A modified air pycnometer for compost air volume and density determination

J.M. Agnew[1], J.J. Leonard[2], J. Feddes[2] and Y. Feng[3]

[1]*Department of Agricultural and Bioresource Engineering, University of Saskatchewan, Saskatoon, Saskatchewan, Canada S7N 5A9;* [2]*Department of Agricultural, Food and Nutritional Science, University of Alberta, Edmonton, Alberta, Canada T6G 2P5; and* [3]*Department of Renewable Resources, University of Alberta, Edmonton, Alberta, Canada T6G 2E3.*

Agnew, J.M., Leonard, J.J., Feddes, J. and Feng, Y. 2003. **A modified air pycnometer for compost air volume and density determination.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **45**: 6.27-6.35. A method of measuring the bulk density and free air space (FAS) of compost that is quick and accurate, and simulates in situ conditions was required for more efficient management of the composting process. An air pycnometer is a device which uses ideal gas principles to determine the amount of air space within a given material. The modified air pycnometer designed and built to meet the objectives of this work included two 30-L PVC vessels for pressure difference determination and an air cylinder activated piston to simulate the stress conditions found at all pile depths. The FAS and bulk density of manure compost, municipal solid waste compost, and mixtures of biosolids and amendment material (leaves, straw, and woodchips) were measured at various moisture contents and compressive loads. The particle densities of the compost materials were roughly similar (1500-1800 kg/m^3), and negatively sloped linear bulk density and FAS profiles (variation with depth) were observed for all materials. The linear relationship between bulk density and FAS had an R^2 value of 0.97. **Keywords**: pycnometer, compressive loading, manure compost, biosolids, amendment material.

Une méthode pour mesurer la masse volumique et la porosité du compost qui soit rapide, précise et qui simule les conditions aux champs était requise pour une gestion plus efficace du processus de compostage. Un pyctomètre à air est un appareil qui utilise les propriétés des gaz parfaits pour déterminer la proportion d'espace vide à l'intérieur d'un matériau donné. Le pyctomètre à air modifié conçu et construit pour atteindre les objectifs de cette application est constitué de deux contenants de 30 L pour déterminer la différence de pression et d'un piston actionné par un cylindre pneumatique qui simule les conditions de compaction qui existent à différentes profondeurs dans les piles de compost. La porosité et la masse volumique d'un compost de fumier, d'un compost produit à partir de résidus solides d'usines d'épuration des eaux urbaines ainsi que d'un mélange de rebus organiques et d'amendements (feuilles, pailles et copeaux de bois) ont été mesurées à différentes teneurs en eau et niveaux de compaction. Les masses volumiques des particules des différents subtrats compostés étaient comparables (1500-1800 kg/m^3) et des profils inversement proportionnels entre la masse volumique et la porosité (variations avec la profondeur) ont été observés pour tous les types de compost. La relation linéaire entre la masse volumique et la porosité avait une valeur de R^2 de 0,97. **Mots-clés**: pyctomètre, contrainte de compression, compost de fumier, rebus organiques, matériel d'amendement.

INTRODUCTION

The composting process has been studied extensively over the past few decades. Properly managed, composting can inactivate pathogens and weed seeds while breaking down the organic matter in wastes into a useable, soil-like product. The effects of waste volume reduction and the possible uses in soil amendment and land remediation have caught the attention of farmers and environmentalists alike.

Although the decomposition of organic materials occurs naturally, the process involves a wide variety of parameters and biological interactions. To optimize the process to shorten composting time and to increase the quality of the end product, producers must manage the most important composting parameters like temperature, carbon to nitrogen ratio, and moisture content. These and other important parameters are often related to the physical properties of compost materials.

The physical properties of compost materials play an important role in every stage of compost production as well as in the handling and utilization of the end product. From the mixing of various feedstocks and process monitoring and maintenance, to the packaging and shipping of the final product, parameters such as bulk density, porosity, and free air space (FAS) dictate the requirements for the optimum composting environment and the design of machinery and aeration equipment used in the system.

The wet bulk density of compost is a measure of the mass of material (solids and water) within a given volume and is important in the determination of initial compost mixtures. The wet bulk density determines how much material can be placed at a certain site or hauled in a truck of a given size. The density of compost also influences the mechanical properties such as strength, porosity, and ease of compaction (Agnew and Leonard 2003). Therefore, knowing the bulk density of the material throughout the pile is important for aeration, handling, and storage requirements.

The air content and air movement throughout the pile is important to maintain an optimum oxygen supply, to remove carbon dioxide and excess moisture, and to limit excessive heat accumulation (Haug 1995). Maintaining adequate FAS levels satisfies the air content and pore continuity levels required to achieve desired composting conditions. Measuring the FAS of compost with existing methods like the specific gravity bottle (Waller and Harrison 1991), water retention apparatus (Raviv et al. 1987; Waller and Harrison 1991), mercury porosimetry and nitrogen adsorption (Marshall and Sixsmith 1974; as cited in Oppenheimer et al. 1996), and paraffin wax methods (Waller and Harrison 1991) are cumbersome, time consuming, and inaccurate. Air and water pycnometry methods are more accurate (Leege and Thompson 1997; Mohsenin 1986), but it is difficult to obtain repeated analyses with water pycnometry, and commercial air pycnometers are costly and are too small to analyze representative samples of compost.

Knowing the relationships among the physical properties allows an estimation of the influence of one parameter on another. For example, the FAS is obviously related to the moisture content as the FAS is equal to the total voids minus the water-filled voids. However, the direct relationship between FAS, bulk density, and particle density (mass of solids divided by volume of solids) is less intuitive. The FAS is expressed as a function of bulk density, moisture content, and particle density in Eq. 1 (Agnew 2002).

$$FAS = 100 - BD\left[\frac{MC}{\rho_w} + \frac{100 - MC}{PD}\right] \tag{1}$$

where:

FAS = free air space (%),
BD = wet bulk density (kg/m^3),
MC = wet basis moisture content (%),
ρ_w = density of water (1000 kg/m^3), and
PD = particle density (kg/m^3).

Equation 1 is valid for all materials where each of the variables is known. For compost, the moisture content and uncompressed bulk density can easily be determined. However, the particle density of compost is not as readily determined since it often requires an air volume measurement (Agnew 2002). Indirect methods for determining particle density on the basis of volatile solids and ash content have been described by Schulze (1962) and Haug (1995). These methods assume a specific gravity of 1.0 for volatile or organic matter and 2.5 for fixed solids or ash. Van Ginkle et al. (1999) and Richard et al. (2002) also related the particle density of compost to the relative fractions of constituent material. The authors determined the particle density of ash, cellulose, and organic matter and found the particle density of all materials to fall within the range of 1500 to 2650 kg/m^3. Richard et al. (2002) compared the results of air space determination by the calculation of relative fractions of constituent material with the results obtained from an air pycnometer. The resulting correlation coefficient was 0.98, suggesting that assuming a constant particle density for the organic and inorganic fractions of the matrix is a reliable method of calculating compost particle density. However, the calculation of compost particle density using the empirical relationships developed by these researchers requires the measurement of constituent material content, a time consuming and laboratory intensive practice.

Literature values of the particle density of compost are few and varied, so Eq 1 is not useful for calculating the FAS of compost materials. In addition, the FAS of compost has been shown to change throughout the vertical profile of the pile (McCartney and Chen 2001). Measuring the FAS of compost in situ is impossible using existing methods.

Objectives

The main goal of the research described in this paper was to develop and test a device that could measure both the free air space (FAS) and bulk density of compost while simulating compressive loading in a compost pile. The device needed to be capable of providing accurate and precise measurements of FAS and bulk density of a wide range of compost and compost feedstocks and require minimal handling of the material. Ideally, the apparatus needed to be able to simulate in situ conditions and measure the required parameters with minimal input from the user. The secondary goal was to use the apparatus to develop empirical formulae describing bulk density and FAS of composting materials based on moisture content, material, and pile depth.

DESIGN and CALIBRATION OF PYCNOMETER

Rationale

Air pycnometers provide indirect air space measurements by relating the system's pressures and volumes using Boyle's Ideal Gas Law. The sample is placed in one chamber of known volume while a second chamber is filled with air to a known pressure. The air is allowed to equilibrate between the two chambers and the resulting pressure is used to calculate the air space volume in the sample.

Of the methods available for FAS determination, the air pycnometer has been shown to be the most accurate and reliable (Baker et al. 1998; Oppenheimer et al. 1996; Mohsenin 1986). Water pycnometers are also reliable, but the addition of water makes repeated analysis difficult and may give erroneous values for material with high moisture contents due to surface tension and cohesion effects. Material with small pores filled with water may not completely drain between measurements, or small air pockets may not be expelled during the addition of water, trapping air within the sample.

On the other hand, FAS readings from an air pycnometer are not affected by the moisture content of the material. As well, air pycnometers require minimal handling of the material and, once calibrated, require very little input from the user. The vessels can be scaled up to accommodate larger samples and modified to allow compressive loading for simulation of pile depth. Another advantage of the pycnometer is the ability to accurately measure the sample volume while loading. Therefore, if the mass of the sample is known, the bulk density can be calculated. This allows for the determination of bulk density as well as FAS at all simulated pile depths.

For these reasons, the decision was made to design and build an air pycnometer that could be used with composting materials and with provisions for applying compressive loads to samples.

Pycnometer principle

To obtain air volume readings, the pycnometer uses Boyle's Ideal Gas Law,

$$PV = nRT \tag{2}$$

where:

P = pressure,
V = volume,
n = moles of gas,
R = gas constant,
T = temperature.

A simple schematic diagram of a pycnometer is shown in Fig. 1.

Two chambers are connected with a valve so the compressed air vessel can be isolated. The sample is placed in the sample

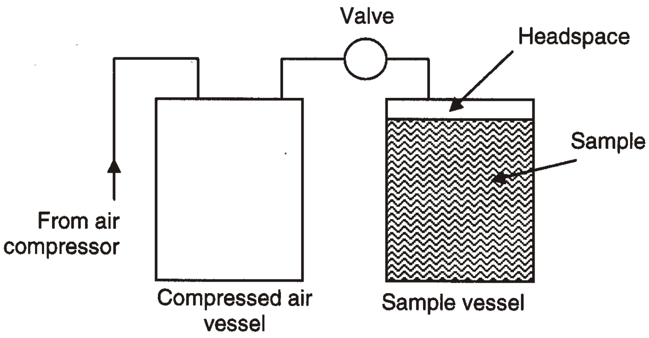


Fig. 1. Simple pycnometer.

vessel and the air vessel is pressurized to a set pressure. The valve is opened and the pressure is allowed to equilibrate. In a closed system with moderate pressures, as in the pycnometer, the temperature remains constant so the term nRT of the ideal gas law remains constant. Thus, if the initial pressure and volume are known, and the final pressure is measured, the final volume can be calculated using the relationship:

$$P_1V_A = P_2V_T \tag{3}$$

where:

P_1 = initial pressure in compressed air vessel (kPa),
P_2 = final pressure of equilibrated system (kPa),
V_A = volume of compressed air vessel (L), and
V_T = volume of overall system (compressed air vessel, sample vessel, pipe, and fittings) (L).

The mass of the air initially in the full sample vessel is assumed to be negligible compared to the mass of the air in the compressed air vessel (Agnew 2002; Baker et al. 1998; Oppenheimer et al. 1996). Expanding the V_T term:

$$P_1V_A = P_2\left[V_B + V_A - V_S\left(\frac{100 - FAS}{100}\right)\right] \tag{4}$$

where;

V_B = volume of sample vessel (L), and
V_S = volume of solid sample (L).

Solving for FAS of the sample:

$$FAS = 100\frac{\frac{P_1V_A}{P_2} - V_B - V_A + V_S}{V_S} \tag{5}$$

When calibrating the pycnometer using water, which has no FAS, the equation simplifies to:

$$P_2 = \frac{P_1V_A}{V_B + V_A - V_S} \tag{6}$$

For sample volumes greater than or equal to 15 L, Eq. 5 resulted in FAS values within 2% of the FAS values calculated using a more complex equation that included the mass and pressure of the air initially present in the sample vessel. The volume and pressure of the air in the headspace of the sample vessel (approximately 2 L and 100 kPa in our apparatus) is insignificant compared to the volume and pressure of the air in the compressed air vessel (30 L, 207 kPa). Baker et al. (1998) and Oppenheimer et al. (1996) derived equations similar to Eq. 5 and also assumed that the mass and associated pressure of the air in the headspace of the sample vessel were negligible.

Air pycnometers are commercially available. However, they are expensive, and the largest sample chamber available is only 0.15 L (Geddis et al. 1996), which is unsuitable for compost mixtures containing woodchips and other large particle sizes.

Pycnometer design

McCartney and Chen (2001), Schaub-Szabo and Leonard (1999), and Das and Keener (1997) used a piston assembly with weights to compress compost samples, but this method was very labour intensive and limited the maximum depth that could be simulated. The loads required to simulate depths of up to 3 m would be very high, so the pycnometer design was modified to incorporate an air cylinder in the sample vessel to minimize manual labour. The three critical components of the design were the sample vessel, the loading cylinder, and the pressure measurement system. These are described below.

Sample vessel The effects of wall friction in the sample vessel needed to be minimized during compression for the applied load to be translated into compression of the sample. Schaub-Szabo and Leonard (1999) showed that these friction effects have significant effects on bulk density measurements in smaller containers (surface area to volume ratio greater than 10 m^2/m^3). Since a container with a surface area to volume ratio of less than 10 m^2/m^3 would be impractically large, this vessel was designed to have a surface area to volume ratio of 10 m^2/m^3. If the surface area was taken as the cylindrical area of the sample vessel wall (πDh) and the volume was the entire vessel volume ($\pi D^2h/4$), where D = diameter and h = height of the vessel, then for a surface area to volume ratio of 10 m^2/m^3, the diameter of the chamber needed to be 0.4 m.

The sample volume must be large enough to accommodate a representative sample of compost material and amendment. In addition, larger containers reduce the effects of volumes of fittings and hoses and errors in volume determination. Baker et al. (1998) used a 22 L sample vessel while Oppenheimer et al. (1996) used a 1 L container. With an optimum diameter of 0.4 m, the 1 L container would have a height of less than 0.01 m. Therefore, a chamber of approximately 25 L was designed, with a diameter of 0.4 m and a height of approximately 0.2 m.

The sample vessel needed to be easy to open, clean, and reseal. A drainage system was incorporated into the sample vessel to accommodate the leaching from wet materials that would naturally occur in compost piles and windrows. The vessel material must be able to withstand at least 200 kPa pressure and be airtight at all operating pressures and temperatures. In addition, the vessel material needed to be able to withstand multiple and long-term loading, be corrosion resistant, and be relatively light and cost-effective. Baker et al. (1998) used custom-made steel chambers, but this material was thought to be too heavy and cumbersome for this project. Schedule 40 PVC pipe of 0.406 m inner diameter and 0.011 m thickness was used for the vessel walls and Schedule 80 PVC with a thickness of 0.022 m was used for the end caps. A detailed drawing of the sample vessel is shown in Fig. 2.

Baker et al. (1998) used an initial pycnometer pressure of 207 kPa, while Oppenheimer et al. (1996) used initial pressures in the range of 300-500 kPa. For a 25-L plastic vessel, initial pressures of 500 kPa are impractical because the forces on the

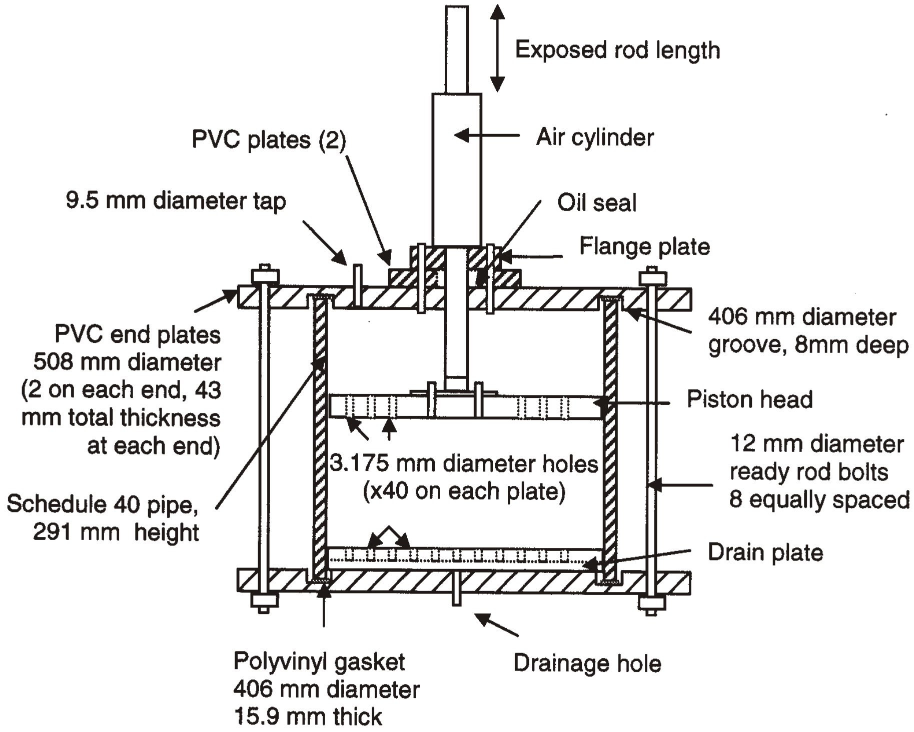


Fig. 2. Details of sample vessel and piston assembly (not drawn to scale).

walls and end-caps would require thicknesses of about 0.10 m (Agnew 2002). A preliminary experiment was performed with the 25 L vessels and a sample of manure compost. Four initial pressures were tested (70, 140, 172, and 200 kPa) and four FAS values were taken at each pressure. There was no effect on temperature at any of these pressures, and the higher pressures resulted in less variable final air volume readings, as shown in Table 1.

Load cylinder To simulate the compaction of material that occurs naturally in compost piles and windrows, a load cylinder and piston apparatus was installed in the sample vessel. Material with an average wet bulk density of 600 kg/m^3 was expected, and at a cross sectional area of approximately 0.130 m^2, the mass contained in 3 m of material (the maximum recommended height of compost piles and windrows) was approximately 225 kg. This translates into a compressive stress of about 18 kPa. To apply this load, a 102 mm diameter, 1700 kPa, double-acting air cylinder (NCA1 Series, SMC Pneumatics Inc., Indianapolis, IN) was selected. Special options included a dual port and manifold for easy extension and retraction, and a double rod so the piston extension inside the vessel could be determined by measuring the exposed rod length. A larger rod diameter (35 mm) was also selected to minimize the chance of fracture at high loads. Subtracting the rod area from the air cylinder area gave the total cross sectional area of the air cylinder as 0.00715 m^2. Thus, to simulate the expected compressive stress of 18 kPa in the "pile" (0.130 m^2 cross-sectional area), approximately 320 kPa pressure needed to be applied to this air cylinder (0.007148 m^2 cross-sectional area) (Agnew 2002).

Table 1. Variation of FAS readings at different operating pressures for manure compost (MC=55% w.b.).

P_1 (kPa)	P_2 (kPa)	FAS* (%)	Standard deviation FAS (%)
70	41	39.92	9.27
140	34	34.72	4.66
172	107	37.52	1.43
200	130	36.07	0.64

* Average of 4 values

Pressure measurement and regulation Oppenheimer et al. (1996) analyzed the performance of their pycnometer and expressed the uncertainty of the FAS reading based on the uncertainty in the volume and pressure readings. Results from the calculations indicated that there was an approximate linear relationship in the uncertainty in FAS due to uncertainty in P_1, $V_{A,}$, or V_B, but the uncertainty in P_1 yielded the greatest uncertainty in FAS. For example, a 1% uncertainty in either V_A or V_B led to approximately 1% error in FAS, but a 1% error in P_1 led to a 3.8% error in FAS. Therefore, it was important to have pressure gauges and pressure regulators that would lead to accurate adjustment and measurement of the pressures in the pycnometer (Oppenheimer et al. 1996). Error analysis specific to the pycnometer designed for this project is found in Agnew (2002).

All pressures were measured using capacitive pressure transducers (DP15TL, Validyne, Northridge, CA), one for vessel pressure determination and one for air cylinder pressure measurement. The signal was passed through a carrier demodulator (CD15, Validyne, Northridge, CA) and the voltage read with a multimeter (HP 34401A, Hewlett- Packard Company, Palo Alto, CA). A variety of replacement diaphragms for the pressure transducers was available to accurately measure the range of expected pressures in the air cylinder. Whenever a diaphragm was replaced, the transducer was calibrated using a dead weight tester (Chandler Engineering, Tulsa, OK). A 1400 kPa full scale analog pressure gauge was also installed on the air vessel for rough pressure determinations.

The pressure of vessel 1 (compressed air vessel) needed to be measured independently from the whole system, and the pressure inside the air cylinder used for compressive loading also needed to be measured independently. A schematic drawing of the overall system is presented in Fig. 3.

System calibration

The pycnometer was calibrated for FAS measurements using tap water since water has no free air space. The sample vessel was filled in 2-L increments with pycnometer readings taken for each addition (Agnew 2002).

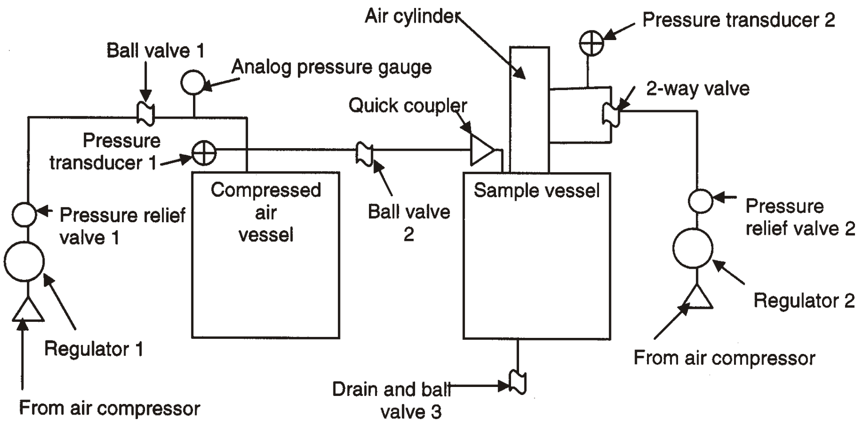


Fig. 3. Schematic drawing of overall system.

During the calibration, the theoretical final pressure readings (P_2 in Eq. 6) were compared with the actual pressure readings. The actual and theoretical final pressure readings were very close, and the calibration equation for P_2 was found by plotting the actual P_2 values versus the theoretical P_2 values (Agnew 2002). Introducing the empirical values calculated with the apparatus accounts for the small variations and errors in hose and fitting volume determinations.

The final, calibrated equation for FAS was

$$FAS = 100\frac{\dfrac{P_1 V_A}{1.0908 P_2 - 2.5234} - V_B - V_A + V_S}{V_S} \qquad (7)$$

The volume of the compressed air vessel (V_A) was 31.0 L. V_A would never change and was found both by calculation and with duplicated water addition. V_B would change depending on the stroke of the piston since the piston rod occupied part of the vessel volume. Therefore, the volume of the sample vessel was found at maximum and minimum piston extensions by duplicated water addition (Agnew 2002). A linear equation was developed so that the total sample vessel volume could be found at all piston heights and is shown in Eq. 8.

$$V_B = 0.00094x + 26.8 \qquad (8)$$

where: x = exposed rod length (mm).

The volume of the sample also changed with compressive loading. As the sample was compressed, some air and water were expelled from voids and the total volume decreased. The volume of the sample within the vessel could be calculated by multiplying the height of the material by the cross sectional area of the vessel. In fact, the cross sectional area of the sample within the vessel remained constant while the height of the sample decreased with compressive loading. This was calibrated for by loading the sample vessel with increments of clean gravel. The actual depth of the gravel in the vessel was measured manually with a tape measure, the lid and piston replaced and the piston extended until it reached the gravel surface. The exposed rod length was then measured and plotted against the actual height of the sample (Agnew 2002). Multiplying the regression equation by the cross sectional area of the sample vessel (0.130 m^2), resulted in Eq. 9 where the sample volume can be calculated at any piston height:

$$V_S = 0.130(x - 125) \qquad (9)$$

Table 2. Initial properties of the materials.

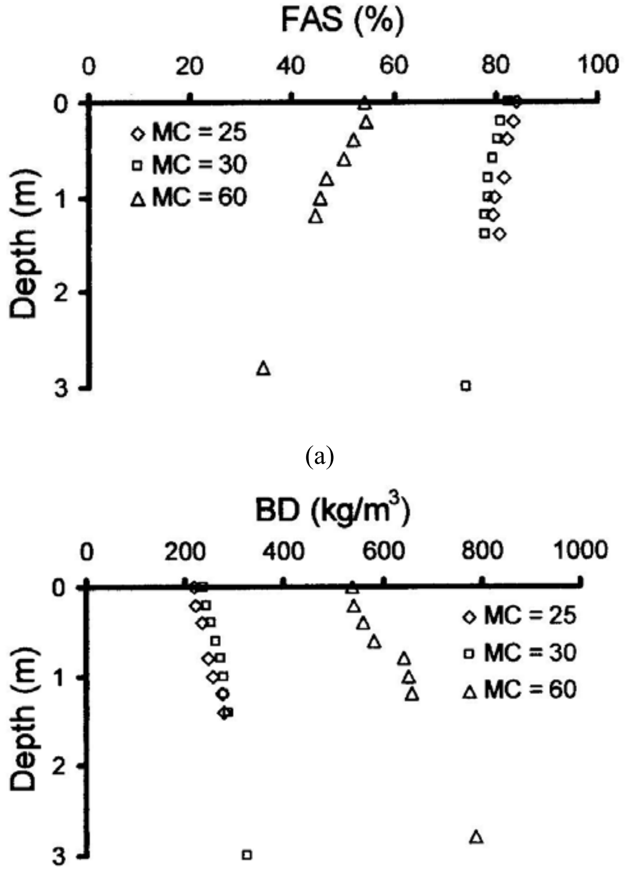
Material	Moisture content (% w.b.)	Wet bulk density (kg/m^3)
Manure compost	25	205
MSW compost	42	440
Biosolids	70	1000
Straw	0.8	51
Woodchips	9	170
Leaves	30	45

MATERIALS and METHODS

A variety of organic materials was available for analysis. Mature manure compost from a lab-scale trial was one of the materials used. This was made from barley straw and a mixture of manure from the University of Alberta's Edmonton Research Station. Composted municipal solid waste (MSW) was obtained from the City of Edmonton Waste Management Center. The material had been curing for approximately six weeks. Pure biosolids were also obtained from the City of Edmonton Waste Management Center and were stored until needed in a sealed plastic container (approximately 2 weeks) at 20ºC. Various amendment materials (leaves, straw, and woodchips) were also tested individually and mixed with the biosolids. The biosolids and amendments were mixed to obtain a target moisture content of 55%. A summary of the initial properties of the materials is presented in Table 2.

The initial wet bulk density of all materials was determined using the mass per unit volume technique (Agnew and Leonard 2003). The exact volume of a plastic pail was determined by measuring the amount of water required to fill the pail to an arbitrary mark. The pail was then filled with the material, dropped 5 times from a height of 100 mm onto a hard surface to expel any large voids, and material was again added until it reached the mark. The mass of the material was determined, and the wet bulk density calculated by dividing the mass by the pre-determined pail volume.

All moisture contents were determined gravimetrically (Agnew 2002). To analyze the same material at more than one moisture content, water was added to the material to reach the desired moisture content. If water was expelled from the material during compression, the mass of leachate was recorded and the new moisture content was calculated based on the mass of material and the initial moisture content. Moisture contents were also determined gravimetrically before and after compression.



(a)

(b)

Fig. 4. Profiles for manure compost: (a) free air space (FAS); (b) bulk density (BD).

To calculate the bulk density of the materials using the pycnometer, the mass of the material added to the sample vessel was measured. For each compressive load, the sample volume could be accurately determined by measuring the exposed rod length and using Eq 9 to calculate the sample volume. Bulk density was then calculated by dividing the mass of material in the vessel by the sample volume.

Experimental and statistical methods are fully described in Agnew (2002). The bulk density and FAS of each material (manure compost, MSW compost, biosolids, and amendment materials) were determined at depths of 0 to 3 m in 0.2 or 0.5 m increments, depending on the initial wet bulk density of the material. Depths were simulated using the air cylinder and piston apparatus installed in the sample vessel. All FAS values were taken in triplicate.

RESULTS

Each material was characterized to obtain bulk density and FAS profiles (variation with depth) as well as to relate wet bulk density (BD) and FAS. The FAS and bulk density profiles for the manure compost at three moisture contents are shown in Fig. 4.

As expected, the BD increased with both simulated depth and moisture content. At higher compressive loads, air voids were displaced and the matrix became denser. At higher moisture contents, the water filled the air voids and increased the overall mass of the sample. Figure 4 illustrates the reciprocity between FAS and BD and Fig. 5 shows the linear relationship between BD and FAS of the manure compost in this study. The magnitude of the FAS and BD values are within the range of values found in literature (Rynk 1992). Baker et al. (1998) observed a linear relationship between the dry density and FAS. Since the researchers related dry density to FAS, the linear regression equation had a different intercept and slightly different slope at each moisture content. Converting the dry densities to wet densities and plotting the wet bulk density and FAS results in a linear regression similar to the one observed in this study. Richard et al. (2002) also observed a linear relationship between wet bulk density and air-filled porosity for dairy manure and paper mill sludge.

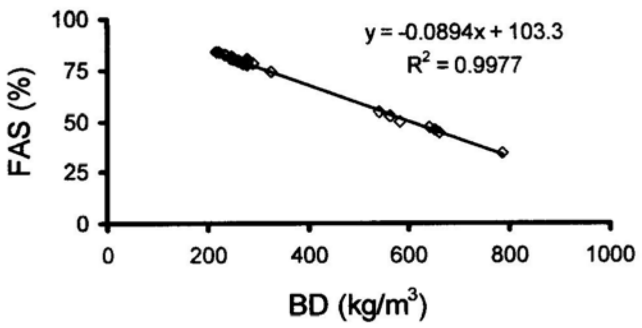


Fig. 5. Free air space (FAS) vs bulk density (BD) for manure compost.

In this case, since the wet bulk density reflects the moisture content, a single linear relationship existed for this material. It is important to note that the linear relationship in Fig. 5 is valid only for moisture contents used (i.e. between 25 and 60% on a wet basis). Further trials could validate this relationship for all moisture contents.

The same relationships existed for the MSW compost, amendment material, and biosolids mixtures; the bulk density increased with moisture content and depth while the FAS decreased with moisture content and depth. However, the magnitude of the wet bulk density and the overall FAS varied with each material.

The MSW compost had higher bulk density and lower FAS values than the manure compost (Agnew 2002). The particle size of the MSW was smaller than that of the manure compost, resulting in a slightly denser and more compact material. As well, the particle sizes were more uniform, eliminating large pore spaces. The relationship between bulk density and FAS was again linear, and the regression parameters were very close to those found for the manure compost (Table 3).

The amendment materials were very light and had large pore spaces, resulting in low bulk density values and high FAS values. The biosolids were very dense and wet and had bulk densities in the range of 900-1100 kg/m^3. The FAS quickly dropped to 0% even at low compressive loads for the pure biosolids and biosolids mixed with leaves. Again, the relationship between the bulk density and FAS of all amendments and biosolids mixtures was linear with regression coefficients that were similar to those found for manure and MSW compost (Table 3).

Table 3. Summary of slope, intercept, and standard error values from BD vs FAS regression equations.

Material	Slope (% per kg/m$^{3)}$)	Standard error for slope	Intercept (%)	Standard error for intercept
Manure compost	0.0957	0.0010	111.22	0.40
MSW compost	0.0894	0.0024	102.69	1.63
Woodchips	0.1479	0.0040	107.91	0.99
Leaves	0.1165	0.0040	96.95	0.68
Straw	0.0891	0.0100	93.53	0.99
Pure biosolids	0.0994	0.0039	109.88	4.083
Woodchips-biosolids	0.0940	0.0080	100.34	5.88
Leaves-biosolids	0.0906	0.0057	96.26	5.60
Straw-biosolids	0.0874	0.0016	96.49	1.18
Cornstalks-manure*	0.1024	0.0030	113.49	2.50
Overall**	0.0840	0.0010	96.30	0.76

* Data from Baker et al. (1998)

** Includes all data (from this study and Baker et al. 1998) in one regression equation

DISCUSSION

Pycnometer performance

Since there are very few existing methods of measuring the FAS of organic materials, it was impossible to directly compare the results found with the pycnometer to literature values to assess the accuracy of the pycnometer. However, during the water calibration, the air space volumes found by the pycnometer were very close to the actual air volume found by subtracting the volume of water from the total vessel volume. In addition, the preliminary trial with gravel indicated the accuracy of the pycnometer. The FAS of the gravel was found by water pycnometry and compared to the FAS found by the air pycnometer. The values were accurate within 3% and the air pycnometer values were consistently higher than those found by water pycnometry. Because of the pressures associated with the air pycnometer, all voids, including the micro pores within the particles, are penetrated. These micro volumes are included in the calculated FAS, resulting in a higher FAS value.

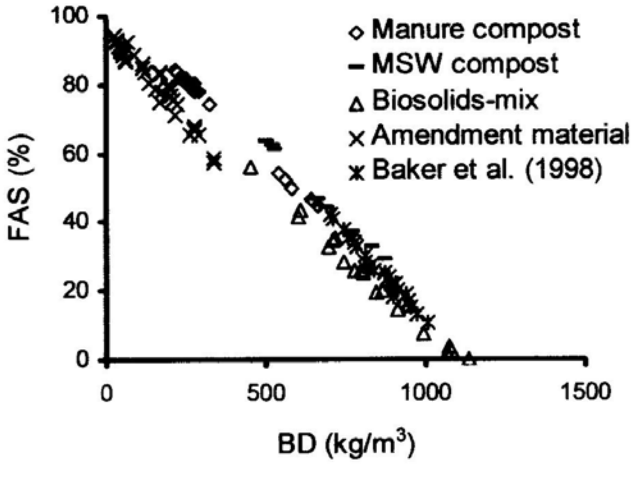


Fig. 6. Free air space (FAS) vs bulk density (BD) summary of all values from this study, including data from Baker et al. (1998).

The FAS values found by the pycnometer also were precise. The variation among repetitions was very low with the relative error of the FAS reading less than 2.3% and the relative error of the equilibrium pressure reading less than 0.4% (Agnew 2002). This indicates that the volume measurements were less precise than the pressure readings. However, the overall FAS values were still accurate and precise.

Interpretation of results

Collecting all of the data from this study together with that from Baker et al. (1998), and forcing the regression line through the point (0,100), resulted in the graph shown in Fig. 6. The overall regression equation (FAS = 100 – 0.0889 BD) had an R^2 value of 0.97.

Thus, it is apparent that, if the BD is known, either measured with the pycnometer or with conventional methods, the FAS can be reliably calculated with the general regression equation:

$$FAS = 100 - 0.09BD \tag{10}$$

Comparing Eq. 10 with the theoretical relationship (Eq. 1), it is apparent that the constant 0.09 is equivalent to the term:

$$\frac{MC}{\rho_w} + \frac{100 - MC}{PD} = 0.09 \pm 0.001 \tag{11}$$

where 0.001 is the standard error of the regression parameter (SAS 1998).

Intuitively, for a given compressive load, the particle density should remain constant at all moisture contents. The mass and volume of solids should be independent of the amount of moisture, assuming that the individual particles do not take up moisture and the water is held only in the empty pores. However, through statistical analysis (SAS 1998), it was found that the particle density changed slightly with increasing moisture (Agnew 2002). In some cases, this could be explained by the uptake of moisture causing the solid particles to swell, increasing the volume and causing an overall decrease in particle density. In other cases, the uptake of moisture may have weakened the particle structure, causing the particle to collapse, lowering the particle volume and increasing the overall particle density. Whether the particle swelled or collapsed depended on the type of material, the strength of the matrix, and the hydrophobic nature of the material.

The particle densities were also analyzed for variation with depth. The assumption was made that the particle mass and volume remained constant with compression and the particle density of material at the bottom of the pile was equivalent to the particle density of the same material at the top of a pile, assuming constant moisture content. For the manure compost and MSW compost, the simulated depth had no significant effect (α = 0.05) on particle density (P = 0.19 for manure compost and P = 0.15 for MSW compost). Since the interaction

Table 4. Particle densities (PD) and standard errors of compost and amendment materials at various moisture contents.

Material	MC (% w.b.)	PD (kg/m^3)	N
Manure compost	35	1554±94	7
	30	1460±67	9
	60	1695±69	8
MSW compost	42	1881±34	3
	55	1725±26	5
Biosolids	76	1750±82	4
Woodchips	9	1019±8	3
	34	860±60	7
	47	741±17	5
Leaves	11	454±20	7
	59	633±90	7
Straw	0.81	466±18	4
	50	568±39	6

between moisture content and depth was significant for the biosolids material, the assumption of constant particle density throughout the pile could not be made for the biosolids material.

Throughout the depth simulation, the moisture content of the manure compost and MSW compost remained approximately constant, even at high compressive loads. Material at higher moisture contents lost some water due to compression, but the overall moisture content changed less than 3% (Agnew 2002). Since the particle density of the manure compost and MSW compost was not dependent on depth, and if the moisture content was assumed constant, the left hand side in Eq. 11 remained constant and there was a linear relationship between bulk density and FAS.

While the particle densities varied slightly with moisture content, the values were similar for each of the materials tested, as seen in Table 4. These particle densities for the composts are also similar to those found for manure and cornstalks compost (1563 kg/m^3, Baker et al. 1998).

The particle densities of the amendment materials, particularly the woodchips, appear to be low, especially at the higher moisture contents. In the material with higher moisture contents, small pockets of air may have been surrounded by moisture, and the pressurized air may not have penetrated these trapped spaces, resulting in a low FAS reading and a subsequently low particle density value. The remaining particle densities correspond with published values (Agnew and Leonard 2003).

The data were also analyzed to test the effect of compost material (manure compost, MSW compost, and biosolids material) on particle density. The material had no significant effect ($\alpha = 0.05$) on the particle density ($P = 0.0554$), suggesting that, like soil, the particle densities of all the compost materials tested are very similar. However, since the P value is less than 0.10, it suggests a trend in the dependence of the particle density on the nature of the material.

The linear relationship between bulk density and FAS and the assumption of constant particle density were confirmed by data from a study involving paper mill deinking sludge (Brouillette et al. 1996). These researchers measured the bulk density of the sludge at several pile depths using the mass per unit volume technique. The FAS was then calculated using an equation similar to Eq. 1 and the assumption that the particle density of the sludge was 1250 kg/m^3. The relationship between the bulk density and FAS of the sludge was linear, namely (Stoffella and Kahn 2001):

$$FAS = 99.9 - 0.0788BD \qquad (12)$$

The coefficients are very similar to those found in this study (Eq. 10). Thus, the linear relationship between bulk density and FAS of compost and sludge materials is verified.

CONCLUSIONS

The ability to reliably determine the FAS and bulk density of compost at any time and under any condition constitutes a valuable tool for compost research and process management.

The modified air pycnometer designed and built for this project provided accurate measurements of FAS and bulk density for a variety of compost and feedstock materials. The variation among repetitions was very low, indicating that the results were also precise. The air cylinder and piston provided for easy and accurate compression, allowing the development of bulk density and FAS profiles, which were previously very cumbersome to determine.

The FAS and bulk density profiles of the compost material followed the trends established by McCartney and Chen (2001) and Baker et al. (1998). The FAS decreased with loading and increasing moisture content while the wet bulk density increased with loading and increasing moisture content.

The relationship between FAS and bulk density was linear and was the same for all the materials tested under loads. The linear relationship, however, is valid only for wet basis moisture contents between 10 and 80%. In addition, the magnitude of the particle densities of the compost material studied was roughly similar, between 1500-1800 kg/m^3 while the amendment material (woodchips, straw, leaves) had lower particle densities (450-650 kg/m^3).

While the pycnometer provided accurate, quick, and reliable FAS and bulk density readings, in its current form it would be impractical and cumbersome to use in the field. However, the development of bulk density and depth relationships and the correlation between FAS and bulk density will make full-scale process management easier and more effective.

ACKNOWLEDGEMENTS

Funding for this work was supplied by the Natural Sciences and Engineering Research Council of Canada. The authors thank the dedication and patience of Mr. R. Holowach during the construction of the pycnometer, and Mr. S. Yu for his insights into the theory and for the continued maintenance of the pycnometer.

REFERENCES

Agnew, J.M. 2002. The free air space and bulk density of compost and compost materials. Unpublished M.Sc. thesis. Edmonton, AB: Department of Agricultural, Food, and Nutritional Science, University of Alberta.

Agnew, J.M. and J.J. Leonard. 2003. The physical properties of compost. *Compost Science and Utilization* 11(3): 238-264.

Baker, S.M., T.L. Richard, Z. Zhang and S. Monteiro da Rocha. 1998. Determining the free air space inside compost mixtures using a gas pycnometer. ASAE Paper No. 98-4094. St. Joseph, MI: ASAE.

Brouillette, M., L. Trepanier, J. Gallichand, and C. Beauchamp. 1996. Composting paper mill deinking sludge with forced aeration. *Canadian Agricultural Engineering* 38(2): 115-122.

Das, K. and H.M. Keener. 1997. Moisture effect on compaction and permeability in composts. *Journal of Environmental Engineering* 123(3): 275-281.

Geddis, A.M., A.G. Guzman and R.L. Basset. 1996. Rapid estimation of solid volume in large tuff cores using a gas pycnometer. NUREG/GR – 6457. Washington, DC: Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission.

Haug, R.T. 1995. *The Practical Handbook of Compost Engineering*. Boca Raton, FL: Lewis Publishers.

Leege, P.B. and W.H. Thompson. 1997. *Test Methods for the Physical Examination of Compost and Composting*. Beltsville, MD: U.S. Composting Council.

Marshall, K. and D. Sixsmith. 1974. Some physical characteristics of microcrystalline cellulose--powders for pharmaceutical use. *Drug Development Communication* 1:51-57.

McCartney, D.M. and H. Chen. 2001. Bench-scale simulation of the composting process: Effect of compression on free air space and microbial activity. *Compost Science and Utilization* 9: 283-302.

Mohsenin, N.N. 1986. *Physical Properties of Plant and Animal Materials,* 2nd edition. New York, NY: Gordon and Breach Science Publishers.

Oppenheimer, J., A.G. Martin and L.P. Walker. 1996. Measurements of air-filled porosity in unsaturated organic matrices using a pycnometer. *Bioresource Technology* 59:241-247.

Raviv, M., S.Tarre, Z.Geler and G. Shelef. 1987. Changes in some physical and chemical properties of fibrous solids from cow manure and digested cow manure during composting. *Biological Wastes* 19(4): 309-318.

Richard, T.L., H.V.M. Hamelers, A.H.M. Veeken and T. Silva. 2002. Moisture relationships in composting processes. *Compost Science and Utilization* 10(4): 286-302.

Rynk, R. 1992. *On-Farm Composting Handbook*. Ithaca, NY: Northeast Regional Agricultural Engineering Service, Cooperative Extension.

SAS. 1998. *SAS System for Elementary Statistical Analysis*. Cary, NC: SAS Institute Inc.

Schaub-Szabo, S.M. and J.J. Leonard. 1999. Characterizing the bulk density of compost. *Compost Science and Utilization* 7(4): 15-24.

Schulze, K.L. 1962. Continuous thermophilic composting. *Compost Science* 3: 22-34.

Stoffella, P.J. and B.A. Kahn. 2001. *Compost Utilization in Horticultural Cropping Systems.* Boca Raton, FL: Lewis Publishers.

van Ginkle, G.T., P.A.C. Raats and I.A. van Haneghem. 1999. Bulk density and porosity distributions in a compost pile. *Netherlands Journal of Agricultural Science* 47:105-121.

Waller, P.L. and A.M. Harrison. 1991. Estimation of pore space and the calculation of air volume in horticultural substrates. *Acta Horticulturae* 294: 29-37.