

Wall Pressures Caused by Wet Woodchips in a Model Biofilter Bin

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ABSTRACT

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 are unknown. Tests were conducted to measure the lateral pressure caused by wet woodchips in a model bin 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 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 0.2, 0.5, 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. Multiple regression analysis was used to develop an empirical prediction equation relating lateral pressure to moisture content and height.

Keywords: Biofilter bin, biofilter media, woodchips, moisture content, wall pressures, pressure equations, Canada.

1. 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:

$$P = whg \left[\frac{\cos^2 \phi}{(1 + \sin \phi)^2} \right] \quad \text{Eq. 1}$$

where,

P = Lateral pressure (kPa)

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

g = Acceleration due to gravity = 9.8 m/s^2

ϕ = Angle of internal friction ($^\circ$)

Rankine (1857) (cited by Manbeck *et al.*, 1995) examined an incompressible, cohesionless, 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:

$$P = whg \left[\frac{1 - \sin \phi}{1 + \sin \phi} \right] \quad \text{Eq. 2}$$

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.

$$P = \frac{wRg}{\mu} \left[1 - e^{-\frac{k\mu h}{R}} \right] \quad \text{Eq. 3}$$

where,

$R = \frac{A}{C}$ = Hydraulic radius (m)

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

C = Perimeter of bin (m)

μ = Coefficient of friction of material on bin wall

k = Pressure coefficient = $\frac{1 - \sin \phi}{1 + \sin \phi}$ Eq. 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:

$$P = \frac{wRg}{\mu} \left[1 - \frac{1}{\left[\frac{\frac{h}{\frac{d}{4\mu k} - \frac{h_s}{3}} + 1}{\right]^2} \right] \quad \text{Eq. 5}$$

where,

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:

$$P = \frac{wdg}{v + \mu} \left[1 - \frac{\sqrt{1 + v^2}}{\sqrt{\frac{2h}{d}(v + \mu) + 1 - v\mu}} \right] \quad \text{Eq. 6}$$

where,

ν = Coefficient of internal friction

d = Width of bin (m)

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 identify an equation for predicting the lateral pressure exerted on the wall of a biofilter bin by wet woodchips. This is to be accomplished by first measuring the lateral pressures caused by woodchips of various moisture contents. The suitability of the existing prediction equations will be determined by comparing predicted and measured lateral pressures. If none of the existing equations is suitable, an alternative equation will be proposed.

2. 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. 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.

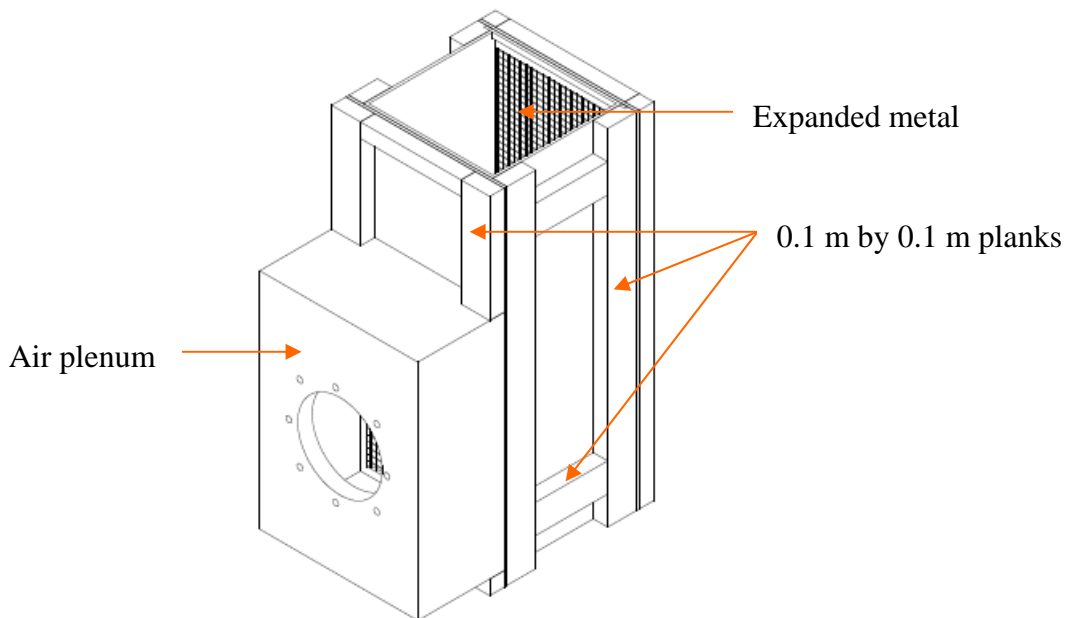


Figure 1. A schematic drawing of the model bin

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. 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. The sensors were connected to a data acquisition unit for data collection.

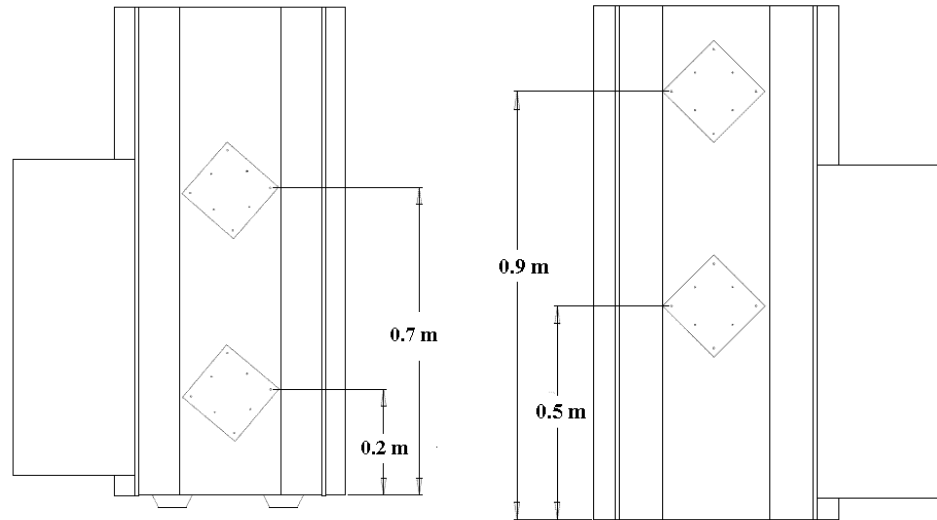


Figure 2. Schematic drawing showing sensor locations on bin wall

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 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 wk. 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 (ϕ) was approximated from filling angle of repose (Ketchum 1919). Pressure coefficient (k) was calculated using Eq. 4 above while coefficient of internal friction (v) was calculated using Eq. 7.

$$v = \tan \phi \quad \text{Eq. 7}$$

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%.

3. RESULTS AND DISCUSSION

3.1. 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 1).

Table 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 1) were used to calculate lateral pressure using the theoretical relationships proposed by Coulomb (Eq. 1), Rankine (Eq. 2), Janssen (Eq. 3), Reimbert (Eq. 5), and Airy (Eq. 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 2). Observed lateral pressures were also tabulated (Table 2).

Table 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)
<u>h = 0.9 m</u>						
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
<u>h = 0.7 m</u>						
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
<u>h = 0.5 m</u>						
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

			<u>$h = 0.2 \text{ m}$</u>			
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 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 result also shows 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 3 shows mean relative percent error (MRPE) obtained by comparing the observed pressure values to the predicted pressure values shown in Table 2. MRPE was calculated using the formula:

$$e = \frac{1}{n} \sum \frac{|p - a|}{a} * 100 \quad \text{Eq. 8}$$

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

Sensor location	MRPE _C [*]		MRPE _R		MRPE _J		MRPE _{Re}		MRPE _A	
on bin wall										
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, Re, and A represent Coulomb, Rankine, Janssen, Reimbert, and Airy, respectively.

3.2. Impact of Material Moisture Content on Pressure

Figure 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 0.2, 0.5, 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%.

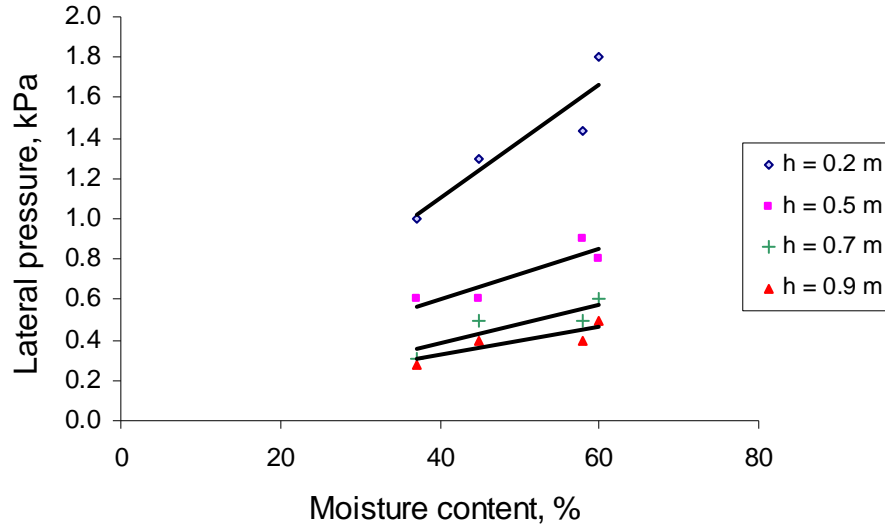


Figure 3. Relationship between lateral pressure and moisture content at four heights

A multiple regression analysis was conducted to relate lateral pressure to both woodchip moisture content and height. As a result, a prediction model that describes lateral pressure as a function of height and moisture content was developed as follows:

$$P = 1.182 - 3.641y + 2.01266 y^2 + 0.0186mc \quad \text{Eq. 9}$$

where,

mc = material moisture content (%)

y = height on bin wall under consideration (m)

The regression model ($R^2 = 0.6001$) shows that the effects of moisture and height are additive rather than interactive in nature. In other words, there is no interaction between the two variables. The relationship between pressure and height under varying moisture content is curvilinear whereas the relationship between pressure and moisture content under varying height is linear.

Analysis of variance (Duncan's means comparison test) performed at 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.

3.3. 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). It was not clear what could have caused the fluctuating behavior.

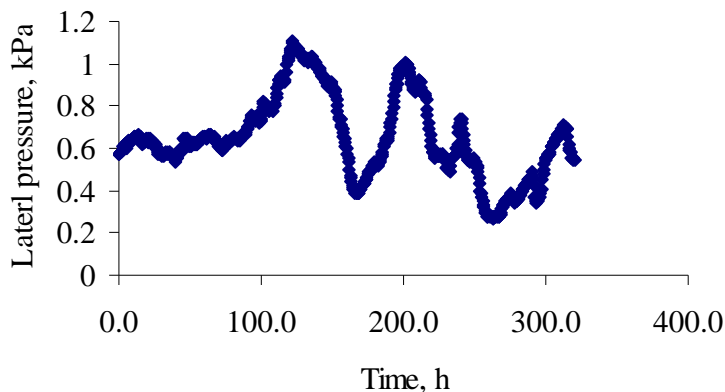


Figure 4. Variation in pressure with time obtained during 37% moisture content test.

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. 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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