EVALUATION OF TECHNIQUES FOR MEASURING AIR FILLED POROSITY IN COMPOSTS OF MUNICIPAL BIOSOLIDS AND WOOD CHIPS

By

Jason S. Annan
AWARE Environmental, Inc.
Charlotte, North Carolina

Richard K. White, Ph.D., P.E.
Department of Agricultural and Biological Engineering
Clemson University
Clemson, South Carolina

ABSTRACT

Air filled porosity, or free air space (FAS), is a fundamental operating parameter of aerobic composting and is a generally accepted measure of the amount of air contained in a compost material. Lack of an adequate FAS can cause anaerobic conditions and lead to prolonged composting time and/or incomplete and unsuccessful composting. Previous studies have found the optimal range of air filled pore volume to be between 30 and 60 percent of the total system volume (Annan, 1998).

As part of this study, samples of compost were tested for FAS content by three direct-measurement techniques: the water pycnometer, a water saturation and draining method, and the air pycnometer. These results were statistically compared to each other and to two formulaic methods for calculating FAS found in the literature: an equation proposed by Schulze (1962) and a fundamental air filled porosity equation common to soil science and promoted for composting applications by Haug (1993).

The results produced by the water pycnometer and air pycnometer were similar, though not statistically identical, and compared well with values generated by the air porosity formula promoted by Haug (1993). The water saturation and draining method and the formula first proposed by Schulze (1962) followed another trend, generally producing disparately lower values of FAS for almost all the mixtures examined.

Based on derivation of weight-volume relationships, the air porosity equation suggested by Schulze (1962) is incorrectly derived, and was found to produce dubious results. Study results also indicate that as a technique for measuring total air-filled pore space in composts, the water saturation and draining procedure is fundamentally flawed and should not be used as a best practice. Based on study results, the air pycnometer, water pycnometer, and the air porosity equation promoted by Haug (1993) are recommended as best practice techniques for measuring compost air porosity. The air pycnometer is proposed to be the method of choice because; 1) it is a simple, repeatable, and quick method, and 2) it more accurately measures the numerous small pore spaces found in any compost sample.

INTRODUCTION

Air filled porosity, or free air space (FAS), is defined as the ratio of gas filled pore volume to total sample volume. Adequate air spaces are needed to provide oxygen to aerobic bacteria, and insufficient FAS can prolong the composting period and may lead to anaerobic conditions. Air spaces and channels also allow mixtures a degree of cooling. As air diffuses through open voids within a compost pile, it carries away excess heat to the open atmosphere.

The presence of air voids in a compost mixture helps explain why optimum moisture levels may not be constant for all substrates. Bulky materials may have considerable FAS, lending themselves to excessive air flow which causes cooling and drying. For such materials, higher moisture levels can be tolerated. For finer materials, the small air spaces between solid particles are easily clogged with excessive moisture or compaction. Moisture and FAS are interdependent. Increased moisture levels correspond to decreases in the volume of air filled pores. Research has indicated that the optimum level of FAS is between 30% and 60% of compost sample volume, while optimum moisture content falls in the range of 50-60% of total sample mass. Bulky materials, known as bulking agents, create air voids in a compost mixture. Wood chips are a common bulking agent. Bulking agents can account for up to 60% of the total cost of a composting system, and their use should be rationed to a level that provides optimum FAS and structural support (Shea, *et* al., 1981).

There are two procedures found in the literature for measuring FAS in a compost: the water pycnometer, explained in detail by Singley, *et* al (1981), and a water saturation and draining procedure written by the U.S. Compost Council and proposed by that organization as a standard test method (U.S. Compost Council, 1997). Both techniques use water to fill in air voids. In addition, there are two mass-volume equations that can be used to predict compost FAS content based on sample bulk density, specific gravity, and moisture content. This study also proposes a FAS measuring fifth technique, the air pycnometer. The air pycnometer uses pressurized air to measure air pore volume. These techniques have not been compared to one another, and a comparison of the methods would benefit industry and researchers. This study will also identify the detractions, if any, particular to each test.

LITERATURE REVIEW

Compost, like soil, is comprised of portions of air, water, and solid particles. Each occupies a fraction of a total sample volume. The total volume is described as

$$v_t = v_a + v_w + v_s \tag{1}$$

where

v_t = total sample volume,
v_a = volume occupied by air,
v_w = volume occupied by water,
v_s = volume occupied by solid matter.

Air-filled porosity is defined as

$$f = \frac{v_a}{v_t} \tag{2}$$

where

f = air filled porosity.

Rather than air filled porosity, Schulze (1962) first coined the term "free air space" for compost applications, which he defined identically, in a verbal sense, to air filled porosity. Hereafter, air filled porosity (f) and FAS will be considered identical.

A detailed derivation of the FAS phase equation (equation 3) is presented in Annan (1998) and is not repeated here. Based on fundamental parameters of soil science, FAS can be expressed as

$$FAS = \left(1 - \frac{\rho_t(dm)}{G_s\rho_w}\right) - (1 - dm)\left(\frac{\rho_t}{\rho_w}\right). \tag{3}$$

where

ρ_t = total (wet) bulk density (M_t/V_t) (g/cm^3),
dm = dry mass (M_s/M_t),
G_s = absolute specific gravity of the compost particles (dimensionless),
ρ_w = density of water (g/cm^3) (usually taken to be 1 g/cm^3),

Schulze (1962) originated the concept of FAS for compost applications and developed the expression

$$\mathrm{FAS} = \left(1 - \frac{\rho_f(\mathrm{dm})}{G_s \rho_w}\right)(\mathrm{dm}). \tag{4}$$

Note that the two FAS equations (equations 3 and 4) are not equivalent. A dimensional analysis of equation 4, presented in detail by Annan (1998), shows that Schulze's equation is not correctly derived.

Instead of using the equations derived above, FAS may be found experimentally. Two techniques are found in the compost literature: a water pycnometer procedure and a saturation and draining procedure referred to in this thesis as the U. S. Compost Council "standard". A "standard" procedure for FAS evaluation is found in section 07.01-A of *Test Methods for the Examination of Composting and Compost* (*TMECC*), draft 3.9.4, currently being developed by the U. S. Compost Council, a professional organization.

In the water pycnometer test, a compost sample is submerged in a known volume of water. The volume of water needed to fill in air spaces within the material is equal to the FAS volume. Water pycnometry has been used for a variety of materials, including soil, coal, and grain. A water pycnometer procedure for compost applications is described in Singley, *et* al., (1982).

In the Compost Council test, a compost sample is first saturated with water. The water is then allowed to drain from the bottom of the cylinder. The weight difference between the saturated and drained states is equal to the volume of water needed to fill all open spaces. This standard method is procedurally very similar to the weight-differences method first developed by Lèamer and Shaw (1941) for soils.

An air pycnometer could be used for composting applications. Torstensson and Eriksson (1936) first developed the air pycnometer for measuring soil porosity. The air pycnometer used in this investigation consisted of a reservoir chamber containing air at a known pressure and a sample chamber filled with a known volume of material, yet initially open to atmospheric pressure. An air valve connects the two chambers. After sealing the system, compressed air from the reservoir is released to the sample chamber by opening the connecting valve. A gauge registers the pressure in the reservoir chamber before and after the connecting valve is opened. Boyle's law can be applied to the pycnometer system by writing the relationship

Pressure x Volume = Constant and constant temperature.

This relationship can be expanded to

$$P_o(V_s + V_r) = P_s V_s + P_r V_r. \tag{5}$$

where

P_o = equilibrium pressure in the entire system,
V_o = gas volume of overall system,
P_s = pressure in sample chamber,
V_s = gas volume of sample chamber,
P_r = pressure in reservoir chamber,
V_r = gas volume of reservoir chamber.

Assuming that P_s is initially zero (since the sample chamber is open to the atmosphere prior to testing) equation 5 can be solved for V_s, the volume of gas in the sample chamber, producing the result of

$$V_s = \frac{(P_r - P_o)V_r}{(P_o)}. \tag{6}$$

In equation 7, P_r represents the initial gauge pressure reading (with compressed air contained only in the reservoir). The final gauge reading is recorded as P_o, the pressure in the entire system. As V_s is the measure of gas volume in the sample chamber (either with or without sample), FAS may be calculated by

$$FAS = \frac{V_s}{V_m} \qquad (7)$$

where

V_m = volume of sample in sample chamber.

Often, the sample chamber is equipped with a cup to hold material. If the sample cup is filled completely, the material volume equals the volume of the cup. This is a convenient way to ensure a constant sample size over a range of tests.

PROCEDURES

Samples of sewage sludge (87% moisture) were mixed with air-dried hardwood wood chips (10-12% moisture) in volumetric proportions of: 0.5:1, 0.75:1, 1:1, and 1.25:1 wood chips to sludge. Two batches of each mixture were prepared at different times. Five samples from each mixture-batch combination were tested for FAS content by each test method. After these tests, a batch of 1.75:1 and 2:1 wood chips to sludge mixtures were prepared and tested.

The procedure for the water pycnometer test is described in Singley, *et* al., (1982). In this study, a four liter, graduated plastic cylinder was filled with 1800 cubic centimeters (cm^3) of compost. The material was compacted by dropping the cylinder from a height of six inches onto a 0.5 inch foam mat. Once filled to the 1800 cubic centimeter mark, the cylinder was weighed to the nearest 0.1 gram, and the material bulk density was calculated. A wire mesh screen was placed atop the compost to prevent material from floating once submerged in water. One thousand mL of deionized water was slowly poured over the compost sample. Additional water, in 500 mL increments, was added if the water level failed to rise above the top of the compost. After the water addition, the cylinder was gently rocked from side to side five to ten times to free trapped air bubbles before recording the final water level. Water levels were recorded to the nearest 10 mL. The cylinder was emptied and cleaned thoroughly after each test.

Sample FAS was calculated by subtracting the final water level reading (in mL) from the zero FAS mark. The zero FAS mark is equal to the sample volume (1800 mL) plus the volume of water added to the sample (1000 mL in most cases). This difference represents the volume of water needed to fill air-pores within the compost.

The procedures for the Compost Council "standard" are presented in Tests 07-01 A in *Test Methods for the Examination of Composting and Compost* (*TMECC*). Per the test procedures, 1800 cm^3 of compost were added to a clear cylinder. The sample is compacted by dropping the cylinder from a height of six inches onto a foam mat. The compacted sample was weighed to the nearest 0.1 gram and the sample bulk density was calculated. The sample was saturated with deionized water (saturation is when the water level was even with the top of the compost). Water was then allowed to drain for at least 15 minutes through four 1/8 inch holes drilled in the bottom of the cylinder. The saturation and draining steps were repeated three times. For a final time, the compost sample was saturated, and the saturated weight of the sample was measured to the nearest 0.1 gram. Water was allowed to drain from the sample through the bottom of the cylinder for four hours. After this time, the compost-filled cylinder was weighed and the weight recorded to the nearest 0.1 gram. As defined by the Compost Council procedures, the difference in weight between the saturated compost and the compost after the four hour drain period is equal to the FAS volume.

The air pycnometer used in this investigation is shown in Figure 1. Prior to conducting tests, the air pycnometer was tested for leaks by pressurizing the entire system and monitoring the pressure gauge for drops. The pycnometer was calibrated using precision steel ball bearings, which allowed for very exact solids volumes to be placed in the sample chamber. Once a given number of ball bearings were placed into the sample chamber, the volume of air space in the cup was found by subtracting the solids volume from the total volume of the sample cup (91.5 cubic inches). A calibration curve was generated, plotting final gauge pressure readings versus FAS content of the sample cup containing different numbers of ball bearings. The curve is shown in Figure 2. This curve was generated using an initial reservoir pressure of 7.50 psi, and is valid for only those tests run at that initial pressure. Using Microsoft Excel's regression programs, a straight line was fitted to the points on the calibration curve. The linear regression equation was used to compute sample FAS from the final gauge pressure reading.

The sample chamber holding cup was filled with compost (about 1500 cm^3). After adding each layer, the cup was dropped from a height of six inches onto concrete. After compacting the third layer by this method, compost was added in excess, without compaction, then smoothed to the top of the sample cup. The filled sample cup was then weighed to the nearest 0.1 gram, and the bulk density of material was calculated.

Once the sample cup had been prepared, it was placed into the sample chamber of the pycnometer. The chamber lid was then secured. The connecting valve (valve E on Figure 1) was closed, while the air release valve (valve F on Figure 1) was opened. The reservoir chamber was filled with pressurized air to a gauge pressure of about 8.5 pounds per square inch (psi). The air entrance valve (valve C on Figure 1) was then shut. The pressure in the reservoir was reduced to exactly 7.50 psi by opening the connecting valve and allowing air to slowly escape through the air release valve. While open, the air release valve prevents pressurized air from entering the sample chamber. Once the reservoir pressure was set, the air release valve was shut, and then the connecting valve was opened. This allowed pressurized air to move from the reservoir into the sample chamber, filling air spaces within the sample. The system was allowed to equilibrate for about one minute, and the final gauge pressure was recorded to the nearest 0.025 psi. The sample FAS was found using the calibration curve (Figure 2). After recording the final pressure, the air release valve was opened, and the sample cup was emptied and cleaned. The average of the three pressure readings was taken as the final pressure reading for the sample.

The equations of Haug (1993) and Schulze (1962) (equations 3 and 4, respectively) were used to determine the FAS for each sample using the bulk density values found from each test method and using the average moisture content and specific gravity for the mixture under study.

RESULTS

Sample compaction affects FAS content, as more compacted samples will have less air voids, and bulk density is a reflection of sample compaction. Initial statistical testing of measured bulk densities revealed that samples were prepared to the same degree of compaction from test to test (see Annan, 1998). With this established, FAS testing techniques were compared.

The next series of tests analyzed the measured FAS values. The objective of this analysis was to determine which measuring techniques were similar. As variations in sludge were found to have statistically insignificant effects on bulk weight, samples were compared across batches for each mixture ratio. A plot of mean FAS percentage as a function of mixture ratio (expressed as percentage wood chips) is shown in Figure 3. Ninety-five percent confidence intervals were ascribed to each mean, as shown on Figure 3.

Two trends are present in the data: an "upper range" of FAS registered by the air pycnometer, water pycnometer, and Haug's equation; and a "lower range" established by Schulze's equation and the Compost Council standard. More advanced statistical testing, presented in Annan (1998) demonstrate that for the most part, the tests did not produce statistically identical results. However, the trends shown in Figure 3 demonstrate relative relationships between test results.

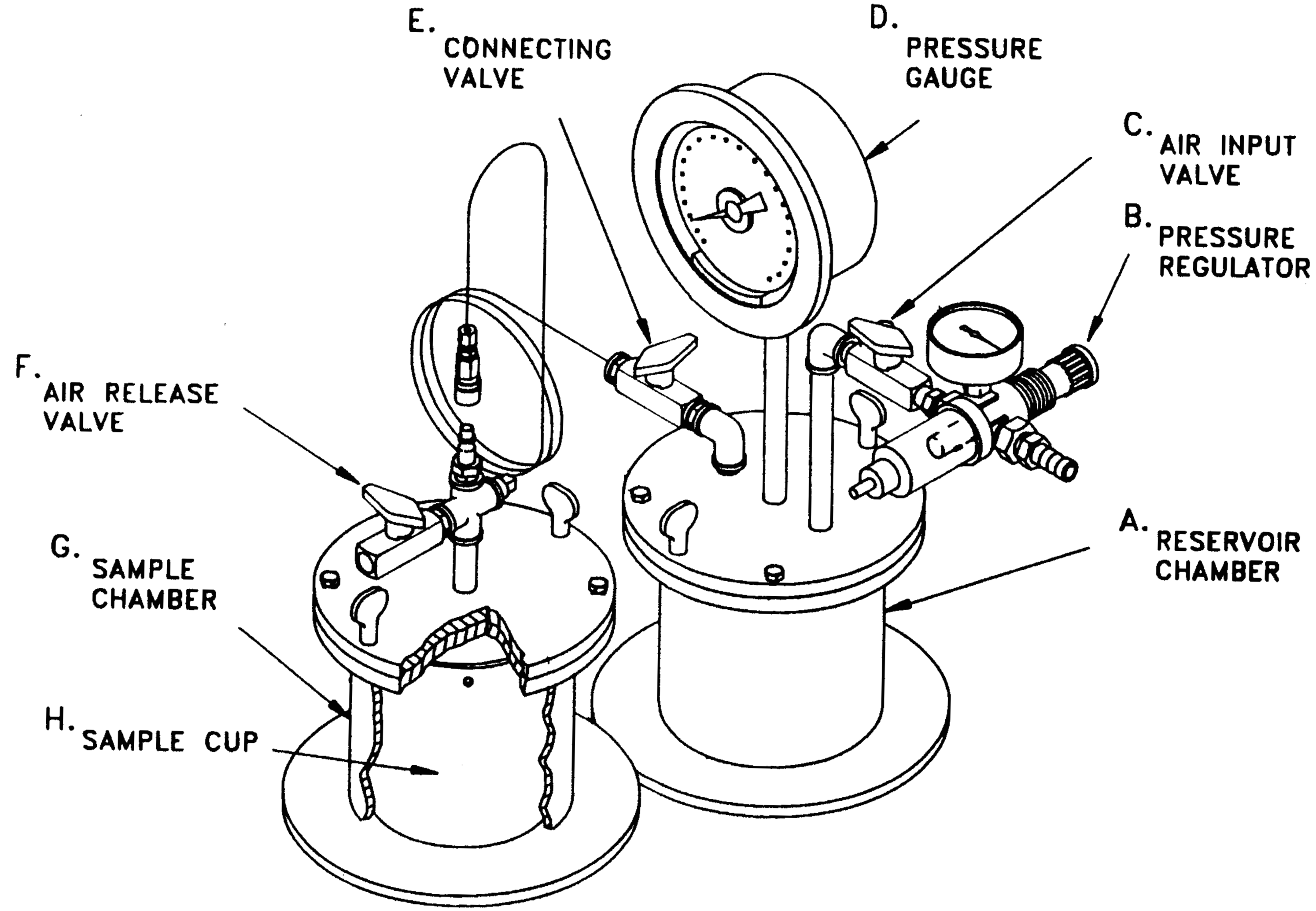

Figure 1. Air Pycnometer

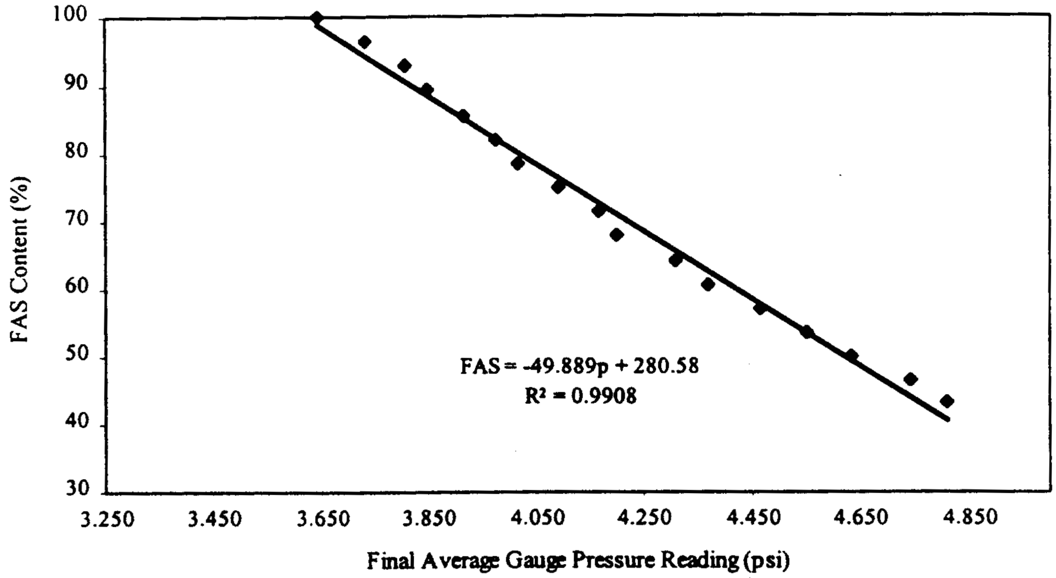

Figure 2. Calibration Curve for Air Pycnometer.

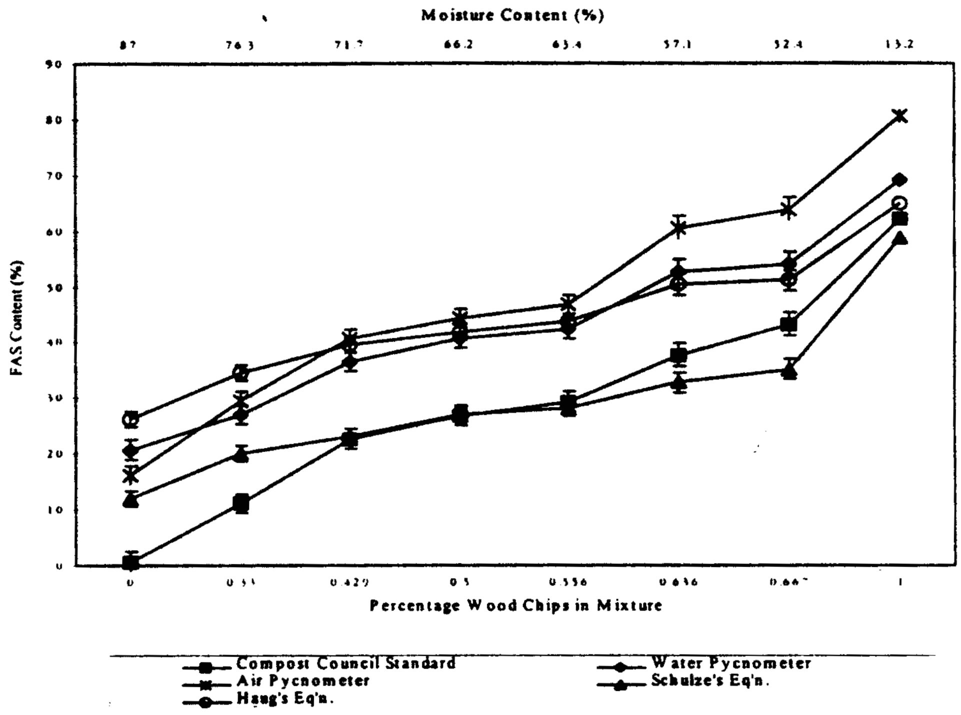

Figure 3. Plot of FAS Content Versus Mixture Wood Chip Content with 95% Confidence Intervals Around Means

Across all mixtures, the water pycnometer differed from the results from Haug's equation by only about 9.5%. Likewise, the results from the air pycnometer differed from those from the water pycnometer by 12.4%, and from Haug's equation by 15%. The pooled results from Schulze's equation differed from the Compost Council standard by 25.4 %.

As observed in Figure 3, there is considerable scatter in the results for the pure sludge (0% wood chips) and 0.5:1 (33% wood chips) mixtures. These mixtures were very wet and compacted easily. There was considerable occlusion of pores in the middle and bottom of the samples. Neither water nor air was able to reach the occluded pores in the bottom of the material. Likewise, the results from the Compost Council standard are suspect. Blocked by compacted material, water was unable to drain from the bottom of the test apparatus as intended, giving an FAS content of essentially zero.

CONCLUSIONS

Water Pycnometer. In general the water pycnometer was a found to be a procedurally simple test that provided adequate measures of FAS content. This test requires only the simplest equipment and is a good "quick and dirty" assessment, taking only about 10-15 minutes to prepare a test a sample.

While testing compost samples with the water pycnometer, air bubbles became trapped within the compost material. These bubbles were plainly visible, yet they could not be dislodged by gentle movement. The presence of bubbles caused a lower than actual recording of FAS content. Cylinders used for the water pycnometer test should be, wide enough to allow compost material to "settle naturally", without binding on the container walls. Singley (1981) recommends using a cylinder with a diameter at least twice as large as the largest compost particle being tested.

Air Pycnometer. The air pycnometer produced results that followed the trends of the water pycnometer and Haug's equation. However, the air pycnometer did produce consistently higher values for FAS content, especially for mixtures containing the greatest amounts of wood chips. This result is explained by the fact that air is a much less viscous fluid than water, and is able to enter the smaller pores that water cannot. In "drier" mixtures (those with higher wood chip content) air was able to enter wood chip pores not sealed with moisture, thus causing the pycnometer to register relatively higher measured values of sample FAS content.

In principle, the air pycnometer produces the most reliable measures of FAS. The air pycnometer does not have the problems of trapped bubbles that plagued the water pycnometer and Compost Council tests. The device is operationally simple and easy to use. After preparing the calibration curve, it required but five minutes to prepare and test a compost sample. No specialized parts are needed to construct the pycnometer. High precision air pycnometers are commercially available, though the sample sizes they are capable of handling are generally too small for compost applications.

Compost Council "standard". The Compost Council standard produced very different results from the air pycnometer, water pycnometer, and Haug's equation. The primary reason for this difference is because the Compost Council procedure, as it is currently written, only measures non-capillary air porosity, or the "larger" air voids that readily release water during draining. Another significant part of total air porosity is capillary porosity—smaller pores that retain water even after prolonged draining. A test of complete FAS should measure both capillary and non-capillary porosity (see Annan, 1998).

The Compost Council procedure does have one other flaw. It is very difficult prepare a saturated sample so that the water level is exactly equal to the level of compost in the container. This is even more a problem when testing raw composts containing large particles, like wood chips. More often than not, some ponding on the compost surface will occur.

The Compost Council test took approximately five to six hours to complete. Material often clogged the drain holes in the bottom of the cylinder preventing water from draining from the sample. Based on the results of this study, the Compost Council standard should be abandoned as a best practice technique for measuring FAS.

The Equations. Haug's equation provided a very good estimate of FAS content for most mixtures, and tracked the water pycnometer and air pycnometer results especially well. The use of this fundamental equation from soil science requires one to know sample moisture content, bulk density, and specific gravity. Of these properties, specific gravity may be the most difficult to measure. A comparison of tests for measuring specific gravity is presented by Annan (1998).

Schulze's equation was found to be incorrectly derived and its use should be abandoned. Unfortunately, this equation has been used by many researchers to establish the ranges of FAS that afford the optimum composting conditions (Jeris and Regan, 1973).

LITERATURE CITED

Annan, Jason S. Comparison of Techniques for Measuring Air-Filled Porosity in Composts of Biosolids and Wood Chips. 1998. Master's Thesis. Clemson Unversity, Clemson, S.C.

Danielson, R. E. and P. Sutherland. 1986. Porosity. In Methods of Soil Analysis, Part I. Physical and Mineralogical Methods. Agronomy Monograph no. 9. Arnold Klute, ed. American Society of Agronomy-Soil Science Society of America. Madison, WI.

Haug, Roger T. 1993. The Practical Handbook of Compost Engineering. Lewis. Boca Raton, Fla.

Jeris, John S. and R. Regan. 1973. Controlling Environmental Parameters for Optimum Composting. Compost Science. 14:8-15.

Leamer, R. W. and Byron Shaw. 1941. A Simple Apparatus for Measuring Non-capillary Porosity on an Extensive Scale. American Society of Agronomy Journal. 33:1003-1008.

Schulze, K. L. 1962. Continuous Thermophilic Composting. Applied Microbiology. 10:108-122.

Shea, T. G., *et* al. 1981 Bulking Agent Selection in Sludge Compost Facility Design. In Composting: Theory and Practice for City, Industry and Farm. Jerome Goldstein, ed. JG Press.

Singley, Mark E., et. al. 1982. Sludge Composting and Utilization: A Design and Operating Manual. New Jersey Agricultural Experimentation Station. Cook College, Rutgers. New Brunswick, NJ.

Torstensson, G. and S. Ericksson. 1936. A New Method for Determining Porosity of theSoil. Soil Science. 42:405-418.

U. S. Composting Council. 1997. Test Methods for the Examination of Composting and Composts. Draft 3.9.3.