THE EFFECT OF SYNTHETIC BULKING AGENTS ON PRESSURE DROP THROUGH FOOD WASTE COMPOST

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SUMMARY

Pressure drop was measured through a column of lettuce and onion food processing waste containing synthetic bulking agents from chemical separations processes. Six different polypropylene bulking agents were compared against the more traditional bulking agent pine bark. The bulking agents were used at various different fractions, or bulking agent densities. The results consistently showed that the synthetic bulking agents caused a pressure drop three to five times lower than pine bark. Pressure drop models suggested by Shedd, Hukill and Ergun were used to fit these data. A parameter in Ergun's equation was used to quantify the fraction of bulking agent necessary to implement 50% viscous energy pressure drop losses.

INTRODUCTION

Vegetable wastes have several characteristics which have made composting problematic, these include high moisture content, low carbon to nitrogen ratio, and often high concentrations of odor causing chemicals such as sulfur. Bulking agents may mitigate problems associated with vegetable waste composting. An ideal bulking agent would contribute pore space throughout the compost pile and process (Haug, 1993). Low-cost synthetic bulking agents might indeed be designed to provide optimal support and void space integrity. Similar criteria have been used for the design of numerous packing materials for gas absorption used in the chemical manufacturing industries. Indeed, low pressure drop is a principal concern in the selection of these inert packing materials (Coker, 1991).

The high moisture content of vegetable waste results in considerable deformation and compaction during the degradation process, causing significant reduction of pore space through which air may flow (Haug, 1993). As pore space is reduced, pressure drop across the compost pile will increase, necessitating higher energy input to the blowers to maintain the air flow (Keener, 1993). These problems may be partially circumvented with bulking materials that provide a relatively constant pore matrix in the compost.

The low C:N ratio of lettuce and onion wastes may cause incomplete microbial digestion. Therefore, these wastes should be augmented with a substrate containing a high C:N ratio. In addition, the high sulfur content of the vegetables (particularly onions) increases the likelihood of odor formation, particularly if an aerobic environment is not maintained (Haug, 1993). Sulfur caused odors may be reduced by augmenting vegetable waste with low sulfur substrates to provide a chemical balance, or by insuring adequate aeration during the entire compost process. Adequate aeration is also facilitated with bulking agents and high pore space.

CORRELATIONS FOR PRESSURE DROP

Numerous correlations are available for predicting pressure drop encountered by fluids flowing through a matrix of porous material such as compost. In general, pressure drop per depth of material (ΔP) is a function of superficial fluid velocity (U). Shedd (1951, 1953) proposed the following equation for airflow through seed and grain:

$$\Delta P = AU^B \quad (1)$$

The superficial air velocity (units of cfm/ft^2, or ft/min) is equal to the volumetric flow rate (Q) divided by the cross-sectional area of the porous material, tangential to the direction of flow. The two terms A and B in Equation 1 are empirically determined. Hukill (1953) modified Equation 1 to account for nonlinearities in the results of Shedd:

$$\Delta P = \frac{CU^2}{\ln(1+DU)} \quad (2)$$

In Equation 2, C and D are empirically determined. Although the pressure drop is normalized by material height, Equations 1 and 2 do not account for the effects of compressible materials such as vegetable wastes. The simplest correlation (Chen, 1980; Higgins et al., 1982; Haug, 1993) for quantifying air flow through a column of compressible materials is:

$$\Delta P = KU^n h^j \quad (3)$$

In Equation 3, the value of K and the exponents n and j are empirically determined. The values of these exponents approach one for laminar flow. The value of j becomes one for non-compressible materials, and Higgins (1982) suggested that j will be one for a depth less than 2.4 meters. Since flow through porous media is turbulent (Schedegger, 1957) values of the exponents are generally not equal to one. More recently Das and Keener (1997) demonstrates the effect of moisture content and compaction on pressure drop. Reynolds (1900) formulated an alternate approach to describe pressure drop as a function of superficial velocity:

$$\Delta P = aU + bU^2 \quad (4)$$

Ergun (1952) is often credited with the application of this equation, as he provided an extensive demonstration of its utility in describing the behavior of oven coke. As in previous equations, Equation 4 has empirical constants which must be determined for the specific material. The first term in Equation 4 represents the viscous energy losses, and is essentially a simplification of Darcy's Law, which regards inertial effects as negligible. Viscous energy losses are caused by the contact of a fluid with the surface over which it is traveling. The second term represents the kinetic energy losses, caused by rapid lateral movement of the fluid as it flows through pore spaces. In completely turbulent flow at high air velocities, kinetic energy losses constitute the principal resistance to flow. Thus the coefficients in Ergun's equation indicate the relative importance of viscous and kinetic energy losses.

An important parameter in composting with bulking agents is the ratio of bulking agent to compostable material, or the bulking agent density (ϕ). One would anticipate that at a given air flowrate increasing the bulking agent density would in general decrease the pressure drop. Increasing the value of ϕ would change the empirical constants in any of the above correlations (Equations 1 - 4). An optimal bulking agent would be one which provides low pressure drop (and associated costs) while maximizing the quantity and quality of the composted material.

The goal of this study was to compare quantitatively several bulking agents for the composting of lettuce and onion waste. The two measures of bulking agent effectiveness are the pressure drop in a column of compost, and the compostability of the mixtures.

COMPOSTING VEGETABLE WASTES

The U.S. 1997 fresh-cut vegetable production was estimated at 830 million pounds (Raynes, 1997). At one processor near Atlanta GA, 83% of total production consists of lettuce and 8% of onions (Raynes, 1997). The industry is very sensitive to vegetable quality, and therefore waste generation almost equals wholesale production. The U.S. annual projected fresh-cut vegetable waste by-products are 790 million pounds (Raynes, 1997), essentially all of which will go directly to landfills. With increasing public

pressure to reduce solid waste disposal reduction or recycle of these vegetable wastes is of growing importance. Composting may provide one alternative to landfilling there highly biodegradable materials. In addition to causing a significant volume reduction, composting can yield a useful soil amendment. However, unlike traditional compost materials such as animal and municipal waste, vegetable waste has several characteristics that may present difficulties to the process (Haug, 1993). Specifically, lettuce and onions are high in moisture, have a low C:N ratio, and can generate odor while composting due to their high sulfur content.

MATERIALS

The organic compostable mixture used in this study consisted of lettuce, onions, poultry litter, and pine sawdust. Lettuce and onions were both obtained as fresh waste from a local vegetable processing plant, the poultry litter from a local farm, and the sawdust from a sawmill (Curl Pack, Suwanee, GA). For size uniformity, the vegetables were manually chopped and screened (2" x 2"). The volume of material was measured to the nearest 0.003 m^3 and routinely stored in 45 gallon covered containers in a cold room (4 °C).

Non-organic bulking materials consisted of random packing materials commonly used in chemical manufacturing industries. Three polypropylene packing materials (shown in Figure 1) were studied: Telpack (Telpack Tower Packing, Boston, MA), Tripac, and Saddles (Jaeger Products, Inc., El Dorado, KS). For each packing material two nominal sizes (1" and 2") were studied. Pine bark (Craven Pottery, Commerce, GA) was also used studied. Table 1 shows pertinent parameters on these seven bulking materials.

Table 1 - Physical properties of the bulking materials

	Nominal Size	Void space (%)	Bulk Density (lb/ft^3)
Tripac	1"	90	6.20
Tripac	2"	93	4.20
Telpack	1"	90	4.30
Telpack	2"	94	3.50
Saddle	1"	91	5.00
Saddle	2"	94	3.25
Pine Bark	0.5-3"	78	10.00

The experimental setup to study the pressure drop consisted of three major components: a column, blowers and associated piping, and two manometers (Figure 2). The column (155 cm by 61 cm diameter) was made of reinforced fiberglass (U.S. Plastics, Lima, OH). The concave column floor averaged 23 cm above the base, yielding an effective depth of 132 cm. Over 40% of this floor was open and covered with an expanded metal and a fine mesh screen to permit airflow and to support the compost material. The top of the column was open to the atmosphere. Two blowers (Dayton Electric Mfg. Co., Niles, IL) attached in parallel via 5 cm diameter PVC piping provided air flow to the column. A single ball valve controlled the combined air flow. Two incline manometers (Dwyer Instruments Inc., Michigan City, IN) were used in this study. A manometer of 0.25 kPa maximum water pressure, calibrated with air flow covering the experimental range, was used to estimate the air flow rate. A 0.12 kPa water pressure manometer allowed measurement of the column pressure. Both manometers had a 0.0012 kPa precision.

METHODS

The compost mixture consisted of organic materials in a mass ratio of 19:23:10:1(lettuce: onions: poultry litter: sawdust) wet basis. In order to achieve this mixture, 0.091 m^3 of lettuce, 0.091 m^3 of onions, 0.04 m^3 of poultry litter and 0.005 m^3 of sawdust were mixed. A selected volume of bulking material was then mixed into the organic material, beginning with the lowest density to be tested. The resulting mixture was carefully placed in the column to avoid packing. Starting with the highest flow rate, the air flow valve

was set to each of five nominal flow rates (0.0075, 0.0107, 0.183, 0.0274, and 0.0366 $m^3/s/m^2$) and corresponding pressure drops across the material were recorded.

After a set of pressure/air flow measurements, the material was taken out of the column, mixed gently and replaced into the column for a subsequent set of measurement. After three replicate measurements were made for a given bulking agent density, additional bulking agent was added to provide the next density.

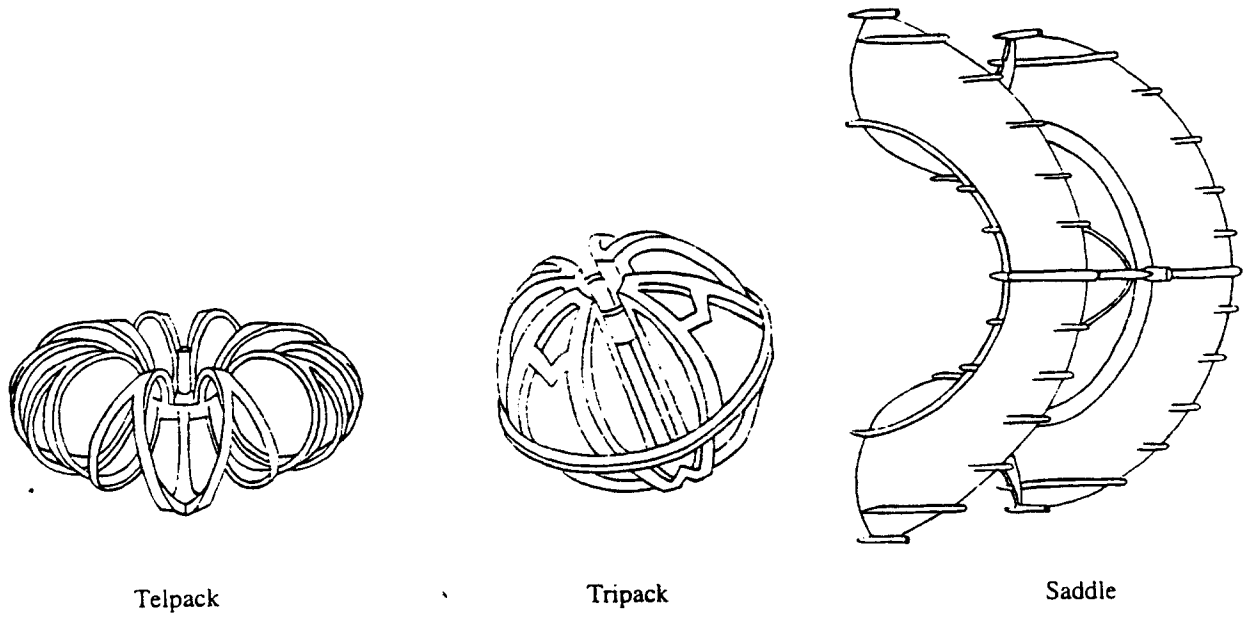

Figure 1: Synthetic Bulking Agent Shapes

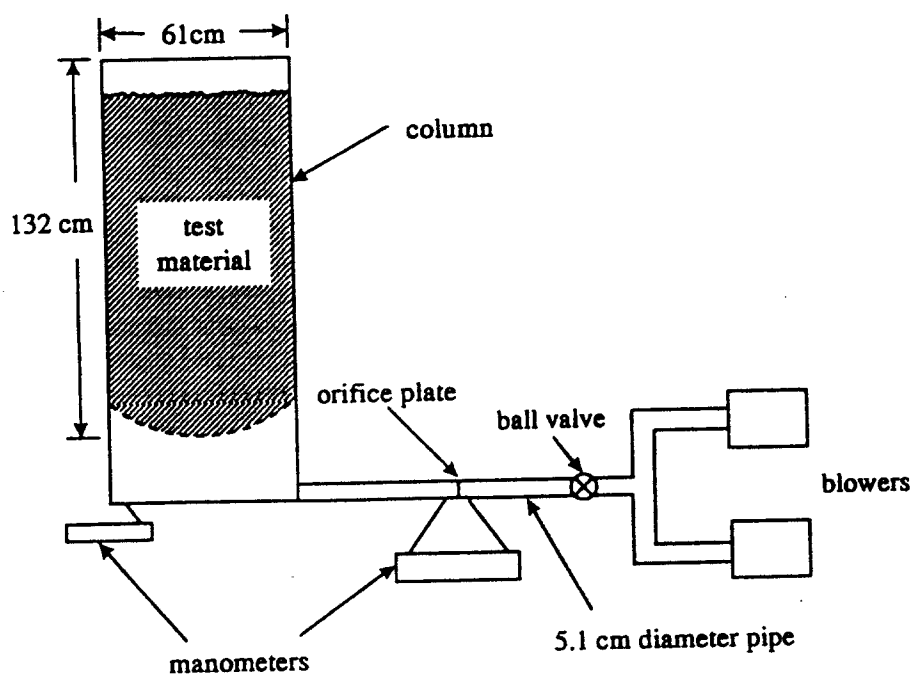

Figure 2: Experimental Setup for Pressure Drop Tests

RESULTS AND DISCUSSION

Table 2 shows the chemical and physical parameters for the four organic substrates. The lettuce and onions were above 90% moisture content and below a C:N ratio of 15.

Table 2: Chemical and physical parameters for substrates

Parameter	Lettuce	Onions	Poultry Litter	Sawdust
Moisture (wet basis)	96.17	91.10	22.70	11.33
Carbon (dry basis)	42.50	43.30	31.90	40.40
Nitrogen (dry basis)	4.13	3.76	3.71	0.05
Sulfur (dry basis)	0.20	0.69	0.68	0.36
C:N ratio	10	12	9	792
Bulk density (kg/m^3)	99.667	421.667	383.380	118.000
Particle density (kg/m^3)	679.333	963.667	1023.550	660.000
Pore space	0.853	0.521	0.623	0.824

Figures 3, 4 and 5 show the pressure drop in the compost column as a function of the superficial air velocity for three selected bulking agents. As expected, increasing the air flow increased the measured pressure drop. Moreover, for each of the bulking agents an increase in the bulking agent density resulted in a significantly reduced pressure drop. Significant differences are also observed between different bulking materials. For example, the measured pressure drop for a compost with 0.00062 m^3/kg of 1" Telpack was approximately 0.018 kPa/m at an air flow of 0.0274 m/s. In contrast, the measured pressure drop at an identical flow and bulking agent density was 0.025 kPa/m for 2" Saddles and 0.040 kPa/m for pine bark. The compost without bulking agent yielded a pressure drop of about 0.070 inches kPa/m at this flow rate. These differences were validated in a statistical analysis which showed a significant difference (at $p < 0.025$) between the trial with no bulking agent and the trials with other bulking agents, and between the trials with pine bark and those with synthetic bulking agents. However, there was no significant difference when comparing the 1" bulking agents to the 2" bulking agents, or when comparing any of the bulking agents of the same size.

Figure 6 shows another way to present the pressure drop measurements for 1" Telpack. For each air flow, increasing the bulking agent density reduced the pressure drop. The differences in pressure drop between the five bulking agent densities was statistically significant (at $p < 0.025$); the only exception to this was between $\phi = 0.00025$ and $\phi = 0.00045$ for the 1" bulking agents for which the hypothesis of equal means was accepted ($p > 0.025$).

A regression was performed to Equation 4 on the pressure drop measurements for each of the seven bulking agents and the material without bulking agent, resulting in correlation coefficients above 95%. The predicted pressure drops resulting from these equations are shown in Figures 3, 4 and 5 for selected bulking agents. As expected, an increase in the bulking agent density resulted in a decrease in the linear coefficient of Ergun's equation. Demonstrating that the linear coefficient, a, is directly related to pressure drop. Therefore, the effect that the bulking agent density, ϕ, has on the value of a indicates the effectiveness of the bulking agent in reducing the pressure drop. Figure 7 shows the relationship between the bulking agent density and the linear coefficient for five of the bulking agents. In each case this coefficient decreased with increasing bulking agent density. Moreover, the synthetic bulking agents were more effective than pine bark at reducing the value of a at any given density.

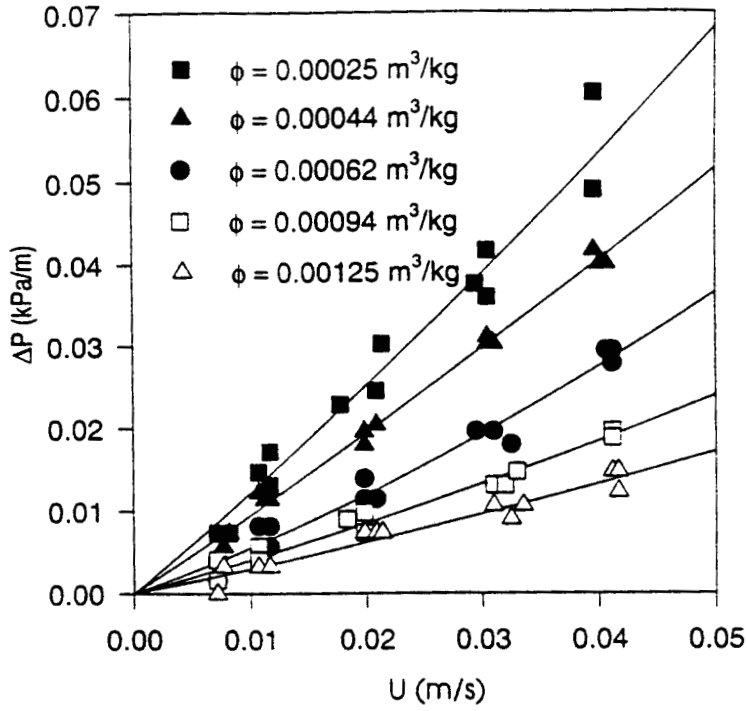

Figure 3: Measured pressure drop across column per unit material height (ΔP) as a function of superficial air velocity (U) for 1" Telpack. Solid curves represent regressions of data to Equation 4 in text.

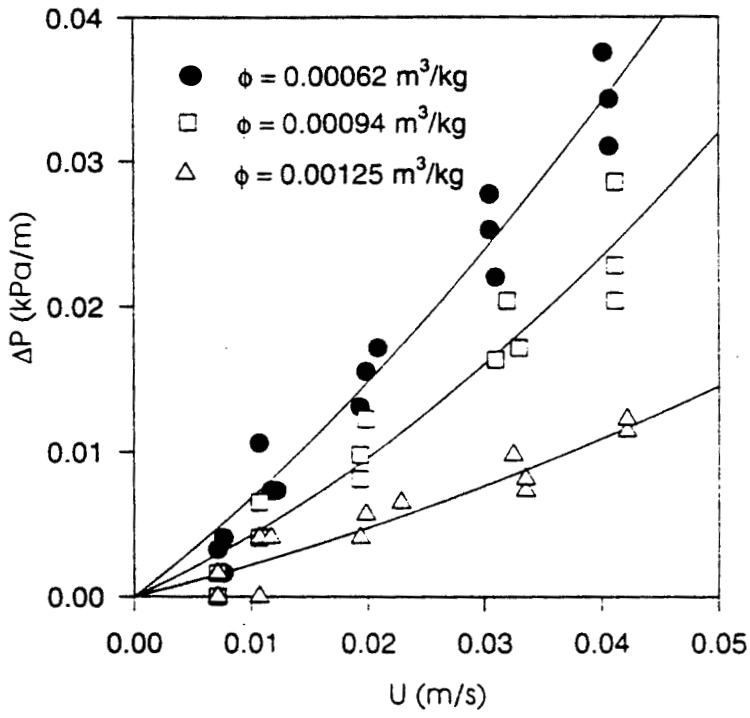

Figure 4: Measured pressure drop across column per unit material height (ΔP) as a function of superficial air velocity (U) for 2" Saddles. Solid curves represent regressions of data to Equation 4 in text.

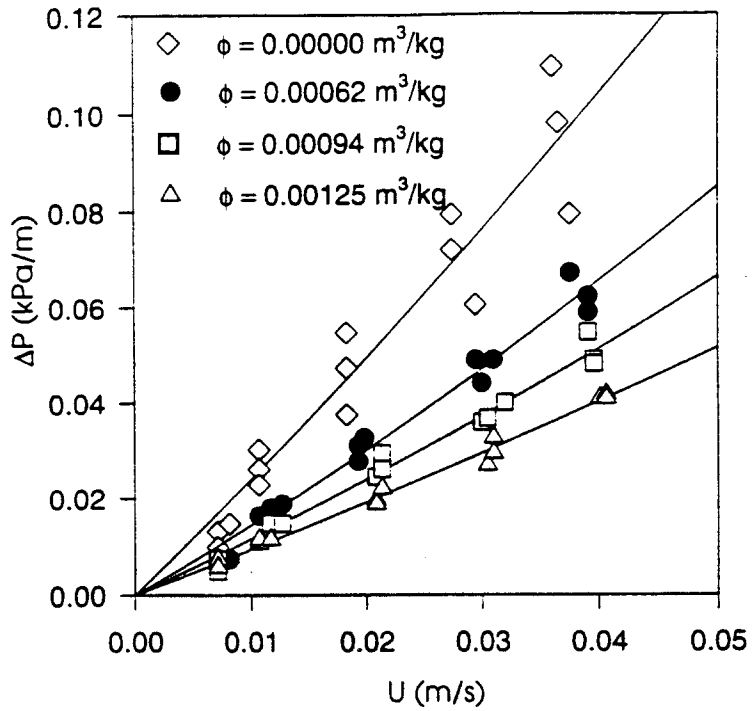

Figure 5: Measured pressure drop across column per unit material height (ΔP) as a function of superficial air velocity (U) for pine bark and without bulking agent. Solid curves represent regressions of data to Equation 4.

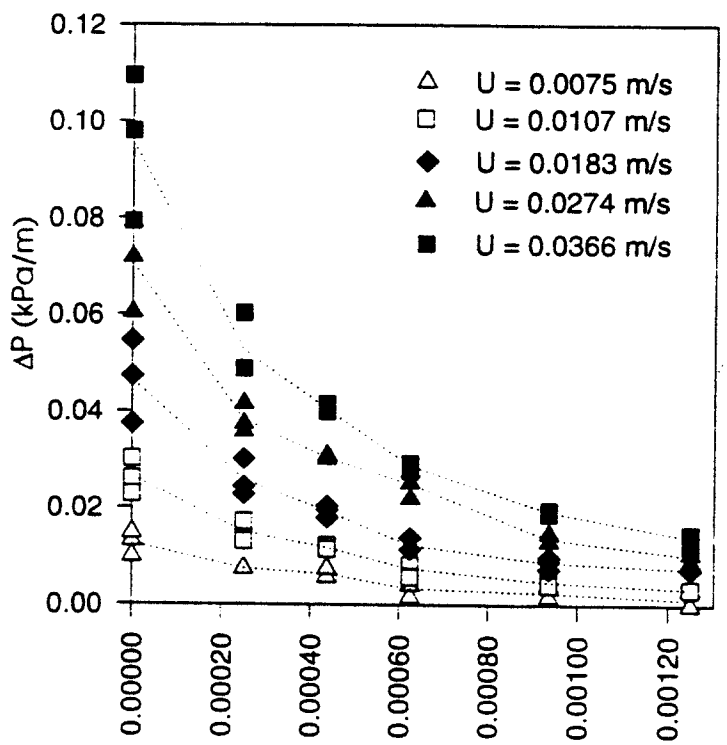

Figure 6: Measured pressure drop across column per unit material height (ΔP) as a function of bulking agent density (Φ) for 1" Telpack.

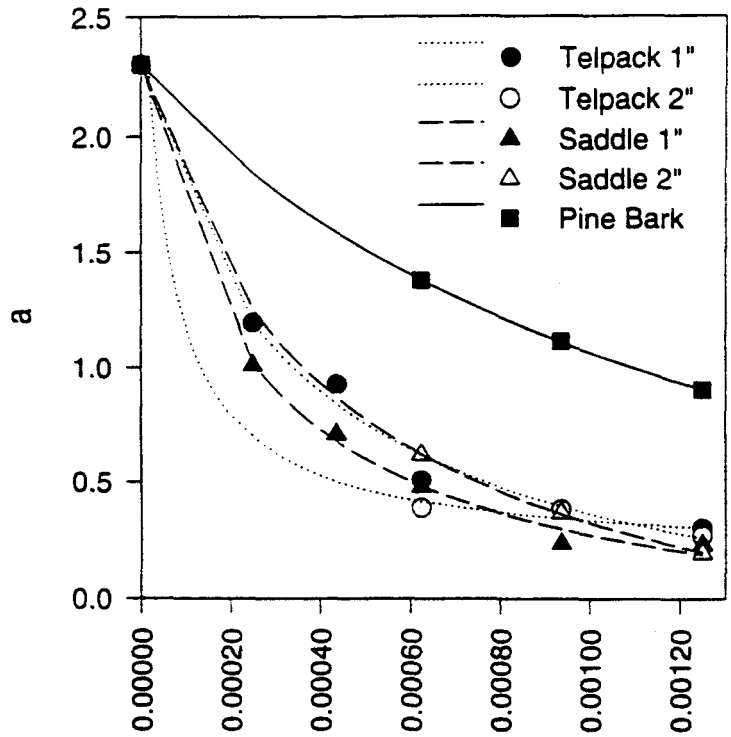

Figure 7: Linear coefficient a versus bulking agent density (Φ).

The relationship between ϕ and a was modeled with the following empirical relationship:

$$\frac{a_0 - a}{a_0} = \frac{C_1\phi}{C_2 + \phi} \tag{5}$$

In Equation 5, C_1 and C_2 are fitted parameters and a_0 is the linear coefficient in Ergun's equation for the case of no bulking agent. Thus, the dimensionless ratio $(a_0 - a)/a_0$ is a measure of the fractional improvement in pressure drop: for a bulking agent which provides no improvement in the linear coefficient over the case of no bulking agent this ratio will be equal to zero, while for a bulking agent which essentially removes pressure drop this ratio will approach one. If the bulking agent density approaches zero ($\phi \leq 0$) then the term $C_1\phi/(C_2 + \phi)$ approaches a value of C_1 for any type of bulking agent. For this case the fractional improvement in pressure drop should approach 1, so that the value of C_1 determined by fitting the data in Table 3 should be close to 1. When $\phi = C_2$, the fractional improvement in pressure drop given by Equation 5 becomes equal to $C_1/2$. If $C_1 \approx 1$, then the fractional improvement in pressure drop is 0.50 when $\phi = C_2$. Thus, this second empirical constant, C_2, is a measure of the bulking agent density required to decrease the linear form of Ergun's equation by 50%. The greater the value of C_2 calculated, the higher the bulking agent density necessary to affect a change in pressure drop. Table 3 shows the resulting best-fit values for the empirical constants (C_1 and C_2) in Equation 5. The resulting equations are also shown in Figure 7 for these selected bulking agents. As Table 3 shows, the value for the constant C_1 for each bulking agent was indeed approximately equal to 1. Of the bulking agents tested, the pine bark had the highest value of C_2, while 2" Telpack (lowest r^2 and three data points) and 1" Saddles (five data points) had the lowest value of C_2. These results demonstrate and quantify the reduction in pressure drop afforded by the synthetic bulking agents over pine bark.

Table 3: Results of Regressing the Linear Coefficient in Ergun's Equation to Equation 5

Bulking Agent	C_1	C_2	r^2
Telpack 1"	1.129	0.000340	0.981
Tripack 1"	1.191	0.000394	0.965
Saddle 1"	1.097	0.000242	0.992
Telpack 2"	0.922	0.000074	0.793
Tripac 2"	1.155	0.000447	0.937
Saddle 2"	1.223	0.000421	1.000
Pine Bark	1.250	0.001322	1.000

For the pine bark and each of the three 2" synthetic bulking agents, the value of this second-order coefficient decreased with increasing bulking agent density. In other words, for these four bulking agents as their density increased, the pressure drop became more linear with superficial air velocity. As expected, the addition of any of these bulking agents serves to reduce the kinetic energy losses.

CONCLUSIONS

The pressure drop data across a column of compost shows a high correlation to Ergun's equation. For all bulking agents an increase in the bulking agent density (ϕ) resulted in an almost linear decrease in pressure drop. The synthetic bulking agents resulted in a significantly lower pressure drop than the pine bark. The 2" synthetic bulking agents resulted in lower pressure drop than the 1" agents. No one particular synthetic bulking agent shape stood out as better than the others across the 1" and 2" sizes.

The synthetic bulking agents provide an advantage over the pine bark by reducing the head differential across a compost reactor. The reduced head differential results in decreased fan power requirements, and thus decreased costs. Synthetic bulking agents cannot provide the nutrient and absorbent advantages of biodegradable agents; however, the synthetic bulking agents can be recovered after composting whereas the pine bark will deteriorate over time. Additional testing should be conducted to determine the suitability of Ergun's model for other compost materials and bulking agents, and to determine if parameter C_2 varies with compost material.

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List of Symbols Used

a, b, A, B, C, D, j, k, n = empirically determined parameters in pressure drop correlations (Eqs. 1-4)

ΔP = pressure drop per foot depth of grain (inches H_2O/ft)

ϕ = bulking agent density (ft^3/lb)

U = superficial air velocity (ft/min)