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Laboratory Determination of Compost Modeling Parameters

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Abstract

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Keywords

physical parameter, biological parameter, air filled porosity, permeability, bulk density, particle size, modeling

Disciplines

Bioresource and Agricultural Engineering | Veterinary Medicine

Comments

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Abstract.

Physical and biological parameters of corn stalks, silage, and oat straw were determined and the variation of airflow characteristics and biological activity were evaluated under varying *moisture contents. The predicted air-filled porosity showed high correlation with measured air-filled porosity over the all materials. A reliable model of air-filled porosity made it possible to predict the effect of varying moisture content and compost bed height on air-filled porosity and permeability. The air-filled porosity decreased with increasing moisture content and compost depth for all materials. Corn stalks and oat straw air-filled porosity was in the range of 69-97% over the all moisture levels and bed heights tested. Silage showed a wider range of air filled porosity than the other two materials, varying from 43 to 89%. The effective particle size of all three materials increased with increasing moisture content from 20% to 80%of WHC. Permeability increased with increasing air filled porosity and decreasing bulk density, but the relationship between permeability and moisture content is complex. Permeability decreased for all materials with increasing moisture content from 20% WHC to 50% WHC, regardless of the depth of the compost bed. Since the particle size increased dramatically near saturation, the influence of aggregated particle size on the permeability is not significant at these relatively low moisture levels. But the permeability increased with increasing moisture level from 50% to 80% WHC at moderate to shallow simulated bed depths (Corn stalks: 2.1 m, Oat straw: 1.5m, Silage: 0.8 m). This results from the relatively large particle size aggregations under high moisture conditions, which compensate for the effect of reduced air filled porosity by compaction and moisture content at moderate to shallow bed depths. In this study the maximum wet bulk density and mechanical strength decreased with increasing the moisture content. The optimum moisture contents for respiration rate of corn stalks, oat straw, and silage are 81%, 64%, and 78% respectively. The method described for determining physical and biological properties under varying moisture content and compost bed depths will be very useful for designing and modeling composting process with a variety of materials.*

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Introduction

Dry, high carbon amendments and bulking materials play important roles in the composting process. Amendments are added to condition wet substrates by reducing bulk weight and increasing air voids and biodegradable organics. Bulking materials provide structural support and maintain air spaces in the mixture (Haug, 1993). Since some materials have characteristics of both dry carbonaceous amendments and structural bulking agents, these terms are often used interchangeably, but it is important to recognize that these properties can be distinct. The physical, chemical and biological properties of compost amendments and bulking materials have significant impacts on compost design and operational parameters such as temperature, oxygen, and moisture gradients, heat and energy balances, and biodegradability.

Mortality composting has been accepted as an option for dead animal management in many regions of the world (Fonstad, 2003). Crop residues, unused bedding materials, silage, manures and similar on-farm materials can be used as co-compost cover materials, along with many off-farm residues and wastes. Since a mortality compost pile cannot be turned until the bio-decomposition of carcass body has been largely completed, the type and thickness of the cover and base layer materials play a key role in influencing the biodegradability of carcasses and the necessary pathogen control.

In order to succeed in a mortality composting process, it is important that guidelines for potential cover materials be able to define proper envelope thickness, placement, and mixing ratio with other cover materials. In this study, design criteria are being developed for thirteen potential cover materials that are available throughout Iowa: Corn stalks, Oat straw, Silage, Wood shavings, Alfalfa hay, Soybean straw, Wheatstraw, Leaves-large, Leaves-small, Turkey litter, Yard waste compost, Beef manure, and Sawdust. A full field evaluation of these 13 different suggested cover materials (at varying application depths and mixing ratios) would be quite costly and time consuming. To reduce the costs of developing guidelines for the potential performance of a broad range of possible cover materials, the properties of these materials are being evaluated in an analytical and modeling framework. Laboratory evaluation of three materials (Silage, Oat straw, Corn stalks) of the total 13 cover materials are currently completed, with the resulting compost modeling parameters for those three materials included in this paper.

For any particular modeling purpose, it is important to select the appropriate parameters and relationships to get useful simulation results. Keener et al.(1993) reported the interdependence relationships between biological and physical parameters in optimizing the composting process. Richard et al.(2002) used physical factors (air-filled porosity and bulk density) and biological factor(microbial respiration rate) to model moisture relationships in the composting process. The parameters examined in this study include both physical and biological properties: moisture content, water holding capacity, bulk density, air-filled porosity, permeability, particle size, mechanical strength, and microbial respiration rate. Many previous researchers addressed the relationship between parameters, but most of relationships are different for different materials, as each materials have different properties (Agnew and Leonard, 2003; Richard et al., 2004).

The objective of this paper is to investigate the physical and biological parameters for each potential compost bulking material and to examine the variation of parameters (airflow characteristics and biological activity) under varying moisture contents and compaction rates.

Materials and Methods

Sample preparation

Three compost-bulking materials that could be useful as cover materials in mortality composting system were investigated for determining the modeling parameters: Corn stalks, Oat straw, and Silage. Corn stalks and Oat straw were chopped to approximately 10 cm lengths. The moisture contents (MC) of three compost-bulking materials were adjusted to 6 different levels for respiration testing and 3 levels for permeability analysis.

Moisture contents(MC), Volatile solids(VS), pH, Electrical conductivity(EC)

Moisture contents throughout this study were measured by drying at 105°C for approximately 24 hours, while volatile solids were measured by combustion at 550°C for 8 hours. The mixing ratio of sample to deionized water was 1:10 based on mass for pH and electrical conductivity measurements. The samples were soaked in water for 30 minutes for pH measurements and 3 hours prior to electrical conductivity measurements(TMECC, 2001).

Water holding capacity(WHC)

A wet sample of known initial moisture content was weighed(W_I) and placed in a beaker. After soaking in water for 1-2 days and draining excess water through Whatman #2 filter paper, the saturated sample is weighed again(W_S). WHC is calculated as:

$$WHC(\%) = \frac{\{(W_S - W_I) + MC_I \times M\}}{W_S} \times 100 \tag{1}$$

Where MC_I =Moisture content of sample(decimal); M =Mass of the wet sample.

Bulk density and Air-filled porosity

Bulk density was measured using an approximately 22-liter volume container. The container was filled with material, and then the material was slightly compacted to ensure absence of large void spaces. The bulk density can be calculated by dividing the weight of the material by the volume of container.

Air-filled porosity(ε_a) was measured using an air pycnometer. Pycnometers are simple devices that work according to Boyle's law. A sample is placed in an airtight chamber(Tank A) with a known volume. Then a known volume of gas at a known pressure(from pressurized Tank B) is released into the sample chamber to equalize the pressure between the two tanks. Based on the change in pressure, the air-filled porosity of the sample can be calculated.

$$\varepsilon_a = \frac{\left(\frac{P_i V_B}{P_f}\right) - V_A - V_B + V_S}{V_S} \quad (2)$$

Where $P_i V_B$ =Initial pressure in the pressurized tank B; P_f = Final pressure; V_A, V_B, V_S =Volume of tanks A, B, and sample.

The measured air-filled porosity values can be checked by the equation 3, using the known density of water(ρ_w ; 1000kg/m^{-3}) and estimated densities of organic matter(ρ_{vs} ;1600kgm^{-3}), and ash(ρ_{ash} ; 2500kgm^{-3}), as well as the moisture content and bulk densities of the sample(Rahman 1995; Van Ginkel et al. 1999; Richard et al. 2002). If the parameters of moisture content(MC), dry matter(DM) and bulk density are known, the air-filled porosity values can be calculated using equation 3 instead of direct measurement.

$$\varepsilon_a = 1 - \rho_{wb} \cdot \left(\frac{MC}{\rho_w} + \frac{DM \cdot OM}{\rho_{om}} + \frac{DM \cdot (1 - OM)}{\rho_{ash}} \right) \quad (3)$$

Permeability and Compaction

Permeability and compaction were measured at three different moisture levels and five different packing densities. Moisture contents of samples were adjusted to 20, 50, and 80% of water holding capacity. Three different moisture levels of samples were weighed and placed in the four containers to a height of 0.2m above a perforated lower plenum. Five different compressive stresses were applied in the range of 0-16,745N/m^{-2}. At each applied stress the samples were compressed for 2 days in order to reach equilibrium. For pressure drop measurement and permeability calculation, a 20psi compressed air flow rate was controlled at 8 different velocities in the range of 0.001-0.014 m/s. The pressure difference was measured using a manometer between upper and lower pressure taps. The height of the sample and pressure were measured before and after compaction.

Permeability theoretical analysis

Permeability indicates the ability of air to flow through a porous material matrix (Lynch and Cherry 1996). If flow is laminar, permeability can be calculated from the following Darcy's law:

$$v = -\frac{\kappa}{\mu}\left(\frac{dP}{dx}\right) \quad (4)$$

Where P =pressure; x = matrix distance; v =superficial velocity; μ = viscosity; κ = permeability.

If flow is not laminar, pressure drop is expressed with a Dupuit-Forcheimer relationship:

$$-\frac{dP}{dx} = \alpha v + \beta v^2 \quad (5)$$

Equation 5 includes a viscous force term (first order) and form drag force term (second order). For any measured pressure drop, the Forcheimer permeability constant(κ) and passability(η) can be calculated from known velocity, air viscosity(μ), and air density(ρ_a) parameters.

$$-\frac{dP}{dx}=\frac{\mu}{\kappa}v+\frac{\rho_a}{\eta}v^2 \tag{6}$$

If the dimensionless Lage number (L) is greater than 1, the viscous forces dominate and the Darcy's law can be applied. The dimensionless Lage number(L) can be identified by the ratio of the viscous and form drag forces.

$$L=\frac{\frac{\rho_a}{\eta}v^2}{\frac{\mu}{\kappa}v}=\frac{\rho_a\kappa}{\mu\eta}v \tag{7}$$

The effective particle diameter(d_p) can be calculated from Equation 8, which predicts permeability as function of air-filled porosity and particle size (Carmen, 1939).

$$\kappa=\frac{{d_p}^2}{A}\frac{{\varepsilon_a}^3}{(1-\varepsilon_a)^2} \tag{8}$$

Where A is 180 (Macdonald et al.,1979).

Compaction theoretical analysis

The bulk density under any applied stress(ρ_{wb,σ_i}) can be calculated using equation 11, which predicts the bulk density as function of the minimum and maximum bulk densities($p_{wb,0}$, $\rho_{wb,\max}$) and the mechanical strength(M).

$$\rho_{wb,\sigma_i}=\rho_{wb,\max}-(\rho_{wb,\max}-\rho_{wb,0})\cdot\exp\left(\frac{-\sigma}{M}\right) \tag{9}$$

The minimum bulk density is the uncompacted material's bulk density, equivalent to what would be observed at the top surface of a compost pile. And the maximum bulk density can be calculated by equation 10, which is derived from equation 3 with air-filled porosity equal to zero.

$$\rho_{wb,\max}=\frac{1}{\left(\frac{MC}{\rho_w}+\frac{DM\cdot OM}{\rho_{om}}+\frac{DM\cdot(1-OM)}{\rho_{ash}}\right)} \tag{10}$$

Respiration test

Microbial respiration rate was measured by the OxiTop method at 5 different moisture levels(20, 50, 80, 90, 98 % of WHC). Each unit of the OxiTop system consists of a 1 liter jar, a pressure sensor – data logger head (OxiTop-C WTW, Weiheim, Germany), and a rubber capsule for NaOH pellets. As oxygen is consumed, CO_2 is produced and absorbed on the NaOH pellets, leading to a pressure drop similar to the Warburg apparatus once commonly used in soil respiration studies. A controller(OxiTop OC 110 WTW, Weiheim, Germany) is used to collect data from the pressure sensor dataloggers. Company supported Software (Achat OC, PC communication software version 2.03) is used to download the data from the controller to a spreadsheet.

Moisture adjusted samples were incubated at 30°C for 2 days in order to acclimate the microbial community. 5-10g of sample was placed in the respirometer jar and incubated for 2 days at 30°C. Pressure in the jar initially increases, due to the difference between room and incubator temperatures. After temperature has equilibrated in the incubator, subsequent carbon dioxide absorption by sodium hydroxide pellets creates a pressure drop measured by the sensor. The oxygen consumption can be calculated from the pressure difference, from which the evolved carbon dioxide-carbon can be calculated assuming a respiration quotient. The assumed respiration quotient is 1:1.

Results and Discussion

General characteristics

The general characteristics of all 13 potential cover materials are shown in table 1. Water holding capacity (WHC) was lower for turkey litter and yard waste compost relative to the other materials tested. Since WHC has very important relationship with physical and biological properties of materials, the moisture levels were set based on the WHC in this study. Electrical conductivity(EC) indicates the total salt content of the material. Alfalfa hay, straw (oat and wheat), and turkey litter show high EC compared with other materials.

Table 1. General characteristics of 13 potential cover materials (N=3 for all tests)

Cover materials	MC[1] (w.b.,%)	VS[2] (d.b.,%)	WHC[3] (w.b.,%)	pH	EC[4] (Ms/cm)	BD[5] (kg/m^3)	Ea[6] (%)
Corn stalks	29.2±0.8	91.5±0.4	82.4±1	6.7±0.3	0.94±0.19	56.9±8.5	88.4±0.6
Silage	74.2±0.8	93.3±0.6	80.2±0.3	3.4±0.0	1.47±0.03	342.3±5.6	66.1±0.4
Oat straw	17.3±0.6	91.8±0.1	79.3±1.4	8.1±0.1	4.71±0.22	38.1±1.9	90.9±1.5
Wood shavings	9.4±0.0	99.4±0.0	76.8±1.8	4.1±0.1	0.39±0.01	99.8±3.7	92.3±2.2
Alfalfa hay	10.0±0.1	89.7±0.1	78.9±0.4	5.7±0.0	9.40±0.57	49.8±3.1	91.4±1.0
Soybean straw	10.8±0.3	91.3±0.5	82.1±0.1	6.9±0.2	1.17±0.21	31.6±0.5	92.7±1.9
Wheat straw	9.1±0.2	91.9±0.2	82.6±0.3	7.4±0.2	3.97±0.21	22.6±0.5	92.5±0.5
Leaves-large	40.5±0.8	87.3±1.3	73.2±1.2	4.0±0.3	0.79±0.11	40.2±2.4	92.4±1.1
Leaves-small	48.1±1.7	80.6±0.8	77.1±0.6	6.3±0.1	0.44±0.04	86.7±0.9	88.7±1.2
Turkey litter	48.2±0.5	72.1±2.9	68.9±2.4	7.5±0.1	5.19±0.35	542.2±20.2	56.7±1.5
Yard waste compost	32.7±0.8	21.5±0.7	53.8±1.1	8.6±0.2	1.33±0.15	629.8±45.4	61.0±1.7
Beef manure	67.9±1.1	64.9±7.2	75.8±0.0	7.8±0.0	2.68±0.26	627.4±27.7	44.5±1.4
Saw dust	8.0±0.0	98.9±0.0	77.7±0.7	4.6±0.1	0.43±0.03	241.3±3.6	82.2±1.9

[1] Moisture content, [2] Volatile solids, [3] Water holding capacity, [4]Electrical conductivity, [5]Bulk density, [6]Air-filled porosity

Mechanical strength and compaction

The influences of applied stress and moisture content on bulk density are illustrated in figure 1. The bulk density at any applied stress (calculated from the mass of the overburden) can be predicted by using equation 9. The parameters needed for predicting the bulk density are presented in table 2.

The maximum wet bulk density decreased with increasing moisture content. This maximum wet bulk density occurs when the air-filled porosity is zero. Since the density of water is less than that of organic matter or ash (see equation 10), a matrix containing more water relative to the solid fractions will necessarily be less dense.

The mechanical strength decreased significantly with increasing moisture content. This occurs because matrices of dry organic materials have greater structural stability and resist compaction better than wet organic materials, which get soft (Richard, 2004).

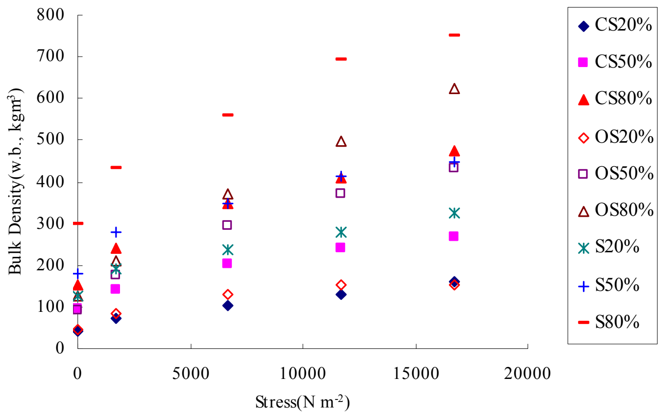

Figure 1. Bulk density as a function of applied stress and moisture content for corn stalks (CS), silage (S), and oat straw (OS).

Table 2. Mechanical strength of cover materials with different moisture content

	Corn stalks			Silage			Oat straw		
	20%[1]	50%[1]	80%[1]	20%[1]	50%[1]	80%[1]	20%[1]	50%[1]	80%[1]
$\rho_{wb,0}$ (kg m^{-3})	42.7	94.0	152.0	46.1	90.5	128.1	124.7	179.4	297.2
$\rho_{wb,\max}$ (kg m^{-3})	1491	1302	1155	1487	1305	1162	1495	1311	1168
M(m^2 N^{-1})	242568	133667	52352	140674	83228	25660	293060	59244	26801

[1] % of Water holding capacity

Air-filled porosity vs Moisture content and bulk density

Using the bulk density and moisture content determined by laboratory experiments, and substituting these measured values into equation 3, the theoretical air-filled porosity can be found for each material. The theoretical values were compared with the measured air-filled porosity values found by the pycnometer in figure 2. The linear relationship between measured and predicted values shows high correlation for all the materials.

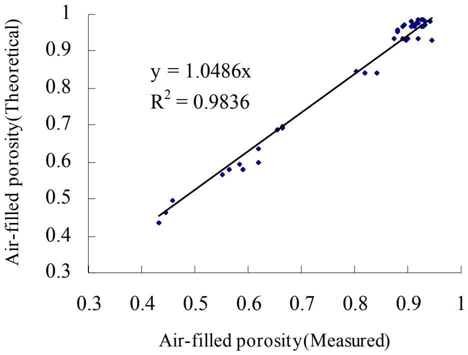

Figure 2. Measured and theoretical air filled porosity for 13 potential cover materials

The theoretical air-filled porosity from equation 3 depends on the bulk density and moisture content of the materials. These interdependent relationships between air-filled porosity and the two measured parameters is presented in figure 3. As anticipated, the air-filled porosity decreased with increasing both bulk density and moisture content. As the moisture content increases, water filled the void air space and therefore the air-filled porosity decreased. Increasing the portion of water in air voids, the mass of the materials increased. The increased mass compresses the porous media matrix, so that the bulk density will also increase.

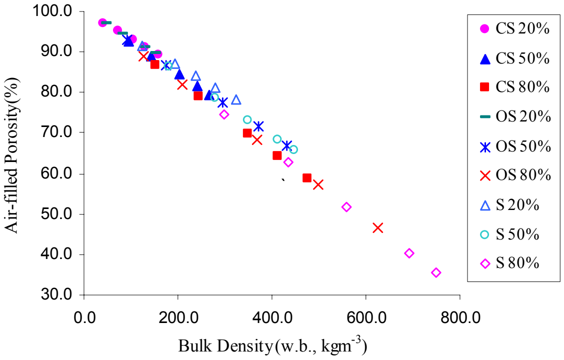

Figure 3. Theoretical air-filled porosity as a function of measured bulk density for corn stalks (CS), silage (S), and oat straw (OS).

Figure 4 shows the air-filled porosity as a function of moisture content and compost bed height for three materials, assuming a 3-meter high pile. The bulk density was modeled as a function of the compost bed height. The bulk density and resulting overburden stress was integrated numerically using a 0.1m compost pile height increment. The air-filled porosity decreased with increasing moisture content and compost depth for all materials. Corn stalks and oat straw has air-filled porosities in the range of 69-97% over the all moisture levels and bed heights. Air filled porosity values of corn stalks are slightly higher than oat straw for the lower moisture level and near the bottom of compost pile. Silage showed a wider range of air-filled porosity than the other two materials, varying from 43-89%.

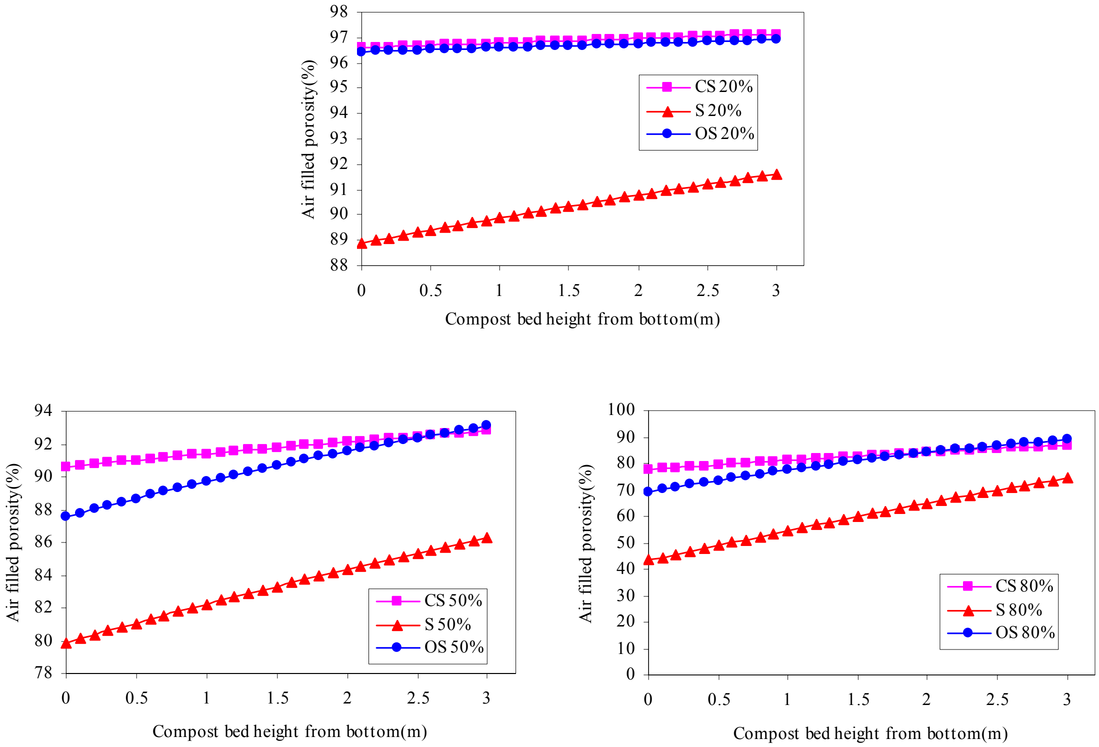

Figure 4. Theoretical air-filled porosity as a function of moisture content and compost bed height for corn stalks (CS), silage (S), and oat straw (OS).

Previous researchers have reported the optimum and minimum range of porosity for aerobic decomposition was 85-90%, and 30% respectively (Shulze, 1962; Rynk, 1992; Nappi and Barberis 1993). Using those higher optimum values, it would appear corn stalks and oat straw are better bulking materials than silage for a static bed aerobic composting process, although if 30% air-filled porosity is adequate, any of these matrices would be fine.

Airflow resistance and air permeability vs Moisture content and bulk density

The general second order equations were acquired from the experimental results of pressure drop with 8 different levels of velocity for three different moisture levels of 3 materials under the four different bulk densities. Since the first term (α) is a simplification of Darcy's law in equation 5, the permeability of each material under the different moisture and bulk density levels was calculated through dividing viscosity (μ) by α.

Permeability increased with increasing air filled porosity and decreasing bulk density (Agnew and Leonard, 2003; Richard, 2004), but the relationship between permeability and moisture content is complex.

Richard(2004), Calderwood(1973), Chung et al.(2001), and Siebenmorgen(1987) reported the permeability increased with increasing moisture content. They suggested that moisture promotes aggregation of particles, and then the increased particle size makes the pore size large. Finally, the large pores increase the permeability. This theory was consistent with effective particle sizes calculated as a function of moisture in this study, as shown in figure 5.

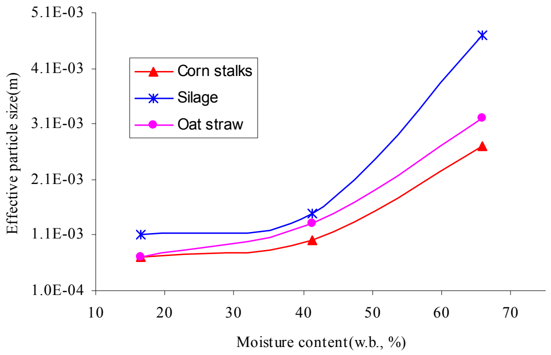

Figure 5. Effective particle size as a function of moisture content(w.b) for corn stalks (CS), silage (S), and oat straw (OS).

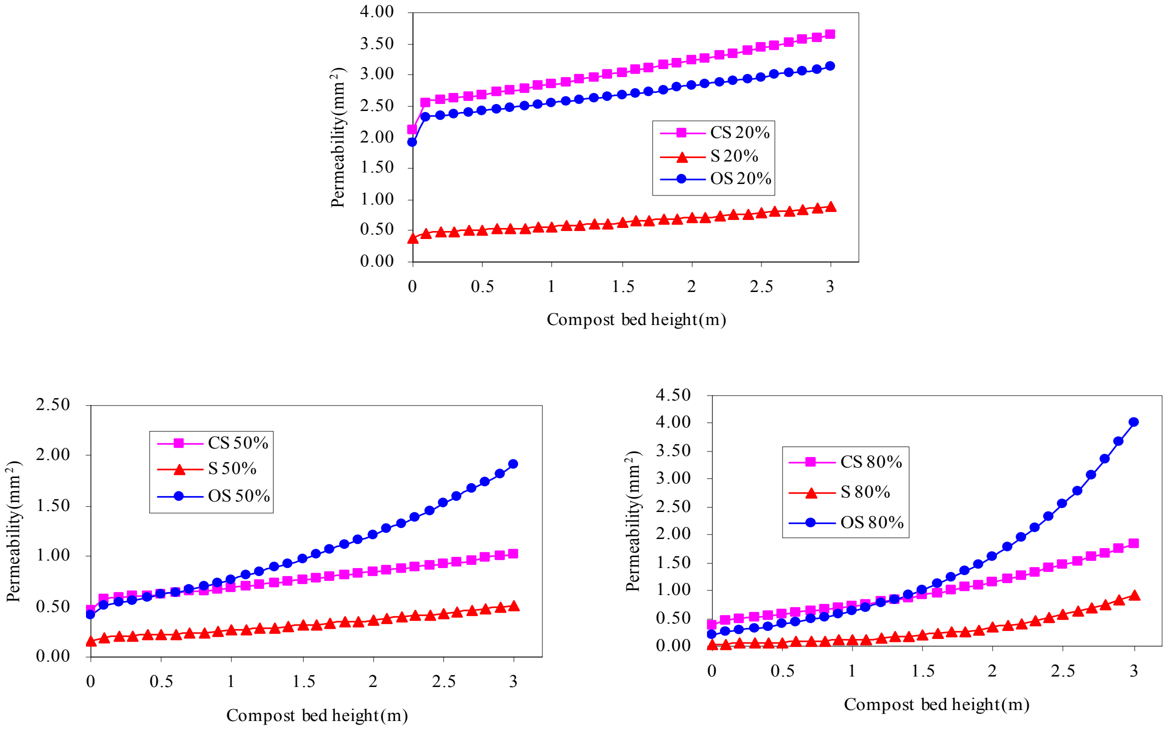

Figure 6. Theoretical permeability as a function of moisture content and compost bed height for corn stalks (CS), silage (S), and oat straw (OS).

Although the effective particle size increased with increasing moisture content throughout the range from 20% to 80% of WHC, figure 6 illustrates that the permeability generally decreased with increasing moisture levels. Permeability decreased for all simulated pile depths and for all materials as the moisture level increased from 20% WHC to 50% WHC. However, this relationship reversed in the surface regions of the bed when the moisture level increased to 80% WHC. The inverse relationship occurred above a particular bed height that varied with material in these simulated 3 meter high piles. These points of inflection for each material were: Corn stalks, 0.9m; Oat straw, 1.5m; and Silage, 2.2m. Although bed height is generally easier to grasp in the figures, these values depend on the simulated overall height which was arbitrarily set at 3 m. Measuring instead from the top of the pile, permeability increased with increasing moisture only within a moderate depth from the pile surface (Corn stalks:2.1m, Oat straw: 1.5m, Silage: 0.8m).

Because the effective particle size increases dramatically near saturation, the influence of aggregated particle size becomes much more significant as the pile nears saturation. With respect to permeability, the relatively large particle size aggregates in a high moisture condition compensates for the effect of reduced air filled porosity near the pile surface, but succumbs to compaction at increasing depth.

Microbial respiration rate vs Moisture content

Peak measured respiration rates are reported in table 3, along with the conditions at which they were measured. These respiration rates were also normalized by dividing by the maximum rate for each material (Figure 7).

The optimum moisture contents for maximizing the respiration rate of corn stalks, oat straw, and silage are 81%, 64%, and 78% (w.b.) respectively. The optimum moisture contents of corn stalks and oat straw were 98% WHC, but only 80% WHC for silage. The air-filled porosities of corn stalks, oat straw, and silage at these maximum measured respiration rates were 83%, 74%, and 86% respectively.

Table 3. Measured optimum moisture for respiration

	Corn stalks	Silage	Oat straw
CO_2-C_{max} (mg CO_2-C g^{-1} VS day^{-1})[1]	5.71± 0.18	15.95±0.08	13.4±0.88
ε_a @ CO_2-C_{max}(%)	83.0	74.4	86.0
θ_w @ CO_2-C_{max}	6.9	2.9	5.7
ε_s @ CO_2-C_{max}(%)	2.1	6.5	2.1
MC_{wb}(%)	80.8	64.2	77.7

[1] N=3

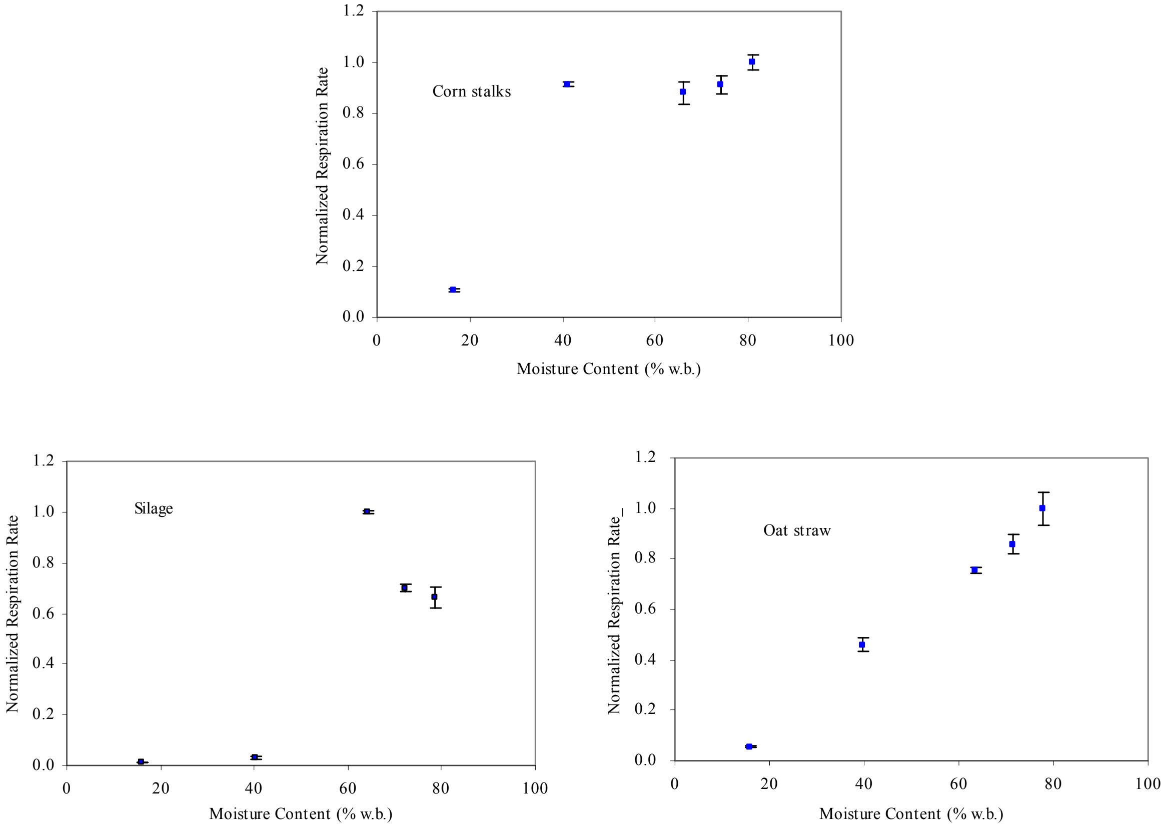

Figure 7. Measured normalized respiration rate as a function of moisture content (w.b.) for corn stalks, silage, and oat straw

Conclusions

The following conclusions can be drawn from this investigation of compost physical and biological modeling parameters for corn stalks, silage, and oat straw.

Using the parameters of minimum and maximum bulk densities and mechanical strength the effects of compaction on air filled porosity and permeability can be estimated. The maximum wet bulk density and mechanical strength decreased with increasing the moisture content in this study.

The predicted air-filled porosity using experimentally determined bulk density, moisture content and organic matter showed high correlation with measured air-filled porosity over all the materials. Ability to reliably predict air-filled porosity using the measured parameters made it possible to evaluate air-filled porosity under the varying moisture content and compost bed configurations. The air-filled porosity decreased with increasing moisture content and compost depth for all materials. Corn stalks and oat straw showed the air filled porosity in the range of 69-97% over the all moisture levels and bed heights with a 3 meter simulated pile. Silage showed a wider range of air-filled porosity than the other two materials, in the range of 43-89%. It would appear corn stalks and oat straw are better bulking materials than silage for a static bed aerobic composting process, although if 30% air-filled porosity is adequate, any of these matrices would be suitable.

Permeability increased with increasing air filled porosity and decreasing bulk density, but the relationship between permeability and moisture content is complex. Several previous researchers reported the permeability increased with increasing moisture content because moisture promotes aggregation of particles and makes the pore size large. The effective particle size of all three materials increased with increasing moisture content from 20% to 80%of WHC in this study, consistent with these previous results. However, although the effective particle size increased with increasing moisture content, permeability decreased with increasing moisture levels throughout much of these simulated piles. Specifically, under low moisture conditions, permeability decreased over the entire simulated 3 m pile height for all materials while increasing moisture from 20% WHC to 50% WHC. Since the effective particle size increases most dramatically near saturation, the influence of aggregated particle size at these low moisture levels had only a small effect on permeability, and reduced porosity and increased compaction dominated the analysis. However, under higher moisture conditions, permeability increased with increasing moisture level from 50% to 80% WHC in the surface regions of the simulated piles. Measuring from the top of the pile, permeability increased with increasing moisture within a moderate depth from the pile surface (Corn stalks:2.1m, Oat straw: 1.5m, Silage: 0.8m).

The physical properties of each material at maximum respiration rate were investigated. The optimum moisture contents for respiration rate of corn stalks, oat straw, and silage are 81%, 64%, and 78% (w.b.) respectively. The air-filled porosities of corn stalks, oat straw, and silage at maximum respiration rate were 83%, 74%, and 86% respectively.

The measurement and prediction of compost physical and biological properties under varying moisture content and compost bed configurations will be very useful in designing and modeling the composting process with a variety of amendments and bulking materials.

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