Lateral pressure variation in a model biofilter bin due to wetting and drying cycles

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Ima, C.S. and D.D. Mann. 2011. **Lateral pressure variation in a model biofilter due to wetting and drying cycles**. Canadian Biosystems Engineering/Le génie des biosystèmes au Canada. 53: 6.1–6.7. Biofilter media are 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 to the required levels. The cycle of drying and wetting is repeated on a daily basis. Tests were conducted to measure the variation in lateral pressure caused by these wetting and drying cycles in model bins using woodchips as the medium. Three model biofilter bins (0.5 m by 0.5 m, and 1.2 m tall) were used. Lateral pressures were measured with flat metal diaphragm transducers 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 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% error rate showed significant differences ($P < 0.0001$) between pressure values observed in the different cycles at each transducer 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) whereas 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. Multiple regression analysis was used to generate a prediction model that estimated peak lateral pressure as a function of media moisture content, bulk density, and height. **Keywords:** lateral pressure, variation, biofilter, woodchips, wetting and drying cycles, media settling.

Le substrat d'un biofiltre est affecté par des changements continus de teneur en eau. Le mouvement de l'air au travers du biofiltre résulte en un séchage du substrat à un point tel que le biofiltre peut devenir inefficace. De l'eau est donc ajoutée pour en augmenter la teneur en eau aux niveaux requis. Ce cycle de séchage et d'humidification est répétée sur une base journalière. Des essais ont été réalisés dans des contenants à échelle réduite remplis de copeaux de bois en guise de substrat dans le but mesurer la variation sur la pression latérale causée par ces cycles d'humidification et de séchage. Trois contenants (0,5m par 0,5m et 1,2m de haut) ont été utilisés. Les pressions latérales ont été mesurées avec des senseurs à diaphragme de métal plat placés sur les parois verticales des contenants à des distances de 0,2, 0,5, 0,7 et 0.9 m au-dessus du fond tandis que la teneur en eau a été mesurée avec des senseurs d'humidité relative disposés à 0,2, 0,6 et 1,0 m au-dessus du fond du contenant. Après chaque cycle, le niveau de tassage du substrat a été déterminé au moyen d'une règle. La surface du substrat était humidifiée avec un arrosoir et un ventilateur était utilisé pour simuler les phases de séchage. Cinq cycles d'humidification et de séchage ont été évalués. Les résultats ont démontré que la pression latérale ainsi que le tassage augmentaient avec une augmentation du nombre de cycles d'humidification et de séchage. L'analyse de variance (test Duncan avec une marge d'erreur de 5%) a démontré des différences significatives ($P < 0{,}0001$) entre les valeurs de pression observées dans les différents cycles par chacun des senseurs pour les trois contenants. La plus grande valeur de pression latérale au cours de chacun des cycles a été observée près du fond du contenant (soit à 0,2m) tandis que la plus grande augmentation de pression ainsi que les plus grands facteurs de surpression dans les bacs 1, 2, et 3 sont survenus à des hauteurs de 0,7, 0,5, et 0,7 m respectivement. Une analyse de régression multiple a été utilisée pour générer un modèle de prédiction qui a estimé la valeur maximale de la pression latérale en fonction de la teneur en eau du substrat, de la masse volumique et de la hauteur par rapport au fond du contenant. **Mots clés:** pression latérale, variation, biofiltre, copeaux de bois, cycle d'humidification et de séchage, tassage du substrat.

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 and 80% w.b. (by weight) for optimum performance (Beerli and Rotman 1989; Devinny et al. 1999; Schmidt et al. 2006). 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 (van Lith et al. 1990; Leson and Winer 1991). 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 a day (Mann et al. 2002; Schmidt et al. 2006). 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.

MATERIALS and METHODS

The experimental apparatus consisted of three model biofilter bins, pressure sensors (four per bin), relative humidity (RH) sensors (three 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. 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.

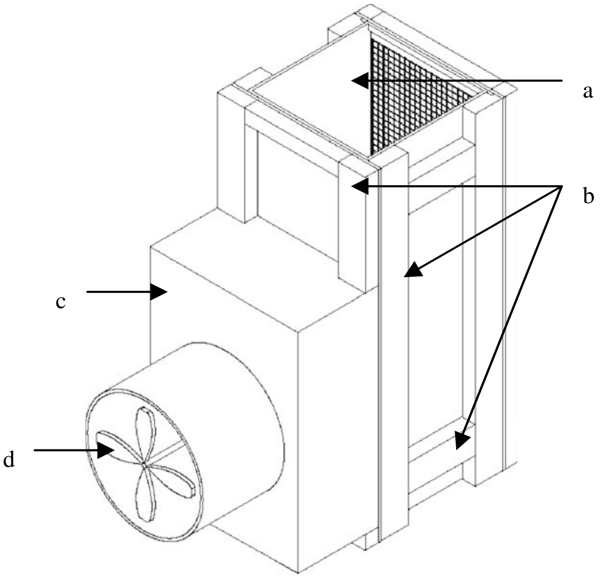

Fig. 1. Schematic drawing of the model bin. a = expanded metal; b = planks; c = plenum; d = ventilation fan.

Four flat metal diaphragm transducers were used to measure lateral pressures on the bin wall. The transducers consisted of an aluminum diaphragm (1.2 mm thick and 127 mm in diameter). The wall of each transducer was made from 6.4-mm-thick aluminum plate. Four strain gauges were bonded on the inner surface of each sensor along a diameter. The gauges were connected as a full Wheatstone bridge to maximize output and minimize thermal sensitivity. The transducers were calibrated with a water column for a pressure range from 0 to 6.9 kPa (R^2 value for each transducer was greater than 0.99). Because the transducers would be used in an environment other than water, dead weight calibration was also performed for each transducer 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 was poured into the container. Dead weights were applied incrementally on the top surface of the media until a pressure of 6.9 kPa was achieved (R^2 values ranged from 0.9042 to 0.9959).

The transducers 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 backplate were used to hold each transducer 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 transducer 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. 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 ran. The tapered shoulder held the sensor in place and

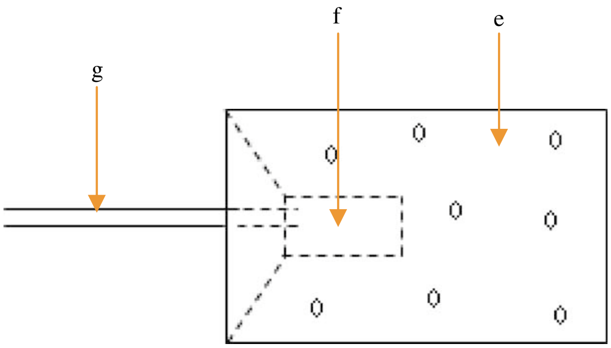

Fig. 2. Enclosed RH sensor. a = perforated plastic cylinder; b = RH sensor; c = connection to data acquisition system.

kept the sensor from falling out during the process of experimentation.

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 compared well with the company calibration (correlation = 1; covariance = 0.02).

Given that the sensor would be used to measure changes in moisture content within the woodchips in the bin, a second calibration test was conducted to determine the relationship between moisture content of the woodchips, relative humidity, and the voltage output from a data acquisition system. Samples of woodchips of varying moisture contents were used for this test. To run a test, a woodchip sample of known moisture content was placed in a clean plastic container. The sensor, connected to a data acquisition system, was buried in the woodchip sample. The set-up was covered and allowed to stay until equilibration. Four samples of woodchips having different moisture contents were used. The data acquisition system recorded the voltage output from the sensor for each of the samples tested. The R^2 values obtained from the relationship 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 approximately 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 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 the analysis of variance (ANOVA) subprogram of the SAS computer package (SAS Institute, Inc. 2002). Furthermore, Duncan's multiple-range test for mean comparison was used to compare the pressure values measured at different depths in each cycle. The error rate was kept at 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.

RESULTS and DISCUSSION

Observed lateral pressure

The lateral pressure followed a cyclic pattern as expected (Figs. 3, 4, and 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 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 indicated 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), and Kebeli et al. (1998, 2000) during studies to determine moisture-induced loads in grain bins. Increased lateral pressure due to the 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.

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 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 pressure acting at the base of the wall.

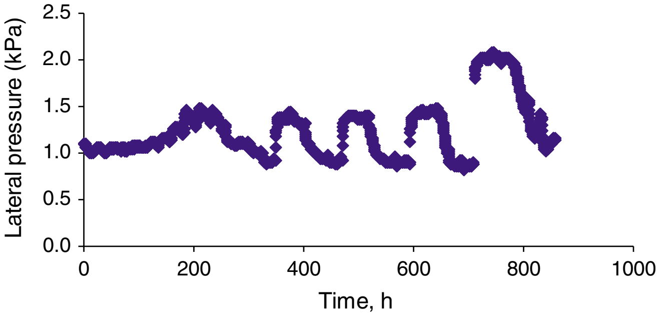

Fig. 3. Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (bin 1).

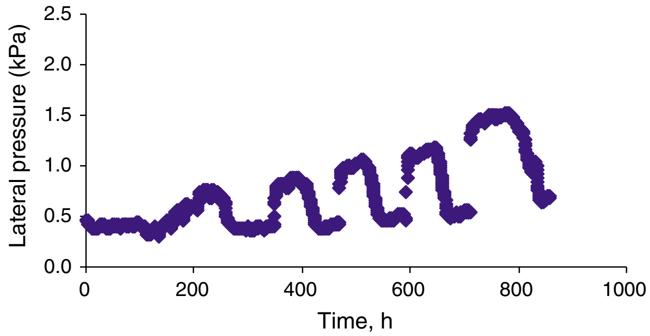

Fig. 4. Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (bin 2).

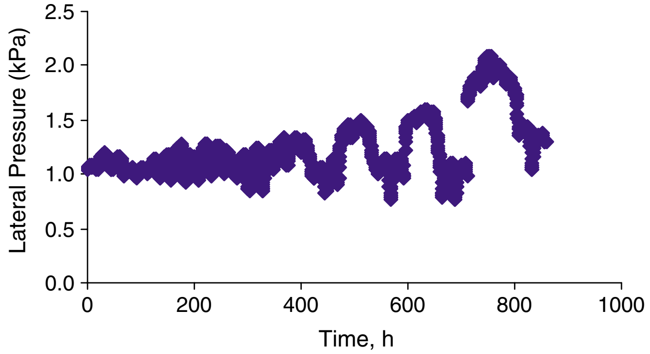

Fig. 5. Variation of lateral pressure during the five wetting and drying cycles at 0.2 m location (bin 3).

The percentage increase in lateral pressure and the overpressure factors in bins 1, 2, and 3 for moisture content increases of 9, 14, and 3%, respectively, are given in Table 2. The overpressure factor refers to the number of times the final peak pressure is greater than the initial peak pressure. In other words, it is the ratio between the pressures measured during the last and the first cycles. Table 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 bins 1, 2, and 3 occurred at 0.7, 0.5, and 0.7 m locations, respectively.

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. 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 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.

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

$$M_s = 0.0335n + 0.0073 \ldots\ldots\ldots (R^2 = 0.9947; \text{bin } 1) \quad (1)$$

$$M_s = 0.0318n - 0.0108 \ldots\ldots\ldots (R^2 = 0.9932; \text{bin } 2) \quad (2)$$

$$M_s = 0.0301n - 0.0041 \ldots\ldots\ldots (R^2 = 0.9962; \text{bin } 3) \quad (3)$$

where M_s is the media settling (cm) and n is the number of cycles.

Table 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}	31	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% error rate.

Table 2. Percentage increase in lateral pressure (PIP) and the overpressure factors (OPF) between first and last cycles for each of the experimental bins.

	Bin 1		Bin 2		Bin 3	
Sensor location	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.

Modeling lateral pressure due to repeated wetting and drying cycles

In previous research, Ima and Mann (2008) proposed an equation for predicting the lateral pressure exerted by woodchips of constant moisture content (Eq. 4). The prediction model predicted lateral pressure based on the moisture content of the woodchips and the height at which pressure was measured. The experimental results obtained from this research were input into the prediction equation to determine whether the equation would adequately model the lateral pressure caused by cycles of wetting and drying.

$$P = 1.182 - 3.641y + 2.01266y^2 + 0.0186mc \qquad (4)$$

where P is the lateral pressure (kPa), mc is the moisture content (%), and y is the height on bin wall under consideration (m).

The mean relative percent error ($\mathrm{MRPE_{Eq4}}$) values obtained by comparing the observed peak lateral pressure (shown in Table 1) to the predicted pressure (calculated using the prediction model shown in Eq. 4) are shown in Table 3. MRPE was calculated using the formula:

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

where e is the mean relative percent error (%), p is the predicted pressure (kPa), and a is the observed pressure (kPa).

In most cases, there were large mean relative percent errors between the observed and predicted pressures (Table 3). This suggests that the prediction equation developed by Ima and Mann (2008) for woodchips of constant moisture content is not appropriate for predicting peak lateral pressures in a biofilter when the woodchips are expected to undergo wetting and drying cycles. Thus, a prediction model was developed for this purpose using multiple regression analysis (centered approach). The model predicts lateral pressure as a function of height on the bin wall (from the bin floor), bulk density, and media moisture content (Eq. 6). The regression model ($R^2 = 0.8196$) indicates that there is a significant interaction between height and bulk density as well as between height and media moisture content. It was also found that bulk density is highly correlated to moisture content (88%). Thus, both variables have similar effects on pressure. The new prediction equation yielded MRPEs less than 73% in all cases. This compares with MRPEs that were as high as 288% for the prediction equation that had been developed under conditions of constant moisture content (Table 3).

$$\begin{aligned} P_i = {} & 0.38871 - 0.81645\,(y - 0.575) \\ & + 5.0467\,(y - 0.575)^2 + 0.0059\,(bd) \\ & + 0.10399\,(y - 0.575)\,(mc - 67.2) \\ & - 0.02221\,(-0.575)\,(bd - 420.127) \end{aligned} \qquad (6)$$

where P_i is the peak lateral pressure (kPa), y is the height on bin wall under consideration (m), bd is the bulk density of material (kg/m^3), and mc is the moisture content of woodchips (%).

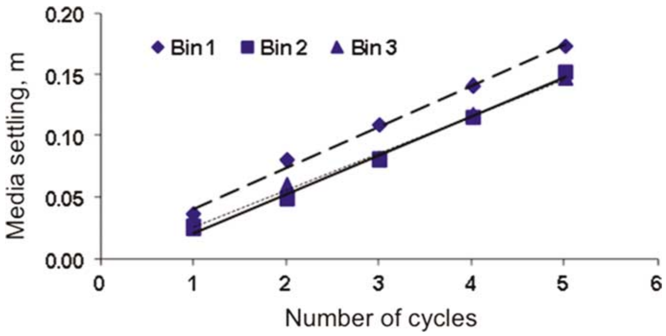

Fig. 6. Relationship between media settling and number of cycles.

CONCLUSIONS

An experiment was conducted to study lateral pressure variation in a model biofilter bin caused by 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.
- 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 pressure acting at the base of the wall.

Table 3. Mean relative percent error (%) calculated as i) the difference between observed pressures and those predicted using the equation developed for constant moisture content conditions ($MRPE_{Eq4}$) and ii) the difference between observed pressures and those predicted using the equation developed for conditions of wetting and drying ($MRPE_{Eq6}$).

	$MRPE_{Eq4}$ (%)			$MRPE_{Eq6}$ (%)		
Sensor location	Bin 1	Bin 2	Bin 3	Bin 1	Bin 2	Bin 3
0.9 m	83.9	41.3	6.9	72.9	23.7	26.2
0.7 m	77.8	[1]–	280.6	29.7	[1]–	36.4
0.5 m	197.0	137.8	288.2	48.2	16.8	61.7
0.2 m	20.3	75.7	21.5	7.5	39.3	8.7

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

- 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 increases in bulk density due to media settling.
- 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.
- Multiple regression analysis was used to generate a prediction model (Eq. 6) that estimated peak lateral pressure as a function of media moisture content, bulk density, and height for wood chips containing biofilters 0.50 m × 0.50 m in size and 1.20 m tall.

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