocovers by preventing heat transfer from the bottom and the surrounding around the column set-up. Moreover, a valve was installed on the bottom of the columns to discharge excessive water at the end of the experiment. An aluminum brace was placed at the bottom of the columns. A perforated stainless steel plate was also placed at the top of the aluminum brace. Due to downward water movement in the columns, accumulation of excessive water might occur at the bottom. An adequate number of holes were made on the stainless steel plate to ease water movement towards the lowest depth of the columns

and the drainage valve. The diameter of the plate is roughly equal to the internal diameter of the column. The space below the stainless steel plate provides sufficient volume for any water accumulation at the base of the column, if necessary. Accumulation of excessive water can impact gas transfer and distribution at the bottom of the columns, if not prevented. A drainage layer which consisted of gravel that ranged from 20 – 30 mm in size was installed at the top of the plate. A gas inlet was installed on the bottom of the columns. The gas pipe that passed throughout the drainage layer was in the shape of a circle. For homogenous gas distribution, the circular part of the gas pipe was perforated. Then, the columns were filled with a well-mixed compost and water to a height of 40 cm. The columns were equipped with various sensors and gas probes at depths of -5, -15, -25 and -35 cm of the biocover profile. Water tapes and O rings were utilized to avoid any leakage; however, all of the ports were checked for leakage prior to the column experiments. CH₄ gas (with a purity of 99%, grade IV from Linde Ltd and rate of 250 g m⁻² day⁻¹) was fed to each of the columns by an injector pipe. Commonly found CH₄ concentrations that are usually injected into landfills were determined based on the data from Bogner et al. (1997). To apply a similar gas flux found in landfills into the columns, the recommended rate of injection is 200 to 300 g CH₄ m⁻² day⁻¹ (Bogner et al., 1997). These values represent the mid to high range of CH₄ concentration, respectively. This value is calculated based on the assumption that a landfill filled with 20 m of waste would generate this average value for the first 10-15 years after waste is buried into the landfill (Willumsen and Bach, 1991). Also, Scheutz et al. (2009) concluded after reviewing numerous studies that 100 to 150 g CH₄ m⁻² day⁻¹ and 200 to 250 g CH₄ m⁻² day⁻¹ could be the average and maximum rates of CH₄ oxidation respectively. Hence, by

choosing this value for the CH₄ injection rate, a conservative approach has been used in the current study. Besides that, the rate of CH₄ injection was controlled by using a product from M+W Instruments, a flow stream controller (D5111), for steady and uniform gas injection over time.



(a)



(b)

Figure 4-2 Schematic diagram of the experimental set-up columns: (a) 2D schematic shape of the column shows arrangement and placement of sensors, compost material and items in main column (b) 2D longitudinal section of the column without the sensors shows the Top, Med and Bottom layers used in post experimental tests

4.2.4. Column instrumentation, monitoring and experimental procedures

4.2.4.1. Procedure

The experimental columns offer the opportunity to compare the THMBC behavior of compost biocovers in this study, including: CH₄ injection without FTCs (0 FTC), after experiencing one FTC and another injection of CH₄ (1 FTC), and after experiencing two FTCs and then injection of CH₄ gas (2 FTCs). Three columns were filled with well-mixed compost and distilled water to a desirable height of 40 cm. The columns were then kept in a room under controlled temperature (23°C) while connected to a CH₄ gas cylinder for 37 days (0 FTC). During this period of time, variations in the water content, gas concentration, temperature and settlement were monitored by using sensors and apparatus which will be described in the following sections along with the depth profile of the columns. Afterwards, the instrumented column (monitored column) and one of the other columns (not instrumented) were submitted to freezing temperature in a cold room. The temperature of the cold room was kept constant at -9°C. The other column was used to identify the geotechnical properties of the compost biocover after 0 FTC. The geotechnical properties that were considered in the experimental plan mainly include hydraulic conductivity, shear strength, consolidation behavior, organic content, and thermal and physical properties. Specimens were removed at various depths (e.g. 0-13, 13-27, and 27-40 cm) of the column. Each depth is assumed to represent the geotechnical properties of one-third of the column height. Eventually, after determining the mentioned geotechnical properties, the grain size distribution of the compost biocover was also evaluated. The two other columns were kept in the cold room for 14 days (freezing period) and then left for 7 days as the thawing period (1st FTC). After the thawing process

was completed, both columns were connected to CH₄ gas again (1 FTC). All of the above parameters were monitored in the instrumented column for the next 35 days and then the instrumented column was placed again into the cold room to experience the 2nd FTC and the auxiliary column was used to evaluate the geotechnical properties of the compost biocover after experiencing one FTC following the procedure previously described. Finally, the instrumented column (the only remaining column) was removed from the cold room and then injected with CH₄ gas for another 35 days (2 FTCs). Afterwards, this last column was used to determine the geotechnical properties of the compost material.

4.2.4.2. Column instrumentation and monitoring

The instrumented column was equipped with temperature and water content sensors, gas ports and a dial gauge (Figure 4-2). All of the sensors and gas probes were established at four different height levels with depth in the biocover profile. The sensor levels were set at a distance of 10 cm from each other (Figure 4-2). The level of the top sensor was placed 5 cm below the biocover surface and the level of the bottom sensor 5 cm above the biocover bottom. The total height of the biocover was 40 cm.

To evaluate the evolution of the temperature, TH-T temperature sensors made by ROCKTEST were employed with an accuracy of $\pm 0.5\%$ F.S. The TH-T sensors use a standard thermistor of 3 k Ω . Four TH-T sensors were set up in the column at depth levels of -5 -15, -25 and -35 cm, respectively. The temperature data were collected and monitored daily.

To determine the settlement behaviour, a dial gauge with an accuracy of 0.01 mm was installed on the top of the columns. To avoid any movement of the dial gauge body, it

was connected to the plexiglass material of the main body of the columns. For measurement purposes, the dial gauge was placed perpendicular to the surface of the compost biocover material and measured the settlement at the center of the surface. Also, the dial gauge was placed into a small and very thin ($t = 1$ mm) circular metal surface with a diameter of approximately 2 cm. The data were read daily at the beginning of the experiment, but not during the freezing-thawing process.

To understand the evolution of the volumetric water content (VWC), 5TM sensors manufactured by Decagon were employed with an accuracy of 1-3% VWC. 5TM sensors are able to measure the VWC of soil via the use of an oscillator that measures the dielectric permittivity of soil. They were installed at the same level as the TH-T sensors. All of the sensors were connected to an Em50 data logger (Decagon Devices). The data were recorded at intervals of twice a day. The data were transferred to a computer and downloaded by software provided by the manufacturer. The evolution of the volumetric water content was recorded for the entire period of the experiment except during the freezing-thawing process.

The gas samples were taken from the gas ports by using 1 mL syringes. To avoid gas leakage, the syringe needles remained in the dense plastic material throughout the carrying time (3-5 minutes) to the lab. Then, they were injected into a gas chromatographic (GC) analyzer. The Series 400 gas chromatograph, thermal conductivity detector (TCD), manufactured by GOW-MAC Instrument Co. USA, is used in the present study. It is equipped with two columns and a TCD. The GC analyzer has two gas valve injection ports. The first one (connected to Column A) evaluated the concentration of O_2 , N_2 and CH_4 gases, and the second one (connected to Column B) evaluated the

concentration of N₂, CH₄ and CO₂. The final concentrations of gases were calculated by using mass balance. The TCD constitutes four 32 ohms of rhenium-tungsten (WX) hotwire filaments which are resistant to any oxidation process. The TCD response time is 0.5 sec. The GC analyzer has two separate valves for independent flow control of each of the columns. The carrier gas for the GC analyzer was helium with a flow rate of 30 mL/min. The helium pressure regulator was set to 40 psig. The injection temperature, isothermal temperature of the column oven (column temperature control) and the temperature of the detector oven (detector temperature control) were selected as 130°C, 120°C and 130°C. Finally, the bridge current control was set to 100 mA.

4.2.4.3. Post-experiment testing methods and procedures

At the end of the operation of the columns, they were brought to the geotechnical laboratory to perform post-experimental tests as described in Section 3.3.2. All the samples taken out from the columns were evaluated in terms of hydraulic conductivity (H), thermal conductivity (T), mechanical (M) properties including shear strength and consolidation behavior, and bio-chemical properties (B-C) (organic content). Moreover, other physical properties (e.g. bulk density and porosity) and grain size distribution were evaluated and tested for each layer and the entire height of the column, respectively.

4.2.4.3.1. Hydraulic conductivity tests

To determine the saturated hydraulic conductivity of the compost biocover samples, hydraulic conductivity testing was performed by using TRI-FLEX II. The flexible wall technique with a hydraulic gradient of 5 kPa was applied and the procedure in ASTM 5048-00 was followed. The samples were cut from a bigger piece of compost medium.

The size of the samples was considered to be the same as that of the cell of hydraulic conductivity. This consideration was due to minimizing possible disturbances which might affect the results. Besides that, they were allowed to be in the flexible wall for 24 hours before the experiment to fully saturate prior to testing. All of the samples were backpressure saturated. The saturation was verified by determining the degree of saturation of the samples at the completion of the hydraulic conductivity tests. All individual tests revealed saturation degree more than 98%. Two samples for each height were examined. A minimum of four readings were taken during the experimental process for more accurate results. The final value was reported based on the average of the results.

4.2.4.3.2. Compressibility (Oedometer test)

A consolidation experiment was conducted on the compost biocover samples with their own density and minimum disturbance by following ASTM D2435. It is known that disturbed samples might influence the accuracy of the results. Therefore, to prevent loss of accuracy, the samples were cautiously placed into the oedometer rings. The geometry dimensions of the oedometer rings were 63 mm in diameter and 20 mm in height. The samples used were cut from larger samples. After preparation, the samples were left under water for 24 hours to reach saturation. Finally, the specimens were loaded to 5, 10, 20, 40 and 80 kPa, for 24 hours each and then unloaded with the same time interval. This period of time was selected based on the study of Moo-Young and Zimmie (1996) who stated that the time is enough to demonstrate the behavior of organic soil in oedometer tests. To ensure the repeatability of the results, each test was conducted twice.

4.2.4.3.3. Shear strength tests

Direct shear testing was carried out on samples taken from the columns to determine the shear strength behavior of the compost material subjected to FTCs. According to studies by Benson and Othman (1993), Puppala et al. (2006), Bajwa and Fall (2011), and Bajwa (2012), direct shear testing is a proper means to evaluate the shear strength of organic soil. Therefore, by using this method, the cohesion (c) and friction angle (ϕ) of the samples taken from the columns are determined. In this method, the experimental procedures from ASTM D3080 are followed. To avoid the presence of extra pore water pressure, a very slow rate of $0.0025 \text{ mm.min}^{-1}$ was selected to perform the testing.

4.2.4.3.4. Thermal properties measurements

The thermal conductivity of the compost biocover was determined via Sh1 probes of a KD2 device. The KD2 device started to record after both needles of the Sh1 probes were carefully and slowly inserted into the compost material in the column at each height level. Approximately 3 minutes was needed to accomplish each reading. The precision of the measurements was about 5% (KD2 Pro Operator's Manual, 2006). For the purpose of reliability and repeatability of the results, each test was repeated for a minimum of three times.

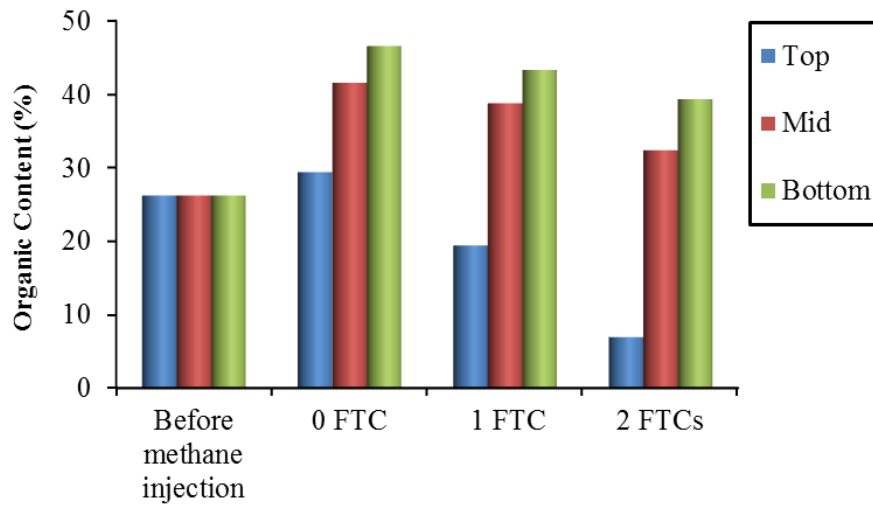
4.3. Results and Discussions

4.3.1. Effect of FTC on the evolution of the index properties and organic content

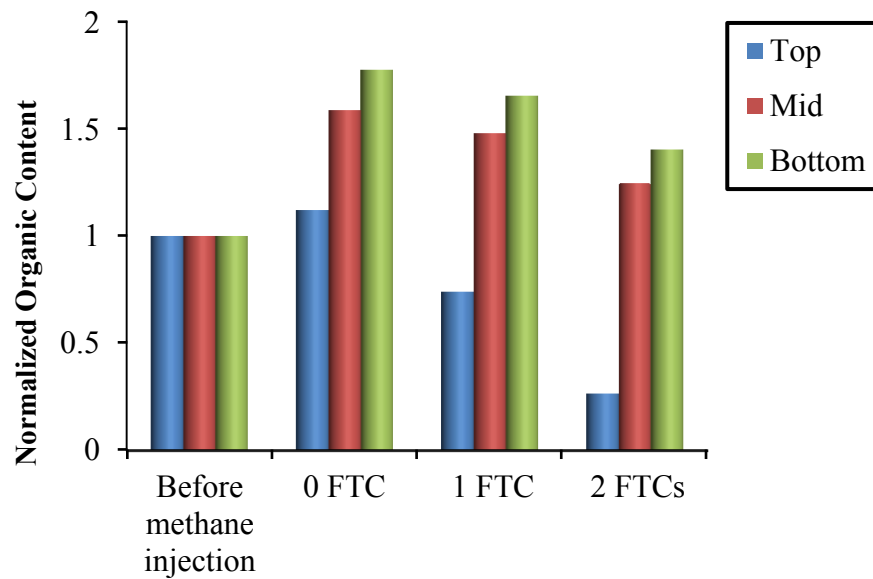
4.3.1.1. Effect of FTC on the evolution of the organic content

The organic content of biocovers is correlated with the rate of CH₄ removal (Hrad, 2010; Börjesson et al., 2004). Higher organic contents lead to higher CH₄ removal in biocovers (Hrad, 2010). Albanna et al. (2007) found that the addition of nutrients to the biocover medium at appropriate water contents could lead to a considerable increase in CH₄ oxidation.

Figure 4-3(a) shows the measured OMC of the compost in percentage at each stage of the experiment, that is, before CH₄ injection (B.M.I.), the initial cycle, at 0 FTC, after 1 FTC and after 2 FTCs. In addition, these results are normalized to OMC at the beginning of the experiment and shown in Figure 4-3(b), in order to demonstrate the contributions of each stage. In these figures “Top”, “Mid” and “Bottom” indicate the three depths at which the OMCs were measured. It was assumed that the OMC is uniformly spread along the height of the column before beginning the experiment (that is, B.M.I.).



(a)



(b)

Figure 4-3 (a) Variation of OM content after each stage of the experiment,
 (b) Normalized OM content with respect to beginning of the experiment.

This figure indicates that after CH₄ injection (0 FTC), the OMC increases in all layers. This increase is more significant in the “Mid” and “Bottom” layers where most of the CH₄ oxidation took place and had higher rates of EPS formation (see Figures 4-7, 4-8 and

4-9). The increase in the quantity of EPS leads to an increment in the organic content (Pokhrel, 2006). This increase is about 12%, 59% and 78% for the “Top”, “Mid” and “Bottom” layers, respectively. The increase can be attributed to the CH₄ oxidation process, in which either OMC is reached or EPS are produced. Notably, this is consistent with the temperature variation shown in Figure 4-16. As explained earlier, since the CH₄ oxidation rate in the lower layers is higher, the consequent production of OMC would be greater when compared to the “Top” layer. This is consistent with the results of other researchers in which the effective CH₄ oxidation zone is placed at a depth of 30 to 40 cm (Hrad, 2010). Therefore, formation of EPS at the bottom of the columns is more common. Another reason that might contribute to this observation is the transportation of OMC through water migration to the lower layers. Viklander (1998) observed that particle movement can occur in the depth profile due to freeze-thaw cycles. Besides that, it should be noted that the reduction in the OMC in the lower layers is much less than the upper layers. The deterioration of the bacterial community and fungi in the column due to the undergoing of multiple FTCs could take place. Sulkava and Huhta (2003) showed that FTCs have an impact on the microbial community. A lower concentration of CH₄ gas available to the bacteria in the upper layer may be another reason attributed to the relative lower rate of regeneration of organic content in the top of the column after FTCs. This is due to the CH₄ oxidation in the lower layers. As discussed, the CH₄ oxidation rate decreases in the upper layer with temperature variation over time. However, in the lower layers, sufficient CH₄ is provided to keep the oxidation process going and produce OMC. Specifically, in the “Top” layer, the OMC decreased about 74% and 27% of its original value from the beginning of the experiment to after 1 FTC and 2 FTCs, respectively. In

the “Mid” and “Bottom” layers, the OMC increased by 48% and 65% after 1 FTC, and about 24% and 40% after 2 FTCs respectively.

Figure 4-4 shows the variation of the normalized OMC versus column height for different stages of the experiment.

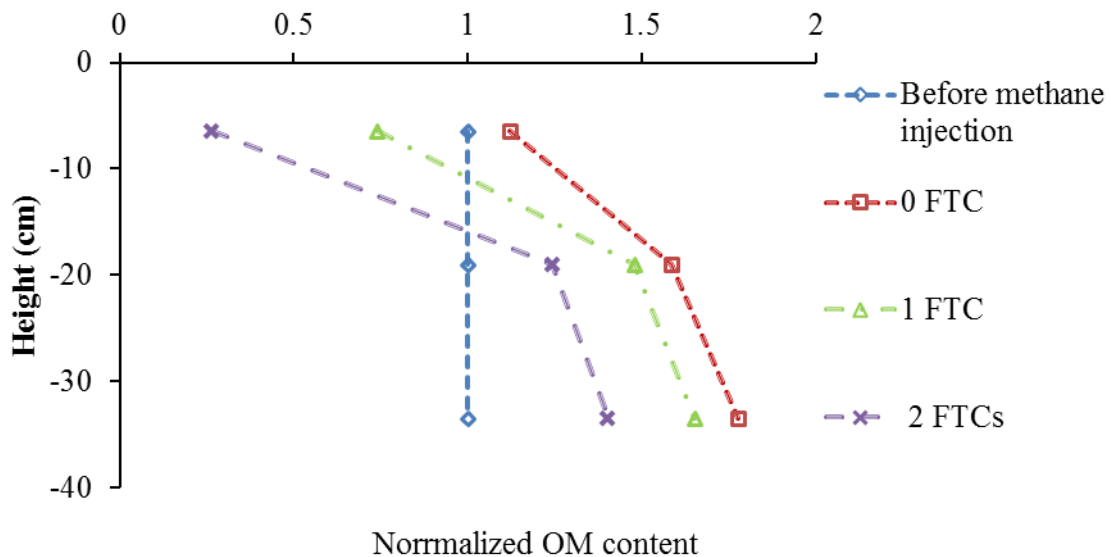


Figure 4-4 Variation of normalized OM content over depth.

This figure clearly demonstrates that the OMC increases with increasing depth for all stages of the experiment, since the majority of the CH_4 oxidation occurs in the lower layers. It is assumed that the OMC linearly varies in between the monitored layers. However, before the FTCs, there was an increase in the OMC. After 1 FTC and 2 FTCs, the OMC in the “Top” layer decreases, while the other two layers show increases. The first slope decreases with an increasing number of FTCs. This might be related to a reduction in the bacterial activity after each FTC, and the concentration of CH_4 oxidation in the lower layers.

4.3.1.2. Effect of FTC on the evolution of Bulk Density

Figure 4-5 shows the variation of the bulk density in the depth profile of the columns in all the stages of the experiment. As can be seen, the bulk density of the compost compacted under its own weight (B.M.I.) is uniformly equal to 548.7 kg.m^{-3} throughout the entire depth of the column. Although the bulk density varies in the depth profile, a bulk density higher than the compost compacted under its own weight was observed in all stages. This behaviour can be explained by the following: (i) settlement in the compost biocover (see Fig 4.23), (ii) water generation as a by-product of CH_4 oxidation reaction and gravimetric downward water movement (see Section 4.3.3.1), and (iii) EPS formation and variation in the organic content (see Sections 4.3.2 and 4.3.1.1). For instance, at 0 FTC, the bulk density in the middle layer was equal to 664.87 kg.m^{-3} , which is higher than that of the top layer. After 0 FTC, the organic content increased from 29.36% (Top layer) to 41.5% (Mid layer). Moreover, by considering the VWC results, a correlation between depth and VWC was observed, thus leading to an increase in bulk density over depth. After 1 FTC, the bulk density at each depth slightly increased. Indeed, the average values rose from 608.4 kg.m^{-3} (0 FTC) to 610.72 kg.m^{-3} (1 FTC). This increase can be justified by the continuing settlement that will be discussed in Section 4.3.5.1. However, the increase in bulk density changed in the stage that followed, after 2 FTCs. The average of the bulk density values of the three depths, at 2 FTCs, was 588.37 kg.m^{-3} . Although this value is more than the bulk density of the compost B.M.I. (548.7 kg.m^{-3}), it is lower than 0 FTC (608.4 kg.m^{-3}) and 1 FTC (610.72 kg.m^{-3}). This reduction can be attributed to the loss of water and organic content (see Sections 4.3.1.1 and 4.3.3.1). Generally, the compaction of biocovers has been negatively

correlated with their performance (Bajwa, 2012). A similar trend in behaviour took place in this study due to the FTCs (see Section 4.3.2). Moreover, as discussed, the average value of the bulk density increases in the column operation. These changes affect other parameters, such as porosity and the void ratio, which are of paramount importance where performance of biocovers is an issue.

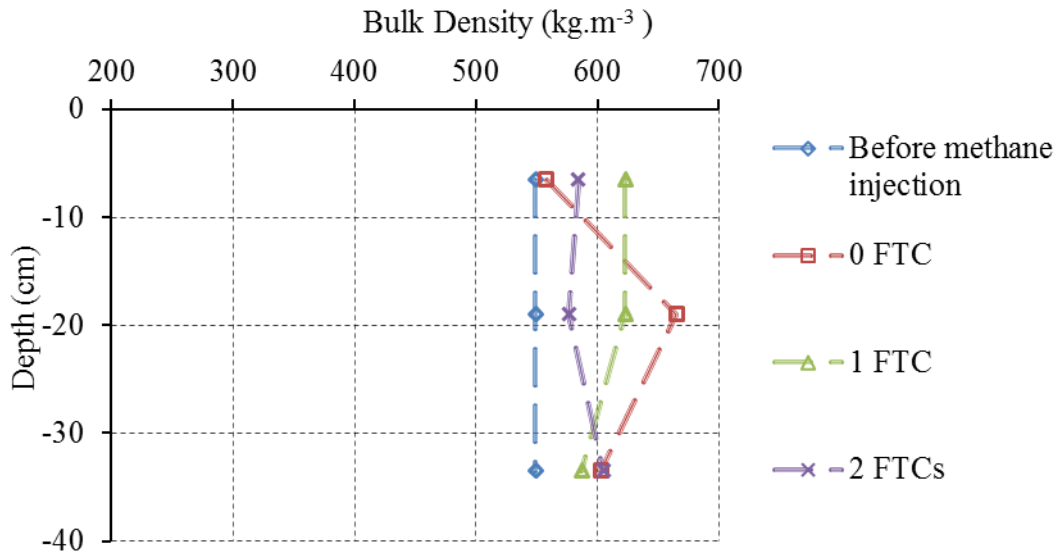


Figure 4-5 Variation of bulk density over depth

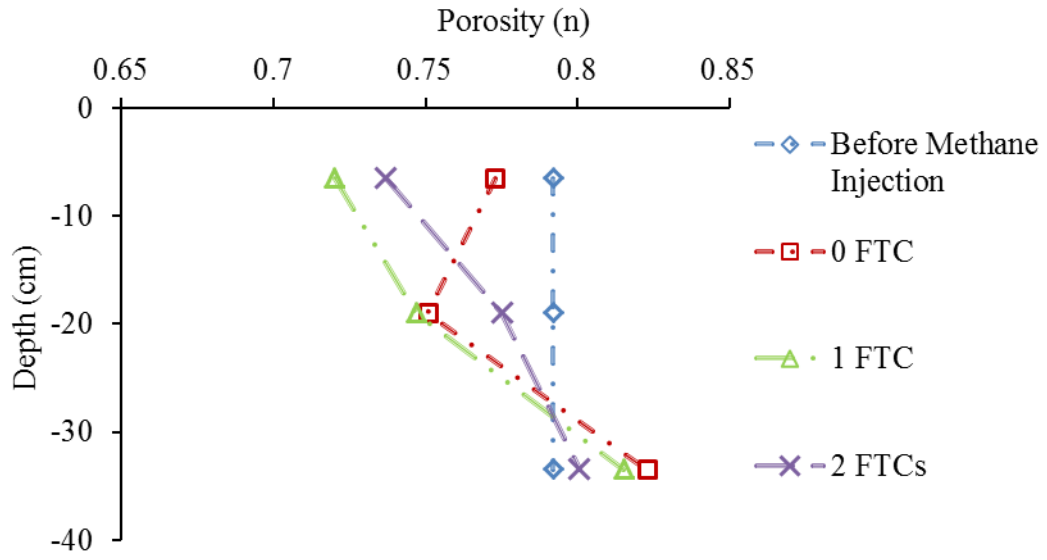
Figures 4-6(a) and (b) illustrate the results of the variation in porosity (n) and void ratio (e) in all stages of the experiment, respectively. As can be seen, the overall trend of variation in the porosity follows a similar trend as the behaviour of the bulk density. For instance, the porosity of the top layer B.M.I. is equal to 0.79. It decreases to 0.77 under the influence of the oxidation process and biocover settlement (see Section 4.3.5.1). This value declines to 0.73 and 0.72 after 1 FTC and 2 FTCs, respectively. This drop in the porosity in the upper layer consequently affects the CH_4 removal in this layer as will be discussed in Section 4.3.2. The same pattern takes place for the void ratio in the top layer. The void ratio decreases from the original value of 3.81 for the compost compacted under

its own self-weight to 3.4 at 0 FTC followed by a sharp decrease to 2.57 and 2.8 after 1 FTC and 2 FTCs.

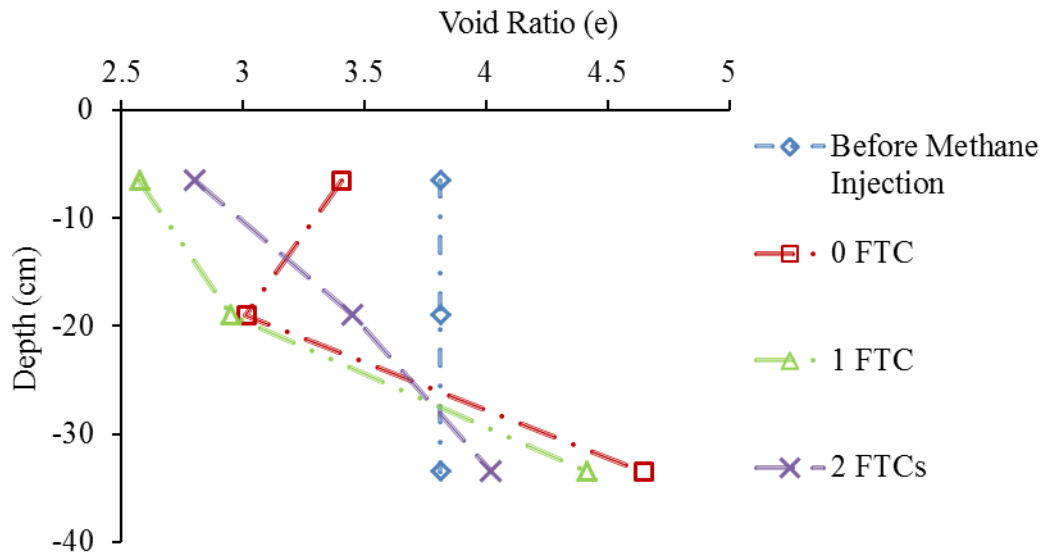
Also, for the “Middle” layer, a similar trend to that of the bulk density variation is repeated for the porosity. The porosity value decreases from 0.79 (B.M.I.) to 0.75 (0 FTC). Almost no significant changes can be seen between 0 and 1 FTC ($n=0.747$) followed by an increase in the porosity to a value of 0.775 after 2 FTCs. This increase might be attributed to the loss in the VWC which can be also seen in Section 4.3.3.1. Again, for the void ratio, due to the same reason, the void ratio increases from 3.81 (B.M.I.) to 3.01 and 2.95 for 0 and 1 FTC respectively, followed by an increase to a value of 3.45 after 2 FTCs.

For the bottom layer, the bulk densities vary between 586 to 604 kg.m^{-3} for all the stages of the experiment except for B.M.I. This narrow range of variation can also be observed in the variation of the porosity. The porosity changes from 0.8 to 0.82 for the same stages. This shows that FTCs do not contribute to major changes in the porosity in the lowest layer. It might be also the reason that there is a similar high performance in the bottom layer of the compost biocover (see Section 4.3.2). However, the porosity increases from 0.792 (B.M.I.) to 0.82 and 0.815 for 0 and 1 FTC respectively, followed by a slight decrease to 0.80 after 2 FTCs. This behaviour might be the result of increasing the VWC in the lower layer (see Section 4.3.3.1). Likewise, the void ratio follows the same trend. The void ratio increases from 3.81 (B.M.I.) to 4.64 and 4.41 for 0 and 1 FTC respectively followed by a decrease to 4.02 after 2 FTCs. The overall void ratio in the bottom layer in all of the stages experiences an increase in comparison to B.M.I. This behaviour can be explained by the same reasons as discussed above.

Overall, both void ratio and porosity decreases in the upper and middle layers, and slight increases in the lower layer, can affect the performance of biocovers.



(a)



(b)

Figure 4-6 (a) and (b): variation of Porosity (n) and void ratio (e) over depth

4.3.2. Effect of FTC on the evolution of gas profiles and methane removal

During the three stages of the experiment, the CH₄ concentration was measured and its variation over time (dimensionless as percentage of volume) is shown in Figure 4-7. As shown in this figure, a similar pattern is observed for all three stages of the experiment. The pattern was also previously observed by other researchers (e.g. Huber-Humer, 2004.).

- CH₄ concentration increases with increasing depth, due to gas injection into the system from below.
- The curves start with a steep slope and decrease afterwards until an equilibrium slope is reached. This clearly indicates that the CH₄ oxidation at the beginning of the experiment in each stage starts quickly and reaches stability after 7-9 days. In other words, bacterial activity starts quickly at first and accordingly the oxidation rate is high, but with an increase in time, the oxidation rate remains approximately constant.

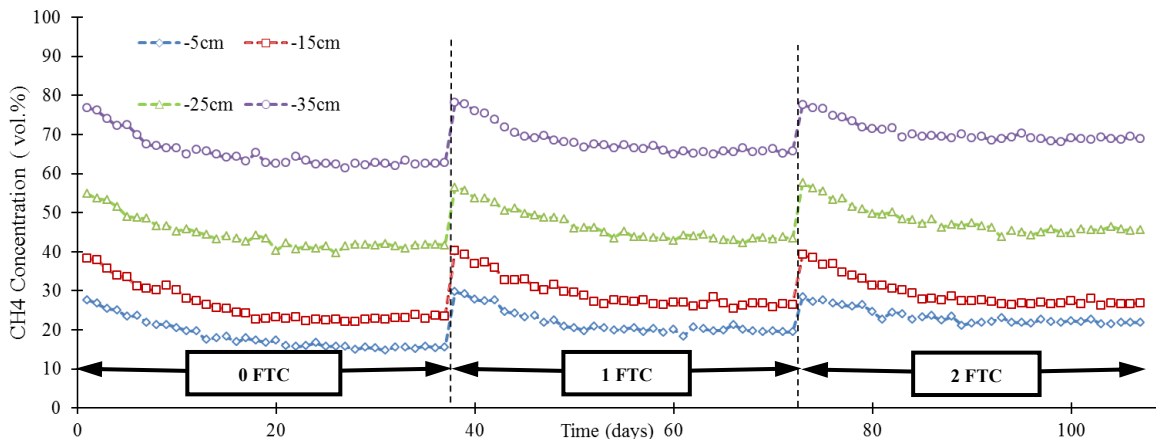


Figure 4-7 Variation of methane concentration during the experiment

Overall, the CH₄ concentration increases with increasing FTCs, which in turn, results in an overall lower biocover performance after each FTC. Note that the difference between the two upper layers (-5 and -15 cm) decreases after each FTC. The explanation is given as follows.

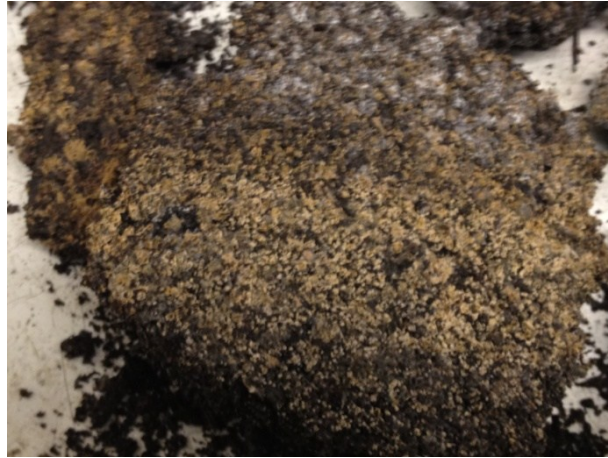
As can be seen in Figure 4-15, the measured peak temperature decreases after each cycle. In other words, the peak temperature for 1 FTC is lower than that of 0 FTC and after 2 FTCs, lower than the peak temperature for 1 FTC. This can be interpreted in a way that the biocover compost considered in this study has a high optimum temperature in which the highest performance is observed. Therefore, at lower temperatures, the performance decreases which explains the higher CH₄ concentration after the FTCs. After each FTC, the organic content was considerably reduced in the “Top” layer which indicates a decrease in CH₄ oxidation and consequently results in a higher CH₄ concentration. Other parameters that might contribute to the reduction in the difference between the layers at -5 and -15 cm after the FTCs are lower VWC and degree of saturation in the upper layers. This results in a lower CH₄ oxidation rate and performance. The variation of the VWC over time will be discussed in Section 4.3.3.1.

During the experiment, small yellow particles formed in the lower layers of the columns. These chemical compounds are known as EPS (Wilshusen et al., 2004), which are part of the produced organic content. They function as an anchorage that links the bacteria to the soil surface (Scheutz et al., 2009). However, some detrimental impacts have been reported about the impact of EPS formation on biocover performance. They have a limiting effect on the gas transfer to the upper layers due to various reasons. These have been well discussed by several researchers, such as Hilger et al. (2000) and Wilshusen et

al. (2004). Scheutz et al. (2009) concluded that the reasons associated with this phenomenon are, first, the clogging of the free pore space by the formation of EPS (see Section 4.3.1.2), and secondly, the reduction of gas diffusion into the biocover medium. Therefore, with the formation of EPS in the lower layers during the FTCs, the overall performance of the biocover compost decreases. Commonly, CH₄ oxidation reaches a peak and then follows a gradual trend of decrease (Scheutz et al., 2009). This behaviour is attributed to the formation of EPS in the bio-reactive material exposed to CH₄ flux (Molins et al., 2008). Figure 4-8 shows the produced EPS at a depth of 30 – 35 cm from the compost surface. The depth in which the maximum presence of EPS was observed agrees with the results of Wilshusen et al. (2004), in which the stated greatest amount of EPS is obtained in the effective zone of CH₄ oxidation.



(a)



(b)

Figure 4-8 EPS formation from the samples that taken out from the column at a depth of 30-35 cm from compost surface.

Figure 4-9 shows the accumulative CH_4 removed (consumed) by each layer for the three stages of the experiment. This figure illustrates the contribution of each stage (FTC) to the CH_4 oxidation process and also the effect of FTCs on each layer.

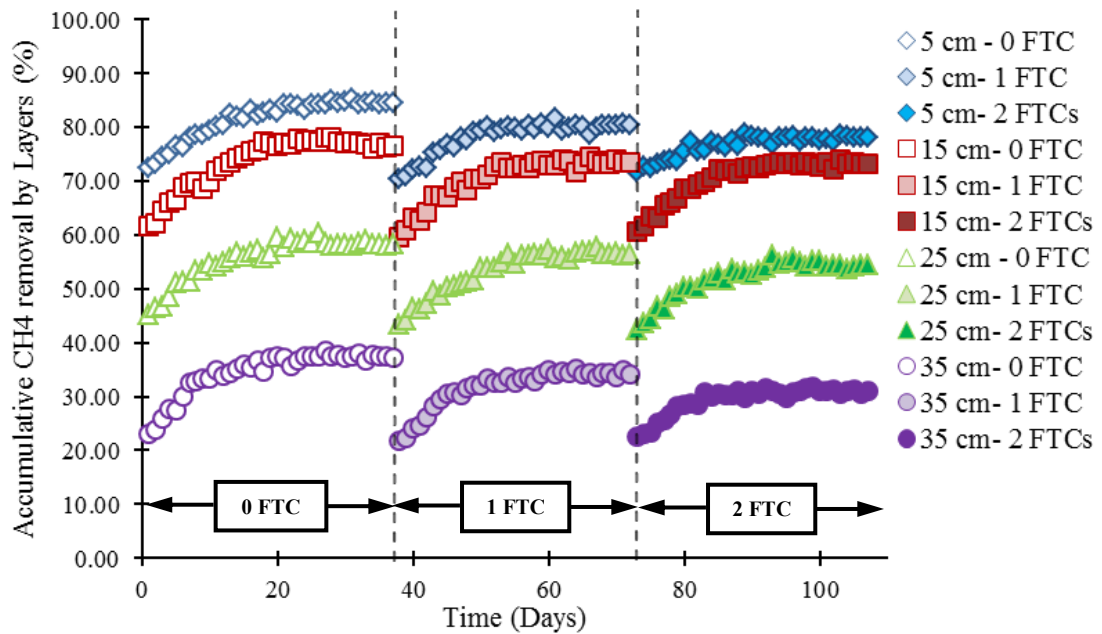


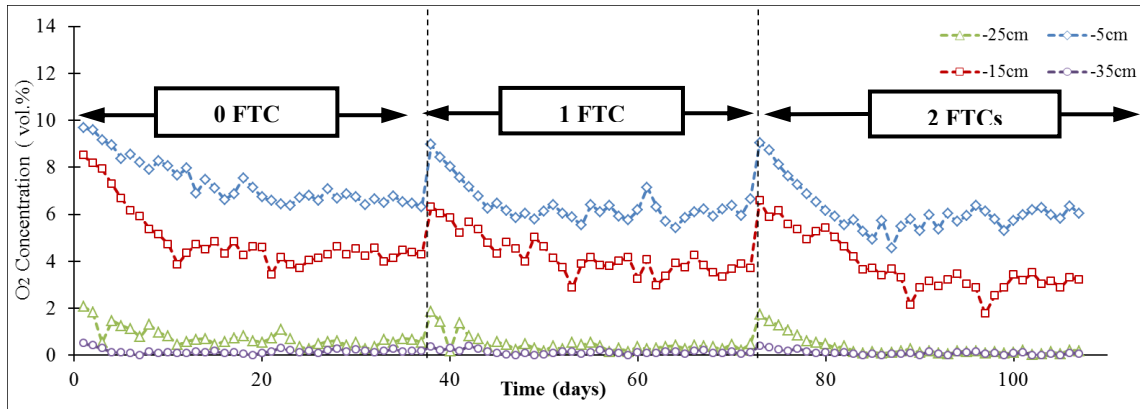
Figure 4-9 Accumulative methane removals by different layers

It can be noted that the FTCs had significant impacts on the upper layers, as the peak accumulative CH₄ consumption by these layers decreased (5-10%), while that of the lower layers (-35 and -25 cm) did not significantly change. This can be attributed to the change in organic content after the FTCs (as discussed in Section 4.3.1.1). This might affect the performance of biocovers. As will be discussed (see Section 4.3.1.1), the VWC is severely decreased in the top layer (depth of -5 cm). This reduction of the VWC is associated with the presence of organic nutrients that are released after each FTC (Schmidt and Lipson, 2004) which might be another phenomenon that affects a reduced amount of CH₄ removal in the top layers. A similar trend in behaviour was observed by Albanna et al. (2007). At a low water content rate, they observed that the presence of organic nutrients negatively impacts the performance of the biocover.

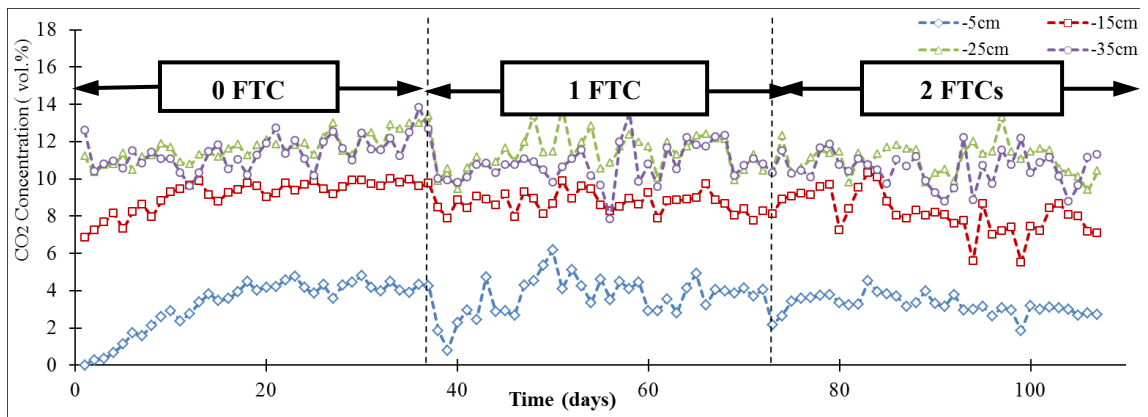
Figures 4-10(a) and 4-10(b) show the variation in the gas concentration of O₂ and CO₂ in the depth profile for different stages of the experiment. As can be seen, the amount of O₂ at depths of -5, -15, -25 and -35 cm for 0 FTC, is 9.67%, 8.51%, 2.09% and 0.5% of the volume, respectively. The amount of O₂ is then decreased at the beginning of 1 FTC to 8.97%, 6.32%, 1.87% and 0.37%, respectively. This decrease could be the result of the reduction in the average porosity of the different compost layers at 0 FTC. This leads to a decrease in O₂ penetration, and consequently, a lower biocover performance. The difference in the average porosity is minimal between 1 FTC and 2 FTCs. Therefore, O₂ penetration remains almost unchanged after 2 FTCs. A significant observation is the gradual decrease in the O₂ concentration throughout the depth profile for all of the stages. In addition, this gradual decrease occurred sharply at the beginning of the 10th to the 14th

day in each stage, while the O₂ concentration remained relatively steady afterwards as the chemical reactions stabilized.

Figure 4-10b illustrates the variation of the CO₂ gas in the depth profile for the different stages. During all of the stages, the average maximum concentration of CO₂ gas was found in the -25 cm layer which almost corresponds with the CO₂ concentration in the -35 cm layer. The CO₂ concentration decreases near the biocover surface. As a result of the FTCs and porosity reduction (see Figures 4-6a and 4-6b), a decrease in the penetration of O₂ (see Figure 4-10a) was observed. In considering that O₂ is a necessary input for CH₄ oxidation, a decrease will lower the amount of output CO₂. Therefore, the produced CO₂ gas was reduced from an average volume of 8.88% at 0 FTC to 8.65% and 8.23% after 1 FTC and 2 FTCs for the whole column.



(a)



(b)

Figure 4-10 (a) Variation of oxygen concentration during the experiment (b) Variation of carbon dioxide concentration during the experiment

4.3.3. Effect of FTC on the evolution of the hydraulic factors

4.3.3.1. Effect of FTC on the evolution of the volumetric water content

Figure 4-11 shows the variation in the VWC with time and versus FTCs. Except for the lowest level (-35 cm), it can be observed that there is generally an increase in the VWC followed by a decrease after reaching its peak value at 0 FTC.

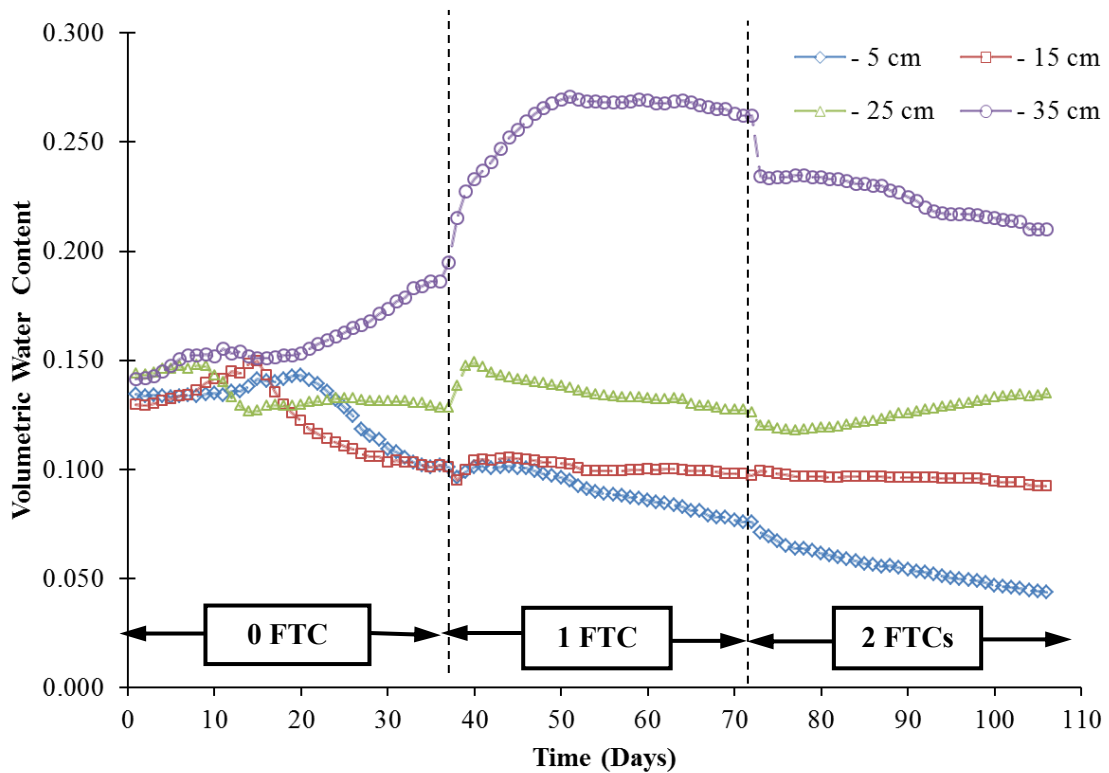


Figure 4-11 volumetric Water Content (VWC) variations during the experiment

As mentioned earlier, during the oxidation process, water and heat are generated (Scheutz et al., 2009). This results in an increase in the VWC at the beginning of the experiment. A reduction in the VWC after reaching the peak values can be attributed to the combined effect of water evaporation and downward movement of water due to gravity. It should be emphasized that the contribution of water evaporation to the reduction of VWC is

reduced with increasing depth. At the lowest level (-35 cm), the VWC continuously increases due to water generation during the CH₄ oxidation process and the downward movement of water due to gravity (Maurice and Lagerkvist, 2003).

After 1 FTC, the VWC at a depth of -15 cm remains somewhat constant, thus indicating a balance between water generation and loss; while at a depth of -5 cm, the VWC is decreased. In other words, at a depth of -5 cm, the rate of water loss exceeds that of water generation. Depths of -25 and -35 cm indicate different patterns. At a depth of -25 cm, similar to 0 FTC, there is an increase in the VWC due to water generation caused by CH₄ oxidation (Maurice and Lagerkvist, 2003), followed by a decrease due to the same phenomena explained earlier. At the lowest depth (-35 cm), the VWC rapidly increases until it reaches its peak and stabilizes after reaching the water holding capacity of the bio-cover compost. The water (generated by CH₄ oxidation and accumulated by gravity) was drained by the gravel layer, which acted as a filter.

After 2 FTCs, similar to 1 FTC, at a depth of -5 cm, water is lost due to gravity and evaporation, while at a depth of -15 cm, there is a constant VWC, which is due to the same reason for 1 FTC. In contrast to the previous stages of the experiment, at a depth of -25 cm, there is a slight increase in the VWC because of water migration after 2 FTCs and water generation during the CH₄ oxidation. It should be noted that the VWC after 2 FTCs at a depth of -35 cm shows a drop and slight decrease. This can be attributed to the freeze-thaw mechanism. During one dimensional freeze-thaw, water migrates to the upper levels and this decreases the VWC at the lower levels (Arenson et al., 2008).

4.3.3.2. Effect of FTCs on evolution of hydraulic conductivity

Figure 4-12 depicts the variation of the hydraulic conductivity in the depth profile for all stages of the experiment. A hydraulic conductivity of $8.27\text{E-}07 \text{ m.s}^{-1}$ was obtained for the compost biocover B.M.I. After 0 FTC, the hydraulic conductivity was decreased in all depths of the biocover. With depth, a lower hydraulic conductivity was observed at 0 FTC. The hydraulic conductivity decreased to $6.27\text{E-}07$, $5.21\text{E-}07$ and $3.82\text{E-}07 \text{ m.s}^{-1}$ for the top, middle and bottom layers, respectively. This behaviour could be attributed to the overall decrease in the porosity after 0 FTC from a quantitative value of 0.79 (B.M.I.) to 0.78 (0 FTC). Moreover, according to Figure 4-5, the average bulk density increases after 0 FTC which might be the reason for the lower hydraulic conductivities at 0 FTC. After 1 FTC and 2 FTCs, a similar trend of changes was observed. The hydraulic conductivity tended to decrease with increases in depth. However, only in the top layer, an increase in the hydraulic conductivity took place for both 1 FTC and 2 FTCs. This could be explained by the following: (i) structural changes, especially at the surface of the biocover due to FTCs, and (ii) downward movement of fine particles. The former was also previously reported by Moghbel and Fall (2013), in that FTCs might change the structural skeleton of organic fibers at the surface of biocovers that had been exposed to cold temperatures. The latter reason might occur since a finer grain size was obtained due to the various FTCs (see Section 4.3.5.4). Downward particle movement together with water generation and migration might move finer particles into the lower layers, thus creating more uniform and larger grain sizes in the top layer. With regards to the discussed reasons, hydraulic conductivity increased to $3.85\text{E-}06$ and $5.34\text{E-}06 \text{ m.s}^{-1}$ for 1 FTC and 2 FTCs, respectively.

In the middle layer, no significant changes were observed. A slight decrease in the hydraulic conductivity can be observed in Figure 4-12, which could be attributed to the increase in the bulk density in the middle layer for all of the stages in the experiment after B.M.I. The highest increase in bulk density occurred at 0 FTC in the middle layer; similarly, the lowest hydraulic conductivity was found in the middle layer at 0 FTC. According to Figure 4-6a, the porosity of the middle layers at 1 FTC and 2 FTCs is roughly the same. This could be the reason for almost similar values in hydraulic conductivity for the middle layer at 1 FTC and 2 FTCs.

In the bottom layer, as the different stages progressed and there were more FTCs, the hydraulic conductivity decreased from $8.27\text{E-}07 \text{ m.s}^{-1}$ (B.M.I.) to $3.82 \text{ E-}07 \text{ m.s}^{-1}$ (0 FTC), $2.25 \text{ E-}07 \text{ m.s}^{-1}$ (1 FTC) and $1.14\text{E-}07 \text{ m.s}^{-1}$ (2 FTCs). This behaviour might be due to the formation of EPS in the bottom layer of the column. The EPS formation might have changed the structure of the compost biocover in a way that leads to a lower hydraulic conductivity in the sample. Besides that, the average bulk density increased after B.M.I. in all of the stages in the experiment. This could have led to a lower hydraulic conductivity in the bottom layer as well.

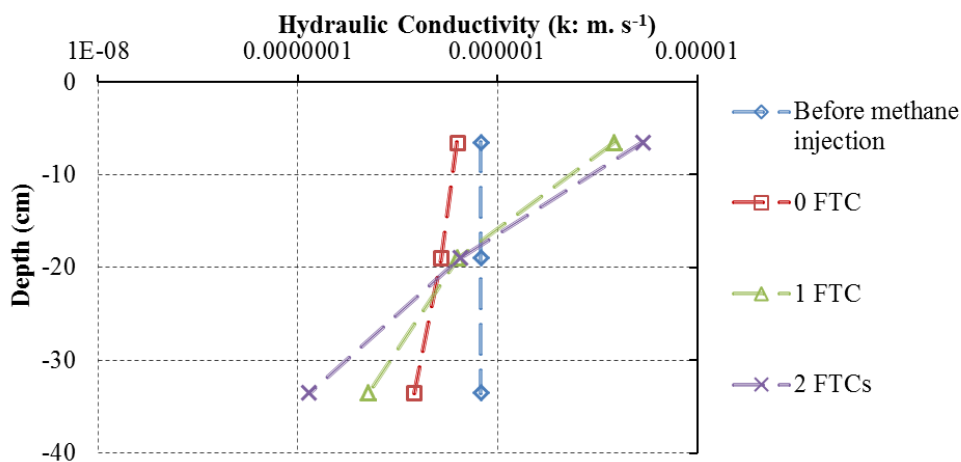
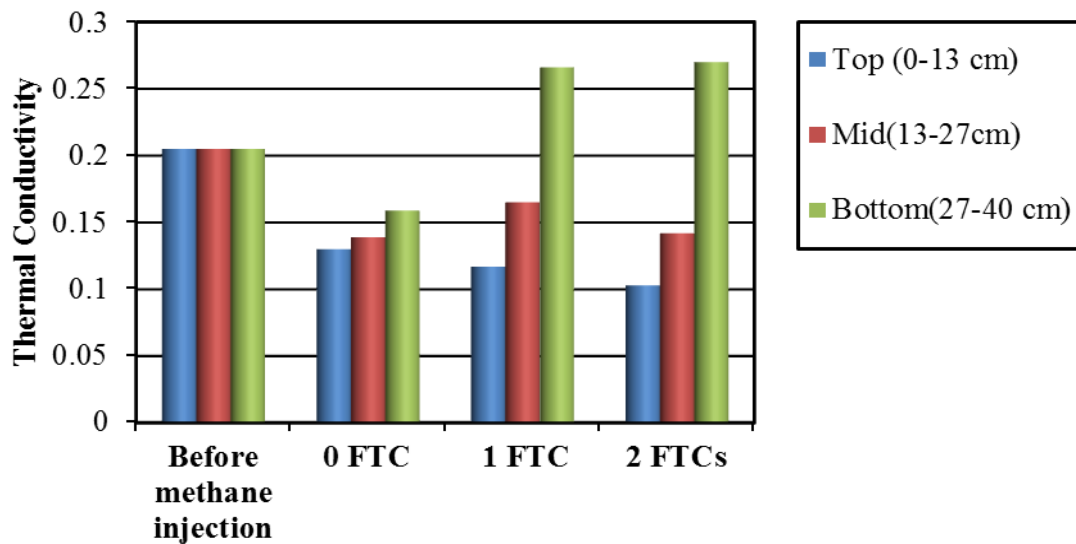


Figure 4-12 Evolution of hydraulic conductivity versus FTC

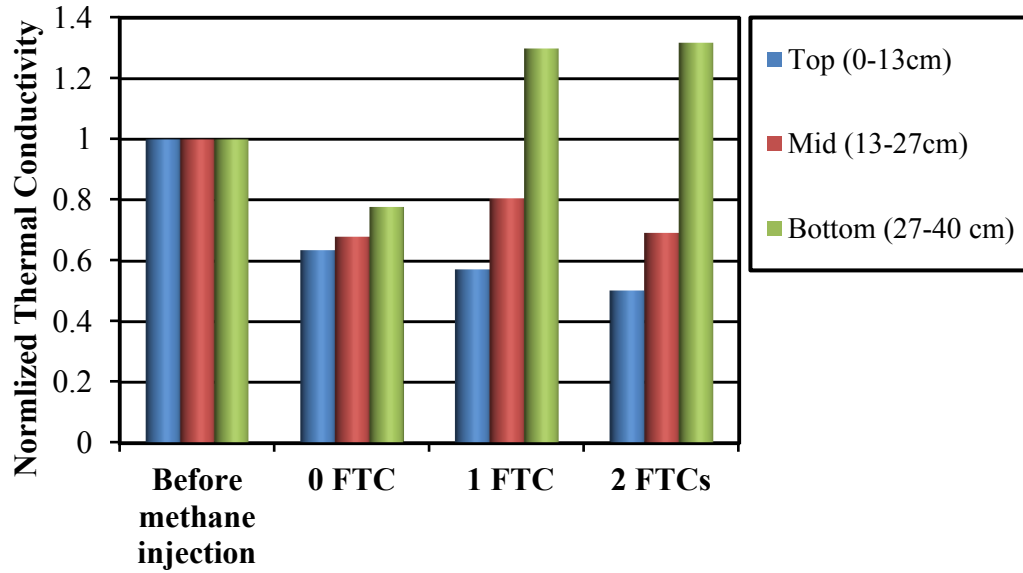
4.3.4. Effect of FTCs on evolution of thermal factors

4.3.4.1. Thermal conductivity

Figure 4-13 (a) shows the measured thermal conductivity at each stage of the experiment including B.M.I., 0 FTC, 1 FTC, and 2 FTCs. In addition, the results are normalized for thermal conductivity with respect to the beginning of the experiment and are shown in Figure 4-13(b), for easier interpretation of the impact of each stage in changing the thermal conductivity. In these figures, “Top”, “Mid” and “Bottom” indicate the three levels at which thermal conductivity was measured. They correspond to a depth range of 0-13, 13-27 and 27-40 cm, respectively. It was assumed that the thermal conductivity was uniformly spread along the height of the columns B.M.I.



(a)



(b)

Figure 4-13 (a) Variation of thermal conductivity after each stage of experiment, (b) Normalized thermal conductivity with respect to beginning of the experiment.

Figure 4-13b indicates that after CH_4 injection (0 FTC), the thermal conductivity decreases in all three layers by 38%, 33% and 22%, respectively. An explanation for such is the increase in OMC and distribution of finer grain size sediments after injection of CH_4 as both have an impact on the thermal conductivity. At the same porosity, finer particles decrease the thermal conductivity of soil (Nakshabandi and Kohnke, 1965; Abu-hamdeh and Reeder, 2000). In the “Top” layer, this decrease further continues into 1 FTC and 2 FTCs.

However, the thermal conductivity in the “Bottom” layer increases to 1.29 and 1.32 times the initial value after 1 FTC and 2 FTCs respectively. In the “Mid” layer, the thermal conductivity increases from 68% (of the original value) at 0 FTC to 80% after 1 FTC. This value later decreases to 69% after 2 FTCs.

The increase in thermal conductivity in the “Bottom” layer is attributed to an increase in the VWC, which in turn, enhances the thermal conductivity of the compost. Overall, an increase in the VWC results in higher thermal conductivity. Thermal conductivity had been correlated to water content and bulk density by several researchers (Fricke et al., 1997; Becker et al., 1992). With regards to Figure 4-11, the VWC is increased at the lowest depth of the columns as the experiment proceeded. This explains why higher values of thermal conductivity occurred at the lowest part of the columns. The decrease in thermal conductivity in the “Top” layer is because of water drainage by gravity and evaporation (Figure 4-11). However, a balance between the VWC (enhancing effect), OMC and grain size distribution (negative impact) in the “Mid” layer is responsible for the fluctuating thermal conductivity.

Figure 4-14 shows the variation in the thermal conductivity with column height. This figure shows that regardless of the stage of the experiment, thermal conductivity increases with increase in depth. The reason might be found in the variation of the VWC (See Figure 4-11). VWC has an enhancing effect and increases thermal conductivity. It was also observed that the VWC is higher at the lower levels since there, the CH₄ oxidation rate is higher and water moves downwards due to gravity. This explains for the increasing thermal conductivity with increasing depth. However, reduction in the thermal conductivity is more significant after FTCs due to the formation of organic medium.

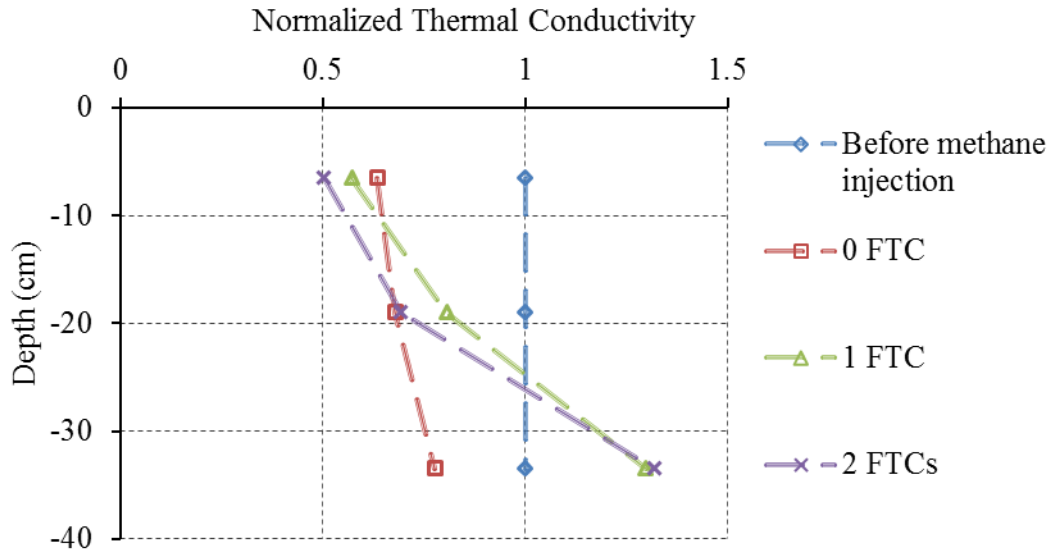


Figure 4-14 Variation of normalized thermal conductivity with depth

4.3.4.2. Temperature evolution

During the CH₄ injection process, the temperature was closely monitored along the height of the column. The variation of the measured temperature with time for the aforementioned levels is shown in Figure 4-15 for the three stages of the experiment, namely, 0 FTC, 1 FTC and 2 FTCs. The temperature at the beginning of the experiment was approximately the same for all four levels, roughly equal to ambient temperature. However, the average temperature of the various depths in the column after injection for all stages is higher than the ambient temperature. Similar results had been obtained by Pedersen (2010). The same temperatures along the depth profile at the beginning of the experiment indicate that the temperature distribution over column height is approximately uniform. However, the temperature near the compost surface is just slightly less than the other three measured temperatures. The reason is that the heat exchange with the surrounding environment at a depth of 5 cm is considerably more significant than the

other three layers. On the other hand, the other three layers, especially the two in the middle of the column, are isolated from the surrounding environment by means of insulation foam around the column perimeter. Note that at the beginning of the experiment, the slope of the diagram for the two lower layers (-25 and -35 cm) is sharper than those of the two upper layers (-5 and -15 cm). In other words, the temperature changes more rapidly in these layers. This can be attributed to the injection of CH₄ from the bottom of the column and heat-generation by the CH₄-oxidation process which was initiated from the bottom of the column and continued onto the upper layers. This results in an increase in the CH₄ oxidation rate in the two bottom layers, which in turn, will increase the rate of temperature increase. On the other hand, the temperature in the two upper layers increases at a slower rate due to lower concentrations of CH₄ that reaches the two upper layers. This is clearly noticeable when the two upper layers are compared: while the temperature at a depth of -15 cm reached its peak value, at a depth of -5 cm, increases in temperature continued until the 25th day. Afterwards, a decrease in temperature was observed after the temperature drops at a depth of -15 cm. Note that the temperature at a depth of -5 cm is lower than that at a depth of -15 cm. This can be attributed to the reduced CH₄ concentration and consequently, reduced CH₄ oxidation process (which is a heat-generating process). Another reason is that heat exchange with the surrounding environment is more significant at a depth of -5 cm, thus leading to a lower peak temperature.

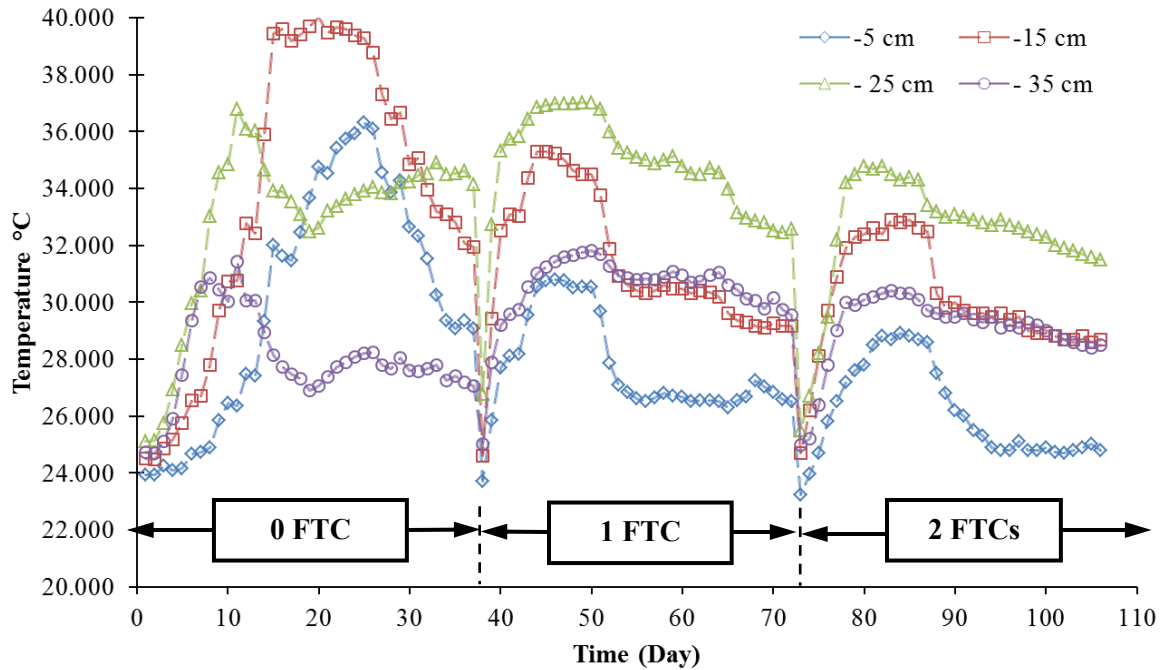


Figure 4-15 Temperature variations during the experiment

The temperature variation at all four levels follows a similar trend of increase in temperature; reaches a peak value (highest CH₄ removal at a given depth) and decreases afterwards. Similar trends in behaviour have been reported by Czepiel et al. (1996).

As mentioned earlier, the increase is related to the heat generation by the CH₄ oxidation process. However, the rate of temperature increase varies with different depths. During the CH₄ oxidation process, heat and water are generated as the products of the CH₄ oxidation reaction (Scheutz et al., 2009) and due to gravity, water tends to flow downward. Consequently, the water content increases with depth as can be observed in Figure 4-11.

On the other hand, during the CH₄ oxidation process, O₂ is consumed. Unlike the top layers, the layers at lower depths are isolated from the surrounding environment and would be deprived of O₂ after a number of days. As a result, the oxidation process slows

down and the VWC increases, thus leading to a decrease in the peak temperature at the lower levels. It can be concluded that the peak temperature decreases with increasing depth, except for the highest level (-5 cm) where the heat is directly transferred to the surrounding environment.

The decrease in temperature after reaching a peak value is associated with the effect of temperature on bacterial activities in the compost (Czepiel et al., 1996). Beyond a certain point, this rise in temperature becomes a threat to the bacterial activity (Zeiss, 2006) which further contributes to temperature decrease.

After the column has undergone 1 FTC and subjected to CH₄ oxidation, the temperature changes were monitored. Overall, all of the levels follow the same pattern: a high rate of temperature increase, a peak value is reached, and finally, a decrease in temperature; these were also observed by Czepiel et al. (1996).

As shown in Figures 4-3 and 4-4, the organic content of the compost after 1 FTC is increased. This increase in organic content might increase their specific surface area; hence, the oxidation process might be accelerated, which results in a steep slope at the beginning of the experiment. It was noted that the peak values after 1 FTC for the upper layers (-5 and -15 cm) are significantly lower than the corresponding values at 0 FTC. The reason might be related to the bacterial community changes under FTCs. It cannot be denied that FTCs have impacts on microbial as well as biological behaviour (Sulkava and Huhta, 2003). After the first FTC, some of the bacteria community might have died, thus resulting in a reduction in CH₄ oxidation and consequently, a lower peak temperature. Again, the peak temperature at a depth of -5 cm is lower than that at a depth of -15 cm, since the former exchanges heat with the surrounding environment. In comparing the

peak values for 0 and 1 FTC for the lower layers (-25 and -35 cm), it is clear that the peak values are in the same order. After reaching the peak values at each layer, the temperature starts to decrease because O₂ in the lower layers had been consumed and the oxidation process slowed down. Accordingly, the temperature in the upper layers decreased until the end of the experiment after 1 FTC. The same holds for the experiment after 2 FTCs. However, after the second cycle of freeze-thaw, the temperature slightly decreased. This can be attributed to the death of a larger portion of the bacteria community after the second FTC. This is shown in the organic content diagrams, see Figures 4-3 and 4-4, respectively.

4.3.5. Effect of FTC on the evolution of the mechanical factors

4.3.5.1. Vertical settlement

Settlement of the biocover under operation is correlated to O₂ penetration into the biocover and therefore, its performance (Bajwa, 2012). Figure 4-16 shows the settlement of the compost surface during 0 FTC, 1 FTC and 2 FTCs.

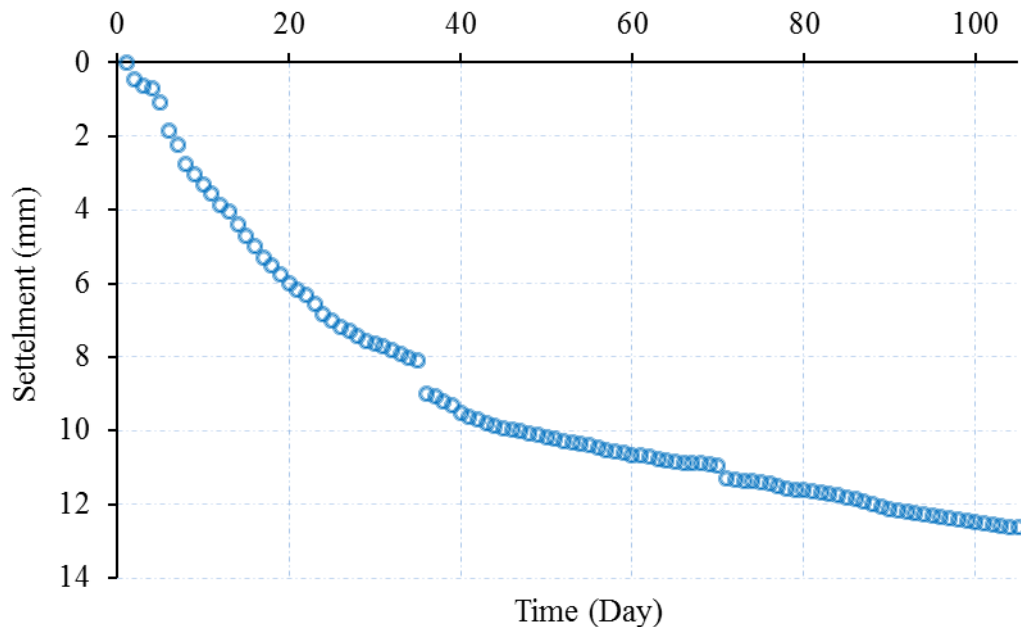


Figure 4-16 Compost surface settlements

The first change in the slope of this diagram is due to the fact that the CH_4 oxidation process effectively begins after 5 days during the initial cycle of the experiment. Afterwards, there is a sharp change in the slope, which shows that effective CH_4 oxidation has commenced. Note that the slope of the diagram decreases with increase in time, thus indicating that the majority of the settlement took place during the initial cycle stage. The reason can be attributed to the majority of CH_4 oxidation that occurred in the initial cycle. This shows that with each FTC, the compost becomes more stable and the stability of the compost will increase with FTCs (Oztas and Fayetorbay, 2003). The total measured settlement is 12.63 mm, while at the end of the initial cycle, a settlement of 8.1 mm was recorded. The contribution of each cycle is shown in Figure 4-17.

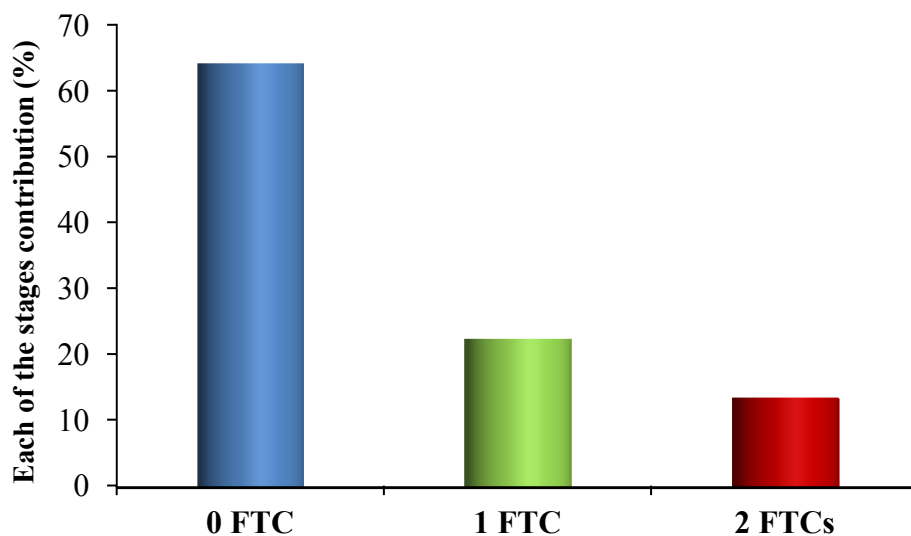


Figure 4-17 Impact of methane injection and FTCs on settlement

This figure indicates that 64% of the settlement took place after the injection of CH₄ at 0 FTC, which left the remaining 36% to take place in the first and second FTCs. About 23% of the total settlement took place in the first FTC and the remaining 13% occurred during the second FTC. This result is also consistent with the changes in grain size distribution, as shown in Figure 4-23, where the majority of change in grain size distribution takes place during 0 FTC. The discontinuities in the diagram are related to the settlement of the compost surface after the first and second FTCs at the beginning of the second and third stages of the experiment, respectively. It is also interesting to note that the gap after the second FTC is significantly less than that of the first FTC. This might also be attributed to the fact that the difference in grain size distribution after 1 FTC and 2 FTCs is insignificant.

4.3.5.2. Consolidation behaviour

Figures 4-18, 4-19, and 4-20 show the variation in the void ratio versus the logarithm of effective stress under loading and unloading conditions for 0 FTC, 1 FTC, and 2 FTCs, respectively. As can be seen, the graphs have been plotted for the specimens in the top (depth= 0-13 cm), middle (depth= 13-26 cm), and bottom (depth= 26-40 cm) layers. The behaviour of the specimens before CH₄ injection has also been plotted for comparison

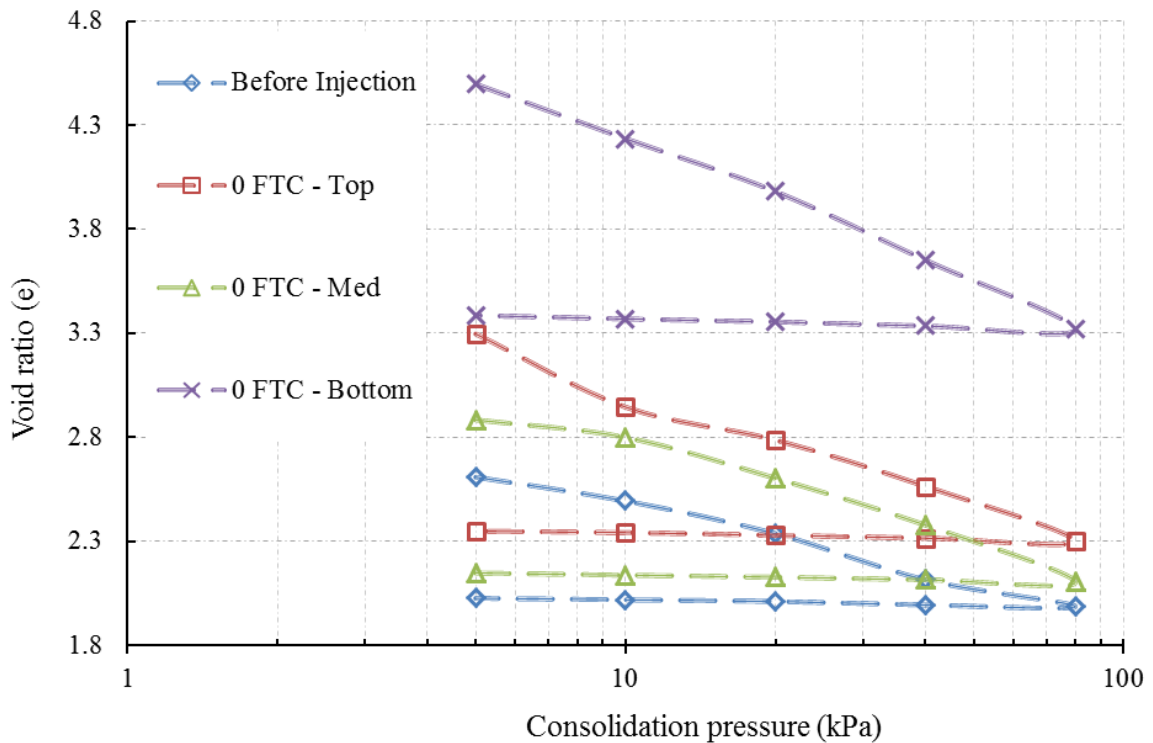


Figure 4-18 void ratio versus the logarithm of effective stress

As can be seen, the void ratio of the soil decreases as the level of the normal stress increases. Also, the magnitude of the decrease in void ratio is significantly higher for the specimens at the bottom in all the scenarios (i.e. 0 FTC, 1 FTC, and 2 FTCs) compared to other depths and also before CH₄ injection. This could be attributed to the higher organic contents available at the bottom of the columns as the testing progressed (see Section

4.3.1.1). This is consistent with the results of Khoshand and Fall (2012), thus showing that the void ratio reduction increases as the organic content of the compost increases. Similarly, maximum swelling was observed for all specimens at the bottom (e.g. 0.068 changes for 0 FTC, Figure 4-18). The final void ratio was found to be higher for the specimens at the bottom after unloading.

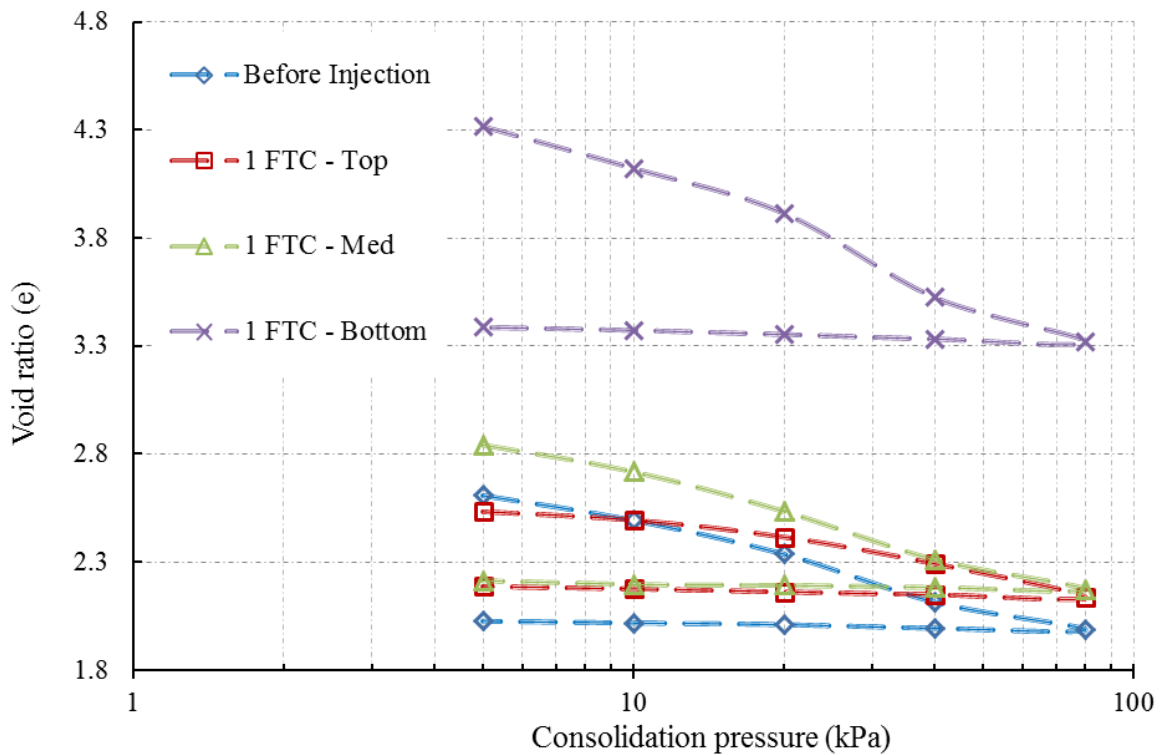


Figure 4-19 void ratio versus the logarithm of effective stress

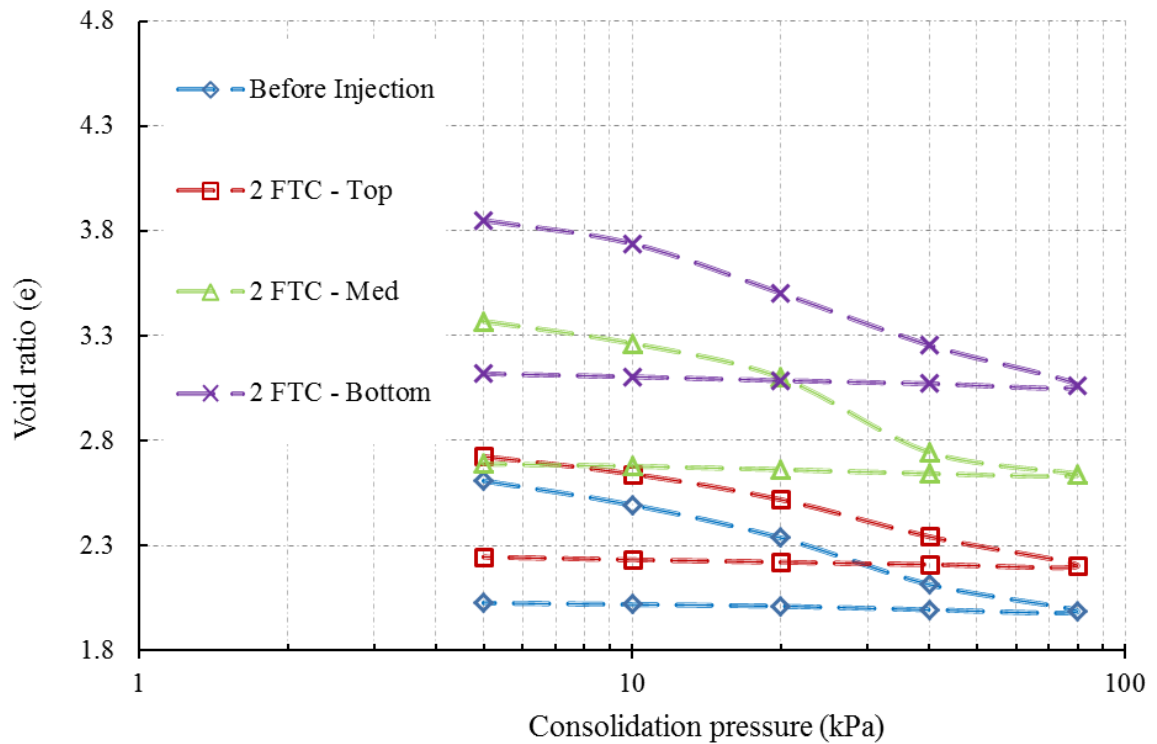


Figure 4-20 Void ratio versus the logarithm of effective stress

The difference between the maximum and minimum void ratios within the specimens for 0 FTC, 1 FTC, and 2 FTCs is 2.35, 2.1, and 1.6, respectively. This could be attributed to the decrease of the average grain size of the compost as the number of FTCs (Figure 4-23) increased, which in turn, decreased the magnitude of the variation in the void ratio under loading or unloading. This could be also associated with the general decrease of the C_c and C_r coefficients as the number of FTCs increased (Table 4-2).

Table 4-2 Variation of consolidation parameters (C_r and C_c) with depth

| | Before Injection | | 0 FTC | | 1 FTC | | 2 FTC | |
|--------|------------------|--------|--------|--------|--------|--------|---------|--------|
| | Cr | Cc | Cr | Cc | Cr | Cc | Cr | Cc |
| Top | 0.036 | 0.5616 | 0.0463 | 0.7141 | 0.0455 | 0.3978 | 0.03157 | 0.4841 |
| Med | | | 0.0378 | 0.7706 | 0.0262 | 0.6037 | 0.04434 | 0.6923 |
| Bottom | | | 0.0562 | 1.0155 | 0.06 | 0.8904 | 0.04725 | 0.7504 |

4.3.5.3. Shear strength

Stability issues in the design of biocovers are of paramount importance (Bajwa, 2012). Figure 4-21 demonstrates the variation in the friction angle versus depth before CH_4 injection, at 0 FTC, and after one FTC and two FTCs. The average of the friction angle values obtained in this study is 56.48° . This is consistent with the results reported by Khoshand and Fall (2012) ($45.8- 54.7^\circ$) for the consolidated drained direct shear tests.

The average of the friction angles for the specimens at the top layer (depth= 0- 13 cm) for all the stages of the experiment was 56.73° which is slightly more than the friction angle of the compost before CH_4 injection (i.e. 55.14°). Similarly, the same observation was found for specimens in the middle (depth= 13-26 cm) and bottom layers (depth=26- 40 cm).

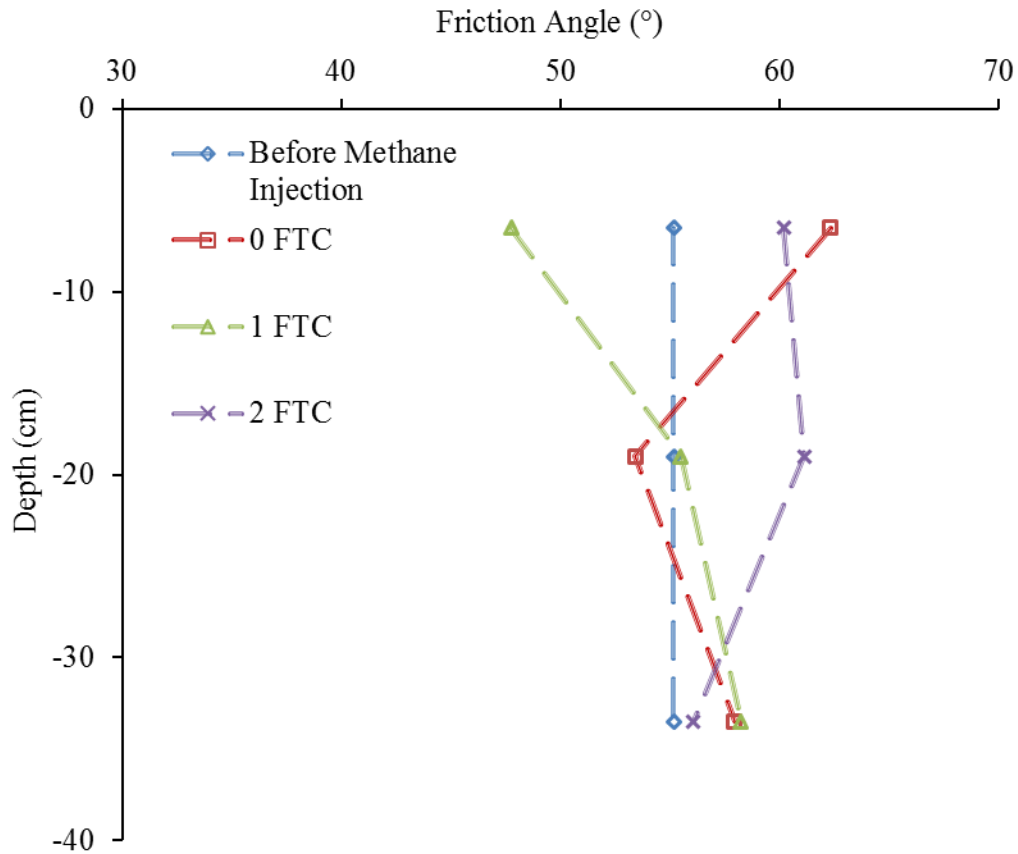


Figure 4-21 Friction angle of top, medium and bottom layers in all the experimental stages

The following mechanisms could be explained as the reasons for friction angle changes:

1. The slight increase of the bulk density due to the settlement of the soil (see 4.3.1.2) induces an increment in shear strength of the compost biocover.
2. The average grain size of the particles decreases as the number of FTCs increases (Moghbel and Fall, 2013). This could in turn impact the shear strength parameters. Khoshand and Fall, (2012) attributed the high friction angles of the pure compost to the fibers which perform as reinforcement. Due to FTCs and methane oxidation reaction compost particles become finer (Figure 4-23). Moghbel and Fall (2013) found that FTC impacts on fiber structures at the surface

of the biocover. Although it seems that after FTCs, finer organic fibers are available in compost biocover, the increase in the number of these finer fibers leads to the increase of shear strength of the compost biocover. This mechanism is valid for the data of current study except for the bottom layers that follow a mechanism explained below.

3. Due to methane oxidation, EPS was formed at the methane oxidation zone (bottom layers) of the columns. Formation of the EPS can alter the structure and texture of the compost biocover. Therefore, it might be one of the main contributors to the increase of the shear strength and the friction angle of it.

Figure 4-22 demonstrates the variation of cohesion (c , kPa) versus the depth (cm). The average of the cohesion at the top of the specimens (depth= 0- 13cm) for all the stages of the experiment is 3.88 kPa that is higher than the cohesion of compost (i.e. before methane injection) at 1.3 kPa. Moreover, the average of the values of the cohesion at the middle and bottom of the specimen at all the stages of the experiment were found to be 3.77 and 1.21 kPa, respectively. The average values of the cohesion at 0 FTC column, 1 FTC, and 2 FTCs column were found 2.13, 3.82 and 2.92, respectively that are significantly more than that of the cohesion for the compost in before methane injection (1.3 kPa).

The average value of the cohesion of all depths and all the stages of the experiment was found to be equal to 2.54 kPa. This is also in agreement with the results of Bajwa and Fall (2011) indicating that the low cohesion could be attributed to the relatively brittle nature of the compost materials.

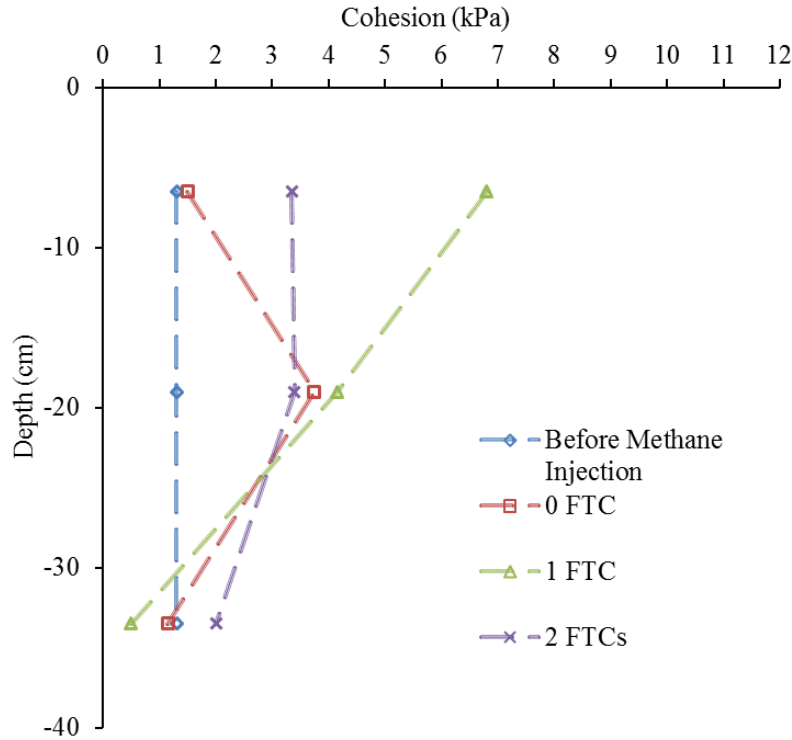


Figure 4-22 Variation of cohesion with depth

The following mechanisms could be explained as the main reasons for the cohesion changes mentioned above:

1. The grain size of the particles decreases due to freeze-thaw cycles and methane oxidation. As a result, the specific surface area (SSA) of the compost increases that in turn could contribute to growth of bacteria. The bacteria which normally stick together might increase the cohesion of the organic soil. The increase of the SSA (e.g. for clayey soils) has been shown to typically increase the cohesion of the soil (Green-Kelly, 1964)
2. Under the process of methane oxidation, a layer of biofilm (EPS) is formed on the porous material which could increase the cohesion of the soil. Reasonably, since

EPS provides the bacteria with opportunity to stick to the biocover particle surface and act like an anchorage between microbial community and soil surface (Scheutz et al., 2009). Besides, according to figure 4-23, higher the length of methane injection and FTC, finer particles with higher SSA produced. These two reasons might contribute to the statement that EPS could increase the cohesion of biocover under the operation and experience of FTCs.

The angle of friction achieved from the experiments have to be deducted by 15–25% (Bagchi ,1990, Irene et al., 2002). The friction angles of the compost subjected to FTCs are larger than 25° regardless of the number of FTCs. Hence, the compost biocover have suitable strength to resist shear failures (for regular slopes of landfills).

4.3.5.4. Effect of FTC on the evolution of the grain size distribution

The grain size distributions for the compost before and after the injection of methane along with those of the first and second FTCs are shown in figure 4-23.

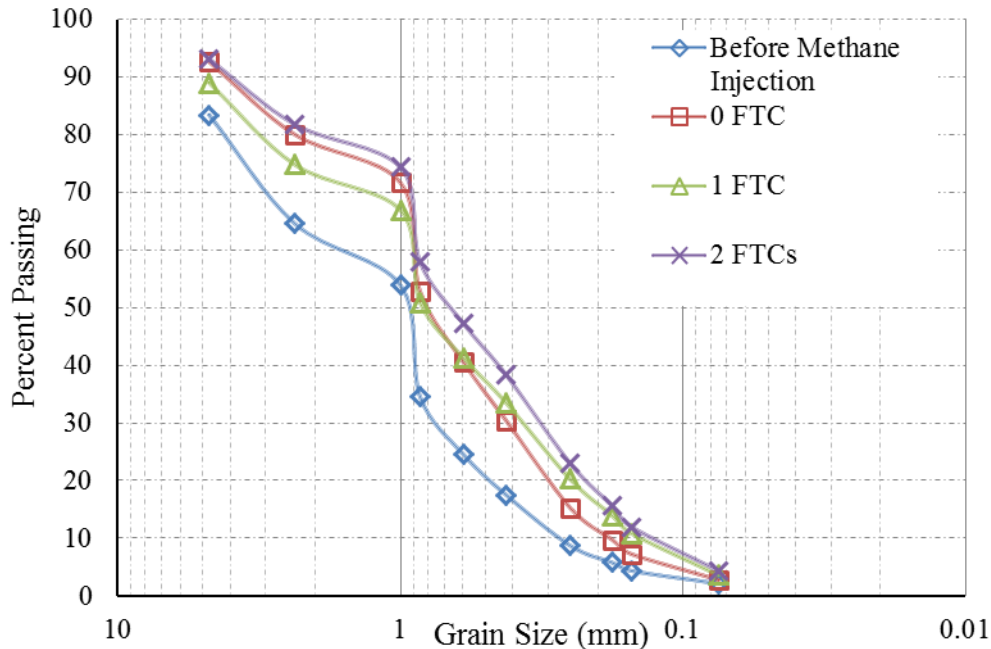


Figure 4-23 Change in grain size distribution of compost at different stages of the experiment

The CH_4 oxidation process changes the organic content of the compost, alters the compost structure, and causes the grain sizes to decrease. This results in finer contents and a major change in grain size distribution after the initial cycle (first CH_4 injection). Similar results obtained by Huber-Humer (2004) have proven a reduction in the grain size of the particles after the period of CH_4 exposure to a bio-reactive medium (CH_4 oxidation reaction). Also, Moghbel and Fall (2013) reported a finer grain size in the compost biocover under FTC conditions (FTC phenomenon). The contribution of 1 FTC and 2 FTCs to grain size changes is less significant than that of 0 FTC. Moreover, the impact of 1 FTC on grain size changes is higher than that of 2 FTCs. Therefore, it can be concluded that most of the changes in the grain size distribution of the compost took place after 0 FTC. After 1 FTC and 2 FTCs, minor changes were observed. These changes in grain size distribution affect the geotechnical properties of the compost (e.g. thermal and hydraulic conductivities).

4.4. Summary and conclusions

The results of the current study show that FTCs impact the THMBC behaviour of compost-based landfill biocovers. Both geotechnical and geo-environmental properties of biocovers can be altered under back-to-back freezing and thawing conditions and CH₄ injection in between. Hence, they affect the performance of biocovers and LFG emissions in biocovers. Moreover, it can be concluded that the performance of biocovers remains at a level that is higher than approximately 80% even after two FTCs despite that many of the aforementioned properties were changed throughout the experiment. Zeiss (2006) had deemed this as the acceptable level of CH₄ oxidation in the cold region of Alberta. Similar to other surveys conducted on biocovers, most of the CH₄ oxidation took place at a depth between -25 cm and -40 cm. Formation of EPS, high temperature, lack of and excessive water and organic contents are found as the triggering parameters for the performance of biocovers in cold regions. Also, a slight enhancement in the mechanical properties of biocovers is obtained.

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Chapter 5

Summary, Conclusions and Recommendations

Summary:

The aim of the current study is to evaluate both the efficiency of biocovers and enhancement of the current knowledge on biocovers towards an optimum design in cold regions. Therefore, an experimental approach has been considered for these purposes.

First, in order to evaluate the performance of biocovers, comprehensive experimental approach is undertaken using several of small compacted samples and in column experiments. The former is carried out to determine the behavior of the thermal properties of compost biocovers under FTCs. First, samples are compacted to corresponding dry densities in a wide range of moisture contents, which varied from 22% to 65%. Then, the thermal properties are evaluated prior to and after the samples were subjected to FTCs. A total of 9 FTCs are taken into account for the experiment. After investigating the obtained experimental data, an empirical formula is proposed and then validated to predict the thermal conductivity changes in compost-based biocovers under FTCs.

Second, to develop a better understanding of the response of compost biocovers to FTCs, column experiments are conducted. In biocovers, the evolution of thermal (T), stress/deformation/settlement (M), gas/fluid flow (H) and bio-chemical (B-C) reactions all take place simultaneously (coupled processes). Three columns of biocover material are built in order to evaluate the THMBC response of biocovers. The columns are subjected to three FTCs: (i) 0 FTC; (ii) 1 FTC; and (iii) 2 FTC. Throughout the periods of

CH₄ injection, numerous parameters such as CH₄ oxidation, VWC, temperature and settlement are monitored. After each cycle of CH₄ injection, small samples from the depth profile of the columns are tested with regard to their mechanical (e.g., shear strength and consolidation), hydraulic (e.g., degree of saturation), thermal (e.g., thermal conductivity) and bio-chemical (e.g., organic content) properties.

Conclusions

The following conclusions are made from the current study.

1. The experimental results reveal that FTCs have impacts on biocover behaviour.
2. Thermal properties (thermal conductivity and thermal diffusivity) of biocovers change due to FTCs. The combined effects of the following phenomena are responsible for changes in thermal properties: (i) FTC induced volume change, (ii) FTC induced reduction of grain size of compost biocover; and (iii) crack formation under freeze-thaw conditions.
3. It is discovered that the contribution of the FTC sequences toward changes in thermal properties is not the same. The first two/three FTCs have greater influence on changes in the thermal properties.
4. An empirical equation has been proposed which is in accordance with the obtained experimental data. The overall trend of the thermal properties of compost-based biocovers under FTCs shows a sharp decrease in first two/three FTCs, followed by a very smooth decrease or constant behaviour in consequent FTCs.
5. The column experiments depict that both the geotechnical and geo-environmental properties of biocovers can be changed under sequential FTCs and CH₄ injection

periods, hence affecting the performance of biocovers and the LFG emissions in biocovers.

6. Most of the CH₄ oxidation takes place at a depth between -25 and -40 cm. This indicates that the lower layers (-35 and -25 cm) play a major role in CH₄ oxidation and that the effect of the upper layers (-15 and -5 cm) are less significant. The formation of EPS, high temperature, lack of and excessive water and organic contents have been found as triggering parameters on the performance of biocovers in cold regions.
7. CH₄ oxidation reaches its peak and then follows a gradual downward trend. This clearly indicates that in each stage at the beginning of the experiment, CH₄ oxidation starts quickly and then stabilizes after a couple of days.
8. The temperature, at which CH₄ oxidation stabilizes, appears to correspond to the time during which the peak temperature is recorded for most cases.
9. The temperature at the beginning of the experiment is approximately the same for all four levels, roughly equal to ambient temperature; however, the average of the temperature at various depths in the columns after operation for all the stages of the experiment is higher than the ambient temperature.
10. During the experiment, small yellow/white textures formed in the lower layers of the columns. It is believed that they are correlated with EPS formation. Therefore, with the formation of EPS in the lower layers during FTCs, the overall performance of the biocover compost decreases. The production of EPS was more often observed at a depth of -30 to -40 cm from the compost surface. Thus, the

greatest amount of EPS formation will take place in the effective zone of CH₄ oxidation.

11. The settlement rate of the compost surface decreases as the number of experimental stages increase. The majority of the settlement takes place during 0 FTC.
12. The average grain size of the particles decreases as the number of FTCs increase. After FTCs, a linear increase in the bulk density is obtained as well as a slight improvement in the mechanical properties of the biocover.
13. Although many of the geotechnical and geo-environmental properties have changed throughout the column experiments, the performance of the biocover remains at approximately 80%, even after two FTCs. This level has been recognised as an acceptable level of CH₄ oxidation by Zeiss (2006). Therefore, the approach that has been examined in the present study can be utilized as a mitigation method for LFG emissions in cold regions such as Canada.

Recommendations

The following recommendations are suggested.

1. Certainly, field-studies can be considered as the most reliable method for evaluating compost biocover performance in cold regions. Hence, the designing and building of a pilot plant in the field, and longer periods of monitoring are highly recommended.
2. Due to the higher costs of construction, operation and monitoring the pilot plant in the field, column experiments as a method of study can still lead to additional

information. Modification in the size of the columns could be effective. A larger column size, especially a larger surface, can provide the opportunity for the evaluation of 3D changes rather than 1D observations which have been obtained in the current study. Therefore, other aspects of study (e.g. lateral gas transport) can also be investigated.

3. In a column study, the use of a wide range of CH₄ injection rates (very low and very high) could be considered for future investigations. The presence of vegetation and their associated biological and physical impacts on compost biocover behaviour can be taken into account as well.
4. To simulate real conditions through column experiments, the presence of snow covers in different thicknesses during the implementation of FTCs on compost biocovers can be considered. Moreover, wet- dry cycles and diurnal and seasonal temperature changes could also be considered in order to create similar conditions as field circumstances. In addition for further studies, the considering of the impact of “heavy rainfalls” due to its relevance to the degree of saturation and gas transfer is highly recommended.
5. The behaviour of biocovers in cold region can be examined by using other material and mixtures. For example, a mixture of sand and compost could be an option.
6. A model could be developed to simulate THMBC responses of biocovers in cold regions.