VERTICAL AND HORIZONTAL AIRFLOW CHARACTERISTICS OF WOOD/COMPOST MIXTURES

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ABSTRACT. *For design purposes, the relation between flow rate through biofilter media and pressure drop across biofilter media is necessary. Vertical and horizontal chambers were constructed to study the effects of airflow direction on the resistance to airflow through biofilter media. The effects of wood–aggregate:compost ratio (100:0, 80:20 and 60:40% measured on a wet mass basis), type of wood aggregate (chips and mulch), two moisture levels, and two compaction levels on the resistance to airflow were measured. Ten airflow rates (ranging between 0.054 and 0.511 $m^3\ s^{-1}\ m^{-2}$) were used throughout the experiments.*

Pressure drop was linearly correlated with bed depth for both wood aggregates regardless of the airflow direction. When pressure drop per unit depth was plotted against airflow rate, on a log–log scale, the data displayed the same linear trend as reported by previous researchers for both biofilter media and grains. Resistance to airflow in the horizontal direction was approximately 0.65 times the resistance to airflow in the vertical direction for media mixtures containing wood chips. Based on lower resistance to airflow, wood chips were observed to be a better aggregate than wood mulch.

Keywords. *Biofilter media, Pressure drop, Airflow resistance, Wood chips, Wood mulch, Compost.*

Biofiltration uses microorganisms to treat low concentrations of highly odorous compounds in gas streams from wastewater facilities, solid waste processing plants, rendering plants, chemical manufacturing facilities, composting operations, and livestock barns. An essential component of a biofilter is the porous bed of media that is typically composed of a mixture of various proportions of biological residues (e.g., compost, peat, soil) and inert bulking agents (e.g., wood chips, activated carbon, polystyrene beads). Microorganisms reside in thin biofilm layers that form on the surfaces of the media particles (Devinny et al., 1999). The microenvironment inside the biofilter bed must be maintained within a limited range of conditions (temperature, moisture content, and pH) to ensure the survival of the microorganisms. In addition to creating a "home" for the microorganisms, the biofilter media must also allow passage of the odorous gas stream. Media with low porosity will require more energy expenditure to create the same airflow increasing both the capital and operating costs of the biofiltration system. Philips et al. (1995) concluded that wood chips offer the most economically acceptable option as a biofilter media with excellent stability, even after wetting. When compared to other packing media such as compost, peat, and coconut fiber, pressure drop across wood chip media was minimal and reduced the overall power consumption for operation of biofiltration systems (Martinec et al., 2000). Nicolai and Janni (2001a) recommended a mixture of 30% compost and 70% wood chips by mass.

Air pressure through porous media is affected by the physical properties of the medium and the fluid velocity. Researchers have identified several factors that affect the airflow resistance through grains including air stream velocity and viscosity; moisture content of the grain; shape and size of the kernels; grain surface roughness; configuration of voids; amount, size, and distribution of foreign material; method of filling; and direction of airflow (Alagusundaram and Jayas 1990; Jayas 1988). It can be assumed that these same factors will be important for biofilter media. Of particular importance would be the shape and size of the media particles and the porosity of bulk media.

Kristensen and Kofman (2000) measured resistance to airflow during ventilation of different types of wood chips ranging from 28 to 200 mm in length. They found that the airflow resistance was correlated with the size of wood particles. The lowest airflow resistance was observed in 200–mm long pieces of willow (2 Pa/m) at an airflow rate of 0.1 m/s while the highest resistance was found in 28–mm pieces of willow and forest material (39 Pa/m).

Nicolai and Janni (2001a) compared mixtures of compost and wood chips ranging from a blend containing no compost (e.g., 100% wood chips) to a blend containing 50% compost (by mass) in 10% increments of compost. Three moisture contents were compared: low (27.6%), medium (47.4%), and high (54.7%). They reported that the pressure drop increased as the amount of compost in the media mixture increased (and the porosity of the mixture decreased). Moisture content had an effect on the pressure drop for media mixtures with low

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Article was submitted for review in February 2002; approved for publication by the Structures & Environment Division of ASAE in August 2002. Presented at the North Central ASAE–CSAE Intersectional Conference in Brookings, S.D. (September 2001) as Paper No. SD01117.

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compost to wood chip ratios, but the difference disappeared at high compost to wood chip ratios. Pressure drop has also been shown to increase over time due to mineralization of the media, accumulation of biomass and fine particulates, and compaction (Yang and Allen, 1994). These phenomena also decrease the porosity.

In addition to the previous factors, the orientation of the media particles could also contribute to significant differences in airflow resistance. Anisotropic resistance to airflow may occur when non–spherical particles lie with their major axes horizontal. This orientation is likely in grain bulks when the grain is loaded into a bin from the top (Lamond and Smith, 1982, cited by Jayas et al., 1987). This orientation creates air passages with different characteristics depending upon the direction of air movement. Large–diameter, short, straight air passages offer less resistance to airflow than small–diameter, long, crooked air passages. In grain beds, resistance to airflow in the horizontal direction was 0.5 times the vertical resistance for wheat and barley (Kumar and Muir, 1986), 0.6 times the vertical resistance for canola (Jayas et al., 1987), and 0.5 times the vertical resistance for lentils (Sokhansanj et al., 1988). Kay et al. (1989) observed similar results for corn and barley. Similar results were observed for materials with much larger diameters (i.e., potatoes). Irvine et al. (1993) observed lower airflow resistance in the horizontal direction than in the vertical direction. Based on this published evidence, it can be hypothesized that the airflow resistance through biofilter media in the horizontal direction will be less than the airflow resistance in the vertical direction.

The main objective of this research was to determine the airflow resistance characteristics through wood and compost mixtures in both the vertical and horizontal directions. The effects of moisture level, compaction level, and wood to compost ratio were investigated for two types of wood aggregate, chips, and mulch. The results from this research can be used in optimizing the design of a biofilter for odor removal.

Materials And Methods

Biofilter Chamber

Two biofilter chambers (1 × 1 × 2.4 m) were fabricated using pressure–treated plywood. The first chamber was placed vertical and the second was placed horizontal (fig. 1). Air was supplied to either the vertical or the horizontal chamber by a centrifugal fan (0.51 m^3/s under a static pressure of 2.0 kPa). Air was directed to the desired chamber by a flap–style valve. The desired airflow rate was obtained using an adjustable valve. Perforated metal sheeting was used to support the media at the bottom of the vertical chamber and at both the inlet and outlet ends of the horizontal chamber. The entire apparatus was mounted on a heavy–duty trailer. The biofilter chambers were filled with a mixture of wood aggregate (chips or mulch) and mature compost.

To compensate for media settlement during the experiments, the horizontal chamber had an inflatable polyurethane bladder between the top surface of the media and the bottom surface of the rigid plywood lid (fig. 1). This polyurethane bladder was pressurized by the fan through a bypass duct from the horizontal airflow plenum to the bladder. Consequently, the pressurized bladder would expand as the media settled to maintain a tight seal between the bladder and the top surface of the media. The seal between the bladder and media surface was necessary to prevent short–circuiting of the air above the biofilter media.

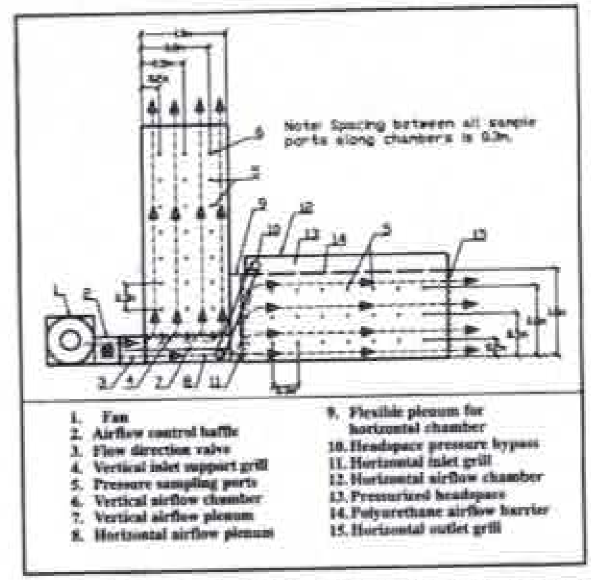

Figure 1. Vertical and horizontal chambers used to determine the airflow resistance characteristics of biofilter media in the vertical and horizontal directions.

Instruments

A wind speed indicator (Davis Instruments Turbo–Meter, Hayward, Calif.) was used to measure air velocity at the inlet to the centrifugal fan. Velocity readings were taken 80 mm from the edge of a cylindrical duct (0.31 m in diameter, 0.49 m in length) mounted at the inlet to the fan. Ambient air temperature and relative humidity were measured using a relative humidity and temperature meter (Omega model number RH 20C). Pressure was measured using two different pressure transducers [Omega model number 242PC05M 0010 (0 to 34.5 kPa) and Omega model number PX 143 (0 to 6.9 kPa)]. Prior to the experiments, both pressure transducers were calibrated against a water column. Pressure readings were taken in the plenum and at eight locations along the longest dimension of the chamber (fig. 1). At each of the eight locations, pressure readings were taken from sample ports located 0.2, 0.5, and 0.8 m along a line perpendicular to the longest dimension of the chamber.

Media Composition

The biofilter media consisted of wood aggregate (either wood chips or wood mulch) mixed with compost. Three ratios of wood aggregate to compost were tested (100:0, 80:20, and 60:40 measured on a wet mass basis). An estimate of the porosity (table 1) was obtained using the "five–gallon pail method" (Rosen et al., 2000, cited by Nicolai and Janni, 2001b). The "five–gallon pail method" determines the volume of water required to fill the pore spaces within a sample of biofilter media compared to the volume of the pail in which the biofilter media is contained. Bulk density was estimated as the mass of media added to each chamber divided by the volume occupied by that mass of media (table 2).

Table 1. Measured moisture content and porosity (mean and standard deviation based on three replicates) for mixtures of wood aggregate and compost.[a]

Wood Aggregate	Composition[b]	Moisture Content (%)	Porosity (%)
Chips	100:0 D	30.8 (1.0)	65.2 (1.7)
	100:0 W	52.7 (2.7)	62.3 (0.6)
	80:20 W	54.5 (1.6)	57.1 (1.9)
	60:40 W	53.0 (0.9)	48.0 (2.3)
Mulch	100:0 D	33.5 (0.8)	64.3 (2.9)
	100:0 W	59.2 (1.0)	54.6 (2.5)
	80:20 W	57.0 (1.9)	51.7 (2.9)
	60:40 W	51.5 (2.4)	46.2 (2.2)

[a] Porosity was obtained using the "five–gallon pail method" (Rosen et al., 2000, cited by Nicolai and Janni, 2001b).

[b] Wood aggregate : compost; D = low moisture content; W = high moisture content.

Composted grocery produce was obtained from Rockwood Agribusiness, Stony Mountain, Manitoba. It had the following characteristics: porosity = 42.6%; moisture content at saturation = 51%; pH = 7; and density at saturation = 1.35 g/cm^3. Details of the composting process were not available from the supplier. It was assumed that the compost had reached maturity because it did not have an unpleasant odor.

The wood chips used in this research originated as debris wood (pine, spruce, fir, cedar, aspen, birch, willow, and alder) on Cedar Lake in northern Manitoba. An industrial knife chipper was used to create chips with a thickness of 3 to 4 mm. Wood chip length varied according to the following distribution (determined by sieving and expressed as a percentage of total wet mass): < 19 mm (70%); 19 to 25 mm (18%); 25 to 31 mm (7%); 31 to 38 mm (3%); > 38 mm (2%). Overall, the wood chip material was homogeneous.

The wood mulch used in this research was obtained from a local supplier and consisted of chipped trees. A typical sample of mulch contained particles ranging from small pine needles to large twigs, and therefore, was not homogeneous. The mulch particles varied according to the following distribution (determined by sieving and expressed as a percentage of total wet mass): <19 mm (51%); 19 to 25 mm (19%); 25 to 31 mm (4%); 31 to 38 mm (1%); stones > 38 mm (4%); twigs > 38 mm (21%). The most important difference between the chips and mulch was the large percentage of long, unchipped twigs.

Table 2. Measured moisture content (mean of three samples) and bulk density for each of the mixtures of biofilter media tested in the vertical and horizontal chambers.

			Bulk Density (kg/m^3)			
		Moisture Content	Uncompacted		Compacted	
Wood Aggregate	Composition[a]	(%)	Vertical	Horizontal	Vertical	Horizontal
Chips	100:0 D	13.8	169	169	184	194
	100:0 W	48.5	301	287	321	313
	80:20 W	51.0	381	371	397	387
	60:40 W	47.1	481	464	494	484
Mulch	100:0 D	23.9	210	202	222	209
	100:0 W	44.7	310	302	317	312
	80:20 W	53.8	465	402	469	414
	60:40 W	42.0	484	469	493	474

[a] Wood aggregate : compost; D = low moisture content; W = high moisture content.

Media Moisture Content

The influence of moisture content was investigated for media consisting of only wood aggregate. "Dry" was the moisture content of the wood aggregate with the addition of no water and "Wet" was the moisture content of the wood aggregate after adding water to create conditions suitable for biofiltration (i.e., 40 to 60% mc) (table 2). Moisture content was determined by drying at 60°C for 72 h (*ASAE Standards*, 1999).

Media Compaction

Over time, biofilter media containing compost will settle and will become denser (Devinny et al., 1999). When settling occurs, it is expected that the media's resistance to airflow will increase. In this research, the biofilter media was artificially induced to settle by subjecting it to mechanical motion. The trailer supporting the biofilter chambers was pulled on a gravel road at a velocity of 40 km/h for approximately 10 km. Before and after the induced media settlement, media depth was determined by measuring the distance from the surface of the media to a reference line. In the horizontal chamber, the smaller cross–sectional area was used to calculate the unit airflow rate. After measuring the airflow resistance characteristics of the compacted media, the chambers were emptied and refilled with a new media mixture.

Results and Discussion

Pressure Drop Across the Media Cross–Section

Readings from the calibrated pressure transducer were taken from three sample ports located along a line perpendicular to the longest dimension of the chamber. Mean, SD, and CV were calculated for each group of three readings for each experimental combination tested. The CV was less than 5 in 76% of the cases. Based on these results, it was assumed that the variation across the media cross–section could be ignored in further analysis. Subsequent analysis is based upon the means calculated for each group of three readings.

Linearity of Pressure Drop with Media Depth

Figures 2 and 3 show average pressure drops across biofilter media containing either wood chips or wood mulch mixed with compost in an 80:20 ratio for seven depths (note: "depth" is used to denote distance in the direction of airflow) and 10 horizontal airflows. Pressure drop was linear with bed depth for both wood aggregates, although the degree of linearity was greater for the media containing wood chips ($R^2 > 0.99$) than for the media containing wood mulch (R^2 ranged from 0.90 to 0.99). This result was expected because the wood chips were more homogeneous than the wood mulch based on particle size distribution. Similar results were obtained for the relationship between pressure drop and bed depth for vertical airflow.

Effect of Induced Media Settlement on Pressure Drop

As a result of the mechanical motion, the bed height decreased in all cases (table 3). The greatest reduction in bed height occurred with the dry 100:0 wood aggregate to compost mixture for both types of wood aggregate and for both the vertical and horizontal chambers. In most cases,

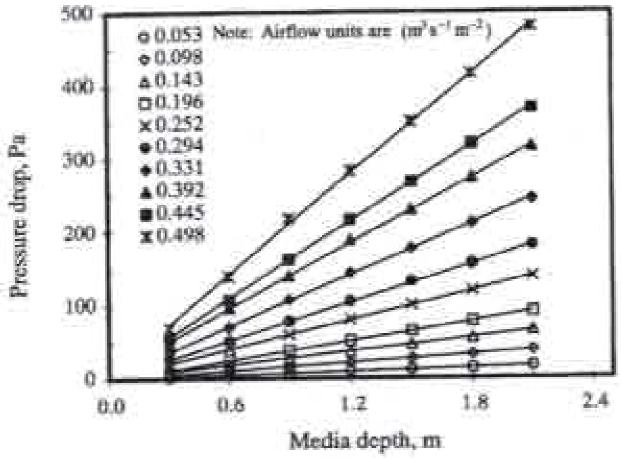

Figure 2. Effect of bed depth (note: "depth" is used to denote distance in the direction of airflow) on pressure drop across wet media consisting of wood chips mixed with compost in a ratio of 80:20 at 10 airflows in the horizontal direction.

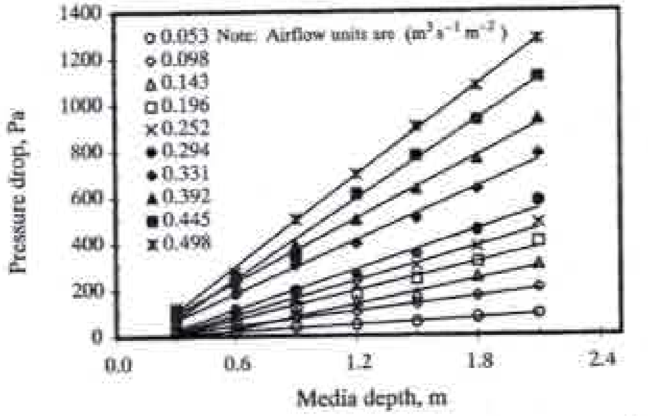

Figure 3. Effect of bed depth (note: "depth" is used to denote distance in the direction of airflow) on pressure drop across wet media consisting of wood mulch mixed with compost in a ratio of 80:20 at 10 airflows in the horizontal direction.

the percentage change in bed height was greater in the horizontal chamber than in the vertical chamber.

Despite the measurable changes in bed height, there was little change in the airflow resistance characteristics (fig. 4). The difference was almost undetectable for media containing both wood aggregate and compost (fig. 4). Apparently, the procedure used in this research to artificially induce settlement was insufficient to create changes in airflow resistance characteristics. Based on this observation, the "compacted" data has been omitted from further analysis.

AIRFLOW RESISTANCE EQUATIONS

Figures 5 and 6 illustrate the correlation between pressure drop per unit depth of biofilter media and airflow rate for all of the media mixtures tested. When plotted on a log–log scale, the data display the same linear trend as reported by previous researchers for biofilter media (Nicolai and Janni 2001b; Mann et al., 2001) and for grains and oilseeds (see *ASAE Standards*, 1999a for a list of papers related to grains and oilseeds).

Table 3. Measured changes in bed height due to artificially induced media settlement.

Wood Aggregate	Composition[a]	Bed Height (% change) Vertical[b]	Bed Height (% change) Horizontal[c]
Chips	100:0 D	–8.6	–12.3
	100:0 W	–5.9	–9.3
	80:20 W	–4.1	–4.6
	60:40 W	–2.4	–4.5
Mulch	100:0 D	–5.8	–3.1
	100:0 W	–2.2	–3.0
	80:20 W	–1.1	–2.5
	60:40 W	–1.7	–1.4

[a] Wood aggregate : compost; D = low moisture content, W = high moisture content

[b] An average bed height before and after compaction was determined based on nine sampling locations.

[c] An average bed height before and after compaction was determined based on 12 sampling locations.

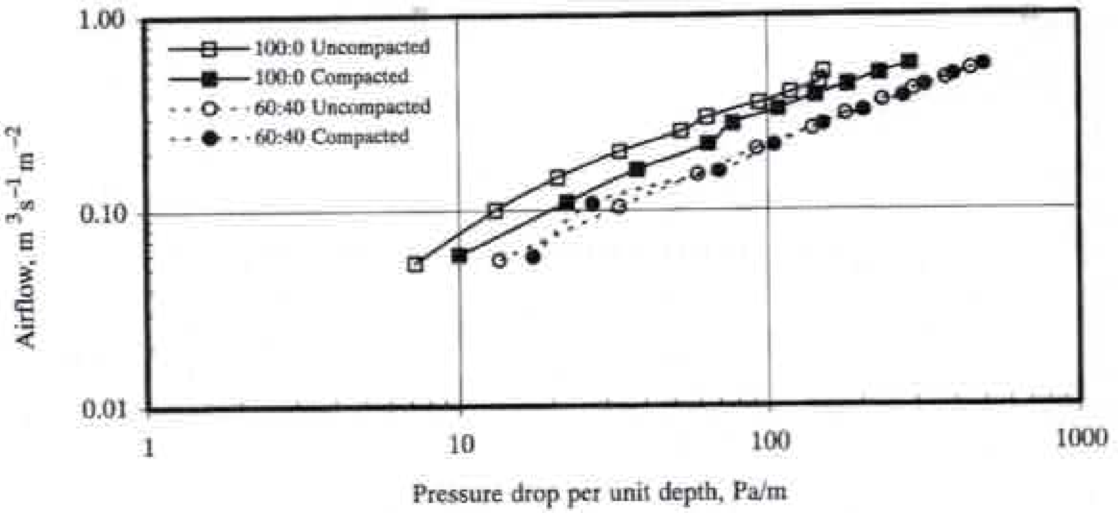

Figure 4. Effect of induced media settlement on the resistance to airflow in the horizontal direction for media mixtures consisting of wet wood chips and compost.

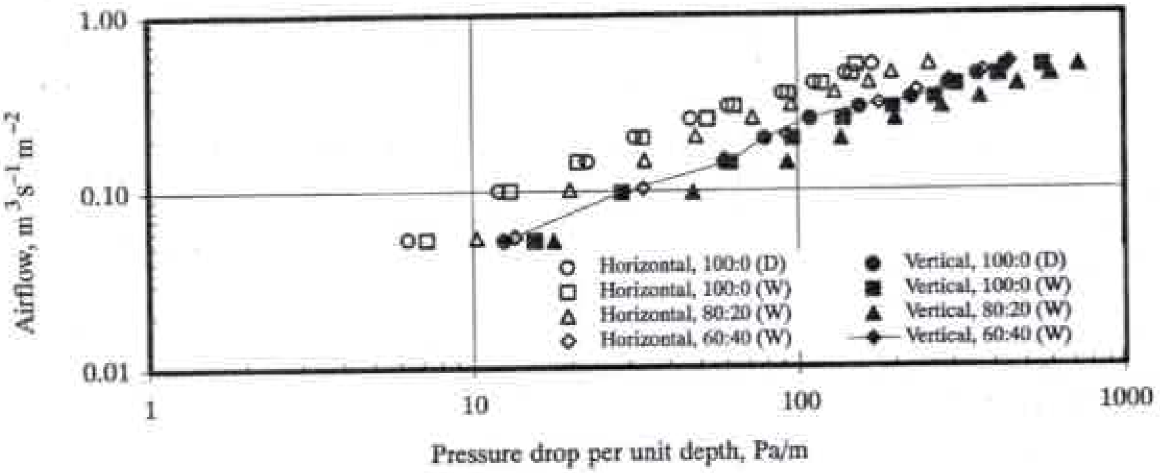

Figure 5. Effect of airflow direction on the resistance to airflow for media mixtures consisting of wood chips and compost. The solid line is used to indicate the positions of the solid diamonds (vertical, 60:40 (W)), which are covered by other symbols.

In the past, several equations have been used to represent airflow resistance data. Two of the most common are the Hukill and Ives (1955) equation (which is also used in *ASAE Standards*, 1999a)

$$\frac{\Delta P}{L}=\frac{aQ^2}{\log_e(1+bQ)} \tag{1}$$

where

Q = airflow rate (m^3 s^{-1} m^{-2})
ΔP = pressure drop (Pa)
L = bed depth (m)
a, b = constants for specific material

and the Shedd's (1953) equation

$$Q=c\left(\frac{\Delta P}{L}\right)^d \tag{2}$$

where

c, d = constants for specific material

Constants a, b, c, and d were calculated for each media mixture tested (table 4). For the airflow ranges listed in table 4, the correlation coefficients (R^2) were greater than 0.94 in all cases.

EFFECT OF AIRFLOW DIRECTION ON PRESSURE DROP

According to figures 5 and 6, there is a definite advantage to blowing air horizontally through a biofilter bed rather than vertically. One possible explanation for this observation is that the bulk density was lower in the horizontal chamber in all but one case. Corresponding with a lower bulk density is a higher porosity; and, consequently, less resistance to airflow. Based on the data for the uncompacted media, the bulk density in the horizontal chamber was, on average, 4.2% lower. It is not known whether such a small change in bulk density could account for the large differences in airflow resistance observed in this research.

A second possible explanation for this observation is anisotropy. As discussed in the introduction, anisotropy has been observed in porous beds of grains and potatoes. It has been hypothesized that the anisotropic behavior is caused by particles orienting themselves with their major axis horizontal when loaded from the top. Because the biofilter media was also loaded into both the vertical and horizontal chambers from the top, it is likely that most pieces of wood aggregate fell with their major axes horizontal. The orientation of the pieces of wood aggregate in this research was not confirmed.

Although the explanation is not certain, it is clear that, for the same airflow rate, horizontal movement of the air required less pressure to be overcome. An estimate of the

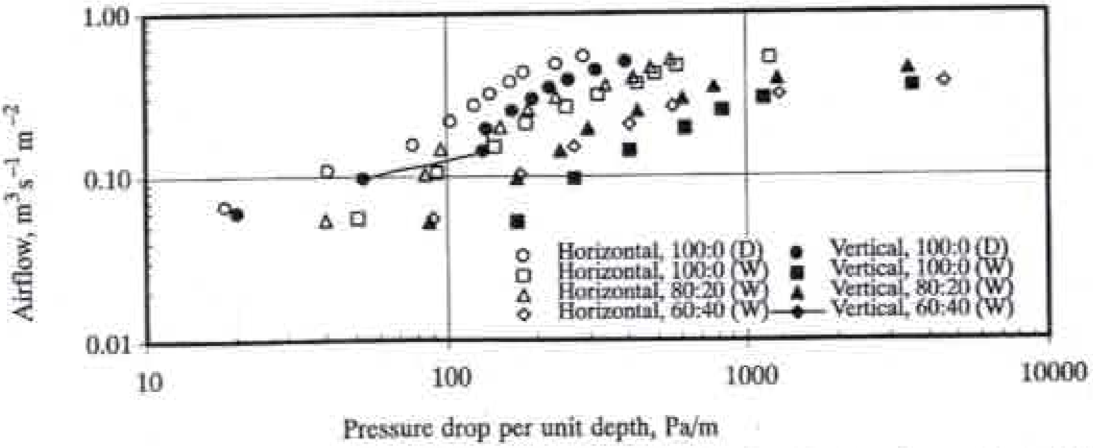

Figure 6. Effect of airflow direction on the resistance to airflow for media mixtures consisting of wood mulch and compost. The solid line is used to indicate the positions of the solid diamonds (vertical, 60:40 (W)), which are covered by other symbols.

Table 4. Coefficients for the Hukill and Ives (1955) equation (a and b) and for the Shedd's (1953) equation (c and d) for each of the mixtures of biofilter media tested.

				Hukill and Ives Equation			Shedd's Equation		
Wood Aggregate	Orientation	Composition[a]	Range of Q ($m^3 s^{-1} m^{-2}$)	a	b	R^2	c	d	R^2
Chips	Vertical	100:0 D	0.055 to 0.514	9993	769	0.9972	0.0165	0.5659	0.9958
		100:0 W	0.055 to 0.514	18627	18627	0.9946	0.0167	0.5459	0.9956
		80:20 W	0.055 to 0.514	13506	256	0.9993	0.0118	0.5736	0.9988
		60:40 W	0.055 to 0.405	14864	23.1	0.9989	0.0040	0.6651	0.9967
	Horizontal	100:0 D	0.056 to 0.528	3386	462.1	0.9988	0.0267	0.5824	0.9969
		100:0 W	0.056 to 0.525	1574	25.0	0.9926	0.0226	0.6165	0.9949
		80:20 W	0.057 to 0.534	3695	127.1	0.9983	0.0193	0.6041	0.9969
		60:40 W	0.057 to 0.484	5397	61.4	0.9994	0.0131	0.6118	0.9992
Mulch	Vertical	100:0 D	0.062 to 0.514	715	1.3	0.9836	0.0032	0.8605	0.9820
		100:0 W	0.055 to 0.304	14803	8.0	0.9949	0.0014	0.7702	0.9920
		80:20 W	0.055 to 0.358	8925	9.7	0.9920	0.0026	0.7443	0.9881
		60:40 W	0.055 to 0.148	21233	5.8	0.9986	0.0006	0.8434	0.9977
	Horizontal	100:0 D	0.068 to 0.564	490	1.4	0.9898	0.0048	0.8498	0.9893
		100:0 W	0.058 to 0.548	30805	30805	0.9435	0.0133	0.5419	0.9593
		80:20 W	0.056 to 0.532	3307	7.9	0.9956	0.0055	0.7218	0.9927
		60:40 W	0.058 to 0.273	7069	5.7	0.9994	0.0018	0.7977	0.9984

[a] Wood aggregate : compost; D = low moisture content; W = high moisture content.

ratio between vertical and horizontal airflow can be obtained using the c and d coefficients calculated for Shedd's equation (table 4). For wood chips, it can be assumed that the d coefficient is constant at 0.60 ± 0.04 for both vertical and horizontal airflow. The intercepts (i.e., the c coefficients) can be used to compare the effect of direction of airflow. The ratios of the intercepts for vertical to horizontal direction varied from 0.61 to 0.74 with a mean of 0.66 ± 0.07 (note: the ratio of 0.31 for 60:40 W was not included in this mean because it seems to be an experimental outlier). Resistance to airflow in the horizontal direction is about 0.65 times the resistance to airflow in the vertical direction. For wood mulch, the ratios of the intercepts for vertical to horizontal direction varied from 0.11 to 0.67 with a mean of 0.40 ± 0.24.

Effect of Moisture Content on Pressure Drop

Comparisons between low and high moisture content media were studied only for media consisting of either 100% wood chips or 100% wood mulch. For both wood aggregates, the pressure drop per unit depth was greater when the aggregate was wet (figs. 5 and 6) although the difference was much more pronounced for wood mulch. It is likely that this difference is due to the decreased porosity that corresponds to the increased bulk density.

Effect of Wood Aggregate on Pressure Drop

Figure 7 shows that the pressure drop per unit depth was greater for wood mulch than for wood chips in both airflow directions. This result was unexpected because large twigs in the wood mulch formed bridges, air pockets, and channels. The result can be explained, however, when the porosity is considered. For the same ratio of wood aggregate to compost, the media containing wood mulch had a lower porosity (table 1).

Conclusions

From the experimental work described in this article, several important conclusions can be drawn. Of most significance, it was shown that the resistance to airflow in the horizontal direction was approximately 0.65 times the resistance to airflow in the vertical direction for biofilter media consisting of wood chips and compost. Of secondary importance, it was shown that wood chips of uniform size had

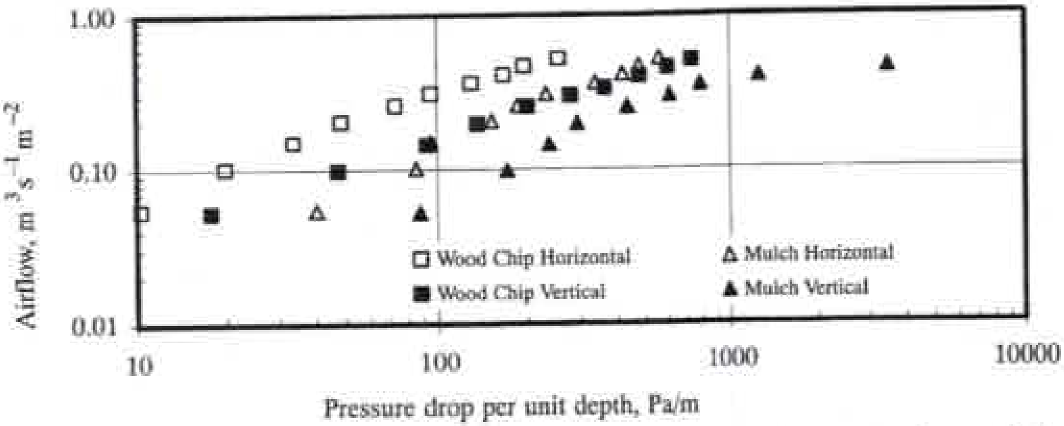

Figure 7. Effect of wood aggregate on the resistance to airflow for media mixtures consisting of wood aggregate and compost in the ratio of 80:20.

greater porosity and offered less resistance to airflow than non–homogeneous wood mulch. Finally, it was concluded that the method used in this research to artificially induce media settlement did not alter the airflow resistance characteristics of the media.

ACKNOWLEDGEMENTS

The authors thank Chemawawin Cree Nation for funding the project and Ed Garlinski, Layne Maciura, Matt McDonald, and Gerry Woods for their technical assistance.

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