PREDICTION OF WOODCHIP-INDUCED LATERAL PRESSURES ON BIOFILTER WALLS

BY

CHUKWUNONYEREM SAMUEL IMA

A Thesis
Submitted to the Faculty of Graduate Studies
The University of Manitoba
in Partial Fulfillment of the Requirements
for the Degree of

DOCTOR OF PHILOSOPHY

Department of Biosystems Engineering
University of Manitoba
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THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

A biofilter containing structure is susceptible to structural failure just like other agricultural storage structures. A major factor that causes structural failure of most bins is the lateral pressure exerted by stored material on the bin wall. Four experimental studies were conducted to evaluate lateral pressures in a biofilter bin using woodchips as medium material. The objective of the first study was to determine the physical properties of media material, which are necessary for calculating wall loads. Porosities, bulk densities, angles of repose, and coefficients of friction of 100:0, 80:20, and 60:40 woodchip:compost mixtures at moisture contents of 40, 60, and 80% were measured. Porosity decreased, but bulk density, angle of repose, and coefficient of friction all increased with increasing moisture content of the media.

The second study measured the magnitude of lateral pressure caused by woodchips of different moisture contents (37, 45, 58, and 60% w.b.) in model bins. Three model biofilter bins were employed. Each bin was 0.5 m by 0.5 m, and 1.2 m tall. Lateral pressures were measured with pressure sensors mounted on the bin wall at 0.2, 0.5, 0.7, and 0.9 m above the bin floor. Lateral pressures increased as the moisture content of woodchips increased. Existing pressure equations did not accurately predict pressures in biofilter bins in most cases.

Biofilters are subject to continuous variation in moisture content because of repetitive wetting and drying phenomenon of the media materials. The third study investigated lateral pressure variation in biofilters due to wetting and drying cycles. The same model

bins described in the second study were used. Lateral pressures were measured at the same locations using the same pressure sensors as in the second study. Media moisture content was measured with relative humidity sensors located at 0.2, 0.6, and 1.0 m above the bin floor. Wetting of the material was achieved by surface irrigation. A ventilation fan was used to facilitate drying of the material. Five wetting and drying cycles were completed. Lateral pressure increased as the number of wetting and drying cycles increased. Analysis of variance performed at 5% significance level showed significant differences ($p < 0.0001$) in lateral pressure between cycles. A prediction model that estimates peak lateral pressure in each cycle was generated.

Changes in moisture content of media material impose hygroscopic pressure on the bin walls. A theoretical model was developed for determining hygroscopic pressure on bin wall. A swell test conducted to determine important parameters of the model showed that change in volume of woodchips is directly proportional to change in its moisture content. The test also revealed the values of k (constant of proportionality between change in volume and change in moisture content of woodchips) and n (constant of power) for woodchips to be $1 \times 10^{-6}\,m^3$ and 1, respectively.

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I appreciate my Uncle and his wife, Dr. and Dr. (Mrs.) B.N.T. Chukwu, for sponsoring my undergraduate education; all my siblings for the amazing support they have given me in various ways; and my Church, Immanuel Fellowship, for their encouragement and prayers. Finally, I appreciate God Almighty for seeing me through this program.

DEDICATION

I dedicate this thesis to my beloved parents, Mr. Okereke and Mrs. Nwadulafo Eunice Ima, who brought me forth into this world and laid a solid foundation for success for me through the grace of God. Their labour of love in my life would remain indelible from my heart.

I extend the dedication of this thesis to my beautiful and precious wife, Dr. Amarachi (Amy) Ima, for her unfailing love to me; for her ceaseless prayers for me; for being so patient with me especially as it relates to spending quality time together; and for continuously being a tremendous support to me.

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1. INTRODUCTION

Storage of bulk solid materials has always been a concern. The first available record of storage of agricultural materials dates back to several centuries ago when Joseph took responsibility for the grain storehouses in Egypt (Kramer 1944) (cited by Blight 1986). From that time until the nineteenth century there was limited information on improved techniques for constructing agricultural storage structures. In the nineteenth century, a carpenter by the name of Oliver Evans, who was born at Newport, Delaware, designed and constructed the first bulk material storage structure using lumber. Although at that time he knew nothing about material pressures, he found by experience that the walls of the structure bulged out of shape and sometimes failed if certain thicknesses of lumber were not used for the walls in structures of various sizes (Kramer 1944). In addition, he found that if the bins were built beyond a certain height, the wood at the bottom of the structure would be crushed under the load. Based on his observation, he developed a second design which was able to carry the loads using the least amount of lumber. Nowadays, storage of agricultural materials has developed into complex systems involving several advancements in technology. However, like most other bulk solid storage structures, agricultural storage structures are subject to structural failure. Structural failure may be in the form of cracking, denting, complete splitting or collapse of the walls of the storage structure (Blight 1986).

Several reports of failures in structures for storing agricultural materials exist. For instance, Wigram (1980) conducted an inventory of Swedish grain silos and reported the walls of 34% of silos investigated were cracked vertically. Other reports of failures in agricultural storage facilities are given by Ravenet (1981), Theimer (1969) (cited by Blight 1986), Jenike (1967) (cited by Blight 1986), and Sadler (1980). Failure of a storage structure can result in a substantial economic loss, comprising of the failed structure, damaged material, and possible personal injury. Several factors contribute to structural failure, namely: improper construction techniques, field alteration of the structure, inferior foundations, change in material properties, unsatisfactory management techniques, and vertical and lateral pressures exerted by the stored material on the walls of the storage structure (Schwab et al. 1989, Weiland 1964). Among these factors, lateral pressure plays an important role.

Estimation of loads in a storage structure is uncertain because any slight change in a single parameter can change the loads that exist within the structure, for example, variations in the flow pattern within a bin, type of material in the bin, the quality of construction of the bin, and variation in material properties (such as moisture content) can have a major effect on the magnitude of the pressures in the storage structure (Blight 1986; Thompson et al. 1995). Thus, lateral pressure is a great concern when dealing with agricultural storage facilities.

Many experimental studies have been conducted to measure lateral pressure exerted by stored agricultural materials on their containing structures. However, all the studies available in the literature relate to grain bins. Little or no documented research has been reported on the lateral pressure exerted by biofilter packing materials on the walls of biofilters. Biofiltration, even though a relatively new technology, is finding wide application in the agricultural industry because of its effectiveness for odour control. In most cases the biofilter media is wet and, therefore, behaves differently in varying environmental conditions as opposed to grain in storage bins which are usually in a dry state, making it difficult to directly apply results obtained from research on lateral pressure in grain bins to biofilters. Thus, the long term objective of this research project is to develop a useful knowledge necessary for understanding the nature of lateral pressures in biofilters.

1.1 Objectives

1. To determine the porosity, bulk density, angle of repose, and coefficient of friction of three typical woodchip:compost mixtures [i.e., 100:0 (100% woodchip and 0% compost), 80:20 (80% woodchip and 20% compost) , and 60:40 (60% woodchip and 40% compost) by mass].

2. To measure lateral pressure caused by woodchips in a model bin.

3. To determine whether existing pressure prediction equations are applicable to biofilters.

4. To determine the influence of moisture content on lateral pressure.

5. To determine the impact of repetitive wetting and drying of woodchips on the lateral wall loads in a model biofilter bin.

6. To develop a theoretical model for determining hygroscopic loads caused by woodchips.

1.2 Thesis Outline

Chapter 1 of the thesis gives an overview and a general concept of lateral pressure as it relates to storage of agricultural materials. Chapter 2 reviews scientific literature pertinent to the studies conducted. Chapters 3 to 6 consists of manuscripts written from the results of the studies conducted. Each chapter of chapters 3 to 6 is written from a distinct experimental study. Current status of each manuscript discussed in chapters 3 to 6 are shown in Table 1.1. General conclusions of the studies as well as recommendations for future research are discussed in chapter 8.

Table 1.1 Current status of each manuscript in chapters 3 to 6.

Objective	Chapter	Status of manuscript	Journal
1	3	Published, Vol. 1X, BC 07 005, 2007.	Agricultural Engineering International
2	4	Published, Vol. X. BC 08 002, 2008.	Agricultural Engineering International
3	5	Submitted	Canadian Biosystems Engineering
4	6	Submitted	Biosystems Engineering

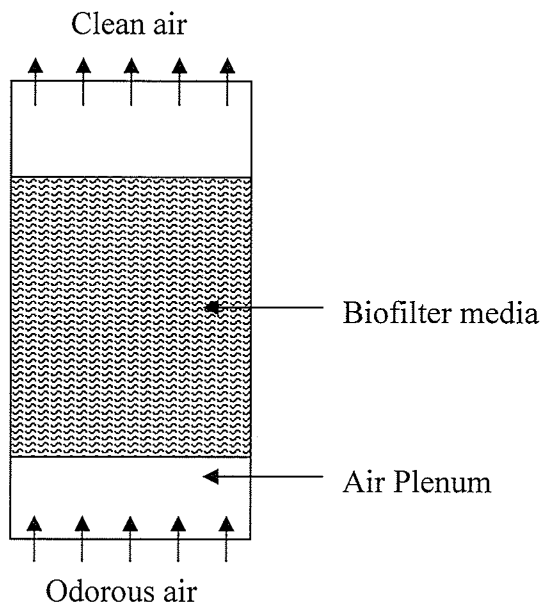
2. LITERATURE REVIEW

2.1. Odour emissions control through Biofiltration

Odour emissions have become a major social and environmental concern as the world population increases. The proliferation of stringent national and international environmental regulations aimed at implementing better odour control measures clearly indicates the importance of odor emissions control. Odorous gases, the source notwithstanding, are offensive and constitute a nuisance to any neighbourhood subjected to them. The perception of a facility by the public, no matter how important the facility seems to be, changes significantly if the facility emits odorous gases into the immediate environment. Given that odorous gases evoke emotional response from residents living close to the odour source, Zhang et al. (2002) pointed out that good odour control programs and facility management practices are essential.

Most of the conventional technologies currently available for treating odorous gases (e.g., incineration) are too expensive for the current operation of livestock units and for small-scale industries. One alternative technology that might be affordable is biofiltration. Biofiltration is a biological odour control technology in which contaminants present in an air stream are broken down or oxidized by microorganisms fixed to a biologically active porous medium. Biofiltration takes place in a device called a "biofilter' (Fig. 2.1). A biofilter could be a container of any shape that has an enclosed plenum, a support rack, and packing materials (media) sitting on top of the support rack (Janni et al. 1998).

Figure 2.1 Schematic of a biofilter.



The biofiltration process starts with transfer of contaminants from the air stream by convection to the biofilter, which contains the media in a wet environment. As contaminants pass through the biofilter, they are either adsorbed on the surfaces of the biofilter medium particles or absorbed into the moist surface layer (biofilm) of these particles (Devinny et al. 1999). Microorganisms (e.g., bacteria and fungi) living on the medium feed on the contaminants and utilize the energy obtained for their growth and maintenance. The metabolic by-products of the biological degradation process are primarily carbon dioxide and water. The process can be expressed as:

Organic Pollutant + O_2 = CO_2 + H_2O + Heat + Biomass (Anit and Artuz 2000)

The biofiltration process can only be successful if the contaminant of interest is biodegradable and non-toxic to the microorganisms carrying out the metabolism.

Biofiltration has been used extensively since the 1920s in wastewater and solid waste treatment. However, it was only in the 1950s that such a technique was first applied to waste gas treatment (Ottengraf and Diks 1992, Kennes and Thalasso 1998). Ever since then, biofilters have been used successfully in different countries such as Germany, New Zealand, Japan, United States, Canada, and Russia to control odours, air toxics, as well as VOCs (Leson and Winer 1991). Bohn and Bohn (1988) and Wada et al. (1986) (quoted by Williams 1993) reported that biofiltration can remove biodegradable odorous compounds such as hydrogen sulfide and nitrous oxides with removal efficiencies of up to 98 – 99%. Beerli and Rotman (1989) reported removal efficiencies of VOCs in the range of 65 - 92% and for specific gases like methane above 95%. Sweeten et al. (1991) studied odour control from a poultry manure composting plant using a soil biofilter and reported removal efficiencies between 87 and 99%. More examples of biofiltration performance data are summarized by Alder (2001). Swanson and Loehr (1997) gave a non-exhaustive listing of specific compounds that have been removed from waste gas streams with biofiltration. Devinny et al. (1999) gives an excellent review of the biofiltration process, including all the important parameters necessary for optimum functional performance of the biofilter.

2.1.1 Advantages of Biofiltration

1. Biofiltration allows for degradation of the contaminants into innocuous or less-contaminating products such as carbon dioxide and water.
2. Biofiltration allows effective pollution control at relatively low capital costs. Usually, biofilters are constructed from locally available materials such as plastic

pipes and lumber. In addition, assembling of the system could be done by the use of carpenters, plumbers, and earthmovers.

3. Cost of operation is generally low. Operating costs include the cost of electricity for operating the fans and monitoring costs.
4. Minimal secondary waste streams requiring a subsequent treatment are produced.

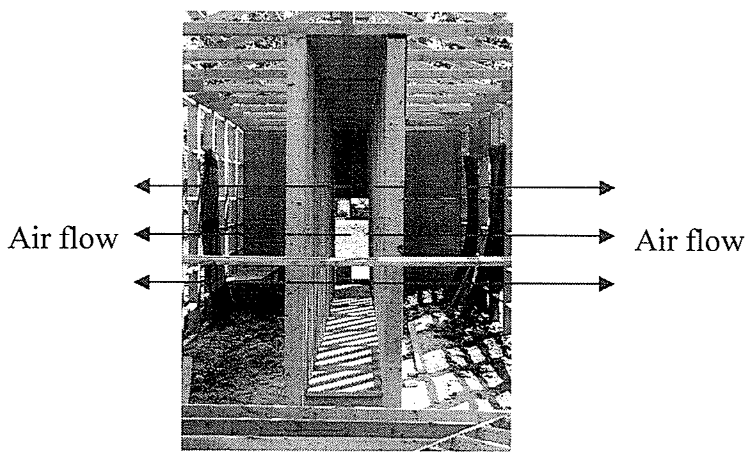
2.1.2 Disadvantages of Biofiltration

1. Biofiltration is only appropriate for treating waste gas streams containing low concentrations of organic compounds (about $1 g/m^3$) or other compounds that are easily degradable (Devinny et al. 1999).
2. Large areas of land may be required especially in industrial applications.
3. Media clogging may occur with time. Clogging hinders the passage of air through the media, thereby causing oxygen limitation and reducing the contaminant removal efficiency of the biofilter.
4. The media will deteriorate with time and would need to be replaced. It is recommended that the media be replaced every 2 - 5 years for optimum performance. Media replacement may take 2 – 6 weeks, depending on bed size (USEPA 2003).
5. It is difficult to control moisture in biofilters due to temperature increases arising from biodegradation process.

2.2 Horizontal Biofilter

In a horizontal biofilter, the inlet air is introduced to a central plenum from where it is pushed sideways into the atmosphere through the biofilter medium. Garlinski and Mann (2002, 2005) (Fig. 2.2) reported the construction and evaluation of horizontal full-scale biofilter. Apart from that, there is limited information about the existence of full-scale horizontal biofilters. However, some research has been conducted with lab scale horizontal airflow biofilters. Choi et al. (2003) conducted a laboratory study to compare the complete removal capacity (i.e., the maximum inlet load of a contaminant that was removed completely) of vertical and horizontal biofilters of the same size and reported a higher complete removal capacity for the horizontal biofilter.

Figure 2.2 Horizontal airflow biofilter.



Sadaka et al. (2002) studied vertical and horizontal airflow characteristics of wood/compost mixtures and reported that resistance to airflow in the horizontal direction was approximately 0.65 times the resistance to airflow in the vertical direction for media mixtures containing woodchips. The difference in airflow resistance was attributed to anisotropy. Anisotropic behaviour occurs when non-spherical particles orient themselves with their major axes lying horizontal when loaded from the top. Since larger, shorter, and straighter air pathways offer less resistance to airflow than smaller, longer, and more crooked air pathways, this orientation creates a situation where more lateral airflow than vertical airflow occurs (Sadaka et al. 2002). Based on their observation, Sadaka et al. (2002) concluded that orientation of media particles can significantly affect the resistance of the particles to airflow.

Anisotropic resistance to airflow has also been noticed in stored grains and oilseeds. Kumar and Muir (1985) compared the pressure data of cleaned wheat and cleaned barley in both horizontal and vertical airflow directions using an arbitrary air velocity of $0.077 m^3/(m^2 s)$. Their result indicated that airflow resistance of wheat and barley were about 50 and 115% higher, respectively in the vertical direction than the horizontal direction. Irvine (1989) conducted research with flaxseed and reported a horizontal airflow resistance of about 0.38 to 0.65 times the vertical airflow resistance. Hood and Thorpe (1992) and Jayas et al. (1987) measured airflow resistance, in both vertical and horizontal direction, of clean canola seeds and of canola seeds containing foreign materials. Their results show that airflow resistance in the horizontal direction was significantly lower than airflow resistance in the vertical direction for both clean canola seeds and canola seeds containing foreign materials. In these studies, anisotropic behaviour was also attributed to orientation of grain and seed particles.

Even though it has been proven that there is less resistance to airflow in the horizontal direction than vertical direction, biofilters are still being typically designed for vertical air flow. This is because horizontal airflow through any material usually faces the problem of short-circuiting in the head space above the material. That is, air travels above the material rather than through the material. Short-circuiting occurs due to media drying and media settlement. Media drying creates air channels in the media through which untreated gas escapes to the top of the bed rather than traveling through the bed. Media settlement, on the other hand, create gaps around the perimeter of the biofilter (i.e., between the media and the walls of the biofilter bin) through which untreated gas escapes to the top of the bed. Short-circuiting will have little effect on a vertical airflow system.

The problem of short-circuiting in horizontal biofilters can be minimized by pressurizing the head space of the biofilter bin (Sadaka et al. 2002, Garlinski 2004, Garlinski and Mann 2005). The field-scale horizontal-airflow biofilter described by Garlinski and Mann (2005) relied on a pressurized headspace created by an inflatable bladder to prevent short-circuiting of air through the biofilter without treatment. Exit velocity uniformity was used to evaluate the pressurized headspace design. The concept of a pressurized headspace was reported to have worked quite well; however, the design is subject to failure if the integrity of the inflatable bladder is jeopardized. Mann et al. (2008) described field-scale horizontal-airflow biofilters with non-pressurized headspace. Solid barriers mounted along the top edge of each biofilter chamber were used to direct the movement of air through the biofilter bed and to avoid vertical movement of the air. Mann et al. (2008) also used exit velocity uniformity to evaluate the non- pressurized headspace design and noted that exit velocity was uniform across the sides, but more air exited through the top surface of the biofilter than was anticipated based on the design of the biofilter.

With horizontal airflow biofilters, a smaller footprint contributes to a taller structure. Increased depth of media yields the potential for lateral pressure on bin wall to become an issue.

2.3 Woodchips as Biofilter Media (Packing Material)

Biofilter medium houses the microorganism and serves as microbial growth environment. It provides physical and chemical conditions appropriate for transfer of contaminants from air to the liquid phase as well as the conditions necessary for biodegradation of contaminants in the biofilm layer. Biofilter media can vary tremendously. Diverse types of organic and inorganic media successfully used in biofiltration have been described in the literature (Kennes and Thalasso 1998). Each media has distinct strengths and weaknesses, which makes it more suitable for some applications than others (Bohn 1996). Most agricultural biofilters use organic media, which could be comprised of 100% inert bulking agents (e.g., woodchips), 100% biological residue (e.g., compost), or a mixture of various proportions of biological residues and inert bulking agents (e.g., 80:20 mixture of woodchips and compost).

There are several advantages in using woodchips as a biofilter media. Woodchips are inexpensive and readily available compared to some other types of biofilter media

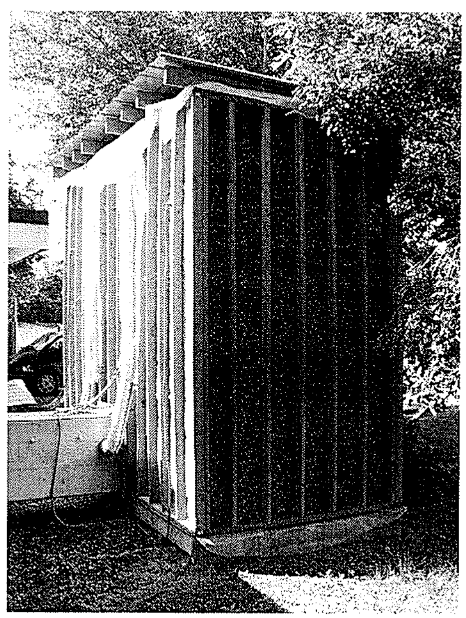
(Skladany et al. 1998, Philips et al. 1995). Woodchips have the excellent quality of resisting bed compaction and allowing for a uniform airflow due to its high porosity. Thus, woodchip media requires less power consumption compared with other media such as compost (Martinec et al. 2000). Wood chips also constitute a reservoir of water that may in some cases reduce fluctuations in packing moisture content due to poor reactor control or excessive heat generation (Devinny et al. 1999). Philips et al. (1995) studied the influence of media settlement and moisture content on pressure drop using 5 different packing materials and reported the least pressure drop per meter of media height for woodchips both during the settling stage and after a wetting period. Even though a 100% woodchip media offers several advantages, it does not contain a sufficient population of microorganisms necessary for biodegradation. Therefore, it may require regular nutrient supply and inoculation (e.g., with activated sludge).

2.4 Structural Performance of Biofilter

The successful operation of a biofilter could be assessed not only by its functional performance, but also by its structural performance. As mentioned previously, bulk material storage structures, in general, are susceptible to structural failure and the biofilter bin is no exception. Structural failure may be in the form of cracking, denting, bulging, complete splitting or collapse of the walls of the storage structure (Blight 1986). Thus, the structural performance of a biofilter could be measured by the durability of the biofilter structure (biofilter bin) and its ability to withstand failure due to pressure exerted by the media materials

Garlinski and Mann (2002) designed the first prototype (Fig. 2.3) of a horizontal airflow biofilter. The biofilter was located at the southwest corner of a research swine unit located at the University of Manitoba Glenlea Research Station. The swine unit consists of several ventilation fans. However, the biofilter was designed to treat exhaust air from only one ventilation fan. The biofilter consisted of two rectangular chambers (filled with woodchips) on each side of a central plenum. Air from the barn ventilation fan was ducted into the central plenum of the biofilter from where it exited to the atmosphere through the woodchip-filled chambers.

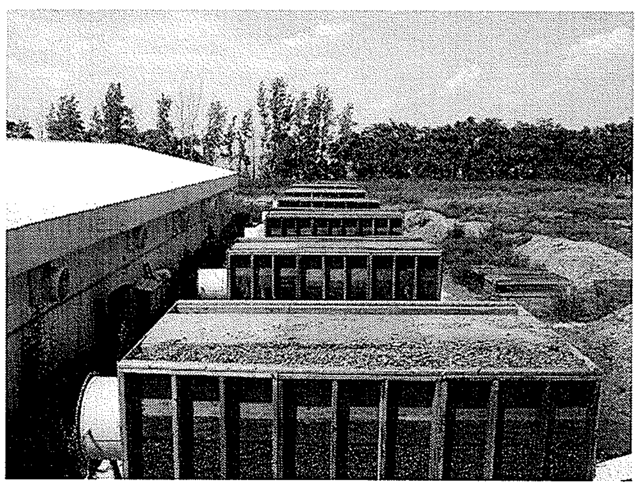
Figure 2.3 First prototype biofilter.



The result obtained from the first prototype showed that the biofilter was useful in reducing odor from the hog barn. However, it was observed that the walls of the biofilter structure were starting to bulge. Bulging of the walls was attributed to lateral pressure exerted by the media materials on the biofilter structure.

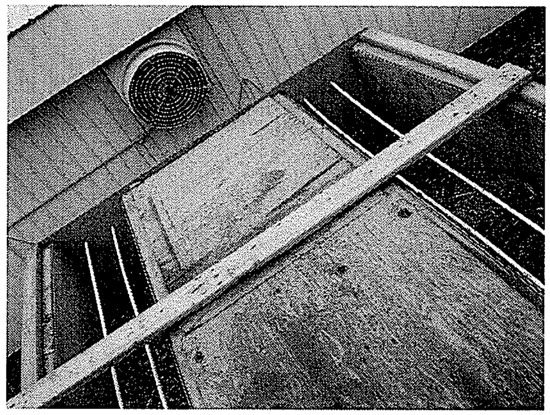
In the summer of 2004, seven full-scale horizontal airflow biofilter units were designed and constructed (Mann et al. 2008) (Fig. 2.4). The biofilters were constructed beside a hog barn located in the rural municipality of Taché, which is about 6 km east of Niverville, Manitoba. The swine unit consisted of seven ventilation fans; so each biofilter unit was meant to treat exhaust air from one of the seven barn ventilation fans. Each biofilter unit consisted of two 0.5 m wide, 3.7 m long, and 3.0 m high woodchip-filled chambers supplied with the same air stream and located on each side of a central plenum. The central plenum in each case was oriented parallel to the direction of airflow from the barn to minimize pressure losses.

Figure 2.4 Full-scale horizontal biofilters.



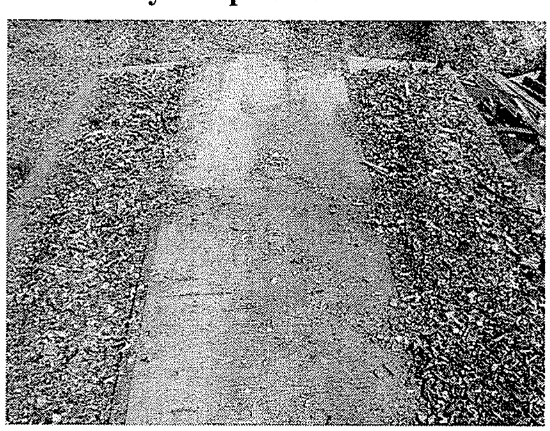
The biofilter units worked quite well functionally. However, it was observed that the walls of the biofilter structures were bulging over time. Bulging of the walls over time was also a major observation in the first prototype biofilter shown in figure 2.3. In order to prevent the structure from an eventual collapse, wooden planks were used as bridges on top of the units to hold the chamber walls of each unit together (Fig. 2.5). This observation was the major consideration that led to the current study of lateral pressures in biofilter bins.

Figure 2.5 A biofilter unit showing bridging plank.



Porous materials in general have the tendency of settling over time. Figure 2.6 shows the initial top view of Fig. 2.5 (i.e., at the time when it was newly filled with filter materials and when settling had not yet occurred). Therefore, it is hypothesized that media settling is a major factor that caused bulging of the walls observed in Fig. 2.5. When media materials settle, they compact and exert additional lateral pressure on the walls of the structure. The lateral pressure may increase over time and eventually cause the structure to fail.

Figure 2.6 Top view of a biofilter unit at the time filling was initially completed.



A major contributor to media settling is fluctuations in moisture content of the media materials (Janni et al. 1998). The recommended optimum moisture content for a biofilter with an organic media ranges between 40 – 80% (Devinny et al. 1999). This implies that the biofilter should be operated within this moisture content range for optimum performance. However, maintaining the optimum moisture content range in a biofilter is a difficult task. This is because of continuous ventilation that takes place and also, because of temperature increases in the system arising from the biodegradation process. These two processes tend to drive away moisture from the system. One way to maintain appropriate moisture content in the biofilter is by surface irrigation whenever the moisture content of the media falls below the desired range. A practical solution for an agricultural biofilter is to design an irrigation system that applies water to the surface of a biofilter once per day (Schmidt et al. 2006; Mann et al. 2002). A consequence of this practical solution is that the bulk material (i.e., the woodchips) would be subject to continuous wetting and drying cycles. Wetting and drying cycles make biofilter operation quite different from operation of other agricultural storage systems such as the grain bin. It is hypothesized that wetting and drying cycles could cause a significant increase in lateral pressure on the wall of the biofilter bin.

2.5 Pressure Theories

2.5.1 Shallow bin theories

2.5.1.1 *Rankine's theory*

The Rankine's (1857) theory is also known as the theory of conjugate pressure. In his experiment, Rankine (1857) (cited by Manbeck et al. 1995) examined an incompressible, cohessionless, granular mass of indefinite extent and having active and passive pressures as the minimum and maximum conditions. The particles are held in position by friction between each other. Hough (1957) defined active pressure as the condition in which the retaining wall moves away from the mass, allowing the material to expand horizontally. This is similar to the phenomenon that occurs in storage bins. Passive pressure, on the other hand, occurs when the wall moves towards the mass, forcing compression of the material. The major assumptions of Rankine include:

1. the pressure at any point in the mass is proportional to the depth below the surface
2. the resultant pressure acts at a point $\frac{2h}{3}$ below the surface of the granular material
3. the presence of the retaining wall does not affect the relationship between the vertical and horizontal pressure in the mass
4. the retaining wall is rigid
5. the resultant pressure on the vertical wall acts horizontally

Based on his assumptions, he developed equations for active lateral pressure:

(a) The lateral pressure at any point is given by:

$$P = w.h.\left[\frac{1-\sin\theta'}{1+\sin\theta'}\right] \tag{2.1}$$

(b) The lateral pressure over the total wall height is given by:

$$P_i = \tfrac{1}{2} w.H^2.\left[\frac{1-\sin\theta'}{1+\sin\theta'}\right] \tag{2.2}$$

where,

P = lateral pressure at any point (kg/m^2)

P_i = total lateral pressure (kg/m)

w = bulk density of granular material (kg/m^3)

h = depth of granular material above the point under consideration (m)

H = total height of wall (m)

θ' = angle of internal friction (°)

The major limitation with Rankine's (1857) theory is the assumption that the presence of the retaining wall introduces no changes in shearing stresses or pressure distribution (Taylor 1948) (cited by Smith and Simmonds 1983). The stress conditions at the wall are definitely different from those within the material because of different conditions of friction and cohesion at the two locations. Thus, this theory is not commonly used in storage bin design (Gupta 1971).

2.5.1.2 *Coulomb's theory*

Coulomb (1776) (cited by Gupta 1971) developed a method for analyzing forces on retaining walls using sliding wedges of material. His method is popularly known as the theory of maximum wedge and is based on the concept of a failure wedge which is bounded by the face of the wall and by a surface of failure that originates at the base of the wall (Ketchum 1919). In his experiment, Coulomb considered the kind of cohessionless material that was used by Rankine (1857) (cited by Manbeck et al. 1995). His major assumptions are:

1. the surface of failure is a plane
2. the thrust on a vertical wall acts in some known direction
3. the resultant pressure acts at a point $\frac{2h}{3}$ below the surface of the granular material

Based on his assumptions and analyses, he developed an equation for active pressure:

$$P_i = \frac{1}{2} w.H^2 . \left[\frac{\cos^2 \theta'}{(1+\sin\theta')^2} \right] \tag{2.3}$$

Coulomb's theory is considered accurate when predicting active pressure in shallow bins (Stewart 1967). However, the equation is not commonly used in agricultural engineering design (Britton 1967).

2.5.2 Deep Bin Theories

2.5.2.1 *Airy's theory*

Airy's (1897) work was an expansion of the work initiated by Coloumb (1776) (cited by Gupta 1971) on sliding wedge theory. Airy (1897) (cited by Smith and Simmonds 1983) gave a valuable discussion on the theory of grain pressures and also the results of a series of experiments to determine the angle of repose, the coefficient of friction of grains on bin walls, and the forces on the plane of rupture. Based on his analyses, Airy (1897) proposed an equation for calculating the pressure of grain on bins. Two different cases were considered: shallow and deep bins. Ketchum (1919) describes shallow and deep bins depending upon the ratio of width and or diameter of the bin to the depth. A shallow bin is described as a bin in which the plane of rupture cuts the surface of the grain within the bin, whereas a deep bin is described as one in which the plane of rupture intersects the side of the bin wall.

Airy's (1897) equation for calculating unit lateral pressure in a shallow bin is such that:

$$P = w.h.\left[\frac{1}{\sqrt{\mu(\mu+\mu')}+\sqrt{1+\mu^2}}\right]^2 \tag{2.4}$$

Airy's (1897) equation for calculating unit lateral pressure in a deep bin is such that:

$$P = \frac{w.d.}{\mu+\mu'}\left[1-\frac{\sqrt{1+\mu^2}}{\sqrt{\frac{2h}{d}(\mu+\mu')+1-\mu.\mu'}}\right]^2 \tag{2.5}$$

where,

d = width of bin (m)

μ = coefficient of friction of material on bin wall

μ' = coefficient of internal friction of material

Airy's (1897) analysis is of the prediction that the horizontal pressures will reach a maximum at some intermediate level and then begin to decrease. This observation occurred because Airy (1897) had neglected the contribution of one of the walls in his force balance (Smith and Simmonds 1983). The relative complexity of Airy's (1897) method renders it unsuitable for design purposes (Smith and Simmonds 1983).

2.5.2.2 *Janssen's theory*

In 1895, Janssen proposed his theory for determining lateral pressure on bin walls. He based his theory on the following assumptions:

1. the bin has a uniform area and a constant circumference
2. vertical pressure is uniform at any horizontal plane
3. horizontal pressure is uniform over a perimeter of cross section
4. the ratio of lateral to vertical pressure is constant throughout the material depth
5. the shear stress at the wall is a linear function of the horizontal pressure

Based on these assumptions, he developed his now famous equation for calculating lateral pressure:

$$P = \frac{w.R}{\mu}\left[1 - e^{-\frac{k.\mu.h}{R}}\right] \qquad (2.6)$$

where,

R = hydraulic radius (m) = A/U

U = perimeter of bin (m)

k = ratio of lateral to vertical pressure

Currently, Janssen's (1895) (cited by Manbeck et al. 1995) theory is most widely used in the design of grain bins (Mosey 1979). Several experimental investigations have shown that values predicted by Janssen's (1895) formula are reasonably accurate for the filling and static situations. Also, numerous codes available to the design engineer for predicting static lateral pressure on bin walls recommend Janssen's equation (Manbeck et al. 1995). Such codes include the Canadian Farm Building Code (CFBC 1990) and ASAE (American Society of Agric Engineers) EP433 (ASAE 1999). The ACI (American Concrete Institute) 313-91 code (ACI 1991) recommends using either Janssen's or Reimbert's equation. The German design code, DIN 1055, (DIN 1987) does not cover static pressure conditions. However, the code recommends the use of Janssen's equation when determining lateral pressures during filling of a bin.

2.6 Properties of Bulk Agricultural Materials

The properties of bulk agricultural materials include bulk density, moisture content, angle of repose, angle of internal friction, coefficient of friction, and pressure coefficient. Each of these properties is defined below.

2.6.1 Bulk density

Bulk density refers to the weight per unit volume of a material. Mathematically, bulk density is expressed as:

$$w = \frac{W}{V} \tag{2.7}$$

Where:

w = bulk density of material

W = weight of V volume of material

V = volume of material

ASAE Standard, SD241.1 gives approximate values of bulk density for some grains and seeds (ASAE 2003). Muir and Sinha (1987) list the bulk densities of cereal and oilseed cultivars grown in Western Canada. Walker (2007) lists the bulk densities of various bulk materials.

2.6.2 Moisture content

Moisture content refers to the amount of water present in the material. Moisture content is usually expressed as a percentage of the entire mass of material:

$$m = \frac{Wm}{W} * 100 \qquad (2.8)$$

Where:

m = moisture content expressed in percentage

Wm = weight of water

W = weight of a given volume of material

ASAE Standards; S352.2, S353, and S358.2 outline the procedures for moisture measurement of unground grains and seeds, meat and meat products, and forages, respectively (ASAE 2003).

2.6.3 Angle of repose

The angle of repose (ϕ) is an engineering property of bulk materials. It could be defined as the maximum angle from horizontal at which a given material will rest on a given surface without sliding or rolling. In other words, it is the angle between the edge of a pile of material poured onto a floor and the horizontal surface under zero normal pressure. The angle of repose is related to the surface area, coefficient of friction, and flowability of the material. Usually, a material having a low angle of repose would form a flatter pile than a material with a high angle of repose. Mujumdar (2006) lists the angles of repose of selected agricultural bulk materials. Muir and Sinha (1987) list the angles of repose of cereal and oilseed cultivars grown in Western Canada.

2.6.4 Coefficient of friction

Coefficient of friction is the ratio of the limiting frictional force to the corresponding normal force. Coefficient of friction is represented as follows:

$$\mu = \frac{F}{N} = \tan\theta \qquad (2.9)$$

Where:

μ = coefficient of friction of material on bin wall

θ = angle of friction of the material

F = frictional force (N)

N = normal force (N)

Mujumdar (2006) lists the coefficient of friction against four different structural materials for selected agricultural bulk materials. Muir and Sinha (1987) list the coefficients of friction of cereal and oilseed cultivars grown in Western Canada.

2.6.5 Angle of internal friction

Angle of internal friction is the angle whose tangent is equal to the coefficient of internal friction of a given material. Surface tension, surface roughness, and interlocking of material particles caused by cohesion affect the angle of internal friction. Angle of internal friction is given by the equation:

$$\mu' = \tan\theta' \tag{2.10}$$

Where:

μ' = coefficient of internal friction of the material

θ' = angle of internal friction (i.e., material on material)

Moya et al. (2002) give the values of angle of internal friction of some granular agricultural materials.

2.6.6 Pressure coefficient

Pressure coefficient refers to the ratio of lateral to vertical pressure of a given material and is symbolized as k. Rankine (1857) proposed a mathematical equation for k (in active case):

$$k = \frac{1-\sin\theta'}{1+\sin\theta'} \tag{2.11}$$

where:

k = ratio of lateral to vertical pressure

The nature of the pressure coefficient has been a debatable factor. Both Janssen (1895) and Airy (1897) assumed k to be constant irrespective of depth of fill while Ketchum (1919), Kramer (1944) (cited by Blight 1986), and Leczner (1963) all reported that k increased with the depth of fill to a certain depth before becoming constant. Jaky (1948) (cited by Smith and Simmonds 1983) proposed the formula:

$$k = k_o = 1 - \sin\theta' \tag{2.12}$$

for calculating the value of k. Both Rankine's (1857) and Jaky's (1948) equations have been found adequate for calculating k under two different stress conditions. Rankine's (1857) formula represents minimum pressure conditions and is commonly used in agricultural engineering applications (NRC 1965, Hall 1961). On the other hand, Jaky's (1948) equation is suitable for static conditions.

2.6.7 Swelling potential

Bulk agricultural materials have the potential to swell when wetted. The extent to which a particular agricultural material swells under a certain moisture content would depend on the physical characteristics of the material and is refereed to as the swelling potential of the material at that moisture content. Currently there is little knowledge related to swelling potential of bulk agricultural materials. However, much research has been conducted in Geotechnical Engineering to determine the swelling potential of soils (e.g., clay). The standard equipment that is used for measuring swelling potential of soils is the oedometer apparatus and the test conducted with the apparatus is referred to as an oedometer test. In the laboratory, swelling potential is determined by measuring change in volume of the test material due to an applied pressure while the specimen is inundated with water (ASTM 1996). Usually, the amount of swell is measured after movement is negligible. Details of the oedometer apparatus and oedometer test are given in ASTM (American Society for Testing and Materials) Standards; D4546 and D2435 (ASTM 1996).

2.7 Past Research on Lateral Pressure of Agricultural Materials

The first recorded experimental study of lateral pressure of agricultural materials was made by Isaac Roberts (1882, 1884) (cited by Smith and Simmonds 1983). Roberts (1882, 1884) carried out his first experiment on bin models using wheat as the fill material. He observed that the pressure exerted by the stored material on the floor of the bins stopped increasing after the depth of fill exceeded twice the diameter of the bin. His observation prompted him to conduct a second experiment on rectangular bins. However, the second experiment yielded the same result as the first experiment. Ever since the publication of the results obtained by Roberts (1882, 1884), extensive research has been done on pressures in agricultural storage structures. In 1895, Janssen published his famous and widely used lateral pressure theory. The objective of his experiment was to determine the pressure of grain on bin walls. He used square model bins of different sizes. The fill materials used consisted of corn, wheat, and other grains. Janssen (1895) (cited by Manbeck et al. 1995) found that the results obtained from his model compared favorably with his experimental results. Airy (1897) (cited by Smith and Simmonds 1983). conducted studies to develop a theory for grain pressures and to determine the coefficient of friction of various grains using the sliding wedge theory. Based on his observations, he reported a decrease in vertical pressure at the bottom of the bin after a certain grain height was achieved. Thus, his results agreed with that reported by Roberts (1882).

Jamieson (1903) (cited by Smith and Simmonds 1983) measured lateral and vertical pressures on full-sized grain bins and found that his results correlated well with Janssen's (1895) values. Bovey (1903, 1904) (cited by Smith and Simmonds 1983) conducted a series of experiments to verify the results obtained by Jamieson (1903). Bovey's (1903, 1904) results agree quite well with the results presented by Jamieson (1903). Ketchum and Williams (1909) (cited by Ketchum 1919) measured vertical and lateral pressures of wheat and found that their result agreed with Janssen's (1895) formula. Another important observation from the study was that the ratio of lateral to vertical pressure, k, increased as the depth of grain increased. Amundson (1945) (cited by Smith and Simmonds 1983) measured lateral pressure of grain in a bin and observed that his result also agrees with Janssen's (1895) equation. Jakobson (1958) (cited by Britton 1969) analyzed the stress conditions in a bulk bin based on the assumption that particles in the bin settle in a vertical manner as load increases. Hence, Jakobson (1958) developed a formula which is very similar to Janssen's (1895) formula.

Britton (1969) studied lateral pressures in deep bulk fertilizer storage bins. Ammonium phosphate and five other commercial fertilizers were used in this study. The material properties were used to calculate theoretical pressures predicted by Janssen's (1895) equation. Predicted pressures were compared to experimental results. Lateral pressures, due to bulk fertilizer in deep bins, were found to be accurately predicted by Janssen's

(1895) equation. However, the results did not confirm the assumption that the ratio of lateral to vertical pressure, k, is constant all through the bin and neither did it confirm the assumption that vertical pressure is constant across a horizontal section of a bin. Caughey et al. (1951) conducted extensive model bin studies to investigate the pressures exerted by various granular materials (namely; corn, soy beans, wheat, cement, sand and pea gravel). In general, Caughey et al.'s (1951) results agree with Janssen's (1895) theory even though the pressures measured from some of the materials were less than the values suggested by Janssen's (1895) theory. Prante (1896) (cited by Smith and Simmonds 1983) reported experiments conducted on full-size cylindrical iron bins using wheat as the fill material. Lateral pressures of wheat at rest were found to be slightly smaller than those calculated using Janssen's (1895) formula.

North (1954) (cited by Smith and Simmonds 1983) studied grain pressure in corrugated metal silos and observed values quite different from that predicted by Janssen's (1895) equation. This difference was attributed to wall flexibility. Gupta (1971) undertook an investigation to determine the lateral pressures exerted by wheat against flexible container walls. Flexible polyethylene containers of sizes varying in diameter and height were used in the study. Lateral pressures in the test containers were determined by measuring percent circumferential elongation in the containers. The material properties were used to calculate parameters in Janssen's (1895) equation. Janssen's (1895) equation was found to be inapplicable in predicting lateral pressures in flexible containers. Dale and Robinson (1954) measured corn pressure and reported that changing the moisture content of a granular material at any point in time affects the pressure value predicted by Janssen's (1895) equation.

Zhang et al. (1993) measured lateral pressures and resultant vertical forces during discharge of wheat, barley, and canola in a smooth and corrugated-walled model bin. They reported that maximum dynamic lateral pressures and resultant vertical forces for the grains were higher than static pressures in both bins. They also observed that lateral pressure and resultant vertical forces reached their peaks in 0.7 and 7.0 s, respectively.

The historical review reveals that quite an extensive amount of work have been done in the past to measure lateral pressure of bulk agricultural material on its containing structure. Nevertheless, all the work was done using grain as the fill materials. Also, all the past research was conducted with the fill material in a dry state, thereby representing the typical conditions in grain bins. Biofilters operate in a wet medium. The recommended moisture content range for optimum biofilter operation is 40-80% by weight (Devinny et al. 1999). This contrast suggests that a biofilter operates in different environmental conditions compared to the grain bin and that lateral pressures on a biofilter structure might most likely be different from that on a grain bin. Furthermore, the issue of wetting and drying cycles, which is a major phenomenon in biofiltration was not discussed in the past research. Given that the use of biofilters for odor control in the agricultural industry is increasing, it is therefore, necessary to study lateral pressures in the biofilter. Thus, four related studies were conducted to determine lateral pressures in model biofilter bins using woodchips as the packing material. The results of the studies were reported in chapters 3 to 6. The studies include:

1. Physical properties of woodchip:compost mixtures used as biofilter media.
2. Wall pressures caused by wet woodchips in a model biofilter bin.
3. Lateral pressure variation in a model biofilter bin due to wetting and drying cycles.
4. Theoretical model for hygroscopic pressure caused by woodchips.

3. PHYSICAL PROPERTIES OF WOODCHIP:COMPOST MIXTURES USED AS BIOFILTER MEDIA

3.1 Summary

Knowledge of the physical properties of biofilter media mixtures is necessary for calculating wall loads in biofilters. The objective of this study was to determine the physical properties of biofilter media consisting of mixtures of woodchips and compost in various proportions. Porosities, bulk densities, angles of repose, and coefficients of friction of 100:0, 80:20, and 60:40 woodchip:compost mixtures at moisture contents of 40, 60, and 80% were measured. Porosity decreased, but bulk density, angle of repose, and coefficient of friction all increased with increasing moisture content of the woodchip:compost mixtures.

3.2 Introduction

Although biofiltration is recognized to be an effective odor control technology, there are a number of factors to be considered in the design of a biofilter. For example, knowledge of the physical properties of biofilter media is necessary to study the loads created on the walls of the biofilter structure. Thus, the objective of this study was to determine the porosity, bulk density, angle of repose, and coefficient of friction of three typical woodchip:compost mixtures (i.e., 100:0, 80:20, and 60:40 by mass).

3.3 Materials and Methods

3.3.1 Woodchips and compost

Materials used in this study consisted of woodchips and compost. Woodchips and compost are both readily available and their mixtures have proven to be efficient in biofilter operations, especially in the agricultural industry (Hong and Park 2004). For this study, the compost was purchased from a garden center located in Winnipeg, Manitoba. Details of the composting process were not available, but the compost did not have any unpleasant odor. As such, it was assumed that the compost had reached maturity. The woodchips were also obtained from a local supplier in Winnipeg, Manitoba, and consisted of chipped lumber. The length of the woodchips varied according to the following distribution (determined by sieving and expressed as a percentage of total wet mass): <2 mm (4.9%); 2 to 2.4 mm (2.5%); 2.4 to 3.4 mm (4.5%); 3.4 to 6.7 mm (14.2%); 6.7 to 19 mm (49.9%); 19 to 25 mm (9.5%); > 25 mm (14.4%). Three mixtures were created by adding woodchips and compost in the following ratios (mass basis): 100% woodchips and 0% compost (100:0), 80% woodchips and 20% compost (80:20), and 60% woodchips and 40% compost (60:40). The initial moisture contents of woodchips and compost before mixing were 15.3 and 61.5%, respectively. Moisture contents were determined by the oven dry method (ASAE 2003, Bundalli and Martinez 1982) and expressed on a wet mass basis.

3.3.2 Porosity

Porosity is the ratio of the pore space to the total volume occupied by the material. The "five-gallon pail method" (Rosen et al. 2000) was used to determine the porosity of the media mixtures. Five gallons of water was placed into a pail and its level was marked on the inside of the pail. After emptying the water, the medium was placed into the pail until it was about one-third full. The pail was dropped 10 times from a height of 15 cm onto the floor. Media was added to fill the pail two-thirds full and the pail was dropped 10 times from a height of 15 cm onto the floor. Media was added to the "full line" mark that was previously made on the pail and the pail was dropped 10 times from a height of 15 cm onto the floor. Media was finally added to fill the pail to the "full line" mark. Water was added to the pail to the "full line" mark. The volume of water added was recorded. The porosity of the media was calculated using the equation provided in Rosen et al. (2000) as follows:

$$P = \frac{V}{5} * 100 \tag{3.1}$$

where, P = Porosity (%), V = Volume of water added (gallons). Six replications were completed.

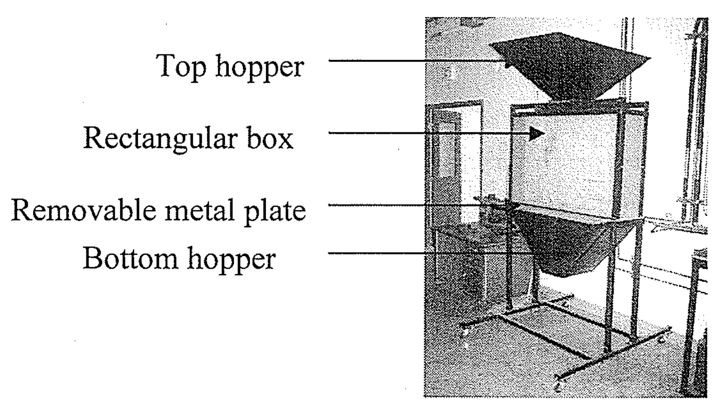
3.3.3 Bulk density

Bulk density refers to the mass per unit volume of a given material. To measure bulk density of the mixture of woodchips and compost, an empty 20 L pail was weighed on a scale and the mass was recorded. The container was then filled to the top with the test material and the mass of the material was recorded. Bulk density was calculated by dividing the mass of the material by the volume of the material (Asoegwu et al. 2006, Pechon et al 2007). Six replications were completed and the average value was recorded.

3.3.4 Angle of repose

Angle of repose can be defined as the maximum angle from horizontal at which a given material will rest on a given surface without sliding or rolling. In other words, it is the angle between the edge of a pile of material poured onto a floor and the horizontal surface under zero normal pressure. The filling angle of repose was determined by measuring the angle of slope of a pile of the test material poured into a rectangular box (Masoumi et al 2003). The box was 122 cm long, 79 cm high and 10 cm wide (Fig. 3.1). The sides of the box representing the width and the back were made of plywood. The front side of the box was made of transparent acrylic material to enable measurement. A hopper located at the top of the box has an adjustable opening at its base through which the material is poured into the box. The base of the box consists of a removable flat metal plate, which also provides a cover to a bottom hopper located beneath the rectangular box. The bottom hopper allows for easy emptying of the material at the end of the test. During testing, the flat metal plate was put in place to cover the bottom hopper and to hold the material inside the box, thereby avoiding spilling of the material onto the floor. After testing, the flat plate is gradually removed to empty the material through the bottom hopper.

Figure 3.1 Apparatus for measuring filling angle of repose.



To run a test, the test material was poured into the box. The height of the pile (measured from the base of the box) and the horizontal distance of spread of the material (measured from the center of the box) were recorded. The angle the pile makes with the horizontal surface is the angle of repose of the material (Muir and Sinha 1988) and it was calculated using the equation:

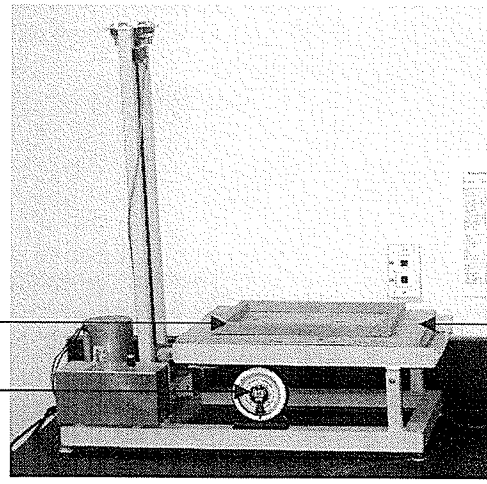
$$\tan\phi = \frac{H_i}{L} \tag{3.2}$$

Where, ϕ = angle of repose (°), H_i = height of pile of material (cm), and L =one half of the total horizontal spread of the material (cm). Six replications were carried out.

3.3.5 Coefficient of friction

Coefficient of friction is the ratio of the limiting frictional force to the corresponding normal force. The coefficients of friction of the media mixtures on a plywood test bed surface were determined using a laboratory slope meter apparatus (Tabatabaeefar et al. 2003) (Fig. 3.2). The apparatus consisted of a tilt indicator and a pivoted test bed, which was capable of inclining or declining. The tilt indicator had a compass which was capable of turning counter-clockwise or clockwise as the test bed inclined or declined, respectively. A motor was used to control the direction of movement of the test bed.

Figure 3.2 Slope meter apparatus.



To measure the angle of slope of the media mixtures, a 46 cm x 33 cm wooden frame placed on the test bed was filled with the test material while the slope meter was level (i.e., angle = 0). The test bed was raised gradually until the wooden frame containing the material began to move. The angle of slope at which the wooden frame started to move was read from the tilt indicator and recorded. The coefficient of friction was determined by taking the tangent of the recorded angle of slope as follows:

$$\mu = \tan^{-1}\theta \qquad (3.3)$$

Where, μ and θ are coefficient of friction and angle of friction (°), respectively. The test was repeated six times and the average value was calculated.

3.3.6 Data Analysis

Data were analyzed using the analysis of variance subprogram (ANOVA) of the Statistical Analysis System (SAS 9.1) computer package. A further analysis of the results was performed using Duncan's multiple-range test for comparison of means. The significance level was kept constant at 5% throughout the analysis.

3.4 Results and Discussion

3.4.1 Porosity

Porosities ranged from 40 to 63% (Tables 3.1-3.3). The 100:0 mixture was the most porous while the 60:40 mixture was the least porous of all the media mixtures at all moisture levels. Duncan's means comparison test indicates that significant differences ($P < 0.05$) exist between the porosities of the different media mixtures at all moisture contents tested. Generally, porosity declined as the proportion of compost in the media increased. This suggests that a higher proportion of woodchips and less compost in the mixture improves the porosity of the media. Improving the porosity of the media, in turn, leads to increased airflow through the media which is necessary for effective biofilter operation. For optimum operation of the biofilter and to reduce the rate of compaction, Sadaka et al. (2002) recommended an 80:20 media mixture. The mean porosities obtained in this study compare well with those obtained by Sadaka et al. (2002); they reported porosities ranging between 48 and 62% for mixtures of woodchips and compost (100:0, 80:20, and 60:40) at a moisture content of approximately 50%.

3.2.2 Bulk density

Material bulk densities ranged from 286 to 529 kg/m^3 (Tables 3.1-3.3). As expected, bulk density increased with increasing moisture content (Jekayinfa 2006) and with increasing proportion of compost in the mixture. Sadaka et al. (2002) reported bulk densities ranging between 301 and 481 kg/m^3 for mixtures of woodchips and compost (100:0, 80:20, and 60:40) at a moisture content of approximately 50%.

Table 3.1 Mean porosities, bulk densities, angles of repose, and coefficients of friction of woodchips and compost at 40% moisture content (n = 6)[1].

Media mixture	Porosity	Bulk density	Angle of repose	Coefficient of friction
	%	kg/m^3	°	
100:0	[2]$63^a \pm 1.3$	$286^c \pm 1.7$	$38^a \pm 1.6$	$0.51^b \pm 0.02$
80:20	$57^b \pm 1.7$	$357^b \pm 1.8$	$35^b \pm 0.8$	$0.55^a \pm 0.03$
60:40	$47^c \pm 1.9$	$478^a \pm 2.1$	$32^c \pm 1.3$	$0.56^a \pm 0.04$

[1] n = number of replications
[2] In each of tables 3.1-3.3, superscripts (a-c) beside the mean values represent Duncan's multiple-range means comparison test results. Means for media types in individual physical property having the same letters are not significantly different at the 5% level of confidence.

Table 3.2 Mean porosities, bulk densities, angles of repose, and coefficients of friction of woodchips and compost at 60% moisture content (n = 6)[1].

Media mixture	Porosity	Bulk density	Angle of repose	Coefficient of friction
	%	kg/m^3	°	
100:0	[2]$61^a \pm 1.4$	$299^c \pm 2.5$	$39^a \pm 1.4$	$0.53^b \pm 0.04$
80:20	$54^b \pm 1.4$	$370^b \pm 2.6$	$37^a \pm 1.2$	$0.59^a \pm 0.04$
60:40	$43^c \pm 1.0$	$497^a \pm 2.1$	$33^b \pm 1.4$	$0.63^a \pm 0.03$

Table 3.3 Mean porosities, bulk densities, angles of repose, and coefficients of friction of woodchips and compost at 80% moisture content (n = 6)[1].

Media mixture	Porosity	Bulk density	Angle of repose	Coefficient of friction
	(%)	(kg/m^3)	(°)	
100:0	[2]$60^a \pm 1.2$	$314^c \pm 2.4$	$41^a \pm 2.1$	$0.53^c \pm 0.03$
80:20	$52^b \pm 1.5$	$392^b \pm 1.9$	$39^b \pm 0.9$	$0.62^b \pm 0.03$
60:40	$40^c \pm 1.6$	$529^a \pm 1.4$	$37^b \pm 1.6$	$0.68^a \pm 0.02$

3.4.3 Angle of repose

Angles of repose ranged from 32 to 41° (Tables 3.1-3.3). The angle of repose of the 100:0 media mixture was the greatest while that of the 60:40 media mixture was the least at all moisture levels tested. Duncan's means comparison test indicates differences ($P < 0.05$) in angles of repose between the media mixtures at different moisture levels. Generally, the angle of repose at a specific moisture level decreased as porosity decreased and as the bulk density increased. However, angle of repose for the different media mixtures increased as the moisture content increased. Muir and Sinha (1988) and Masoumi et al. (2003) also observed increases in the mean angles of repose for cereal crops and garlic, respectively, as moisture content increased.

3.4.4 Coefficient of friction

Coefficients of friction ranged from 0.51 to 0.68 (Tables 3.1-3.3). The friction coefficient of the 60:40 media mixture was the greatest while that of the 100:0 media mixture was the least at all moisture levels tested. Duncan's means comparison test indicates differences ($P < 0.05$) in friction coefficient between the media mixtures at different moisture levels. In general, the friction coefficient at any specific moisture content tested increased as porosity and angle of repose decreased, but increased as the bulk density increased. The results also indicate that friction coefficient increased for the different media mixtures as moisture content increased. This result is similar to that obtained by Muir and Sinha (1988) and Masoumi et al. (2003) for cereal crops and garlic, respectively.

3.5 Conclusions

In this study, methods used to determine the physical properties of mixtures (100:0, 80:20; and 60:40% by mass) of woodchips and compost were described. The properties measured include porosity, bulk density, angle of repose, and coefficient of friction; the three moisture contents tested were 40, 60, and 80%. Porosity decreased, but bulk density, angle of repose, and coefficient of friction all increased with increasing moisture content of the woodchip:compost mixtures. Understanding the physical properties of woodchips and compost is vital when designing a biofilter that utilizes woodchips and compost as media materials. Therefore, the results from this study can be used by a design engineer to determine the structural load caused by the biofilter media on the walls of the biofilter structure.

3.6 Acknowledgements

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4. WALL PRESSURES CAUSED BY WET WOODCHIPS IN A MODEL BIOFILTER BIN

4.1 Summary

Bulk materials, such as the woodchips used as media in a biofilter, exert pressure on the walls of their containing structure. The magnitude of lateral pressure caused by wet woodchips on the walls of a biofilter structure is unknown. Tests were conducted to measure the lateral pressure caused by wet woodchips in a model bin and to determine whether existing pressure prediction equations are applicable to biofilters. Three model biofilter bins (0.5 m by 0.5 m, and 1.2 m tall) were employed. Lateral pressures were measured with pressure sensors mounted on the bin wall at 0.2, 0.5, 0.7, and 0.9 m above the bin floor. Woodchips of four different moisture contents were tested (37, 45, 58, and 60% wet basis). Three replications of the test were performed for each moisture level. The results showed that wall pressures increased as the moisture content of the woodchips increased. At any sensor location, the lowest and highest observed pressures were measured during the 37 and 60% moisture content tests, respectively. Analysis of variance (Duncan's means comparison test) performed at the 5% significance level revealed significant differences ($p < 0.0001$) between pressures obtained at different moisture contents. The percentage increase in pressure from the lowest to the highest moisture content was 80, 33, 100, and 67% at the 0.2, 05, 0.7, and 0.9 m locations, respectively. Existing prediction equations did not accurately predict pressures in the biofilter bin in most cases. Percentage errors ranged between 26 and 78%. In addition, existing prediction equations do not seem to account for changes in moisture content of

the medium material. Thus, the existing pressure equations are not appropriate for predicting lateral pressures in a biofilter bin.

4.2 Introduction

Agricultural materials impose pressures on bin walls (Eltawil et al. 2006, Mijinyawa et al. 2007). The first recorded experimental study to measure the pressure of agricultural materials was that conducted by Isaac Roberts (1882) (cited by Smith and Simmonds 1983) on model bins using wheat as the fill material. Based on his observation, Roberts (1882) concluded that pressure on the bin ceases to increase after the depth of fill has exceeded twice the diameter of the bin. Prior to Roberts (1882), Coulomb (1776) (cited by Gupta 1971) developed a method for analyzing forces on retaining walls using sliding wedges of cohesionless material. His method is based on the concept of a failure wedge that is bounded by the face of the wall and by a surface of failure that originates at the base of the wall (Ketchum 1919). Based on his assumptions and analyses, he developed an equation for lateral pressure:

$$P = whg\left[\frac{\cos^2\theta'}{(1+\sin\theta')^2}\right] \tag{4.1}$$

where,

P = lateral pressure (kPa)

w = bulk density of material (kg/m^3)

g = acceleration due to gravity = 9.81 m/s^2

θ' = angle of internal friction (°)

Rankine (1857) (cited by Manbeck et al. 1995) examined an incompressible, cohessionless, granular mass of indefinite extent and having active and passive pressures as the minimum and maximum conditions. The particles of the material were held in position on each other by friction. Based on his assumptions, Rankine (1857) developed an equation for active lateral pressure at any point along the bin wall:

$$P = whg\left[\frac{1-\sin\theta'}{1+\sin\theta'}\right] \tag{4.2}$$

In 1895, Janssen published his famous equation for determining lateral pressure in bins (Eq. 3). The objective of his experiment was to determine the pressure of grain on bin walls. Janssen (1896) (cited by Manbeck et al. 1995) used model bins of different sizes and the fill materials consisted of corn, wheat, and other grains.

$$P = \frac{wRg}{\mu}\left[1-e^{-\frac{k\mu h}{R}}\right] \tag{4.3}$$

where,

R = hydraulic radius (m)

μ = coefficient of friction of material on bin wall

$$k = \frac{1-\sin\theta'}{1+\sin\theta'} = \text{pressure coefficient} \tag{4.4}$$

h = depth of fill (m)

Jamieson (1903) (cited by Smith and Simmonds 1983) measured lateral pressure of wheat and reported that his results correlated well with Janssen's equation. Caughey et al. (1951) (cited by Smith and Simmonds 1983) measured lateral pressure of several granular materials: corn, soy beans, wheat, cement, sand and pea gravel. In general, their results agreed with Janssen's theory. Britton (1969) studied lateral pressures of assorted bulk commercial fertilizers. Predicted pressures calculated with Janssen's equation were compared to experimental results. Lateral pressures due to bulk fertilizer were found to be accurately predicted by Janssen's equation. Kovtun and Platonov (1959) (cited by Thompson et al. 1998) measured lateral pressure during filling of grain bins. Lateral pressures at different depths of fill were observed to be slightly higher than those calculated using Janssen's (1895) equation. Gupta (1971) undertook an investigation to determine the lateral pressures exerted by wheat against flexible container walls and reported that Janssen's equation was not applicable for predicting lateral pressures in flexible containers.

Reimbert (1955) (cited by Smith and Simmonds 1983) conducted studies on full sized grain silos considering the material cone commonly found on top of silos as surcharge. Based on his findings, Reimbert (1955) developed the following equation (referred to as Reimbert's method) for predicting lateral pressures on bin walls:

$$P = \frac{wAg}{\mu C}\left[1 - \frac{1}{\left[\dfrac{h}{\dfrac{d}{4\mu k} - \dfrac{h_s}{3}} + 1\right]^2}\right] \qquad (4.5)$$

where,

A = cross sectional area of bin (m^2)

C = perimeter of bin (m)

d = width of bin (m)

h_s = height of surcharge (m)

Reimbert's method is quite similar to the Janssen's (1895) equation and has presently become a recommended practice as an alternative method to Janssen's equation when calculating static loads (Smith and Simmonds 1983).

Airy (1897) (cited by Smith and Simmonds 1983) gave a valuable discussion on the theory of grain pressures and also the results of a series of experiments to determine material properties of grain. Airy's work was an expansion of the work initiated by Coloumb (1776) on sliding wedges. Thus, Airy (1897) proposed the following equation for calculating the pressure of grain on bins:

$$P = \frac{wdg}{v+\mu}\left[1 - \frac{\sqrt{1+v^2}}{\sqrt{\frac{2h}{d}(v+\mu)+1-v\mu}}\right] \qquad (4.6)$$

where,

v = coefficient of internal friction

Numerous codes available to the design engineer for predicting static lateral pressure on bin walls recommend Janssen's equation (Manbeck et al. 1995). Such codes include the Canadian Farm Building Code (CFBC 1990) and ASAE (American Society of Agric Engineers) EP433 (ASAE 1999). The ACI (American Concrete Institute) 313-91 code (ACI 1991) recommends using either Janssen's or Reimbert's equation. The German design code, DIN 1055, (DIN 1987) does not cover static pressure conditions. However, the code recommends the use of Janssen's equation when determining lateral pressures during filling of a bin.

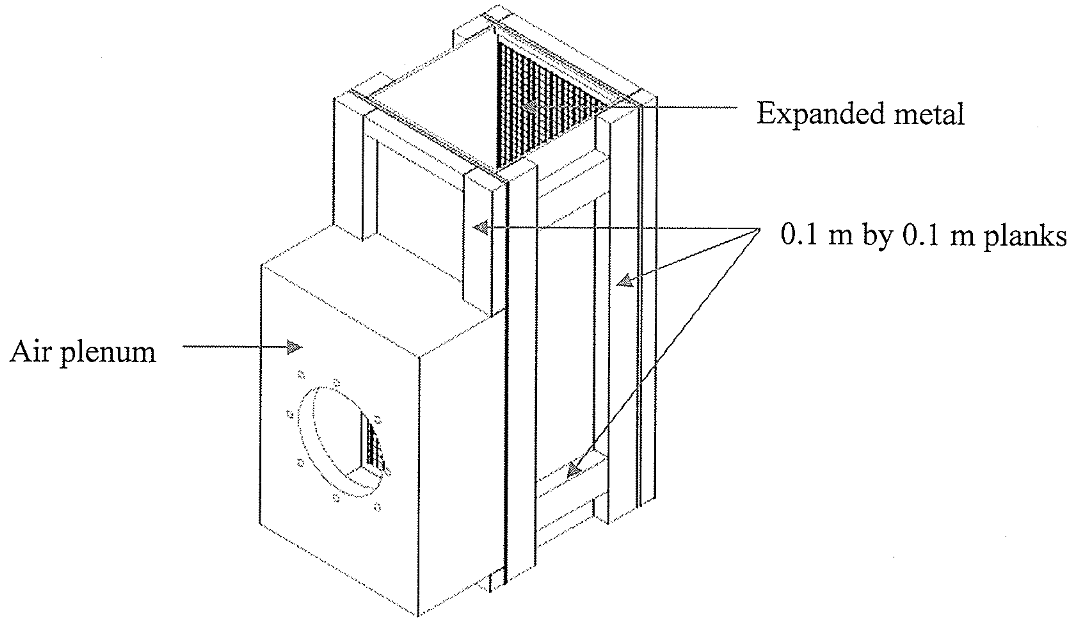
Although much has been published describing lateral pressures exerted on bin walls, there is one important limitation with the current knowledge. Most agricultural materials that are stored in structures must be dry or they will spoil. There is little or no information describing the lateral pressures exerted by wet materials. A biofilter is a device for treatment of odor which relies on microorganisms fixed to a moist, porous medium to break down contaminants present in an air stream. Thus, biofilter structures must be capable of withstanding the lateral pressures exerted by moist media. The lateral pressures exerted on the biofilter structure are likely to differ from the lateral pressures caused by grain due to differences in both bulk density and moisture content. Biofilter media is typically less dense than grain; however, the moisture content is higher. Dale and Robinson (1954) stated that changes in the moisture content of granular materials at any point in time affects the pressure value of such materials. Zhang et al. (1998) and Kebeli et al. (2000) measured moisture-induced loads in grain bins and reported increases in lateral pressure near the bin floor to be 8.6 and 5 times the original pressure values for increases in average moisture content of approximately 7 and 11% d.b., respectively.

To be able to adequately design the structural members of a biofilter wall, it is necessary to be able to predict the lateral pressures caused by wet biofilter media. Thus, the objective of this research is to measure the lateral pressures caused by woodchips of various moisture contents and to determine the suitability of the existing prediction equations for woodchips. The suitability of the existing prediction equations will be determined by comparing predicted and measured lateral pressures.

4.3 Materials and Methods

The experimental system consisted of three model bins, pressure sensors, a data acquisition unit, and biofilter media material (woodchips). Each model bin was 0.5 m by 0.5 m by 1.2 m tall, and was constructed from wood and expanded metal. The bin had four vertical walls and a floor (Fig. 4.1). The wall made of expanded metal was detachable from the bin structure to allow for easy emptying of the bin. The bin was reinforced on all sides with 0.1 m by 0.1m planks. The model bin was designed with a plenum on the inlet to enable horizontal airflow through the biofilter, but this feature was not used in this study.

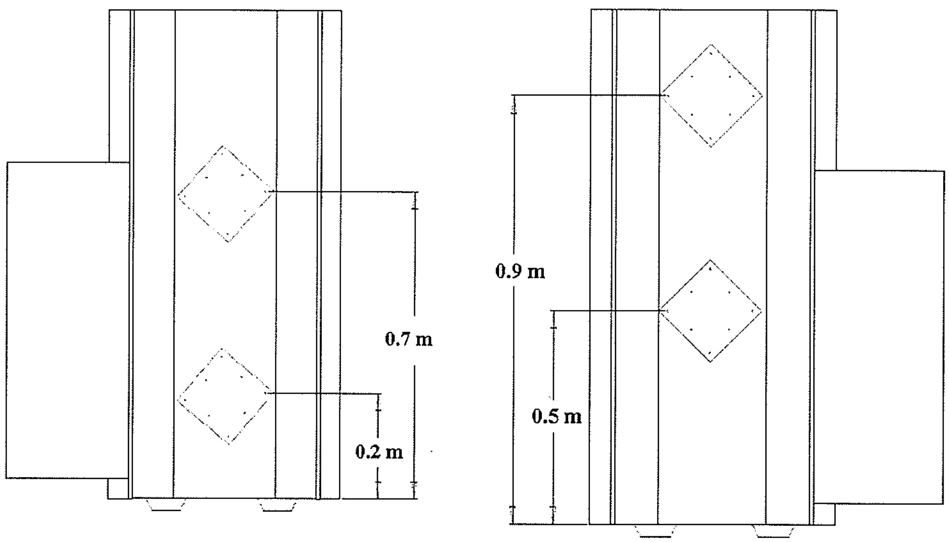
Figure 4.1 Schematic drawing of the model bin.



Four pressure sensors were used to measure lateral pressures on the bin wall. The sensors were made of aluminum diaphragm 1.2 mm thick and 127 mm in diameter. Aluminum was chosen over other metals because of its low modulus of elasticity. The wall of each sensor was made from 6.4 mm thick aluminum plate. Four strain gages were bonded on the inner surface of each sensor along a diameter. The gages were connected as a full wheatstone bridge to maximize output and minimize thermal sensitivity. The sensors were calibrated with a water column for a pressure range from 0 to 6.9 kPa (R^2 value for each sensor was greater than 0.99). Since the sensors would be used in a different environment other than water, dead weight calibration was performed for each sensor using a cylindrical container 127 mm in diameter and 152 mm high. Both ends of the cylindrical container were open. The container was centered on top of the transducer after which the media material was poured into the container. Dead weights were applied incrementally on the top surface of the media material until a pressure of 6.9 kPa was achieved (R^2 values ranged from 0.9042 to 0.9959).

The sensors were mounted on the centerline of the bin wall and located 0.2, 0.5, 0.7, and 0.9 m above the bin floor (Fig. 4.2). Two screws placed through the 6.4 mm thick aluminum back plate were used to hold each sensor in place on the bin wall. The screws were aligned with the bin centerline to avoid possible effects of wall deflection or negative pressure. Sensors were connected to a data acquisition unit for data collection.

Figure 4.2 Schematic drawing showing sensor locations on bin wall.



Lateral pressure of the media material was tested at moisture contents of 37, 45, 58, and 60%. This moisture range was chosen because Devinny et al. (1999) recommends moisture content ranging between 40-80% for optimum biofilter operation. Three replications of the test were performed for each moisture level. In each case, a plastic bag was placed in the bin before filling the bin to the top with the media material. After filling the bin, the plastic bag was used to seal the material. It was expected that sealing the material in a plastic bag would keep the moisture content constant throughout the testing period. Each test lasted for 2 weeks. Pressure readings were collected at 30-min intervals using the data acquisition system. The final moisture content of the material was obtained using the oven dry method (ASAE 2003).

The theoretical models proposed by Coulomb, Rankine, Janssen, Reimbert, and Airy were used to predict the lateral pressure exerted by woodchips on a wooden biofilter structure. Several material properties were needed to make the predictions; they were determined using the experimental methods described by Ima and Mann (2007). Angle of internal friction (θ') was approximated from filling angle of repose (ϕ) (Ketchum 1919). Pressure coefficient (k) was calculated using Eq. 4.4 above while coefficient of internal friction (v) was calculated using Eq. 4.7:

$$v = \tan\theta' \tag{4.7}$$

Data were analyzed using the analysis of variance subprogram (ANOVA) of the Statistical Analysis System (SAS 2002) computer package. Further analysis of the results was performed using Duncan's multiple-range test for comparison of means. The significance level was kept at 5%.

4.4 Results and Discussion

4.4.1 Empirical observation and theoretical estimates

The material properties of bulk density, angle of repose, coefficient of friction, coefficient of internal friction, and pressure coefficient were determined for woodchips for moisture contents of 37, 45, 58, and 60% (Table 4.1).

Table 4.1 Material properties for woodchips of different moisture contents.

Moisture content (%)	Bulk density (kg/m^3)	Angle of repose (°)	Coefficient of friction	Coefficient of internal friction	Pressure coefficient
37	286 ± 1.7	38 ± 1.6	0.51 ± 0.02	0.78 ± 0.05	0.24 ± 0.02
45	293 ± 2.3	38 ± 0.6	0.52 ± 0.01	0.78 ± 0.02	0.24 ± 0.01
58	308 ± 1.8	40 ± 1.0	0.53 ± 0.01	0.84 ± 0.03	0.22 ± 0.01
60	314 ± 2.4	41 ± 2.1	0.53 ± 0.03	0.87 ± 0.07	0.21 ± 0.02

The material properties (Table 4.1) were used to calculate lateral pressure using the theoretical relationships proposed by Coulomb (Eq. 4.1), Rankine (Eq. 4.2), Janssen (Eq. 4.3), Reimbert (Eq. 4.5), and Airy (Eq. 4.6). Predicted lateral pressures were calculated for each of the four moisture contents (37, 45, 58, and 60%) and each of the sensor heights (0.2, 0.5, 0.7, and 0.9 m) (Table 4.2). Observed lateral pressures were also tabulated (Table 4.2).

Table 4.2 **Mean lateral pressures (kPa) measured at each location (n = 3)[1] and predicted values calculated using existing pressure equations.**

Final moisture Content (%)	Observed pressure (kPa)	Coulomb equation (kPa)	Rankine equation (kPa)	Janssen equation (kPa)	Reimbert equation (kPa)	Airy equation (kPa)
			h = 0.9 m			
37	0.3 ± 0.2	0.2	0.2	0.1	0.2	0.3
45	0.5 ± 0.1	0.2	0.2	0.1	0.2	0.3
58	0.5 ± 0.1	0.2	0.2	0.1	0.2	0.2
60	0.6 ± 0.1	0.1	0.1	0.1	0.2	0.2
			h = 0.7 m			
37	0.3 ± 0.1	0.3	0.3	0.3	0.3	0.4
45	0.4 ± 0.1	0.3	0.3	0.2	0.4	0.4
58	0.5 ± 0.2	0.3	0.3	0.2	0.3	0.4
60	0.8 ± 0.2	0.3	0.3	0.2	0.3	0.4
			h = 0.5 m			
37	0.6 ± 0.3	0.5	0.5	0.3	0.4	0.5
45	0.6 ± 0.5	0.5	0.5	0.3	0.4	0.5
58	1.2 ± 0.9	0.5	0.5	0.3	0.4	0.5
60	1.0 ± 0.5	0.4	0.4	0.3	0.4	0.5

			h = 0.2 m			
37	1.1 ± 0.2	0.6	0.6	0.4	0.5	0.6
45	1.4 ± 0.5	0.6	0.6	0.4	0.5	0.6
58	1.4 ± 0.6	0.6	0.6	0.4	0.5	0.6
60	1.9 ± 0.7	0.6	0.6	0.4	0.5	0.5

[1] n = no of replications.

The result on Table 4.2 shows that the observed and predicted pressure values for any specific moisture content increased as the depth of fill increased. The predicted pressure values were similar to the observed values in some cases. However, the observed values were larger than the predicted values in most cases. In addition, the margin between observed and predicted values increased as depth of fill increased. Thus, the prediction models did not accurately predict pressures in the bin. The results also show that the predicted pressures calculated at any location and moisture content are quite similar to each other. This observation seems to suggest that the existing prediction equations do not account for changes in moisture content of the woodchips.

Table 4.3 shows mean relative percent error (MRPE) obtained by comparing the observed pressure values to the predicted pressure values shown in Table 4.2. MRPE was calculated using the formula:

$$e = \frac{1}{n}\sum\frac{|p-a|}{a} * 100 \tag{4.8}$$

where,

e = mean relative percent error (%)

p = predicted pressure value (kPa)

a = observed pressure value (kPa)

n = number of observations

Percentage errors ranged between 26 and 78%. The lowest and highest percentage errors at any location were obtained from Airy's equation and Janssen's equation, respectively.

Table 4.3 Mean relative percent error (MRPE) between observed and predicted pressure values.

Sensor location on bin wall	$MRPE_C$*	$MRPE_R$	$MRPE_J$	$MRPE_{Re}$	$MRPE_A$
m	%	%	%	%	%
0.9	59	59	78	55	42
0.7	32	32	46	26	26
0.5	38	38	61	48	36
0.2	57	57	71	64	58

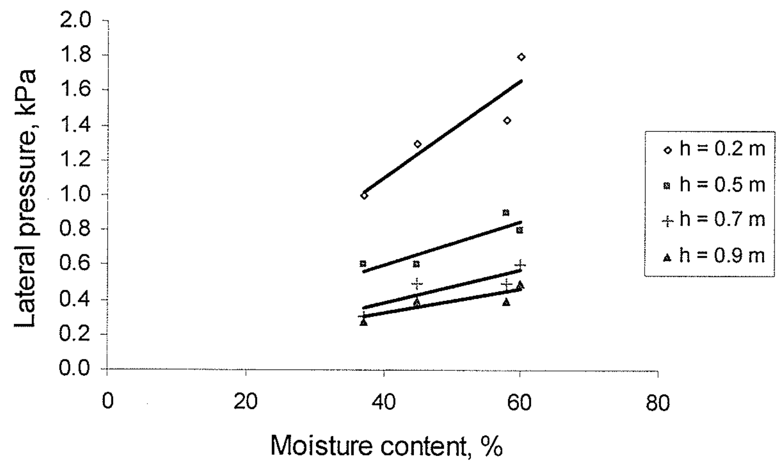
*The subscripts: C, R, J, R_e, and A represent Coulomb, Rankine, Janssen, Reimbert, and Airy, respectively.

4.4.2 Impact of material moisture content on pressure

Figure 4.3 shows the relationship between moisture content and lateral pressure at the four sensor locations. The results indicate that lateral pressure increased as moisture content of the filter material increased. The percentage increase in pressure from the lowest to the highest moisture content was 80, 33, 100, and 67% at the 0.2, 05, 0.7, and

0.9 m locations, respectively. The lateral pressure measured near the bin floor (at 0.2 m from the bin floor) was 1.8 times the original value for a moisture increase of 23%.

Figure 4.3 Relationship between lateral pressure and moisture content at four heights.

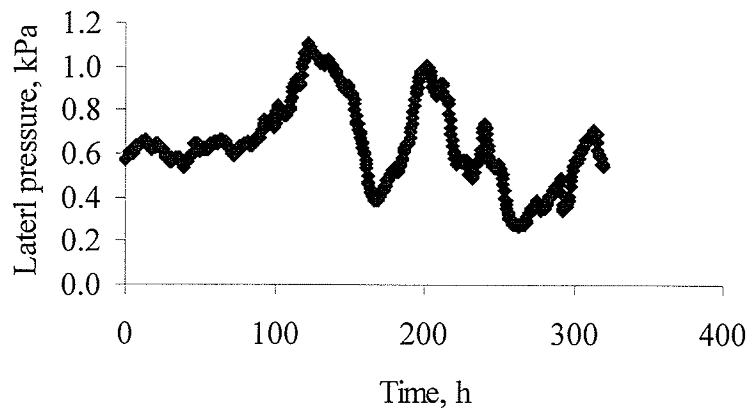


Analysis of variance (Duncan's means comparison test) performed at the 5% significance level showed significant differences ($p < 0.0001$) between the pressure values obtained at different moisture contents. At any location on the bin wall, the highest and lowest pressures were measured during 60 and 37% moisture content tests, respectively. This implies that the moisture content of the filter material affects the pressure exerted on the biofilter wall.

4.4.3 Variation in wall pressure over time

Pressures measured at any location varied with time. Out of the 48 graphs plotted (i.e., 12 sensors and 4 moisture levels), 42 had negative slopes while 6 had positive slopes. In most cases, lateral pressure initially increased to a peak and then decreased with time in a fluctuating manner (Fig. 4.4). It was not clear what could have caused the fluctuating behavior.

Figure 4.4 **Variation in pressure with time obtained during 37% moisture content test.**



The initial hypothesis was that pressure would increase with time in a linear fashion with a positive slope in all cases. The hypothesis was formed because bulging of a biofilter wall had been observed in a previous prototype (Garlinski and Mann 2002). Bulging of the wall was attributed to lateral pressure exerted by the media materials on the biofilter structure. The observation from this study was contrary to the hypothesis. A potential explanation is that moisture content of the woodchips was constant throughout each experiment in this research, but woodchips actually undergo a series of wetting and drying cycles during the operation of a biofilter (i.e., periods of irrigation followed by periods of drying due to a continuous stream of air). Perhaps settling and compaction occur with each wetting/drying cycle, causing increased lateral pressure. This hypothesis requires further investigation.

4.5 Conclusions

Lateral pressure on the wall of a biofilter structure caused by wet woodchips was studied. Tests were conducted with woodchips ranging in moisture content between 35-75%. The observed pressures during the experiment were compared to predicted pressures calculated using existing pressure prediction equations. The results showed that:

1. Lateral pressure increased as the moisture content of the woodchips increased. The percentage increase in pressure from the lowest to the highest moisture content was 80, 33, 100, and 67% at 0.2, 0.5, 0.7, and 0.9 m locations, respectively.
2. Lateral pressure increased as depth of fill increased.
3. Existing prediction equations did not accurately predict pressures in the biofilter bin in most cases. Percentage errors ranged between 26 and 78%.
4. The predicted pressure values obtained at any location remained the same irrespective of moisture content. Thus, existing prediction equations do not seem to account for changes in moisture content of the medium material.
5. Lateral pressure initially increased to a peak and then decreased in a fluctuating manner. The original expectation was that pressure would increase over time in a linear fashion with a positive slope. Contrary to expectation, variation in pressure with time followed a linear trend with a negative slope.

Placement of the woodchips inside plastic bags (to maintain constant moisture content through experimental tests) is a potential limitation of this study. The presence of plastic between the woodchips and the bin wall may have influenced the interaction between the fill material and the wall. This limitation was necessary, however, to ensure constant moisture content throughout the data collection period.

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5. LATERAL PRESSURE VARIATION IN A MODEL BIOFILTER BIN DUE TO WETTING AND DRYING CYCLES

5.1 Summary

Biofilter media is subject to continuous variation in moisture content. Movement of air through the biofilter causes drying of the media to the extent that biofiltration would be inefficient. Water is added to increase the moisture content back to the required levels. The cycle of drying and wetting repeats on a daily basis. Tests were conducted to measure variation in lateral pressure caused by these wetting and drying cycles in model bins using woodchips as the media material. Three model biofilter bins (0.5 m by 0.5 m, and 1.2 m tall) were used. Lateral pressures were measured with pressure sensors mounted on the bin wall at 0.2, 0.5, 0.7, and 0.9 m above the bin floor while moisture content was measured with relative humidity sensors located at 0.2, 0.6, and 1.0 m above the bin floor. A metric ruler was used to measure the amount of settling of the media material that occurred after each cycle. Wetting of the material was achieved by surface irrigation using a watering can. A ventilation fan was used as a means of facilitating the drying phase. Five wetting and drying cycles were examined. The results showed that both lateral pressure and amount of settling increased as the number of wetting and drying cycles increased. Analysis of variance (Duncan's test) performed at the 5% significance level showed significant differences ($p < 0.0001$) between pressure values observed in the different cycles at each sensor location for the three bins. The greatest value of lateral pressure in each cycle was observed near the bottom of the bin (i.e., at the 0.2 m location) while the greatest pressure increase as well as the greatest overpressure factors in bins 1, 2, and 3 occurred at 0.7, 0.5, and 0.7 m locations, respectively.

5.2 Introduction

A biofilter is intentionally designed to be a container filled with wet bulk media (typically woodchips are used in biofilters for agricultural applications). It is recommended that the moisture content of the biofilter media be kept between 40 – 80% w.b. (by weight) for optimum performance (Devinny et al. 1999, Schmidt et al. 2006, Beerli and Rotman 1989). However, maintaining optimum moisture content is difficult because of the continuous stream of air through the biofilter that tends to cause drying. The generation of heat caused by the biodegradation process also tends to cause drying. These two processes cause moisture to be lost from the system (Leson and Winer 1991, van Lith et al. 1990). One way to maintain the appropriate moisture content is by surface irrigation whenever the moisture content of the media falls below the desired range. A practical solution for an agricultural biofilter is to design an irrigation system that applies water to the surface of a biofilter once per day (Schmidt et al. 2006, Mann et al. 2002). A consequence of this practical solution is that the bulk material (i.e., the woodchips) will be subject to continuous drying and wetting cycles.

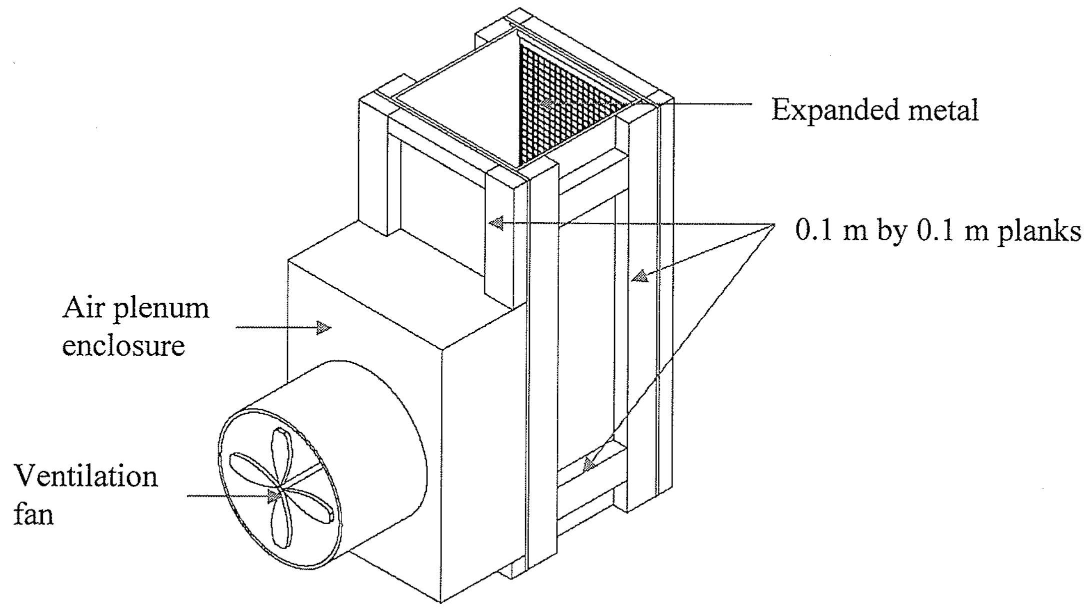
It is well known that bulk materials impose lateral pressures on the walls of any structure designed to contain that bulk material. It is also well known that the magnitude of the lateral pressure will depend on the moisture content of the bulk material (Blight 1986, Horabik and Molenda 2000). Ima and Mann (2008) recently confirmed that the lateral pressure imposed by woodchips increases with increasing moisture content of the woodchips (for experiments conducted with constant moisture content). Research conducted with stored grain has shown that fluctuations in moisture content affect both particle and bulk properties of grain, as well as grain-wall interactions, thus affecting bin loads (Dale and Robinson 1954, Zhang et al. 1998, Kebeli et al 2000). Dale and Robinson (1954) observed that pressures developed as grain re-wets were large as evidenced by i) difficulty in probing the grain and ii) deformation of the storage structure. Thus, fluctuations in moisture content of a bulk material should be considered when designing its storage structure.

The effect of repetitive wetting and drying of biofilter media on lateral wall pressure has never been studied. Therefore, the objective of this research was to determine the impact of repetitive wetting and drying of woodchips on the lateral wall loads in a model biofilter bin.

5.3 Materials and Methods

The experimental apparatus consisted of three model biofilter bins, pressure sensors (4 per bin), relative humidity (RH) sensors (3 per bin), a data acquisition unit, and biofilter media (woodchips). Each model bin was 0.5 m by 0.5 m by 1.2 m tall, and was constructed from wood and expanded metal. The bin had four vertical walls and a floor (Fig. 5.1). The wall made of expanded metal was detachable from the bin structure to allow for easy emptying of the bin. The bin was reinforced on all sides with 0.1 m by 0.1m planks. The model bin was designed with a plenum on the inlet to enable horizontal airflow through the biofilter. A ventilation fan with a capacity of 0.38 m^3/s was connected to the plenum to facilitate the drying phase of the cycle.

Figure 5.1 Schematic of the model bin.

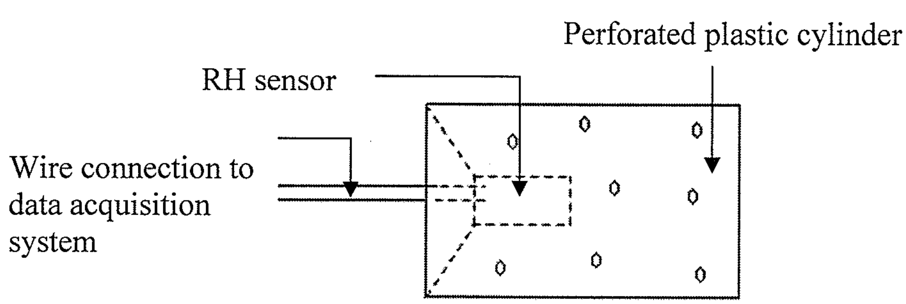


Four pressure sensors were used to measure lateral pressures on the bin wall. The sensors were made of aluminum diaphragm (1.2 mm thick and 127 mm in diameter). The wall of each sensor was made from 6.4 mm thick aluminum plate. Four strain gages were bonded on the inner surface of each sensor along a diameter. The gages were connected as a full wheatstone bridge to maximize output and minimize thermal sensitivity. The sensors were calibrated with a water column for a pressure range from 0 to 6.9 kPa (R^2 value for each sensor was greater than 0.99). Since the sensors would be used in a different environment other than water, dead weight calibration was performed for each sensor using a cylindrical container 127 mm in diameter and 152 mm high. Both ends of the cylindrical container were open. The container was centered on top of the transducer after which the media material was poured into the container. Dead weights were applied incrementally on the top surface of the media material until a pressure of 6.9 kPa was achieved (R^2 values ranged from 0.9042 to 0.9959).

The sensors were mounted on the centerline of the bin wall and located 0.2, 0.5, 0.7, and 0.9 m above the bin floor. Two screws placed through the 6.4 mm thick aluminum back plate were used to hold each sensor in place on the bin wall. The screws were aligned with the bin centerline to avoid possible effects of wall deflection or negative pressure. Each sensor was connected to a data acquisition unit for data collection.

Three HIH-4000 series RH sensors manufactured by Honeywell International Inc. (HII) (2005) were installed in the bin at 0.2, 0.6, and 1.0 m above the bin floor to measure moisture content of the woodchips. Each sensor measures relative humidity within the range of 0-100% and has an accuracy of ±3.5% (HII 2005). Before installing the sensor in the bin, the sensor was enclosed in a perforated plastic cylinder, 0.03 m in diameter and 0.08 m high (Fig. 5.2), made of polyvinyl (pvc) material to protect it from being damaged by woodchips during testing. The perforations on the cylinder allowed for airflow through the sensor without obstruction. Each cylinder had a tapered shoulder on the end through which the wire runs. The tapered shoulder holds the sensor in place and keeps the sensor from falling out during the process of experimentation.

Figure 5.2 Enclosed RH sensor.



Each sensor came with manufacturer's calibration data at room temperature, including the calibration equation and the value of voltage output at 75.3% RH. However, a one point calibration was conducted in the laboratory for each sensor, using sodium chloride (NaCl) as the standard salt solution, to verify the initial company calibration. NaCl was used because its RH is approximately 75.3% at room temperature. The result obtained from the laboratory calibration compares well with the company calibration (Correlation = 1; Covariance = 0.02). Since the sensor would be used to measure changes in moisture content within the woodchips in the bin, a second calibration was conducted using samples of woodchips of varying moisture content. Woodchip samples of known moisture content were put in a clean plastic container. The sensor, connected to a data acquisition system, was buried in the woodchips. The set-up was covered and allowed to stay until equilibration. Four samples of woodchips having different moisture contents were used. R^2 values ranged from 0.9546 to 0.9961.

The bins were filled to the top with woodchips using a pail. The total amount of woodchips poured into each bin was 92.5 kg. The woodchips varied according to the following distribution (determined by sieving and expressed as a percentage of total wet mass): <2 mm (4.9%); 2 to 2.4 mm (2.5%); 2.4 to 3.4 mm (4.5%); 3.4 to 6.7 mm (14.2%); 6.7 to 19 mm (49.9%); 19 to 25 mm (9.5%); > 25 mm (14.4%) (Ima and Mann 2007). Moisture content was determined to be 33% using the oven drying method as recommended by ASAE Standard S358.2 (ASAE 2003). Porosity (62%), bulk density (294 kg/m^3), angle of repose (35°), and coefficient of friction (0.48) were determined using the methods described by Ima and Mann (2007).

Wetting of the woodchips was achieved by sprinkling water onto the top surface using a watering can. Approximately 48 L of water were added to the woodchips over a period of 1 h. After wetting, the woodchips were allowed to sit for 3 d without ventilation. Subsequently, the ventilation fan installed in the bin was turned on to facilitate the drying process. Drying continued for the next 4 d before beginning the next cycle (i.e., addition of water). Thus, each cycle lasted for a period of 7 d. Overall, five wetting and drying cycles were created. During tests, readings from the pressure and RH sensors were recorded at 30-min intervals using an Agilent 34970A data acquisition unit connected to a computer. Data were analyzed using Statistical Analysis Software (SAS 2002) at a significance level of 5%.

Settling over time is a characteristic behavior of porous biological materials used as biofilter media (Devinny et al. 1999, Sadaka et al. 2002). Thus, the height of the surface of the woodchips was measured at the end of each cycle using a metric ruler in order to determine the amount of settling that occurred.

5.4 Results and Discussion

5.4.1 Observed lateral pressure

The lateral pressure followed a cyclic pattern as expected (Figs. 5.3, 5.4, and 5.5). In each cycle, lateral pressure increased steadily during the wetting period. After the wetting period, lateral pressure continued to increase until it reached a maximum value at approximately 30 h after the commencement of wetting. Pressure then started decreasing.

Starting the ventilation fan 30 h after the commencement of wetting facilitated the drying phase and caused lateral pressure to decrease more rapidly.

Continued increase in lateral pressure after wetting had stopped indicates that the bulk of woodchips was expanding due to swelling of the individual particles. Lateral expansion of the woodchips was restricted by the bin wall. This restriction imposed additional pressures on the bin wall. This observation is similar to observations reported by Zhang et al. (1998), Zhang and Britton (1995), Horabik and Molenda (2000), Blight (1986), Kebeli et al. (1998), and Kebeli et al. (2000) during studies to determine moisture-induced loads in grain bins. Increased lateral pressure due to expansion of biofilter media during and after wetting could partly explain why there was bulging of the wall in the biofilter prototype built by Garlinski and Mann (2005). It is possible that the increased lateral pressure imposed on the wall by the media due to repeated wetting and drying cycles caused a lateral displacement of the wall.

Figure 5.3 Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (Bin 1).

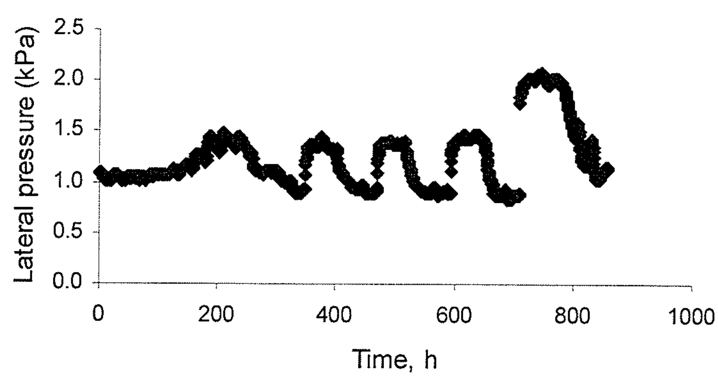


Figure 5.4 **Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (Bin 2).**

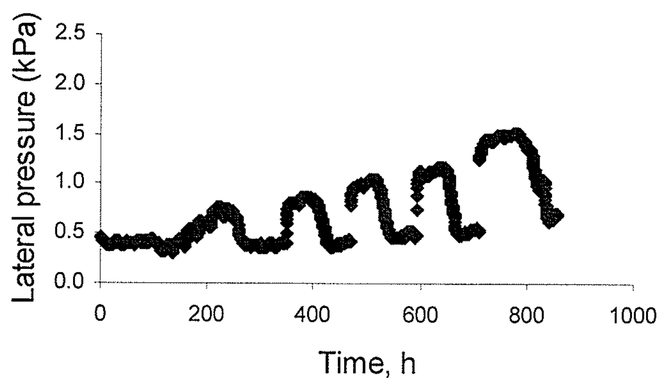
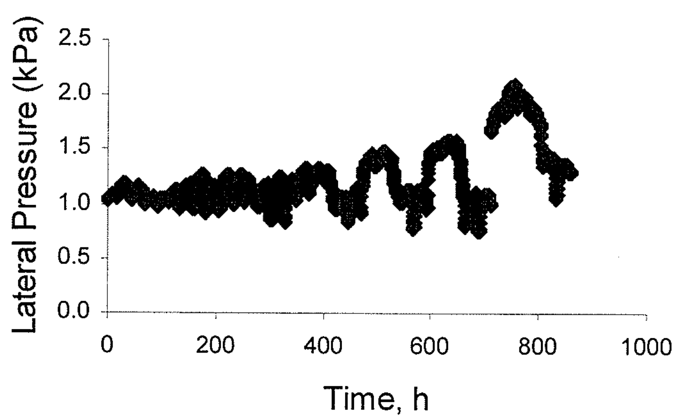


Figure 5.5 **Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (Bin 3).**



The lateral pressures measured at the peak of each wetting and drying cycle in each bin and the moisture content at which the pressures were measured are shown in Table 5.1. There is some evidence that peak lateral pressure increased with each subsequent cycle. Analysis of variance (Duncan's test) performed at a 5% error rate showed that the observed differences were significant ($p < 0.0001$). As expected, the greatest lateral pressures were observed near the bottom of the bins (i.e., at the 0.2 m location). Thus, the major concern in the design of a biofilter bin is the pressures acting at the base of the wall.

Table 5.1 **Peak pressures observed for each cycle at each of the four sensor locations ($P_{0.9}$, $P_{0.7}$, $P_{0.5}$, and $P_{0.2}$), and the moisture content measured when the peak pressure occurred. Bulk density was calculated based on the moisture content and the decreasing volume occupied by the woodchips (as the media settled).**

Bin	Cycle	$P_{0.9}$ (kPa)	$P_{0.7}$ (kPa)	$P_{0.5}$ (kPa)	$P_{0.2}$ (kPa)	Moisture content (%)	Bulk density (kg/m^3)
1	1	[2]0.4^b	0.6^b	0.4^b	1.5^a	60	380
	2	0.5^a	0.4^d	0.4^b	1.4^b	67	413
	3	0.4^b	0.4^d	0.4^b	1.4^b	69	427
	4	0.5^a	0.5^c	0.3^c	1.5^a	69	439
	5	0.4^b	0.9^a	0.4^b	2.1^c	69	452
2	1	0.4^d	[1]-	0.3^c	0.8^e	61	383
	2	0.4^d	-	0.3^c	0.9^d	60	387
	3	0.6^c	-	0.6^b	1.1^c	69	420
	4	0.8^b	-	0.6^b	1.2^b	75	446
	5	1.0^a	-	1.2^a	1.5^a	75	463
3	1	0.9^b	0.3^b	0.4^b	1.3^d	70	404
	2	0.7^d	0.1^d	0.2^d	1.3^d	64	400
	3	0.7^d	0.2^c	0.3^c	1.5^c	63	408
	4	0.8^c	0.3^b	0.3^c	1.6^b	64	422
	5	1.1^a	0.6^a	0.5^a	2.1^a	73	458

[1] - = reading at 0.7 m location was erroneous and, therefore, omitted.

[2] Superscripts (a-e) represent Duncan's test results. Pressure values, obtained at different cycles for each particular location, having the same letters are not significantly different at the 5% significance level.

The percentage increase in lateral pressure (PIP) and the overpressure factors (OPF) in bins 1, 2, and 3 for moisture content increases of 9, 14, and 3%, respectively, are given in Table 5.2. The overpressure factor refers to the number of times the final peak pressure value is greater than the initial peak pressure value. In other words, it is the ratio between the pressure values measured during the last and the first cycles. Table 5.2 shows positive values for pressure increases and overpressure factors in all cases. The greatest pressure increase as well as the greatest overpressure factors in bin 1, 2, and 3 occurred at 0.7, 0.5, and 0.7 m locations, respectively.

Table 5.2 Percentage increase in lateral pressure (PIP) and the overpressure factors (OPF) between first and last cycles for each of the experimental bins.

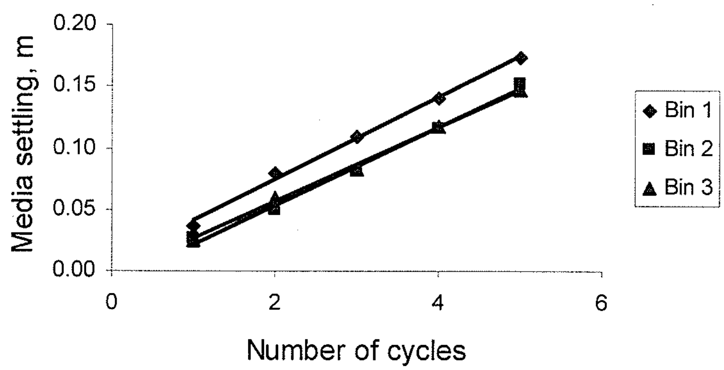
Sensor location	Bin 1		Bin 2		Bin 3	
	PIP (%)	OPF	PIP (%)	OPF	PIP (%)	OPF
0.9 m	0	1.0	150	2.5	22	1.2
0.7 m	50	1.5	[1] -	-	100	2.0
0.5 m	0	1.0	300	4.0	25	1.3
0.2 m	40	1.4	88	1.9	62	1.2

[1] - = reading at 0.7 m location was erroneous and, therefore, omitted.

5.4.2 Media settling and compaction

Measurements taken with a metric ruler at the end of each cycle indicated that media settling occurred with each cycle of wetting and drying (Fig. 5.6). In all cases, media settling increased linearly as the number of cycles increased. Using the observed changes in media height, bulk density was calculated for each cycle (Table 5.1). Bulk density increased with each cycle. It is reasonable to conclude that the increased bulk density caused the peak pressures to increase with each subsequent cycle.

Figure 5.6 Relationship between media settling and number of cycles.



Regression equations for the curves and their R^2 values are as follows:

$M_s = 0.0335n + 0.0073$ .... ($R^2 = 0.9947$; Bin 1) (5.1)

$M_s = 0.0318n - 0.0108$ .... ($R^2 = 0.9932$; Bin 2) (5.2)

$M_s = 0.0301n - 0.0041$ .... ($R^2 = 0.9962$; Bin 3) (5.3)

where,

M_s = media settling (m)

n = number of cycles

A field-scale biofilter would experience a lot more than 5 wetting and drying cycles. It is possible that settling of the medium material might level off after certain number of cycles, depending on the characteristics of the material. Future research should look into this.

5.5 Conclusions

An experiment was conducted to study lateral pressure variation in a model biofilter bin due to repeated wetting and drying cycles. From the work described in this manuscript, the following important conclusions can be drawn:

- Lateral pressure increased steadily during the wetting period and decreased rapidly during the drying period.
- Lateral pressure increased with each cycle.
- Both bulk density and media compaction due to settling increased as the number of cycles increased. Thus, it seems that the observed increase in lateral pressure with each subsequent cycle was caused by change in bulk density and swelling of the woodchip bulk.
- The greatest lateral pressure in each cycle was observed near the bottom of the bin (i.e., at the 0.2 m location). Thus, the major concern in the design of a biofilter bin should be on the pressures acting at the base of the wall.
- The greatest lateral pressure increases in bins 1, 2, and 3, for moisture content increases of 9, 14, and 3%, occurred at 0.7, 0.5, and 0.7 m locations, respectively.

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6. THEORETICAL MODEL FOR HYGROSCOPIC PRESSURE CAUSED BY WOODCHIPS

6.1 Summary

Increasing the moisture content of packing material (e.g., woodchips) in a biofilter bin causes the material to expand, thereby imposing hygroscopic pressure on the bin wall.

A theoretical model was developed for calculating hygroscopic pressure on a bin wall.

A swell test conducted to determine important parameters necessary to evaluate the model revealed the values of k (constant of proportionality between change in volume and change in moisture content of woodchips) and n (constant of power) for woodchips to be $1 \times 10^{-6}\,m^3$ and 1, respectively. The test also confirmed that change in volume of woodchips is directly proportional to change in its moisture content.

6.2 Introduction

Over the years, the focus on agricultural biofilter operation has been on the functional performance of the system, which could be measured in terms of removal efficiency and elimination capacity. Little or no attention has been paid to the structural performance of the biofilter bin. One major factor of interest has been the moisture content of the media materials. This is because the microorganisms that carry out the biodegradation process require a moist environment for their growth and metabolism. However, besides its functional relevance, media moisture content plays an important role in the structural performance of the biofilter as well. Structural performance could be measured by the durability of the biofilter structure (biofilter bin) and its ability to withstand failure due to pressure exerted by the stored media materials.

Ima and Mann (2008a, 2008b) reported that increasing the moisture content of the biofilter media (woodchips) increased loads on the biofilter wall. Increased wall load was attributed to swelling of individual woodchip particles and the consequent expansion of the woodchip bulk. Expansion of the woodchip bulk imposed additional pressures, called hygroscopic pressure, on the bin wall. This observation was similar to that reported by Britton et al. (1993) and Zhang and Britton (1995) in grain bins. Dale and Robinson (1954) stated that hygroscopic pressure is an important consideration because it is a threat to structural failure and should, therefore, be given adequate attention. As structurally important as it is, no theoretical model currently exists for determining hygroscopic loads in a biofilter bin. Therefore, the objective of this study is to develop a theoretical model for determining wall loads caused by woodchips.

6.3 Materials and Methods

6.3.1 Theory

Ima and Mann (2008a) reported that lateral pressure on biofilter bin wall increased as moisture content of media material (woodchips) increased. The relationship between lateral pressure and media moisture content was found to be linear. Thus, it was hypothesized that the observed increase in lateral pressure occurred because the volume of the media material increased due to moisture absorption. This hypothesis implies that change in volume of media material is proportional to change in moisture content and could be expressed mathematically as:

$$\Delta v \alpha (\Delta mc)^n$$

$$\Rightarrow \Delta v = k(\Delta mc)^n \tag{6.1}$$

where,

Δv = change in volume of material (m^3)

k = constant of proportionality (m^3)

Δmc = change in moisture content of material (%)

n = constant of power

Assuming that both the bulk material and the material of the bin wall are linearly elastic; then Hooke's law applies as follows (Popov 1990):

$$\sigma = E.\varepsilon \tag{6.2}$$

where,

σ = stress (kPa)

E = modulus of elasticity (kPa)

ε = strain

According to generalized Hooke's law (Popov 1990):

$$\varepsilon_m = \varepsilon_x + \varepsilon_y + \varepsilon_z = \frac{1-2v_m}{E_m}(\sigma_x + \sigma_y + \sigma_z) \tag{6.3}$$

where,

ε_m = volumetric strain of material

v_m = poisson's ratio of material

P = hygroscopic pressure (kPa)

In the biofilter, the top surface of the material is free to move since there is no restriction to movement at the top. Thus, $\sigma_y = 0$

$$\Rightarrow \varepsilon_m = \frac{1-2v_m}{E_m}(P+P) \tag{6.4}$$

By definition, volumetric strain is determined as:

$$\varepsilon_m = \frac{\Delta v}{V_o} \tag{6.5}$$

where,

V_o = original volume of material (m^3)

$\Delta v = k(\Delta mc)^n$ (from Eq. 6.1)

$$\Rightarrow \varepsilon_m = \frac{k(\Delta mc)^n}{V_o} \tag{6.6}$$

Substituting Eq. (6.6) in Eq. (6.4),

$$\frac{k(\Delta mc)^n}{V_o} = \frac{1-2v_m}{E_m}(P+P) \tag{6.7}$$

$$\Rightarrow P = \frac{k(\Delta mc)^n E_m}{2V_o(1-2v_m)} \tag{6.8}$$

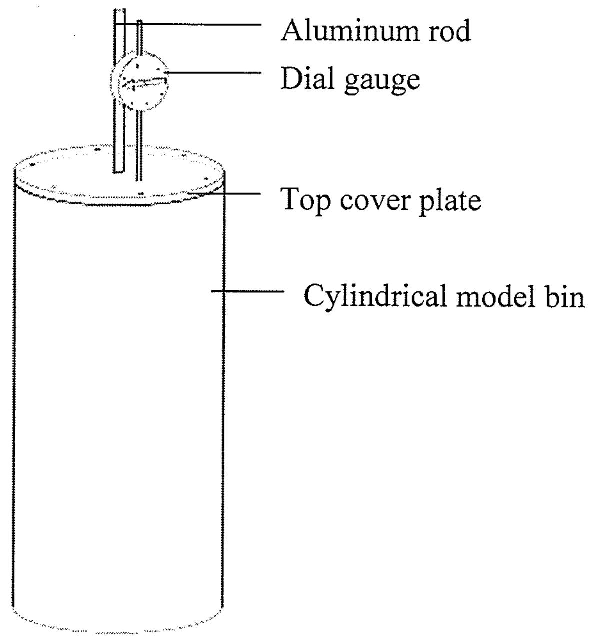
Equation (6.8) represents the situation where the bin is rigid so that there is no deflection of the bin walls.

The values of the variables: k (constant of proportionality), n (constant of power), E_m (modulus of elasticity), and v_m (poisson's ratio) in Eq. (6.8) for a particular material would have to be determined by experimental study if they do not currently exist. The method (swell test) and apparatus (modified oedometer apparatus) used to determine the k- and n-values for woodchips are described in sections 6.3.2 to 6.3.4 below.

6.3.2 Test apparatus

Swell tests were conducted with a modified oedometer apparatus (Fig. 6.1) to determine the values of k and n for woodchips. A modified oedometer apparatus was used because the standard oedometer apparatus (ASTM 1996; D4546 and D2435) is not suitable for the physical properties of woodchips. The modified apparatus consisted of a cylindrical model bin, dial gauge, and nominal weight. The bin was made of polyvinyl (pvc) material and was 254 mm by 533 mm by 13 mm in diameter, height, and thickness, respectively. The bottom of the bin was sealed permanently with a pvc plate so that the bottom plate is non-detachable. The top cover plate of the bin was attached to the remaining structure by means of screws. Thus, the cover plate could be removed whenever necessary.

Figure 6.1 Modified Oedometer apparatus.



Two holes, 10 mm each, were created on the top cover plate. One hole (the center hole) was located at the center of the plate while the other hole (the side hole) was located 51 mm from the edge of the plate. The center hole provides a free passage for an aluminum rod, which forms a part of the nominal weight. The side hole was used for pouring water into the bin through a funnel during test.

The nominal weight constituted the seating pressure. It consisted of an aluminum rod (10 mm in diameter and 711 mm long) and a perforated pvc plate (250 mm in diameter and 13 mm thick) attached to the base of the aluminum rod. The dial gauge was attached towards the other end of the aluminum rod. During tests, upward movement of the plate as a result of swelling of woodchips causes displacement to occur in the dial gauge. The amount of displacement that occurred in the dial gauge is an indicator of change in volume of the material.

6.3.3 Physical properties of media material (woodchips)

The particle-size distribution of woodchips was determined by sieving and expressed as a percentage of total wet mass as follows: <2 mm (4.9%); 2 to 2.4 mm (2.5%); 2.4 to 3.4 mm (4.5%); 3.4 to 6.7 mm (14.2%); 6.7 to 19 mm (49.9%); 19 to 25 mm (9.5%); > 25 mm (14.4%) (Ima and Mann 2007). Initial physical properties of the woodchips are as follows: moisture content (26%), porosity (63%), bulk density (281 kg/m^3), angle of repose (34°), and coefficient of friction (0.47). Moisture content was determined by oven drying method (ASAE 2003) while other properties were determined using the methods described by Ima and Mann (2007).

6.3.4 Experimental procedure

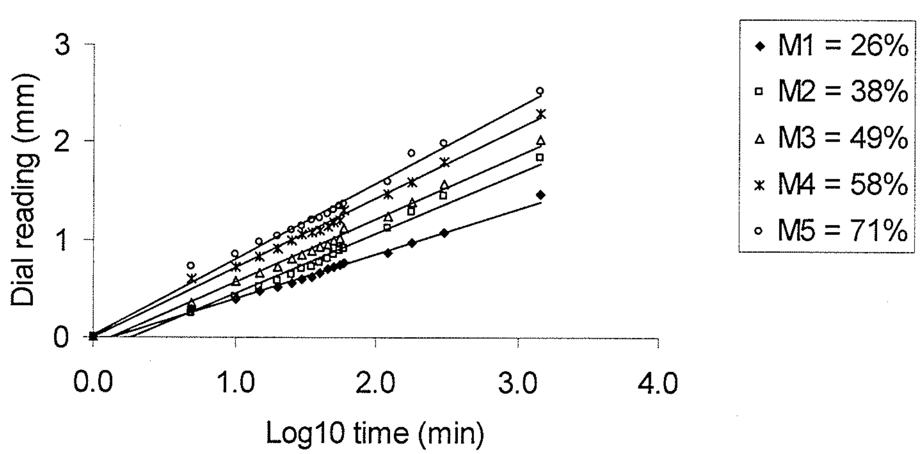
A woodchips sample of known moisture content was poured into the bin. The perforated plate at one end of the nominal weight was placed on the surface of the sample and the bin was covered with the top cover plate. The dial gauge was put in place. 1.5 L of water was poured into the bin through the side hole created on the top cover plate of the bin. As swelling of the material occurred, dial gauge readings were recorded at 5 min, 10 min, 15 min, 20 min, 25 min, 30 min, 35 min, 40 min, 45 min, 50 min, 55 min, 1 h, 2 h, 3 h, 5 h, and 24 h. Recording was stopped at the 24 h reading because preliminary tests conducted with a similar sample showed that swelling was completed within 24 h of commencing the test. The overall volume change for the sample was recorded at the end of the test. At the end of a test, the top cover plate of the oedometer apparatus was removed to change the woodchip sample for the next test. The initial volume of sample poured into the bin before addition of water was kept constant in all tests for consistency in determining change in volume of the material. The test procedure was carried out with five woodchip samples. The moisture content of the woodchip samples were determined by oven dry method and found to be 26, 38, 49, 58, and 71%.

6.5 Results and Discussion

6.5.1 Swelling characteristics of woodchips

Figure 6.2 shows that the relationship between dial reading (swelling of woodchips particles and the consequent expansion of woodchips bulk) and logarithm, to base 10, of time is linear. Figure 6.2 also shows that dial reading increased as moisture content of woodchips increased.

Figure 6.2 **Swelling of woodchips under varying moisture content.**



This result indicates that the wetter the woodchips particles, the greater the amount of expansion (i.e., increase in volume) of the woodchips bulk that would take place due to swelling of the individual particles. The result agrees with the explanations given by Kebeli et al. (2000) and Ima and Mann (2008a).

6.5.2 Swelling potential of woodchips

The swelling potential of woodchips is shown in Fig. 6.3. Swelling potential refers to total change in the volume of woodchips that could be obtained for any change in moisture content of woodchips.

Figure 6.3 Swelling potentials of woodchips

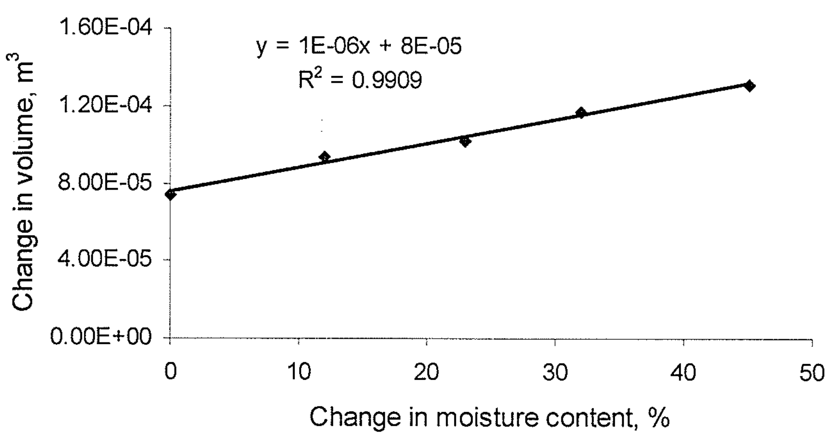


Figure 6.3 indicates a linear relationship between volume change and change in moisture content. Thus, the hypothesis made in the model development (Eq. 6.1) is true. The slope of Fig. 6.3 represents the constant of proportionality, k (1 x 10^{-6} m^3), for the woodchips. In addition, the relationship in Fig. 6.3 is linear; thus, indicating that $n = 1$.

6.5.3 Model validation

The results obtained by Ima and Mann (2008a) was used to validate the model shown in Eq. 6.8. Ima and Mann (2008a) measured wall pressures in a model biofilter bin at 0.2, 0.5, 0.7, and 0.9 m above the bin floor using woodchips as the media material. The modulus of elasticity (E_m) and the poisson's ratio (v_m) of the woodchips used in the study were not known. Thus, in the validation process, the modulus of elasticity and the poisson's ratio of woodchips were assumed to be 3.6 GPa and 0.35, respectively. These values correspond to the bulk modulus and poisson's ratio of cedar wood (Northern white - softwood) (Forest Products Laboratory 1999). The percentage error between predicted and observed pressures obtained at the 0.2, 0.5, 0.7, and 0.9 m locations were 204, 185, 660, and 440%, respectively. The percentage errors are quite large. Assumption of the model parameters could have contributed to large errors. Thus, for a better assessment of the model, it would be useful to generate data to predict the modulus of elasticity and poisson's ratio for the media material used. Another factor that could have contributed to large errors is the limitation in the experimental procedures used in the study.

6.6 Conclusions

Wetting of biofilter media materials (e.g., woodchips) cause individual particles of the material to swell and the entire bulk to expand. Expansion of the bulk of the material, in turn, imposes additional pressure, termed hygroscopic pressure, on bin wall. A theoretical model was developed for determining hygroscopic pressure in a bin. The model is based on the assumption that bulk material (woodchips) and the material of the bin wall are linearly elastic. Knowledge of the swelling potential of the material is important in determining some material properties necessary for evaluating the model. Thus, a swell test was conducted. The result showed that change in volume of woodchips is directly proportional to change in its moisture content. The values of k (constant of proportionality between change in volume and change in moisture content of woodchips) and n (constant of power) for woodchips were found to be 1×10^{-6} m^3 and 1, respectively. The model developed was validated using the data obtained by Ima and Mann (2008a). The percentage errors obtained at the 0.2, 0.5, 0.7, and 0.9 m locations on the bin wall were 204, 185, 660, and 440%, respectively.

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7. CONCLUSIONS AND RECOMMENDATIONS FOR FUTRE RESEARCH

7.1 Conclusions

The following conclusions were drawn from the study:

1. Moisture level affects the physical characteristics of biofilter media, and hence, the wall loads in a biofilter. Porosity decreased, but bulk density, angle of repose, and coefficient of friction all increased with increasing moisture content of proportionate mixtures of woodchip and compost. The result provides useful information to the design engineer on the parameters necessary for determining structural load in biofilters.

2. The magnitude of lateral pressure caused by wet woodchips on the walls of a biofilter structure was successfully measured. Lateral pressure increased as the moisture content of woodchips increased. The percentage increase in pressure from the lowest to the highest moisture content was 80, 33, 100, and 67% at 0.2, 0.5, 0.7, and 0.9 m locations on the bin wall (from the bin floor), respectively. Existing pressure equations did not accurately predict lateral pressures in the biofilter bin in most cases. Percentage error of prediction ranged between 26 and 78%.

3. Repetitive wetting and drying of biofilter media affect structural loads and cause lateral pressure variation in the biofilter. Lateral pressure increased steadily during wetting and continued to increase after wetting had stopped until it reached a maximum value before it started decreasing. Turning on the ventilation fan

during drying phase caused a rapid decrease in lateral pressure. The peak lateral pressure increased significantly with each cycle. The least and greatest pressure increase observed were 22 and 300%, respectively. The greatest lateral pressure in each cycle was observed near the bottom of the bin. Thus, the major concern in the design of a biofilter bin should be on the pressures acting at the base of the wall.

4. A theoretical model was developed for determining hygroscopic pressure in a bin. The model was based on the assumption that the media material and the material of the bin wall are linearly elastic. Woodchips were used as the media material. Important parameters necessary for evaluating the model were obtained by conducting a swell test using a modified oedometer apparatus. The swell test showed that change in volume of media material is directly proportional to change in its moisture content, thus, confirming the initial assumption made in the model development. The values of k and n for woodchips were found to be 1×10^{-6} m^3 and 1, respectively.

7.2 Recommendations for Future Research

The following recommendations would be useful for future research:

1. Wetting of woodchips was achieved with a watering can that has a perforated sprinkler at one end. A watering can was used to ensure uniform distribution of water in the woodchip bulk. Even though the watering can served the purpose, there could be other better ways of wetting the woodchip bulk. Future research

could compare pressures obtained by manual irrigation to that obtained through other systems (e.g., pre-humidification) to determine whether there is significant difference in wetting method.

2. One of the experimental studies was conducted in a building outside the laboratory. The building was subject to variations in environmental conditions. Such situation could affect effective comparison of research data and should be avoided in future research.

3. In one of the tests, woodchips were placed in plastic bags to ensure constant moisture content throughout data collection period. Placing woodchips in plastic bags is a potential limitation to the study because the presence of plastic material between the woodchips and the bin wall may have influenced the interaction between the material and the wall. Other ways of keeping moisture content constant that eliminates any interface between the material and bin wall (e.g., the use of controlled chambers) should be explored in future research.

4. To get a better assessment of the theoretical model developed, it would be useful to generate data to predict the modulus of elasticity and poisson's ratio for woodchips or any other media material used. Future research would look into this.

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