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A Method for Characterizing the Bulk Density of Compost
and Other Compressible Materials

by

Stacey Monica Schaub

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfillment of the requirements for the degree of Master of Science.

in

Bioresource and Food Engineering

Department of Agriculture, Food, and Nutritional Science

Edmonton, Alberta

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Stacey Schaub

Stacey Monica Schaub
40 Deercrest Way S.E.
Calgary, Alberta
T2J 5W2

30 SEPT 97

University of Alberta

Faculty of Graduate Studies and Research

The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for Acceptance, a thesis entitled A Method for Characterizing the Bulk Density of Compost and Other Compressible Materials submitted by Stacey Monica Schaub in partial fulfillment of the requirements for the degree of Masters of Science in Bioresource and Food Engineering.

Dr. J.J. Leonard
(Supervisor)

Dr. W.B. McGill

John Feddes
Dr. J.J. Feddes

J A Robertson
Dr. J.A. Robertson

30 SEP 97

ABSTRACT

Bulk density of compressible materials depends on the compressive load to which they are subjected. This results in bulk density variations within piles of such materials. However, it is difficult to measure bulk density *in situ* without disturbing the sample or a load on it. A laboratory method was developed to simulate the variation of density with depth of material. This was used with compost, peat, wood shavings, and straw. To help characterize the test materials, moisture content, ash and organic matter content, particle-size and particle density were measured before bulk density measurements were conducted. Work was done to identify a test container size that would minimize friction effects created by the container wall, while still being convenient and practical. A 40 cm-diam. container with a fill height of 38 cm was found to be suitable. This container size was used to evaluate the relationship of moisture content and bulk density.

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CHAPTER 1

INTRODUCTION

The physical characteristics of various composts and constituent compressible materials are of great importance to the design of storage structures and materials-handling systems, and are a subject of interest to waste management, biological, and agricultural engineers. Physical characteristics are important in describing the bulk properties and individual components of materials. Considerable attention has been given to bulk density, porosity, and free air space. However, many of these properties change when materials are in bulk and understanding how these properties and others, like moisture content, particle density, and particle-size, interact is important for the preservation and processing of many materials.

A literature review by Leonard and Ramer (1993) presented the need for acquiring baseline data on various composts and compressible feedstock materials. From the baseline data, acceptable standard methods of measuring compost properties can be determined so there is uniformity in reporting and comparing data from various sources. The research that is discussed in this paper has been carried out in response to these recommendations. The main focus is to validate a bulk density measurement method that takes into account the compressibility of materials and the density change in a pile due to the mass of material above it. The method has the potential to be applied to a wide range of materials and therefore, the approach was tested with various types of compost, peat at different moisture contents, wood shavings, and straw.

COMPOSTING PROCESS OVERVIEW

Before describing the research in detail, it is appropriate to place it in context by outlining the composting process and how this process is influenced by the physical properties of the materials involved. Composting is "the biological decomposition and stabilization of organic substrates, under conditions that allow development of thermophilic temperatures as a result of biologically produced heat, to produce a final product that is stable, free of pathogens and plant seeds, and can be beneficially applied to land" (Haug 1993). To ensure that the process proceeds, the environment in the mixture must be suitable for the microorganisms to decompose the organic materials. Environmental parameters of importance include moisture content, carbon : nitrogen (C:N) ratio, temperature, pH, oxygen concentrations and particle-size (Haug 1993; Rynk 1992). Independent of the composting method used, these parameters should be within specified ranges to ensure optimum microbial decomposition.

Before decomposition can occur, the compost materials must have a C:N ratio that permits microbial activity and should be in the range of 25:1 to 35:1 (Haug 1993; Mathur et al. 1993; Rynk 1992). Therefore, mixtures of materials are often required to provide a suitable C:N ratio. If the C:N ratio is too low, excess nitrogen is often lost as ammonia, resulting in odour problems. If the carbon content is too high, the available nitrogen is used up before the carbonaceous material is completely decomposed.

In some instances, a carbon source may also be a bulking agent to ensure the mixture has good porosity. Porosity is an indication of the matrix structure which consists of solid particles and pore spaces. Porosity depends on the particle-size and the pore space within the mixture (Leonard and Ramer 1993; Nakaski et al. 1987). The pore space can be filled with gases, like oxygen and carbon dioxide, and with water. However, as decomposition proceeds, the large organic particles are broken down into smaller particles that lower the porosity (Raviv et al. 1987). The decrease in particle-size is important as there is increased surface area available for microbial decomposition. However, this decrease in porosity can alter the movement of air, heat, and water, which is essential for composting (Leonard and Ramer 1993; Levanon 1988; and Miller 1993). Therefore, bulking agents which have a larger particle-size may be incorporated into the mixture at the beginning of the composting process to ensure there is adequate air-filled porosity. These bulking agents are not necessarily decomposed and can be screened out at the end of the process for reuse.

Within the mixture, the moisture content should be kept in the range of 40% to 60% (wet basis) to typically maintain aerobic conditions (Rynk 1992; Haug 1993). This range ensures that adequate heat and gas (oxygen and carbon dioxide) transfer occurs so that the microbes can decompose the organic material. The moisture can be higher so long as the pore spaces are not filled with water. If this should occur, there would be a deficit of oxygen available to the organisms and decomposition would become anaerobic (Finstein and Hogan 1993; Miller 1993). This occurs because gas diffusion through a liquid phase is lower than through a gas phase (Finstein and Hogan 1993; Nakaski et al. 1987). Anaerobic decomposition results in a number of offensive smelling and undesirable by-products (i.e. hydrogen sulfide, volatile organic acids, methyl sulfides, and mercaptans).

Ideally the pH should range between 6 and 8 to allow for optimal decomposition. If the pH is outside this range, microbial activity will be compromised and decomposition will be slowed or stopped (Miller 1993; Rynk 1992). To adjust the pH to this range amendments, such as lime, ashes, and sulfuric acid, may be added to the mixture.

If the above requirements are satisfied, microbial activity will generate heat and increase temperatures in the compost and promote or regulate microbial growth. Consequently, a series of microbial populations, each with an optimal temperature range, decomposes materials. The easiest materials to decompose include starches, sugars, lipids, fats, while the more difficult materials to decompose include cellulose, hemicellulose, and lignin.

Bacteria are better adapted to breaking down easily degradable material like starches and sugars, while fungi are adapted to breaking down the more difficult decomposable material such as cellulose (Miller 1993; Rynk 1992; Schultz 1962). The initial decomposers are mesophilic bacteria with optimal temperature ranges between 10°C to 40°C. As a result of microbial activity, the temperature rises to exceed the mesophilic ranges and thermophilic bacteria take over between 40°C to 70°C (the optimal range is 50°C to 65°C) (Haug 1993; Schultz 1962). These thermophilic temperatures persist during the initial stage of high-rate decomposition. As a result, the high temperatures achieved during composting considerably reduce the number of plant and animal pathogens (Rynk 1993) such as pathogenic bacteria, weed seeds, and other undesirable organisms. To ensure this, compost must be maintained at temperatures above 55°C for 3 to 15 days depending on the composting method (CCME 1996). Following this, the temperature will fall and mesophilic organisms will continue the process at a slower rate. As the composting process progresses, thermophilic and mesophilic fungi decompose cellulose and lignin (Levanon 1988; Rynk 1993). Cellulose and lignin are structural compounds found in straw and woody materials and require a longer time to decompose.

The curing period which follows active composting occurs in the low mesophilic range and compost piles should have low oxygen consumption rates, heat generation, and moisture evaporation (Haug 1993). This stage allows aerobic decomposition of organic acids, large particles and difficult compounds like lignin (Rynk 1993). The curing stage also gives the compost the added time to make nutrients available to plants (i.e. nitrogen, potassium, phosphorous) and to bring the C:N ratio to around 20:1 (Haug 1993; Raviv et al. 1987). The curing time required to produce a good quality compost depends on the carbon content for the initial ingredients and can be as short as a few months or as long as two years. As a result of decomposition, the compost will have a bulk density greater than when the feedstock materials were initially mixed (Schultz 1962) because the reduction in particle-size. Therefore, the method of storing the compost during curing is important because aerobic conditions still need to be maintained.

After the compost has cured and meets the applicable quality standards for final use, it can be incorporated into the soil to enhance soil structure. Adding organic matter to the soil increases the water-holding capacity and available water for plants and decreases the bulk density and soil strength making root penetration easier (Dick and McCoy 1993; Raviv 1987; Sharifat and Kushwaha 1996; Vomocil 1957).

GENERAL

Processes in compost and soil occur in a structural solid matrix and each exhibit similar spatial (physical and chemical) characteristics. However, "composting matrices are primarily organic with a high density of available substrate ready for decomposition" (Miller 1993). This is unlike soil which has nutrients available for plants and organic matter at concentrations typically less than 3% (Sharifat and Kushwaha 1993). Furthermore, the compost matrix is influenced by parameters (i.e. pH, moisture, temperature, porosity) that constantly change the internal composting environment and by measuring these parameters, changes can be predicted. By characterizing the feedstock materials that make-up the organic material in a compost pile and mixing them in suitable ratios, the desired parameters can be optimized and composting processes can be achieved. Essentially, this means characterizing the physical, as well as the chemical properties of both the individual particles and the bulk materials.

The physical properties that have the greatest influence on the composting process include bulk density, particle-size, porosity, particle density, free air space and moisture content. These properties have been researched extensively for peat soils (Chow et al. 1992; Farnham and Finney 1965; Wilson 1983), various types of compost (Das and Keener 1995; Glancey and Hoffman 1994; Hogan et al. 1989; Raviv et al. 1987; Schultz 1962) and organic amended soils (Dick and McCoy 1993; Ekwue and Stone 1994; Mays et al. 1993; Sharifat and Kushwaha 1996; Tisdall and

Oades 1982). Less literature has been found for feedstock materials (Gislerod et al. 1985; Haug 1993; O'Dogherty and Gilbertson 1988).

As stated earlier, these parameters are important for engineers, biologists, and system designers. More importantly, defining material characteristics is fundamental for material processing and handling. However, a physical characteristic that has not been measured adequately for compressible materials is bulk density. When compost and feedstock materials are stored in bulk, the property of bulk density is less easily measured and predicted compared to more rigid-solid materials.

Generally, as the load on compressible materials increases, the matrix undergoes some physical change, usually pore space reduction and more parallel particle orientation. This increases the bulk density and decreases the materials' capacity to conduct and retain air, water, and heat, all of which affect the success of composting (Leonard and Ramer 1994; Oades 1984; Rynk 1992; Haug 1993).

AIMS AND SCOPE OF THE RESEARCH

An understanding of bulk density is based on numerous physical characteristics of the bulk material and the individual particles. Characterizing the properties of materials helps to predict change in bulk density and to understand the interactions of other physical properties that may occur in bulk. Five physical and chemical properties, particle-size, particle density, organic matter, ash and moisture content, were measured for compost, peat, wood shavings and straw and the results are discussed in Chapter 2. Chapter 3 describes a method for measuring the bulk density of these previously tested compressible materials. The method described provides the framework for the final chapters. The bulk density measurement method was tested using cylindrical containers with heights and diameters of 250 mm by 250 mm, 400 mm by 380 mm and 500 mm by 500 mm (Chapter 4). The objective was to identify a practical and convenient container size so that when a load was applied to the material, the friction against the sides of the container would not prevent the compression of the material. Chapter 5 outlines how the container size, identified in Chapter 4, was used to determine a relationship between bulk density and moisture content for compost and peat. Finally, Chapter 6 provides an overview of Chapters 1 through 5 and makes concluding remarks.

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CHAPTER 2

MATERIAL CHARACTERIZATION

INTRODUCTION

The materials used in the work described in this thesis were prepared and used during two time periods (1995 and 1996). A qualitative description of the test materials is shown in Table 2-1. The same source of material used in 1995 for straw, wood shavings, and peat was also used in 1996. The last four materials were tested only in 1995 by Guenther (1995).

Table 2-1. Test material composition.

MATERIAL	DESCRIPTION
Straw	Barley straw.
Wood shavings	Mixture of softwood sawdust and wood shavings.
Peat	Commercial peat from plastic-wrapped bale. Water was added to bring the material to the desired moisture content.
Compost - in-vessel (I)	Straw/animal manure mixed with mushroom compost, grass, molasses, sewage sludge. Maturity time three-weeks.
Compost - partially decomposed (PD)	Straw/dairy manure mixture. Straw partially decomposed.
Compost - commercial (CM)	Earthgro Composted Steer Manure plus Compost 1-1-1.
Compost - industrial (ID)	Bell's Premium Potting Soil.

Physical characteristics were measured to describe and compare materials and to predict their behaviour. In particular, properties like particle-size, particle density, organic matter content, and moisture content, all have an influence on bulk density because they affect the susceptibility of materials to conditions like compaction. Compaction refers to the increase in bulk density of a soil as a result of an applied pressure (Baver et a.. 1972). Characterizing the bulk properties of a material is important in these conditions because stored materials require the transfer of oxygen, heat and water; these are affected by porosity and bulk density.

The measurement of these aforementioned physical properties has been conducted for test materials like grains, mulches, peat soils, and agricultural and organic amended soils. Standards have been developed for characterizing the properties of individual particles and their bulk matrices, and these have been published by organizations such as the American Society of Testing and Materials (ASTM) and the American Society of Agricultural Engineers (ASAE) (e.g. ASAE 1993, ASAE 1992, ASTM 1971, and ASTM 1987). Furthermore data from these test materials have been used as references for the less-studied materials like wood shavings, bark, and straw.

A quantitative understanding of key physical and chemical properties was needed to fully describe the materials to be used for investigating bulk density, compression, and friction. Consequently, moisture content, percent organic matter, ash content, particle density, and particle-size, were chosen to characterize the test materials.

MOISTURE CONTENT

The moisture content of the test materials was recorded as the average of three 100 gram samples taken at the beginning, middle, and end of each bulk density measurement. Moisture contents were determined according to the procedures for organic soils and peat (ASTM 1987, method A). Samples for each material were emptied into an aluminum tray and placed in an oven. The material was dried to a constant weight, at 105°C or 110°C for at least 16 hours. The test materials were dry in the recommended 16 hours and this was confirmed by research carried out by Guenther (1995). Table 2-2 compiles the test materials' mean as-received moisture contents and their standard deviations.

Table 2-2. Mean moisture contents and standard deviations.

	Moisture Content (% w.b.)		
Material	Large$^{\psi}$	Medium$^{\psi}$	Small$^{\psi}$
Straw	12.3 ± 1.46	12.7 ± 1.06	12.8 ± 0.10
Wood shavings	8.9 ± 0.43	9.1 ± 0.56	9.6 ± 0.23
Peat - dry	53.4 ± 0.30	52.1 ± 0.6	52.5 ± 0.26
Peat -interm.	57.2 ± 5.20	59.0 ± 0.26	59.0 ± 0.12
Peat - wet	77.1 ± 0.35	74.1 ± 0.06	75.5 ± 0.06
Compost - PD	62.6 ± 1.66	no test	no test
Compost - I - dry	no test	24.1 ± 0.29	no test
Compost - I -interm.	no test	32.0 ± 0.7	no test
Compost - I - wet	47.4 ± 0.73	47.0 ± 0.21	46.3 ± 0.68

Note: interm. indicates intermediate moisture level.
ψ denotes container size.

The different moisture contents for the compost and the peat were adjusted simply by adding water, thoroughly mixing the material, and then covering the piles with plastic (2 to 3 days) to allow the material to equilibrate. During this equilibrium stage the pile was mixed daily. To determine if the material was at an appropriate moisture content the microwave determination method was used to give approximate percentages (Leonard and Ramer 1995). If the material's moisture content was too low then the procedure was repeated.

PERCENT ASH AND ORGANIC MATTER

Soil matrices typically range (1% to 10%) in organic matter. The presence of organic matter in soil improves the water-holding capacity, reduces the soil strength and bulk density, and increases nutrients and porosity (Chapter 1). In addition, organic matter is effective in binding pesticides and reducing their concentrations in soil solution (Dick and McCoy 1993). Two excellent sources of organic matter are manure and compost originating from decomposed plant residues (Inbar et al. 1993) and both have higher organic matter contents than that noted for soils. Compost has greater organic matter contents than soil matrices because soil consists largely of mineral matter (i.e. sand, silt, clay) and the composting feedstocks are primarily organic matter.

The ash and organic matter content for the test materials, excluding compost, was measured according to ASTM 1987 (method C) using a 440°C oven temperature. The oven temperature for ashing compost was 550°C according to the procedure for organic conditioners (CAN/BNQ 1996). Percentages for all the test materials were expressed on a dry basis. Organic matter content was determined using triplicate samples except for the last three compost types (shown in Table 2-1) where five samples were used.

Ash is material remaining after combustion and represents the approximate mineral and other inorganic matter content in the material (ASTM 1987). Organic matter is determined by subtracting the percent ash from one hundred. The range of organic matter contents for the various feedstock and compost materials is shown in Table 2-3.

Table 2-3. Mean organic matter, particle density, and porosity for various materials.

	Organic Matter % (d.b)	Particle Density* g/cm^3	Porosity %
Straw	95.7	2.32	97.6
Wood shavings	99.0	1.25	92.1
Peat	92.9	1.78 (77% m.c.)	93.6
Compost - I	59.0	no result	no result
Compost - PD	82.3	1.14	91.5
Compost - CM	94.5	1.92	no result
Compost - ID	48.2	1.70	no result

Note: Effective bulk density values for porosity calculation located in Table 3-1.
No result means that no data was collected to allow for determining the value.
* results and method by Guenther 1995.

Standards for soil conditioners specify that compost must have an organic matter content in the range of 30% to 50% (CAN/BNQ 1996) or less than 60% (CCME 1996) and these composts meet these criteria. The feedstock carbon content and other constituents determine the rate of composting which affects the amount of organic matter produced. Therefore, comparing organic matter contents for different compost was not meaningful because the composting method and the feedstock materials were unknown.

PARTICLE DENSITY AND POROSITY

Particle density is the density of the individual solid particles (Haug 1993). By definition it is the ratio of the total mass of the solid particles to their total volume excluding pore spaces (Blake 1965; Haug 1993; Leonard and Ramer 1993). Particle density is important for calculating the porosity of the material. Porosity and free air space (FAS) indicate the structure of the mixture, but these depend on the size, shape, and moisture content (m.c.) of feedstock materials. Free air space is a measure of air-filled pores that allow for aerobic conditions to persist. These pores affect the permeability of heat, water, and oxygen through the material. The following formulas describe these relationships:

$$porosity = 1 - \frac{DryBulkDensity}{ParticleDensity} \tag{2.1}$$

$$FAS = porosity(1 - m.c.) \tag{2.2}$$

Particle density is an important property and may give more information on other sources of materials that could be used as a comparison. In this experiment, particle density of the materials was not tested. However, Guenther (1995) measured particle densities of similar materials using a kerosene vacuum method. The method used resulted in particularly high particle densities which may have been a result of the kerosene dissolving the test material. Results for particle density were an average of five samples and are shown, along with porosity, in Table 2-3 for the various materials.

PARTICLE-SIZE

Particle-size is a property that affects the porosity, bulk density, and free air space within materials (Chapter 1). Particle-size analysis can be used to characterize soil permeability and particle orientation in bulk materials (Baver et al. 1972). The analysis is conducted by placing a known amount of material on a stack of sieves with openings of known sizes (Lambe 1951). As the material falls through the sieves the particles are segregated by their diameters. The data may be calculated and recorded as the percent of the total mass retained for that sieve opening (ASTM 1971) according to peat standards, or the total percent of material passing for each sieve (ASTM 1990) according to soil standards. To stay consistent, particle-size results for compost and wood shavings are presented in the format according to the peat standard. The test materials were air-dried for the particle-size analysis but since the materials still contain some moisture, the results are expressed on a wet basis. Wet basis moisture content is defined as the mass of water divided by wet mass (solid plus water) whereas the dry basis moisture content is the mass of water divided by the dry mass (solid only). Means and standard deviations are shown in Appendix A, Table A-4.

Particle-size analysis for the different test materials followed their standards when they were available. However, only straw and peat had particle-size analysis standards and their procedures were conducted according to ASAE (1992) that determined particle-size of chopped forages and ASTM (1971) that determined particle-size of peat materials, respectively. The standard for straw was necessary as straw consists of elongated particles and the shaking time affects the amount of material left on a sieve. The straw particle-size analysis was conducted at the University of Saskatchewan by the Agricultural and Bioresource Engineering Department.

Standards were not found for compost or for wood shavings and therefore, procedures for soil (ASTM 1990) and peat were used as guidelines. The range of sieve openings chosen for the particle-size analysis of these materials was also applied to the peat particle-size analysis. This was necessary to allow for comparison between the compost and the peat because the peat standard only had three sieves.

The sample size for the analysis of compost and wood shavings was based on trials of different sample sizes. Samples approximately 50 grams in size were chosen for both materials. Larger sample sizes resulted in too much material on the sieves and this restricted smaller particles from passing through. This was determined by shaking a sieve over a tray to see if any particles passed through after the allocated shaking time. Particle-size analysis was not conducted on the partially decomposed compost.

To conduct the particle-size analysis, compost, peat, and wood shavings were randomly sampled from holding piles or bins and air dried for 60 hours. This was necessary so that single particles of material were measured, not clusters of material, and to increase the amounts that could be sieved (Marshall and Holmes 1979). Oven drying was not considered as the particles may have become too brittle for this procedure. A sample splitter was used to separate the material to the appropriate sample sizes (50 g or 20 g). The splitter was practical as it ensured an equal opportunity for all particles to be part of the sample. A range of U.S. standard sieves was chosen for each of the materials, following standard procedures, and placed on a Ro-tap shaker, Humboldt MFG. Co. Chicago, IL. Shaking times were 10 minutes for compost and peat, and 5 minutes for wood shavings. Straw was collected and sieved on an as-received basis following the ASAE (1992) procedure and approximately 300 grams was used. This amount was enough to cover 1/3 of the top sieve.

Results from the particle analysis experiment are presented in Table 2-4 and are based on the average of three samples for straw, six samples for in-vessel compost, wood shavings, and peat.

Table 2-4. Mean particle-size for the test materials.

	Total Mass Retained									
	Size of Opening (mm)									
	12.7	9.52	4.76	2.000	0.840	0.420	0.250	0.149	0.074	pan
Mesh #	1/2	3/8	4	10	20	40	60	100	200	pan
Compost - I	0	1.5	10.10	30.54	34.07	13.60	5.88	2.58	0.82	0.89
Peat*	0	1.02	12.19	48.67	17.89	18.63	11.06	9.49	6.64	3.84
Wood shavings	0.42	2.64	8.23	29.92	36.70	16.0	3.94	1.5	0.51	0.14
Straw	Geometric mean length = 8.98 mm; standard deviation by mass = 4.27									

Note: *** particle-size analysis according to standard (8 and 20 mesh sieves) are shown in Appendix A, Table A-4. Test materials were air-dried before sieved.**

DISCUSSIONS AND CONCLUSIONS

The physical behavior of a material is the result of the interaction of individual particles and the bulk properties of materials. Therefore, the size, shape and the orientation of the individual particle will influence bulk density. The five physical and chemical properties tested were conducted on the test materials to give a better characterization of the individual particles and the bulk material. The particle-size analysis for peat distinguished the amount of material retained on the 8-mesh sieve, 20-mesh sieve, and the pan as coarse, medium, and fine fibers, respectively. Unfortunately, the 8-mesh sieve was only used in the standard peat particle-size analysis (Appendix A, Table A-4) and was not used in the wood shavings or the compost sieve analysis. Therefore, the research will interpret coarse fiber as the amount of material retained on the 4-mesh sieve and medium fiber as the amount of material retained on the 20-mesh sieve. This ranking provides information about how coarse or fine the test material's particles are in comparison to each other.

Straw had the most coarse particles, then wood shavings, compost and then peat had the most fine particles (Figure 2-1).

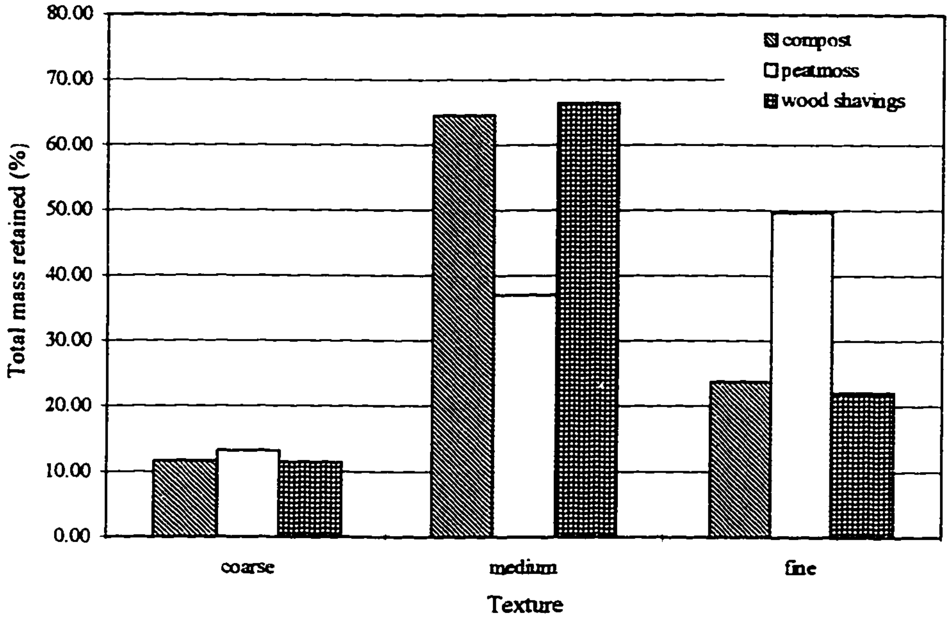

Figure 2-1. Mean percent of the total air-dried mass retained on the sieves for compost, peat, and wood shavings. Coarse size opening from 12.7 to 4.76 mm, medium from 2 to 0.840 mm, and fine from 0.420 to the pan.

Further investigation of the particle-size and shape should give some indication to the material's porosity. However, as described in Chapter 1, these parameters are only one of many that affect the bulk density and the compressibility of the materials. Generally, materials that have smaller particle-sizes pack closer together and fill the pore spaces (Marshal and Holmes 1979). Furthermore, fine textured materials have greater resistance to gas and heat diffusion because there are more particles to act as obstacles (Miller 1993). These trends, however, are dependent on the moisture content and the water-holding capacity for a material and may also depend on the weight of the material that exerts vertical pressure on the material. Consequently, all these parameters affect the particle orientation and gas diffusion.

LIMITATIONS

Further work is required to standardize a method for particle-size analysis on the wood shavings and the compost. The method used for compost assumed the particles to have soil-like properties. However, compost has elongated particles, unlike the more spherical soil particles, and shaking time affects the amount of material left on a sieve. This characteristic has been recognized by the need to have a special method for straw analysis (ASAE 1992).

This characteristic was further tested for wood shavings because some particles are elongated. Therefore, two shaking times were tested (5 and 10 minutes) to check for significant differences (α=0.5) in the percent total mass on the sieves. A significant difference was noted for the 9.52 mm sieve, and the 4, 10, and 20 mesh-sieve (SAS 1994). Generally, the 10 minute shaking time resulted in greater amounts of materials on the smaller mesh openings.

Consequently, the sieving method used for these materials has its limitations (Baver et al. 1972; Day 1965). Therefore, by limiting shaking time, the material remaining on a particular sieve would likely represent the long side of the particle rather than the short side of the particle. This is more meaningful since a particle whose shape permits its passage only in a certain orientation has a limited chance of getting through, except after prolonged shaking. This was noted in the case of the wood shavings. For this reason, a five minute shaking time was used because the wood shavings consisted of elongated particles.. Finally, to achieve good reproducibility careful standardization of the size and shape of sieve openings and of shaking time is required.

The method for calculating the moisture content of compost was also taken from standards developed from peat and organic soils. However, research by the United States Composting Council[1] has indicated that oven temperatures should be lower for testing compost moisture contents so that the loss of volatile carbon is reduced. Therefore, they suggest using a horizontal forced-air oven at temperatures ranging from 70°C to 75°C.

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[1] Sampling procedures and methods stated during the Best Practices Workshop on Composting developed by the United States Composting Council, Alexandria, Virginia.

The limitations presented support the need for research that will take into account the nature of compost and at times the lack of material homogeneity. The research would develop tests that could better reflect the physical and chemical properties of the compost than the present standards do. Finally, the procedures should be made available promptly so that continued research in this area can use the results to further develop baseline and comparable data.

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CHAPTER 3

VALIDATION OF A BULK DENSITY MEASUREMENT METHOD

INTRODUCTION

Any description of a material would be incomplete without consideration of the physical properties of that material. For materials that exist as particles in a bulk, the properties of the bulk material are often as important as properties of the individual particles, and perhaps the most basic bulk property is bulk density. This is simply defined as the mass of a bulk material divided by the volume that the mass occupies.

For relatively hard materials, such as soil or grain, measurement of bulk density can be carried out very simply by measuring the mass of material required to fill a container of known volume or measuring the volume occupied by a known mass of the material (Mohsenin 1986; Stroshine and Hamann 1994). If the particles making up the bulk are non-uniform some shearing or shaking of the bulk may be necessary to pack the particles into their most dense configuration, but if they are incompressible, this can be assumed to give the maximum bulk density of the material. Furthermore, this value can be used with confidence as a design value for the entire bulk mixture.

However, if the material is compressible, bulk density values obtained from small, disturbed samples will reflect only the properties of the material on the surface of a bin or pile. Material at some depth will have higher bulk densities due to compression under the weight of the material above it (Vomocil 1957). In other words, the bulk density of a compressible material will be a function of a load applied to it and, in the case of a pile of material, will depend on the location of the material in the pile. This could be significant in determining the mass of material in a pile of a given volume, or in the estimation of other physical parameters (such as thermal conductivity, porosity, or resistance to air flow) deep within piles of such a material (Leonard and

Ramer 1993). As the materials are compressed, the particles will adopt a closer parallel orientation and the free air space will decrease. Consequently, as the applied load increases, these changes are more pronounced (Felt 1965).

From the above, it may be deduced that there are two problems associated with characterizing the bulk density of compressible bulk materials. The first problem is how to obtain values for the bulk density of material at any location in a pile or bin. The second problem is to come up with a single, representative "effective" bulk density value for the whole pile or bin.

One approach to the first problem is to obtain and test samples of material from locations of interest. However, this invariably involves disturbing the sample to some extent, or disturbing the surrounding material so that a load on the sample is changed, or both. This research describes an alternative approach in which the loading at any depth in the bulk is simulated to obtain a relationship between depth and bulk density. This relationship can then be used to derive a value for the effective density of the entire mass of material.

Definition of the problem arose out of the need to characterize the bulk density of compost at various processing stages. The objective was to develop a method of characterizing bulk density that was cheap, simple, precise, and accurate. Preliminary work to establish a workable method was carried out by Guenther (1995) and the objective of the work described here was to test and validate the method with different materials.

MATERIALS AND METHODS

The basic apparatus required was a container for the material, a set of weights with which to apply vertical loads, and a platform scale. In order to minimize friction against the sides of the container which would prevent the compression of the material, a large cylindrical steel container, approximately 500 mm in diameter and with a height of 750 mm, was used.

The test materials included compost, peat, wet peat, wood shavings, and straw. The materials were mixed and stored in containers to ensure that there was enough material for at least two triplicate runs. Quantities were in the range of 0.06 to 0.60 m^3.

Bulk density measurements were conducted at the University of Alberta's Edmonton Research Station over a period of two years. The same source of straw, wood shavings and peat were used in both years but, due to limited availability, different composts were used each year. The moisture content of these materials was taken at the beginning, middle, and end of each run. Chapter 2 discusses the procedure; for composition of the materials is Table 2-1.

Containers were weighed and a fill line was marked on the inside, 500 mm from the bottom. Tape was applied along the mark to make it easier to identify when the material reached the line. The containers were filled with water to these marks and weighed. Assuming the density of water to be 1000 kg/m^3, the volume of the container to the fill mark (V_{500}) was determined. This step was necessary because the steel containers were not perfectly cylindrical and had corrugated sides and bottoms.

The material for which the bulk density was to be measured was placed in the container to a level exceeding the mark and shaken manually to ensure the material settled. Material above the mark was removed, then the container was weighed and the bulk density (D) of the material was determined according to:

$$\begin{aligned} D &= \left(M_t - M_c\right)/V_h \quad \text{kg/m}^3 \\ &= M_m/V_h \quad \text{kg/m}^3 \end{aligned} \tag{3.1}$$

where: M_t = Total mass of the material and container,
M_c = Mass of the container,
M_m = Mass of material, and
V_h = Volume to fill line.

This represents the bulk density in the top 500 mm of a pile. The next step was to determine the bulk density in the next 500 mm layer. To do this, a load equivalent to M_m was applied to the material in the container by placing known masses on top of the material. To ensure uniform loading, the masses were placed on a plywood disk with a diameter slightly less than the container. This loading compressed the material and was applied for long enough so that the material could consolidate to a constant volume. The time required varied for different materials but was in the order of one hour.

To record the depth of compression, a straight edge was placed across the top of the cylinder and a tape measure was used to determine the distance from this to the underside of the loading disk at three equally spaced locations around the circumference. These compression values were averaged and, to calculate the depth of material in the container after one hour, the average value was subtracted from the 500 mm (fill mark).

The loading system was then removed and more material was added. To estimate how much material should be added for the subsequent layer the average depth of compression was divided by the depth of material in the container with a load applied. For example, if the final depth of compression was 40 mm, then the depth of the material in the container would be 460 mm and the estimated amount of material to be added would be 8.7% (40/460 x 100) of the initial mass. After adding the material, the previous load was reapplied to consolidate the newly-added material. The level of material was then checked to see if it was at the fill mark. Adjustments were made as required by adding or subtracting material until the level was at the mark. The added mass plus the previous mass of material represented the final mass of the second layer.

The bulk density (D_2) of this material, representing the second 500 mm-thick layer in a pile, was then calculated using Equation 3.2:

$$D_2 = \left[M_t - \left(M_c + M_{m1}\right)\right] / V_h \qquad \text{kg/m}^3 \qquad (3.2)$$

where:

M_t = Total mass of container, load and material, and
M_{m1} = Mass of material in layer #1
= Mass of applied load.

The above procedure could be repeated for any number of layers. In general, the bulk density (D_n) of the nth layer is given by:

$$D_n = \left[M_T - \left(M_c + \Sigma_{i=0}^{n-1} M_{mi}\right)\right] / V_h \qquad \text{kg/m}^3 \qquad (3.3)$$

The above procedure was repeated, layer by layer, to simulated depths of 3.5 m (i.e. seven layers) and resulted in a set of bulk density determinations corresponding to successive 500 mm layers of material. These were plotted against depth and a least-squares regression routine was used to fit curves to the plotted points.

Once a bulk density versus depth curve had been obtained, an effective density (D_{eff}) value could be defined as the bulk density which, if constant with depth (z), would give the same area under a bulk density-depth curve as the experimental values. Effective density can be thought of as the mass of a column of material with unit cross-sectional area and height z. This is expressed mathematically in Equation 3.4 as follows:

$$D_{eff} = \frac{1}{z} \int_0^z D \, dz \qquad \text{kg/m}^3 \qquad (3.4)$$

The data obtained were tested statistically using Analysis of Variance routines from SAS (1994) to ensure that there was no significant difference in material or measurement techniques from year to year. The data are expressed on a wet bulk density basis, defined as the wet mass (solid plus water) per unit volume.

RESULTS

The general form of the compression curves was similar for all the materials. Two typical curves are shown in Figure 3-1. The figures showing the curves for the remaining test materials are shown in Appendix B.

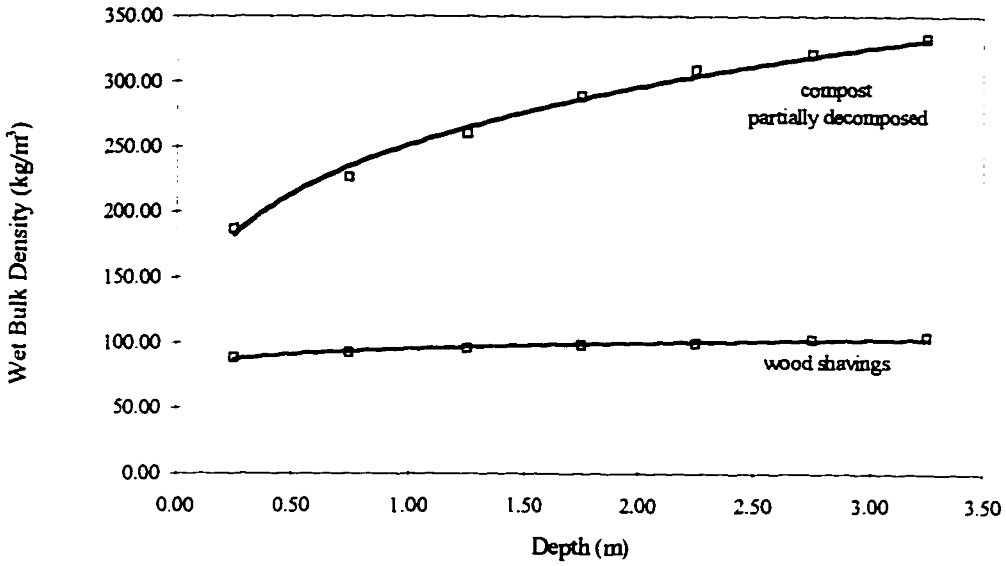

Figure 3-1. Power function curves for wood shavings and partially decomposed compost. This figure shows the wet bulk densities for each layer plotted at the midpoint of the layer. The data points are the averages of three samples for compost and six samples for wood shavings. These curves were selected to illustrate the difference between compressible and non-compressible materials. In this case, partially decomposed compost was the most compressible material; the least compressible of the seven materials tested was wood shavings. The straw curve resembled the wood shavings while the remainder of the materials had slopes that fall somewhere between these two curves.

In fitting curves to the data, the best-fit was obtained in all cases by a second order polynomial. However, because this would imply a decrease in density at large depths, it was rejected in favor of a simple power function which gave the next best-fit. The selected best-fit equation was of the form:

$$D = Az^{B} \tag{3.5}$$

where D represents bulk density, z represent depth, and A and B are constants that depend on the material. The regression equations and moisture content for all the materials are given in Table 3-1 together with R^2 and effective density values calculated according to Equation 3.4 and integrating between depths of zero and 3.5m. The R^2 values from fitting equations to the bulk density values for the container ranged from of 0.93 to 0.98. The lowest value was for wood shavings and peat at the intermediate moisture content.

Table 3-1. Mean moisture contents, power function equations, R^2 values and wet effective density values.

Material	M.C. % (w.b)	Equation	R^2	Effective Density kg/m^3
Wood shavings	8.9	$D = 106.50\, z^{0.075}$	0.93	108.87
Straw	12.3	$D = 61.81\, z^{0.184}$	0.96	65.73
Peat - dry	53.4	$D = 245.54\, z^{0.140}$	0.97	256.70
Peat - interm.	57.2	$D = 235.16\, z^{0.124}$	0.94	244.44
Peat - wet	77.1	$D = 464.65\, z^{0.180}$	0.98	493.51
Compost - I	47.4	$D = 495.17\, z^{0.103}$	0.96	510.85
Compost - PD	62.6	$D = 254.63\, z^{0.25}$	0.98	278.89

Comparison of the effective density values showed no significant difference ($\alpha = 0.05$; $P=0.056$) between years. In addition, the interaction between the year and material was not significant with a $P= 0.115$. The standard deviations for the effective density and the equations are shown in Appendix A, Table A-2. The standard deviations for the moisture content are shown in Table 2-2. Therefore, the results from the two years were pooled for straw and wood shavings. The pooled analysis excluded compost since different compost was tested in each trial and this created more variation than years. The experiment was analyzed as a completely randomized design.

DISCUSSION

The method of bulk density characterization presented above was conceptually simple and did not require any expensive or particularly sophisticated equipment. The two separate trials using the large steel container were not significantly different.

The use of regression equations to describe the behavior or properties of materials must be tempered by the need for the equations to have physical meaning and relevance. Thus, although second (and higher) order polynomials would have provided a better fit to the data, they would not accurately represent the behavior of the materials outside the range of depths that were used in the tests described. In contrast, the power function was consistent with generally expected behavior. In addition, the coefficients and exponents in the power function equations can be interpreted to have some physical meaning.

As can be seen from the equations in Table 3-1 the coefficients provide an indication of the order of magnitude for the effective bulk density of the material. The exponents, on the other hand, give an indication of the compressibility of the materials. The larger the exponent, the greater the compressibility. A completely incompressible material whose bulk density was constant with depth would have an exponent of zero. Examination of the equations in Table 3-1 show that wood shavings was the least compressible and had the smallest exponent of 0.075, while partially decomposed compost was the most compressible material and had the largest exponent of 0.25.

The values of effective density shown in Table 3-1 are very close to the coefficients in the power function equations and are in general agreement with bulk density values for compost (Leonard and Ramer, 1993), straw (Rynk, 1992), and peat (Wilson, 1983) found in the literature. However, published values do not take account of compression effects and comparisons must take into account the different moisture contents for the various materials. In the work reported here, the moisture contents varied between the two years and even within the replicates of the same material. If, on the other hand, the moisture content could have been controlled more closely for replicates of the same material, the R^2 values may have been even higher.

There were differences in the exponents and the coefficients between trials. However, an overall comparison of the equations indicates similar trends for compressible and non-compressible materials. Values for homogenous materials like peat and wood shavings generally varied less than those for compost. Compost variability was a result of many uncontrollable factors. These include the length of compost maturity time after thermal decomposition, the amount of material handling prior to testing, the composting method (windrow or in-vessel), and the quantities and types of materials that were used in the compost recipes.

Although power function equations, as described above, provide a convenient description of the bulk density of compressible materials, practicality demands a single number to characterize this property. Effective density is proposed as this number on the grounds that it is more representative and, potentially, of greater practical significance than a simple average of a number of measurements. By definition, determination of effective density requires measurements of bulk densities at a range of compressions and, the larger the range, the better will be the estimate of effective density. This encourages a complete characterization of the behavior of the material rather than simply taking a few measurements at the surface or at low levels of compression which are not representative of most of the bulk.

The formula for effective density (Equation 3.4) is based on the area under the density-depth curve. This area has units of kg/m^2 which, multiplied by gravity, are easily converted to N/m^2. This is an indicator of the vertical load exerted by a pile of material with a height corresponding to the integration interval in Equation 3.4. The values is then divided by the depth to give units of kg/m^3. Similarly, the total mass of material in a pile can be calculated easily using effective density directly without the need to make further allowances for variation of density with depth.

CONCLUSIONS

The bulk density measurement method described, based on simulating the compression of materials due to self-loading, provides a simple, low-cost, and repeatable method for characterizing the bulk density of compressible materials.

Tests on five different materials indicated that the relationship between bulk density and depth within a pile of material was given by a power function equation.

In the power function equation, the exponent provides an indication of the compressibility of a material. Incompressible materials have an exponent of zero and the exponent increases with compressibility.

Effective density was based on an equation that accounted for the area under a density-depth curve and provides a useful single-number measure of bulk density. The reproducibility of this method is supported by the high R^2 values 0.93 to 0.98 and the similar values between the effective density and the coefficient in the power function equation.

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CHAPTER 4

DETERMINING A CONTAINER SIZE THAT IS PRACTICAL FOR BULK DENSITY MEASUREMENT METHODS

INTRODUCTION

The distribution of individual particles within bulk materials is influenced by a number of parameters including moisture content, particle-size, particle density, and the quantity of material being stored. These parameters provide useful indicators of how the bulk density of materials will vary under conditions like compaction. Furthermore, understanding how a material behaves provides the framework for designing optimum storage structures to contain large quantities of material.

Stockpiling and enclosing materials is useful for preserving the quality or specific conditions within materials. For example, in grain and oil seed crops, storage in silos ensures a safe and high quality material. For composting, to sustain microbial populations, the bulk material must be stored in quantities which are large enough to permit heat, water, and oxygen exchange. However, at the same time, the quantities cannot be too large or porosity and free air space will be reduced.

Chapter 3 describes the development of a test method that accounted for the change in bulk density with increased depth for compressible materials. The method was tested using a large metal container. However, this size of container was too large for practical bulk density measurements in the field or when heavier materials were tested. The amount of material that was required was substantial for each run, and was heavy in these large quantities and as the moisture content increased. Besides, as the depth increased, balancing the weights became difficult and the loading method became increasingly time consuming because heavier weights were required to represent a load exerted on the material at that depth. The loading would not be a factor if a hydraulic loading press could be designed. For these reasons, different container sizes were designed.

In designing the smaller containers, the smallest practical size was unknown However, the container had to be large enough so that when a load was applied to the material, the friction against the sides of the container would not prevent the compression of the material. As the bulk density of the material increases due to compression, the wall of the container will exert a resisting frictional force on the material which may not compact to the same extent as with a larger container. This could result in underestimating the bulk density for that test material. Therefore, the objective was to design smaller containers that would minimize the friction effects created by the wall of the container but still be convenient and practical.

The main factors that would restrict this compression would be coefficient of friction (ASAE 1995, Manbeck 1988). The coefficient of friction is a value that characterizes the opposing frictional forces between two materials moving in contact with each other (Stroshine and Hamann 1994). In this application, the value is dependent on the type of material the container wall is made from and the type of material stored inside the container. As well, the moisture content and particle-size of the material in the container affects the coefficient of friction.

METHODS AND MATERIALS

The bulk density method was tested initially with cylindrical steel containers each with a fill mark and diameter of 500 mm and denoted as large. To make the bulk density measurement method more practical, two containers with smaller dimensions were designed to reduce the amount of materials need for each measurement. The smallest container, denoted small, was approximately half the dimensions of that for the large container. In order to have geometrically similar containers, the third container, denoted medium, was designed to have diameters and fill marks between these two sizes.

Steel cylinders with the smaller dimensions were not available or could not be made easily and, therefore, cylinders made from other materials were selected. The medium container was made from cylindrical cardboard concrete forms that had a smooth plastic finish on the inside. The wall thickness was approximately 6 mm, the diameter approximately 400 mm and the fill mark was 380 mm from the bottom. The small containers were made from schedule 40 polyvinylchloride pipe with an approximate diameter of 300 mm and the fill mark was 250 mm from the bottom. The bulk density measurements for each of the three containers were conducted for wood shavings, straw, compost, and peat at three different moisture levels. The description of these test materials are in Table 2-1. The materials listed in this table were the same ones used for these bulk density measurement experiments except for the compost because a source of partially decomposed compost made with the same feedstock materials and at the same decomposition stage was not available. Therefore, in-vessel compost was used in the experiments.

The procedure to calculate the bulk density was the same as that described in Chapter 3. Equations 3.1 through 3.5 were applied to these data, except that V_h would correspond to the respective fill marks for a particular container. Seven loads was applied and the data were plotted and represented by a power function equation ($D=Az^B$). The 'A' indicates the order of magnitude of the bulk density of the material and 'B' indicates the compressibility of the material.

The effective densities (equation 3.4) were determined for all the test materials at each container size and were tested statistically using Analysis of Variance routines from SAS (1994). Densities were expressed both on a wet basis (mass of solid matter plus water per unit volume) and a dry basis (mass of solid per unit volume). Moisture contents of the materials were expressed on a wet basis defined as the ratio of total water content of the mixture to its total mass (solid matter plus water).

RESULTS

Table 4-1 shows wet and dry effective density and their moisture contents for all materials and their containers. The method for determining moisture content and their standard deviations was discussed in Chapter 2. The general trend for the materials, expressed on a wet or dry basis, was a decrease in effective density when smaller container sizes were used. Analysis of the effective densities on a wet basis (wet effective density) showed no significant difference ($\alpha = 0.05$) between peat measured using the large and medium containers at the intermediate moisture level, peat measured using the small and medium containers at the wet moisture level, and the straw measured using the medium and small containers. To reduce the number of wet effective densities that were significantly different, analysis of the effective densities was repeated using a dry basis (dry effective densities) so that there was no variation due to moisture content.

Analysis of variance for the dry effective densities showed no significant difference between the use of different container sizes for two test materials, Table 4-1. The dry effective densities of straw measured with the small container were not significantly different ($P = 0.1084$) to those measured with the medium container. Similarly, for the peat at the various moisture levels, 11 of the 12 combinations measuring dry effective density using different container sizes were not significantly different. Dry effective densities of peat at the wet moisture level measured with the medium container were significantly different ($P = 0.0264$) when compared to peat at the dry moisture level measured in the small container. Comparisons between and within the remaining materials and containers, expressed on a dry basis, were significantly different ($P=0.0001$).

Effective density was determined for materials measured in the medium and small container size using triplicate samples. The effective densities using large containers were determined as discussed in Chapter 3. These results have been brought forward.

Table 4-1. **Mean effective densities and moisture contents for the test materials.**

	Effective density (w.b.) kg/m^3			Effective Density (d.b.) kg/m^3			Moisture Content % (w.b.)		
Material	Large	Medium	Small	Large	Medium	Small	Large	Medium	Small
Compost	510.85	465.22	415.09	269.05	253.35	227.19	47.4	47.0	46.3
Peat - dry	256.70	182.72	163.04	119.62	90.34	81.08	53.4	52.1	52.5
Peat -interm.	244.44	227.51	199.96	102.37	96.13	84.19	57.2	59.0	59.0
Peat - wet	493.51	329.40	335.97	113.18	88.86	85.35	77.1	74.1	75.5
Wood shavings	108.83	98.18	83.73	99.15	90.66	75.70	8.9	9.1	9.6
Straw	65.73	47.79	42.80	57.65	43.20	38.39	12.3	12.7	12.8

The general slope of the power function curves was similar for all materials as shown in Figure 3-1 and 4-1. These figures show the dry bulk densities for each layer plotted at the midpoint of the layer. Figure 4-1 shows the decrease in dry bulk density with the use of smaller container size. The order of the curves for container size correspond to those of the in-vessel compost for all materials, except peat at the wet moisture level. As seen in Figure 4-1, the curve for peat measured in the smaller container is slightly above the curve for the medium container, but this was not significantly different.

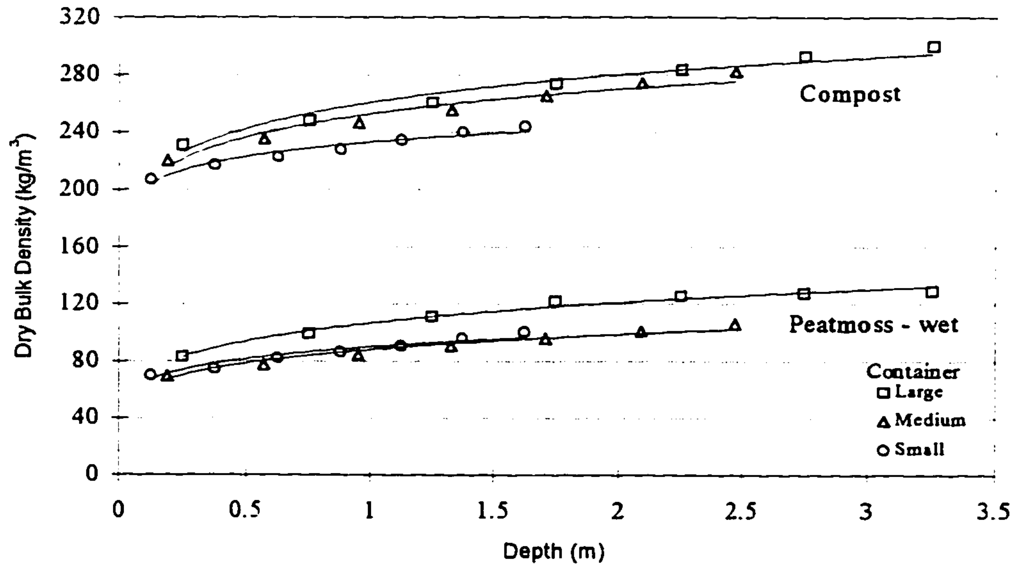

Figure 4-1. Power function curves for different size containers.

The tests conducted on materials in the different containers showed similar compressibility (B in equation $D=Az^B$) trends to that of materials in the large container as shown in Table 4-2. That is, in general, materials with greater compressibility in the large container also had greater compressibility in the smaller containers.

Table 4-2. Mean power function equations showing dry bulk density and compressibility values for materials in three containers.

	Container Size		
Material	Large	Medium	Small
Compost -I	$D = 260.79\ z^{0.103}$	$D = 252.79\ z^{0.095}$	$D = 233.10\ z^{0.063}$
Peat - dry	$D = 114.42\ z^{0.140}$	$D = 89.98\ z^{0.119}$	$D = 84.36\ z^{0.101}$
Peat -interm.	$D = 98.51\ z^{0.124}$	$D = 95.82\ z^{0.109}$	$D = 87.52\ z^{0.098}$
Peat - wet	$D = 106.55\ z^{0.181}$	$D = 88.10\ z^{0.163}$	$D = 90.00\ z^{0.141}$
Wood shavings	$D = 97.03\ z^{0.075}$	$D = 90.64\ z^{0.053}$	$D = 78.19\ z^{0.045}$
Straw	$D = 54.20\ z^{0.184}$	$D = 42.98\ z^{0.130}$	$D = 39.94\ z^{0.160}$

Compressibility values decreased with smaller container size. The compost compressibility values were significantly different between the small container and medium container usage ($P=0.0217$) and the small container and large container usage ($P=0.0066$). The wet moisture level peat and the dry moisture level peat compressibility values showed a significant difference for the small container and large container usage ($P=0.0084$ and $P=0.0079$, respectively). The intermediate moisture level peat compressibility values were not significantly different among the containers. The straw compressibility values were significantly different when the small container was used compared to when the medium container was used ($P=0.0001$), when the small container was used compared to when the large container was used ($P=0.0001$), and when the large container was used compared to when the medium container was used ($P=0.0221$). The wood shavings compressibility values were significantly different between the small and the large container ($P=0.0051$).

The R^2 values from fitting equations to the bulk density values for the three different size container usage trials range from 0.93 to 0.98. Using the small container, R^2 values range from 0.94 to 0.97; using the medium container, R^2 values range from 0.95 to 0.98. Both containers when used, produced the lowest values for straw and wood shavings. R^2 values produced when the large container is used are shown in Table 3-1.

DISCUSSION

The minimum container size that could be used for the experiment was governed by the maximum particle-size. Therefore, the container dimensions needed to be large enough so that, when the load was applied, the friction against the sides of the container would not prevent the compression of the material. The tests conducted using the smaller containers show similar compressibility trends to that of the large container. In the three cases, the R^2 values were high (0.93 to 0.98) which further supported the repeatability of this method.

As can be seen from the equations in Table 4-2, the coefficients provide an indication of the order of magnitude of the bulk density of the material. These are very close to the dry effective density which is based on the area under the density-depth curve (equation 3.4). This value is the proposed bulk density as it is more representative and has greater practical significance than a simple average of a number of measurements. The exponents, on the other hand, give an indication of the compressibility of the materials. The large container test described in Chapter 3, showed wood shavings to be the least compressible and partially decomposed compost to be the most compressible material tested. However, because partially decomposed compost was not available during tests using the smaller containers, the next most compressible materials were straw and peat at the wet moisture level, as shown in Table 4-2. The straw and the peat had maximum exponents of 0.180 and 0.181, respectively.

These general conclusions were also evident in the smaller container trials, but the magnitude of the difference in compressibility was less noticeable. Using the small container, the most incompressible material was wood shavings with an exponent of 0.045, but the most compressible material was wet peat with an exponent of 0.141. The trial using the medium container had the same ranking for compressibility with an exponent of 0.053 for wood shavings and 0.163 for wet peat.

Figure 4-1 shows that the peat bulk density curve, at the wet moisture level, for the small container was slightly above the bulk density curve for the medium container. However, there was no significant difference between measured bulk densities and compressibility for the medium and the small container. The wet peat compressibility value in the large container was significantly greater compared to the values from the small container. The significance was likely a result of the wetter and heavier mass of material compressing the peat in the large container. The relationship between bulk density and moisture content will be discussed in Chapter 5.

The bulk densities measured with the smaller containers were lower than those measured with the large container. This difference was significant for most of the test materials. The differences in bulk density and compressibility were likely a result of increased friction due to the smaller container diameter and the influence of particle-size. However, trials with the smaller container were more practical especially for the heavier materials, like wet peat and compost, because the mass required to simulate the final depths was more manageable. Therefore, to account for any difference and to better represent the behaviour of the materials, a correction factor may need to be developed.

Particle-size restricts the diameter of a container that can be used for bulk density measurements. This is likely the case for straw because this was the only material where compressibility decreased with smaller container size compared to wood shavings. Studies for straw have found that bulk density decreases with increasing length and that the orientation of straw greater than 200 mm was predominantly horizontal. However, straw lengths less than 200 mm were oriented in a three-dimensional manner (O'Dogherty and Gilbertson 1988). Therefore, the straw is likely oriented in the containers three-dimensionally because the particle size was approximately 9 mm as shown in Table 2-4. However, this orientation is less likely as the diameter of the container decreases because the container would then restrict the movement of straw. Consequently, the straw may revert back to its horizontal orientation. This may explain why the smaller container appeared to have less straw along the sides of the container during bulk density measurements. In conclusion, this suggests that the large container is more suitable for testing straw at this length. This is further supported by the no significant difference (P=0.1084) in bulk density found between medium and small container usage.

The containers for this experiment had surfaces of galvanized sheet metal (large), smooth plastic (medium), and polyethylene (small). For a particular type of test material the coefficient of friction value will differ for each container surface. In addition, the coefficient of friction value changes depending on the particle-size and the moisture content for a test material. As well, it is assumed that as the diameter of a container gets larger, these coefficient of friction values have less influence on the compressibility and the bulk density.

Coefficient of friction values for galvanized sheet metal and polyethylene surfaces have been determined for various types of materials (chopped alfalfa, fish meal, straw, barley, oats) (Manbeck 1988; Stroshine and Hamann 1994). In the tests with these materials, generally a larger coefficient value was noted for the polyethylene surface compared to the sheet metal surface. This means polyethylene surfaces would give greater resistance to compression, however, the moisture content and particle size will influence the coefficient of friction value. Therefore, it would be of interest to carry out coefficient of friction tests for each surface type with changing container size and then see how these factors affect the compressibility and bulk density. My research was unable to answer this question because different materials were used for the three container sizes and comparing compressibility or bulk density values to coefficient of friction values for container type would not be meaningful. Therefore, until similar materials can be found for the containers testing this theory with the present materials will not be pursued.

Besides contending with the friction created by the walls of the container, particles coated with organic material also exert friction (Sharifat and Kushwaha 1996). Therefore, the peat and compost would likely have more friction between particles than would the wood shavings and the straw, as they exhibit more soil-like properties. Consequently, the compressibility could be affected by both the container wall friction and the organic coating on particles.

CONCLUSIONS

The data collected from using the three container sizes were fitted to a power function equation. The coefficient provided an indication of the order of magnitude of the bulk density of the material and the exponent indicated the compressibility of the material. The general conclusions noted from the large container experiment in Chapter 3 were also evident in the smaller container trials, but the magnitude of the difference in compressibility was less noticeable. In the three cases, the R^2 values were high (0.93 to 0.98) which further supported the repeatability of this method.

The bulk densities measured with the smaller containers were generally lower than that of the large container. This difference was significant for most of the test materials. The differences in bulk density and compressibility were likely a result of increased friction due to the smaller container diameter and the influence of particle-size. However, trials with the smaller container were more practical especially for the heavier materials, like wet peat and compost, because the mass required to simulate the final depths was more manageable. Therefore, to account for any difference and to better represent the behaviour of the materials, a correction factor may need to be developed.

The amount of material used, the weight required to simulate a load, and the manual energy exerted for the bulk density measurement method decreased as smaller container sizes were used. Besides, shaking the containers for one minute to ensure the materials settled was easier in the smaller containers. it was easier to shake the smaller containers for one minute to ensure the material settled. Since the test materials used in the bulk density experiments ranged in particle-size the medium sized container was found to be the best size to handle the limitations previously mentioned.

It would be of interest to conduct further research on the coefficient of friction values for each surface type with changing container size and then see how these factors affect the compressibility and bulk density. This research was unable to answer this question because the experimental design was not set-up to provide meaningful results. Literature has shown that for a particular type of test material the coefficient of friction value will differ for each surface. Besides. depending on the particle-size and the moisture content for a test material the coefficient of friction value would change. Therefore, these properties would be important to include in reports carrying out coefficient of friction tests.

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CHAPTER 5

BULK DENSITIES AT VARIOUS MOISTURE CONTENTS

INTRODUCTION

The structure, bulk density, moisture content, porosity, and water-holding capacity for materials are influenced by a material's physical and chemical properties (Dick and McCoy 1993; Leonard and Ramer 1993; Nakaski et al. 1987). The interactions of these properties within materials are extensive and often changing one affects another in some capacity. One such property that has this influence is moisture content.

Moisture content is measured because water alters many physical properties within materials. For example, a soil at 1.3 bar water potential will compress more than a dry soil, and more than a saturated soil (Felt 1965; Marshall and Holmes 1979). Further, as compression increases, air and water are expelled and the aggregates get closer. Eventually, a load that is applied to the materials is supported by the water in the pore spaces and less by the surface area of the particles. Materials with high moisture contents under these compressive loads will have decreased porosity because water can be released from the material into the pore spaces, reducing the free air space (Leonard and Ramer 1993; Schultz 1962; Wilson 1983). In composting, decreased free air space would be undesirable because the composting process would become anaerobic (Miller 1993). Further discussion can be found in Chapters 1 and 2 which describe how the amount of free air space is dependent on the type of material and the size and shape of individual particles.

The relationship between moisture content due to increased compaction has been studied through soil matrices (Ekwue and Stone 1995; Lambe 1951; Morgan et al. 1993; Sharifat and Kushwaha 1996). These studies determined the moisture content of the soil and then the soils' susceptibility to pressures like agriculture equipment and farm animals. These pressures affect the soil aggregate orientation and can result in soil structural damage. This damage could cause a decrease in soil water-holding capacity and increased bulk density and strength. These conditions are not favorable for plant growth and water infiltration (Sharifat and Kushwaha 1996).

The bulk density measurement method was tested with materials at different moisture contents to see if and how moisture content influenced the bulk density curves described in Chapters 3 and 4. Understanding this relationship would be beneficial as it may provide further information to optimize conditions needed for composting and material storage and handling. The bulk density measurement was tested on peat and compost.

METHODS AND MATERIALS

The test materials selected for this study were peat and compost as they were readily available and had similar particle-size (Chapter 2). These materials were also used rather than straw and wood shavings because their moisture contents could be determined more easily.

Previously determined bulk density measurements and moisture contents for peat (Chapter 4) established the three moisture levels for this study as shown in (Table 5-1). The moisture contents from these measurements were recorded as wet, intermediate, and dry. The maximum moisture content that was practical for compost bulk density measurements was 47% because higher moisture contents would make the manual loading method extremely difficult. Therefore, the wet moisture level was applied to the compost at the 47% moisture content.

Table 5-1. Mean moisture contents for compost and peat at three moisture levels.

	moisture content (% w.b.)		
moisture level	dry	intermediate	wet
compost	24	32	47
peat	52	59	74

The moisture contents for the compost at the dry and intermediate levels were determined by following the peat example; approximately 15% less from wet to intermediate and approximately 8%

from intermediate to dry. The mean compost and peat moisture contents were each determined from triplicate samples.

The testing of the bulk density measurement method using different sized containers was discussed in Chapter 4 and identified the medium container as the most practical for use in the moisture content study. The dimensions of the cardboard medium container were described in the Methods and Materials section in Chapter 4. The procedure for the bulk density measurement method and equations 3.1 to 3.5 were discussed in the Method and Materials section in Chapter 3. A total of seven loads were applied for each moisture content of each material and the data were plotted and represented by a power function equation ($D=Az^B$). The 'A' indicates the order of magnitude of the bulk density of the material and 'B' indicates the compressibility of the material.

The effective densities and the compressibility determined for each material were tested for significant differences between each moisture level using Analysis of Variance routines (SAS 1994). Densities were expressed both on a wet basis (mass of solid matter plus water per unit volume) and a dry basis (mass of solid per unit volume). Moisture contents of the materials were expressed on a wet basis defined as the ratio of total water content of the mixture to its total mass (solid matter plus water).

RESULTS

Mean moisture content, effective density and compressibility were calculated and their standard deviations are shown in Table 5-2.

Table 5-2. Mean moisture content, compressibility, wet and dry effective density and standard deviations for compost and peat.

Material	M.C. (% w.b.)	Effective Density (kg/m^3) Wet basis	Effective Density (kg/m^3) Dry basis	Compressibility
Compost - I - dry	24.1 ± 0.61	333.46 ± 5.42	139.21 ± 2.23	0.070 ± 0.00
Compost - I -interm.	32.0 ± 0.87	397.80 ± 3.03	165.96 ± 1.12	0.067 ± 0.00
Compost - I - wet	47.0 ± 0.57	465.22 ± 5.94	253.35 ± 2.13	0.095 ± 0.01
Peat - dry	52.1 ± 1.09	182.72 ± 2.27	90.34 ± 0.46	0.119 ± 0.01
Peat - interm.	59.0 ± 0.23	227.51 ± 1.38	96.13 ± 1.15	0.109 ± 0.00
Peat - wet	74.2 ± 0.63	329.40 ± 4.66	88.86 ± 1.42	0.163 ± 0.00

The R^2 values from fitting equations to the dry bulk density values for the compost and the peat container range from 0.97 to 0.99. The dry effective densities for peat showed no significant difference (α=0.05) between the dry and intermediate (P=0.0946) and dry and wet (P = 0.6654) moisture levels. But, the dry effective densities for the peat intermediate and wet moisture levels were significantly different (P = 0.0373). As well, the effective density value for the peat at the wet moisture level was smaller than the effective density values for the intermediate and dry moisture levels. Expressing the effective densities on a wet basis resulted in the material's bulk density increasing with moisture content and the effective density for peat was significantly different (P=0.0001) between the three moisture levels. On the other hand, the effective densities for compost (expressed on a dry and wet basis) were significantly different between the three moisture levels (P=0.0001) and increased with moisture content.

The most compressible material for peat was at the wet moisture level and the least compressible material was at the intermediate moisture level, as shown in Table 5-2. However, the compressibility values between the intermediate and the dry moisture levels were not significantly different (P=0.4893). On the other hand, compost was the most compressible at the wet moisture level and least compressible at the dry moisture level. The compressibility values among the moisture contents were significantly different.

Results are presented with effective densities expressed on a wet and dry basis. However, effective densities were significantly different among the moisture levels so to remove the variation due to moisture analysis was conducted on a dry basis. But, in the design of storage structures and material handling systems the wet basis of materials would be more meaningful as this reflects the material that is being processed.

DISCUSSION

The load required to simulate the depth of material during the bulk density measurements was manageable for the heavier and wetter materials in the medium container. The fit of the data to the power function equations was good, as indicated by the high R^2 values which ranged from 0.97 to 0.99. The method of manual loading was feasible but balancing a load became more difficult as bulk density measurements approached the final three layers. Therefore, before further bulk density measurement tests are conducted, a hydraulic loading press should be developed. The press would not only save time and physical energy, but would also reduce bulk density variations among trials.

Particle-size is important to characterize as this is just one property that affects the bulk density and the water-holding capacity for materials (Das and Keener 1995; Raviv 1987). Since there has been limited research on compost physical properties and their relationships, trends from soil studies have been the best source of comparative data to discuss the results from the bulk density measurement method for compost and peat. However, when water is added to soil, the structure of the particle is different than the structure of compost, peat, and the other test materials used for the bulk density measurements. Therefore, caution must be applied to the interpretation of the results when comparing the behaviour of soils to the test materials. Furthermore, the particle-size distinction discussed in

Chapter 2 was used to label the peat as a fine-textured material and the compost as a coarse-textured material. This labeling will help to extrapolate soil trends that discuss differences between fine and coarse textured materials at different moisture contents.

The peat bulk densities (expressed on a wet and dry basis) were lower than the compost wet bulk densities even when the peat moisture contents exceeded 70%. This was likely a result of the material's fine-texture which typically has a greater water-holding capacity than coarse-textured soils because the percentage of the total volume occupied by pore space is greater (Baver et al. 1972; Chow et al. 1991; Sharifat and Kushwaha 1996). Furthermore, the peat pore spaces under the increased loads were likely filled with water and air, both of which have a lower density than do the solid particles (Felt 1965).

Another possible reason for the lower peat effective densities could be the high (92.9%) amount of organic matter. Sharifat and Kushwaha (1996) determined that as the percentage of organic matter in a soil approaches 100%, the buoyancy effects that occur result in low bulk densities. This may be another reason why the effective densities for compost were greater because compost had organic matter contents of less than 60% which means greater mineral contents. The organic matter contents of peat and compost are shown in Table 2-2.

The relationship between particle-size, free air space and moisture content may explain why the dry effective density for peat at the wet moisture was lower than the dry effective density at the dry moisture level. In extremely wet and fine particle-sized materials, compression is resisted because a load is supported by the water which fills the pore spaces (Marshall and Holmes 1979). This is in contrast to drier materials where the aggregates flatten and the increase in surface area and particle contact reduces the compressive stress.

For peat there were no significant differences between the compressibility values for the intermediate and the dry moisture levels. This was likely due to the relatively close moisture range (approximately 7%) between the two levels. However, peat at the intermediate moisture level had smaller compressibility values than at the dry moisture level. This was probably because when water is added to materials the particles tend to swell. This swelling increases the friction on the sides of a container confining the material. The friction on the container sides supports some of the vertical load and this results in reduced amounts of compression (Marshall and Holmes 1979).

The compressibility values for the test materials were the largest for materials at the highest moisture content because the compressibility value portrays the total mass (solid and water) in the material (Table 5-2). The higher moisture contents increase the mass of the material resulting in an increase in bulk density when expressed on a wet basis. Consequently, compressibility values increase because the mass of material would be heavy enough to compress the aggregates and pores. Therefore, if the compost moisture content could have been raised to that of the peat moisture contents the compost compressibility values would have likely exceeded the peat compressibility values. The compressibility were approaching this trend because the dry peat (52% m.c.) had a compressibility value of 0.119 and wet compost (47% m.c.) had a compressibility value of 0.095. This is likely the reason why the compost compressibility values were significantly different among the moisture levels.

Generally, the compost standard deviations were greater than those of the peat standard deviations (Table 5-2). This difference was likely due to the compost particle-size, greater mineral matter content, and the relatively heterogeneous make-up. The standard deviations for peat were smaller which likely reflects the homogeneous and fine particle-size consistency.

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CHAPTER 6

SYNOPSIS

Physical characteristics are useful for describing the bulk properties of mixtures and individual components. Considerable attention has been given to bulk density, porosity, and free air space. However, many of these aforementioned properties change when materials are piled at some depth and understanding how these properties, and others, like moisture content, organic matter, particle density, and particle-size interact is important for the preservation and processing of many materials and the design of storage structures and materials-handling systems.

The main focus of this research was to validate a bulk density measurement method because, as mentioned above, bulk density is important for materials-handling systems and storage structures. Furthermore, when compost and feedstock materials are stored in bulk, the property of bulk density is less easily measured and predicted compared to more rigid-solid materials. Therefore, the method accounted for the compressibility of materials and the density change in a pile due to the mass of material above it. Since the method has the potential to be applied to a wide range of materials, the method was tested with various types of compost, peat (at different moisture contents), wood shavings, and straw.

The bulk density measurement method presented in this thesis was conceptually simple and did not require any expensive or particularly sophisticated equipment. The method described was based on simulating the compression of materials through a procedure of self-loading which provided a low-cost and repeatable method for characterizing the bulk density of compressible materials. Further, the validations of the method in the two separate trials (conducted by two different researchers) were not significantly different for the test materials and the R^2 values were high: 0.93 to 0.99. These results supported use of the method for measuring the bulk density of compressible materials and, therefore, allowed two other aspects to be investigated. The first of these was the identification of a container that was large enough so that when a load was applied to the materials, the friction against the sides of the container would not prevent the compression of the materials. The other aspect investigated was the relationship between bulk density and moisture content for compost and peat. Before the conclusions of these investigations are discussed, a brief section on the limitations of the methods used to characterize the physical properties, as well as the bulk density measurement method, will be outlined.

LIMITATIONS

Trends from soil studies have been the best source of comparative data to discuss the results from the bulk density measurement method for compost and peat. These sources were consulted because there was limited research on the physical properties of compost (for example particle density, particle-size, and organic matter). However, referencing soil studies implies that the test materials have similar physical and chemical properties and this is not the case for the test materials.

Limited research has been conducted on wood shavings and compost for many of these aforementioned properties. Therefore, procedures for testing moisture content, organic matter content, ash content, particle density, and particle-size were developed from peat and organic soil standards. The limitation for using the procedures from these standards was that the materials were not necessarily similar in physical and chemical properties to the materials for which the standards were developed. Therefore, the procedure may not account for the material's shape, size, or chemical make-up, and this may give results that do not reflect the true nature of the material. This was evident when conducting particle-size analysis on the wood shavings and the compost. The standard particle-size analysis method for soil was used but these materials have spherical particles, unlike the test materials which have elongated particles, and shaking time affected the amount of material left on a sieve. This characteristic has been recognized by the need to have a special method for straw analysis (ASAE 1992).

The lack of appropriate standards for the physical and chemical properties of the compost has been recognized and new procedures that take into account the material's make-up are continually being developed. For example, research by the United States Composting Council[2] has shown that oven temperatures for compost moisture determination should be lower than for soils.

The limitations of the bulk density measurement method were the amount of material used, the weight required to simulate a load, the ease of shaking the containers to ensure the material settled, and the manual energy exerted. However, these limitations decreased as smaller container sizes were used. Nevertheless, before further bulk density measurement tests are conducted, a hydraulic loading press should be developed. The press would not only save time and physical energy, but could also reduce the bulk density variation among trials.

It would be of interest to conduct further research on the coefficient of friction values for each surface type with changing container size and then see how these factors affect the compressibility and bulk density. My research was unable to answer this question because the surface of the containers was made from different materials. Furthermore, for a particular type of test material the coefficient of friction value will differ for each container surface and the value would change depending on the particle-size and the moisture content for a test material. Therefore, these properties would be important to record while doing the friction tests.

Bulk density values for homogenous materials like peat varied less than for heterogeneous materials like compost and typically had smaller standard deviations. Variability in the bulk densities and compressibility values for the compost (in-vessel and partially decomposed) was a result of the length of compost maturity time after thermophilic decomposition, the amount of material handling prior to testing, the composting method (windrow or in-vessel), and the quantities and types of feedstock materials and the incorporation of soil and mineral matter. Therefore, to increase the database and comparative data in this study area, these parameters should be included in reports.

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[2] Sampling procedures and methods stated during the Best Practices Workshop on Composting developed by the United States Composting Council, Alexandria, Virginia.

SUMMARY AND CONCLUSIONS

Prior to any bulk density measurements several physical and chemical properties were measured (Chapter 2). These were necessary to provide a full description of the test materials and allowed for comparisons. The straw and the wood shavings had the lowest moisture contents at approximately 12 % and 9 %, respectively. On the other hand, depending on what aspects were being investigated, compost moisture contents were approximately 62 %, 47%, 32% and 25 % and the peat moisture contents were approximately 77 %, 59 % and 52 %. The organic matter contents were tested for each of the materials and in-vessel compost had the least (59%) and wood shavings the greatest (99%) values of the test materials. The particle-size analysis determined straw to be the most coarse followed by wood shavings, compost, and peat. This distinction was useful when comparing soil properties to compost and peat.

The bulk density of the test materials was represented by a power function equation of the form $D=Az^B$, rather than a polynomial, because the coefficient (A) and exponent (B) could be interpreted to have some physical meaning (Chapter 3). The coefficient indicated the order of magnitude of the bulk density of the material and the exponent indicated the compressibility of the material. Incompressible materials have an exponent of zero and the exponent increases with compressibility.

The results from the bulk density measurement method provided a convenient description of the bulk density of compressible materials, but practicality demands a single number to characterize this property. Effective density is proposed as this number on the grounds that it is more representative and, potentially, of greater practical significance than a simple average of a number of measurements. Therefore, analysis and discussion of bulk density was primarily based on the effective density values for the test materials. The similarity between the effective density values and the coefficient values further support the bulk density measurement method.

General trends noted from the large container bulk density measurement trials were evident in the smaller container trials, but the magnitude of the differences in compressibility between materials were less noticeable (Chapter 4). In most of the container sizes used, wood shavings was the least compressible and the wet peat was the most compressible. The bulk density measurement method was most practical using smaller container sizes especially for the heavier materials, like wet peat and compost, as the required load was more easily achieved. A 40 cm-diameter container with a fill height of 38 cm was found to be suitable for most materials. However, for large particle-size materials (straw) bulk density values were better determined using a larger container size.

Effective density values were in agreement with literature for straw, compost, and peat independent of the container size. Generally, the bulk densities measured with the smaller containers were lower than those from the larger container. The lowest bulk density was for straw and the greatest was for compost. Differences in effective density and compressibility values measured using the three container sizes were likely a result of increased friction due to the smaller container diameter and the influence of particle-size.

Compressibility and wet effective density values for the compost and the peat were the greatest for materials at the highest moisture contents (Chapter 5). To reduce the variability and allow for comparisons between test materials, dry effective densities were determined. This resulted in the peat at the wet moisture level having a lower dry bulk density compared to peat at the low moisture levels. However, in the design of storage structures and materials handling systems wet effective bulk density values would be more meaningful.

FURTHER RESEARCH

The research for this thesis has been the beginning of a three stage project. It is hoped that through continued studies the last stage will lead to a tool that can determine the bulk density in the field for a compost pile. However, to achieve this final stage baseline data were needed and this was the essence for this thesis. The next stage will be to develop a method to test for a relationship between bulk density and air permeability. Literature has shown that as the bulk density for a material increases the resistance to air flow also increases. Therefore, if a test can be designed that can show a relationship between these parameters, then calculating the bulk density may become as easy as inserting a probe into a compost pile, reading a resistance to air flow value from a pressure gage, and inserting that value into an equation that would give a bulk density value. Furthermore, besides calculating the bulk density value, the method may also indicate if a compost pile has adequate air filled porosity. This would benefit compost operators when they are determining turning schedules for minimizing odours and anaerobic conditions.

APPENDIX A

Mean and standard deviations for the moisture content, effective bulk density, compressibility, and particle-size expressed on a dry and wet basis for the various container sizes and test materials.

Table A-1. **Dry effective density means and standard deviations.**

	Effective Density (kg/m^3)		
Material	Large	Medium	Small
Compost -PD	104.3 ± 3.30	no test	no test
Compost - I - dry	no test	139.21 ± 2.23	no test
Compost - I -interm.	no test	165.96 ± 1.12	no test
Compost - I - wet	269.05 ± 3.44	253.35 ± 2.13	227.19 ± 2.36
Peat - dry	119.62 ± 0.67	90.34 ± 0.46	81.08 ± 0.56
Peat - interm.	102.37 ± 3.94	96.13 ± 1.15	84.19 ± 0.46
Peat - wet	113.18 ± 2.25	88.86 ± 1.42	85.35 ± 2.89
Wood shavings	99.15 ± 3.17	90.66 ± 6.39	76.70 ± 7.06
Straw	57.65 ± 5.36	43.20 ± 0.52	38.39 ± 6.87

Note: PD = partially decomposed; I = in-vessel; interm. = Intermediate
N =3 for compost and peat; N=6 for straw and wood shavings.

Table A-2. **Wet effective density means and standard deviations.**

	Effective Density (kg/m^3)		
Material	Large	Medium	Small
Compost -PD	278.95 ± 5.87	no test	no test
Compost - I - dry	no test	333.46 ± 5.42	no test
Compost - I -interm.	no test	397.80 ± 3.03	no test
Compost - I - wet	510.87 ± 9.80	465.22 ± 5.94	415.09 ± 3.44
Peat - dry	256.70 ± 1.13	182.72 ± 2.27	163.04 ± 3.23
Peat - interm.	244.44 ± 17.30	227.51 ± 1.38	199.96 ± 1.07
Peat - wet	493.51 ± 8.75	329.40 ± 4.66	335.97 ± 10.04
Wood shavings	108.83 ± 3.78	98.18 ± 6.86	83.73 ± 7.68
Straw	65.73 ± 6.34	47.79 ± 0.28	42.80 ± 7.80

Table A-3. Compressibility means and standard deviations.

	Compressibility		
Material	Large	Medium	Small
Compost -PD	0.251 ± 0.024	no test	no test
Compost - I - dry	no test	0.070 ± 0.001	no test
Compost - I -interm.	no test	0.067 ± 0.003	no test
Compost - I - wet	0.103 ± 0.012	0.095 ± 0.005	0.063 ± 0.006
Peat - dry	0.140 ± 0.003	0.119 ± 0.001	0.101 ± 0.003
Peat - interm.	0.124 ± 0.012	0.109 ± 0.001	0.098 ± 0.004
Peat - wet	0.181 ± 0.018	0.163 ± 0.003	0.141 ± 0.013
Wood shavings	0.075 ± 0.020	0.053 ± 0.01	0.045 ± 0.009
Straw	0.18 ± 0.045	0.13 ± 0.01	0.1 ± 0.018

Table A-4. Particle-size means and standard deviations expressed on a wet basis.

	Total Mass Retained (%)										
	Size of Opening (mm)										
	12.7	9.52	4.76	2.38	2.000	0.840	0.420	0.250	0.149	0.074	pan
Mesh #	1/2	3/8	4	8	10	20	40	60	100	200	pan
Compost - I	0	1.5 (1.86)	10.10 (0.49)	-	30.54 (2.05)	34.07 (1.81)	13.60 (0.53)	5.88 (0.72)	2.58 (0.37)	0.82 (0.40)	0.89 (0.38)
Peat*	0	1.02 (0.77)	12.19 (1.83)	-	19.24 (0.77)	17.89 (0.99)	18.63 (0.61)	11.06 (0.46)	9.49 (0.70)	6.64 (0.82)	3.84 (2.09)
Peat**	-	-	-	29.43 (2.62)	-	20.90 (1.00)	-	-	-	-	49.66 (2.32)
Wood shavings	0.47 (1.16)	2.72 (1.85)	8.23 (0.96)	-	29.85 (1.67)	36.66 (1.89)	15.97 (0.93)	3.95 (0.46)	1.5 (0.13)	0.51 (0.14)	0.14 (0.09)
Straw	Geometric mean length = 8.98 mm; standard deviation by mass = 4.27										

Note: () = standard deviations
* = not according to standard.
** = according to ASTM standard (1971).
N = 3 for straw; N = 6 for compost, peat, and wood shavings

APPENDIX B

Power function curves for different size containers expressed on a dry and wet weight basis for compost, peat, straw, and wood shavings.

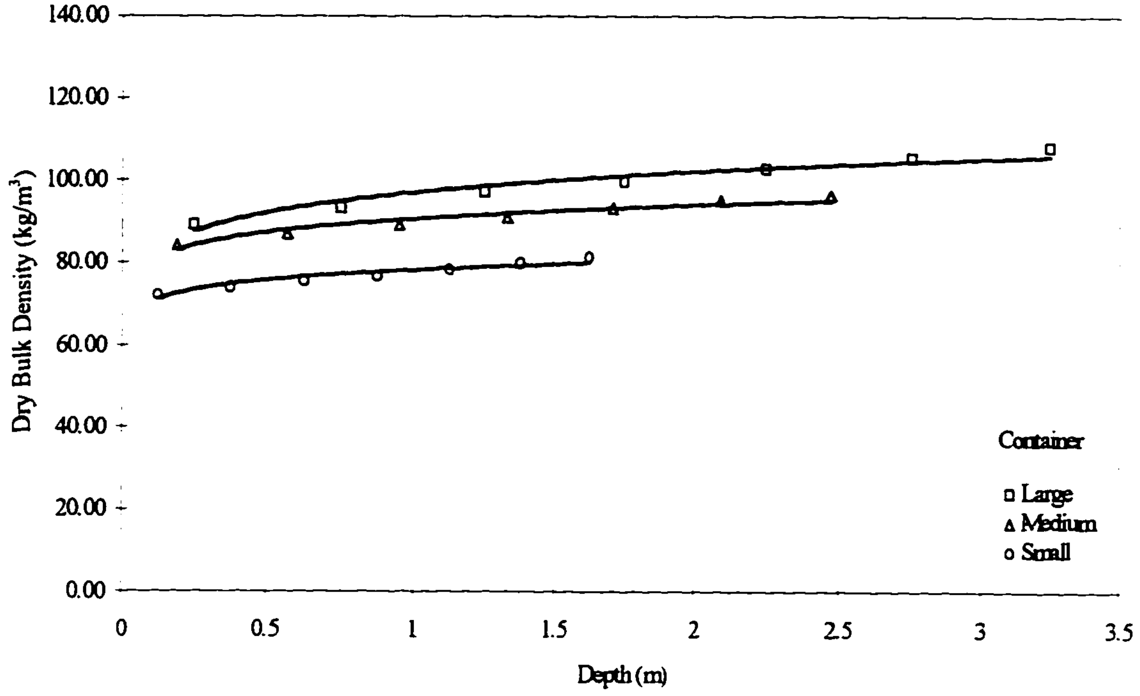

Figure B-1. Power function curves for wood shavings.

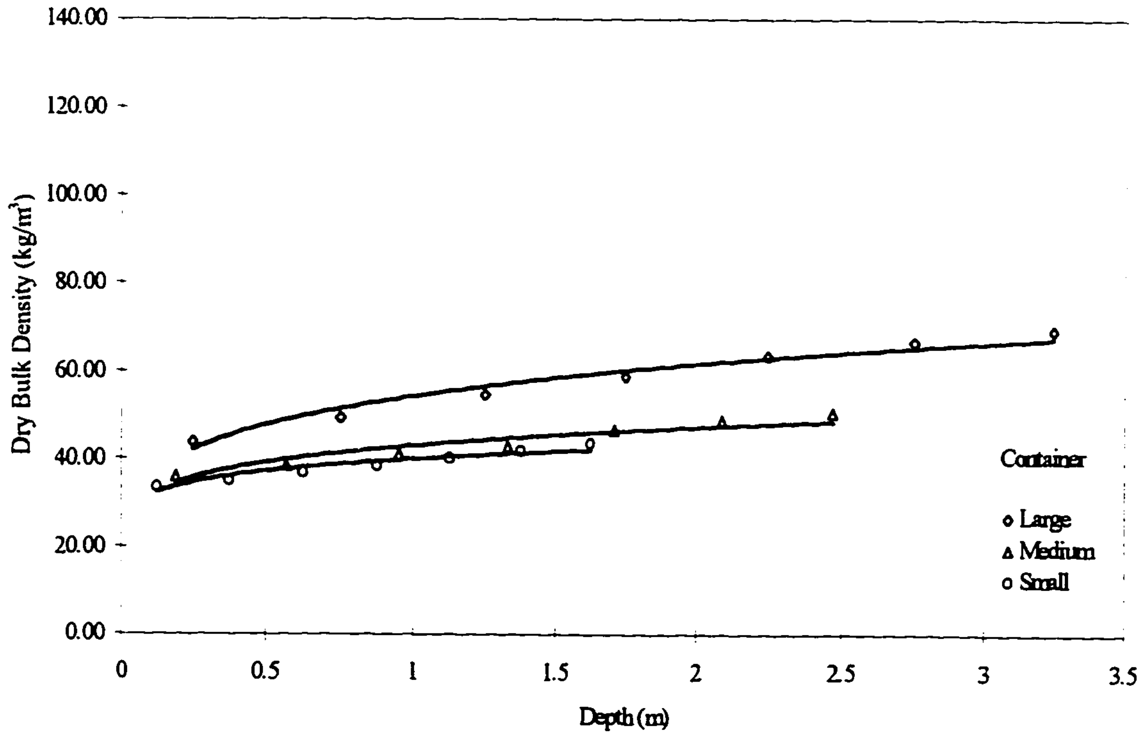

Figure B-2. Power function curves for straw.

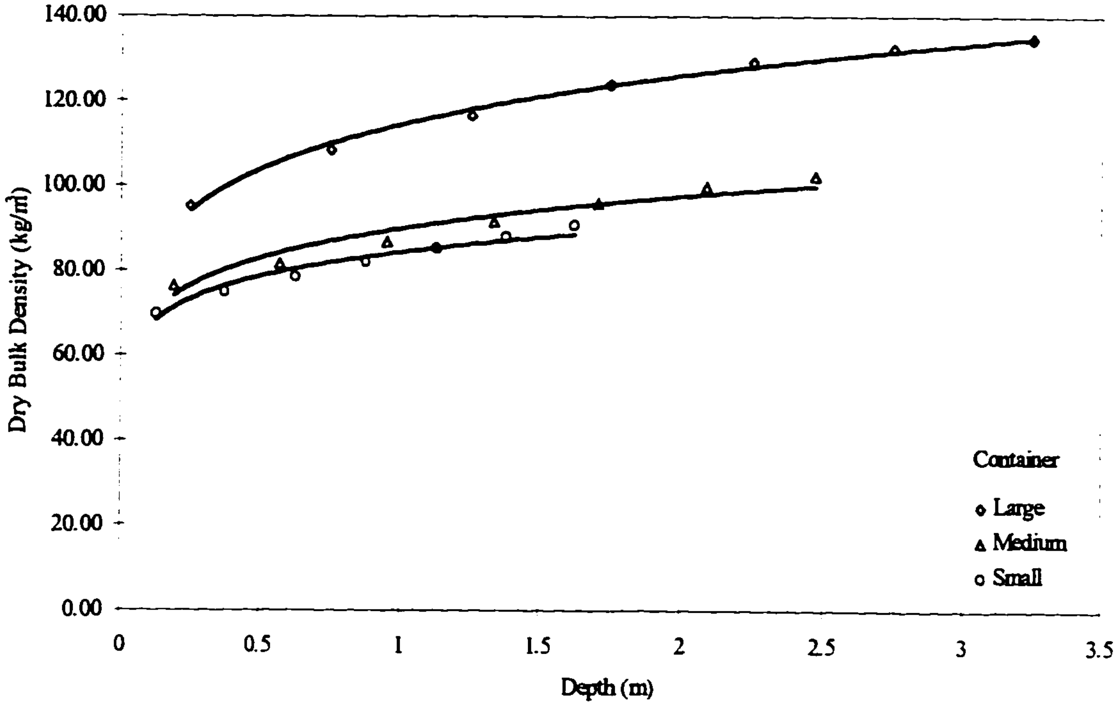

Figure B-3. Power function curves for peat at the dry moisture level.

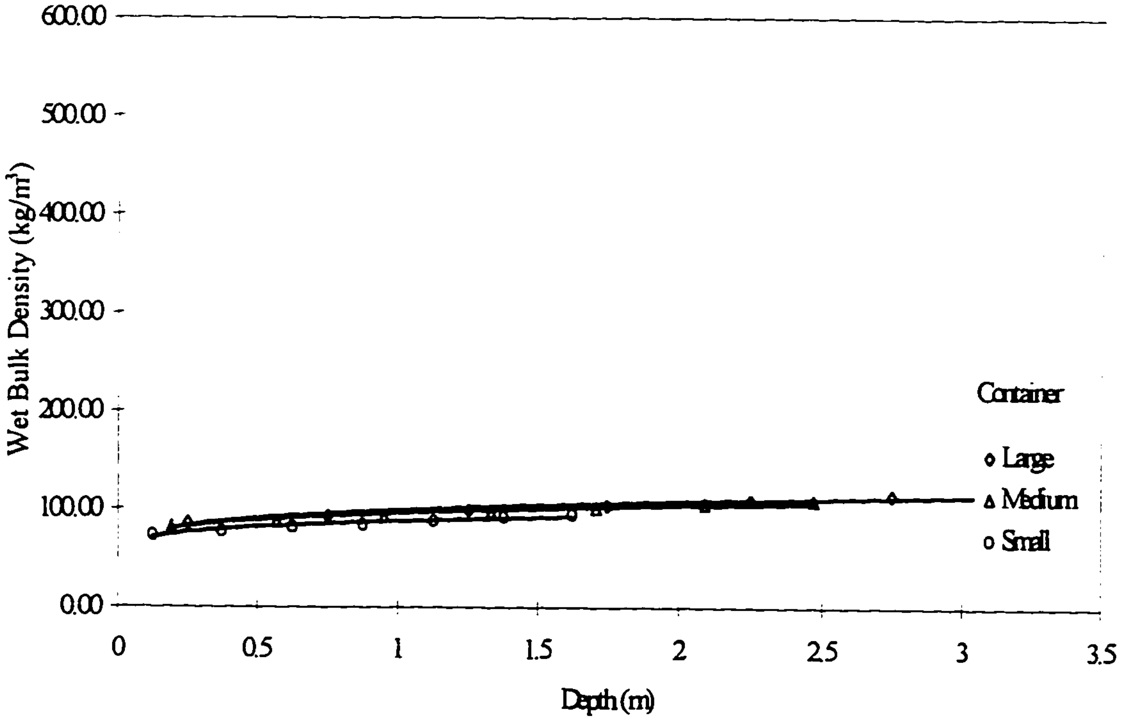

Figure B-4. Power function curves for peat at the intermediate moisture level.

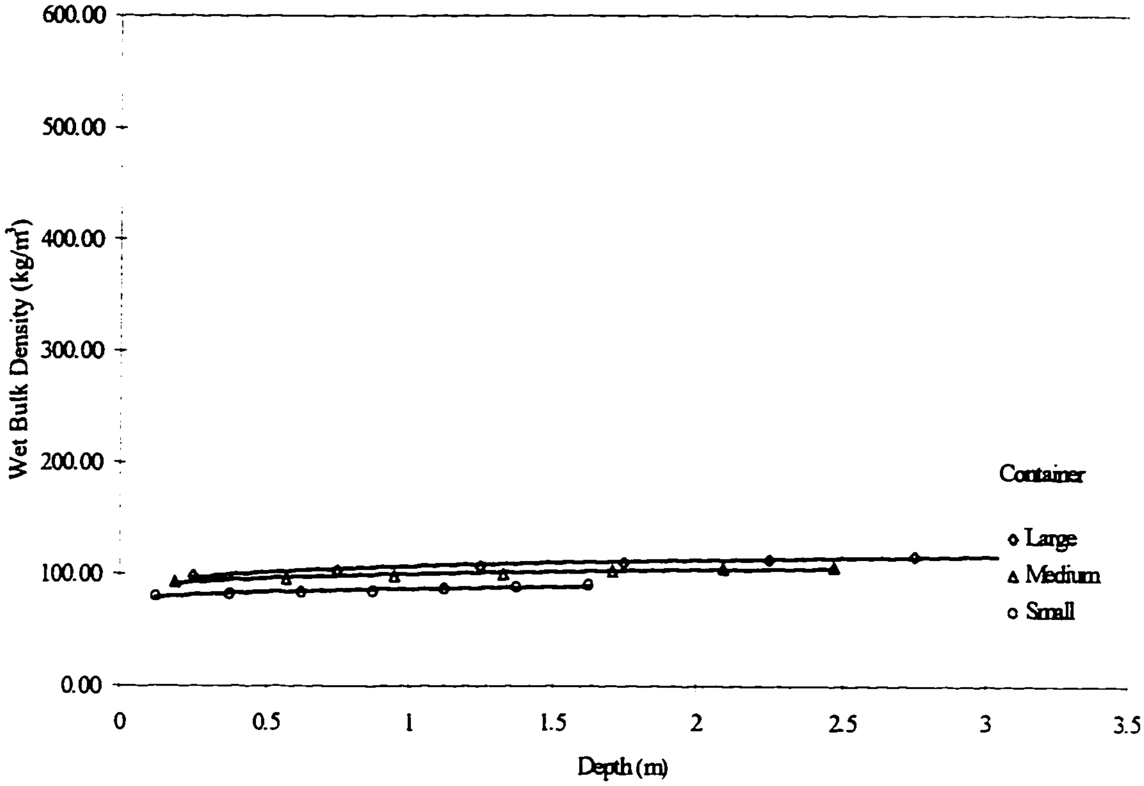

Figure B. 5 Power function curves for wood shavings.

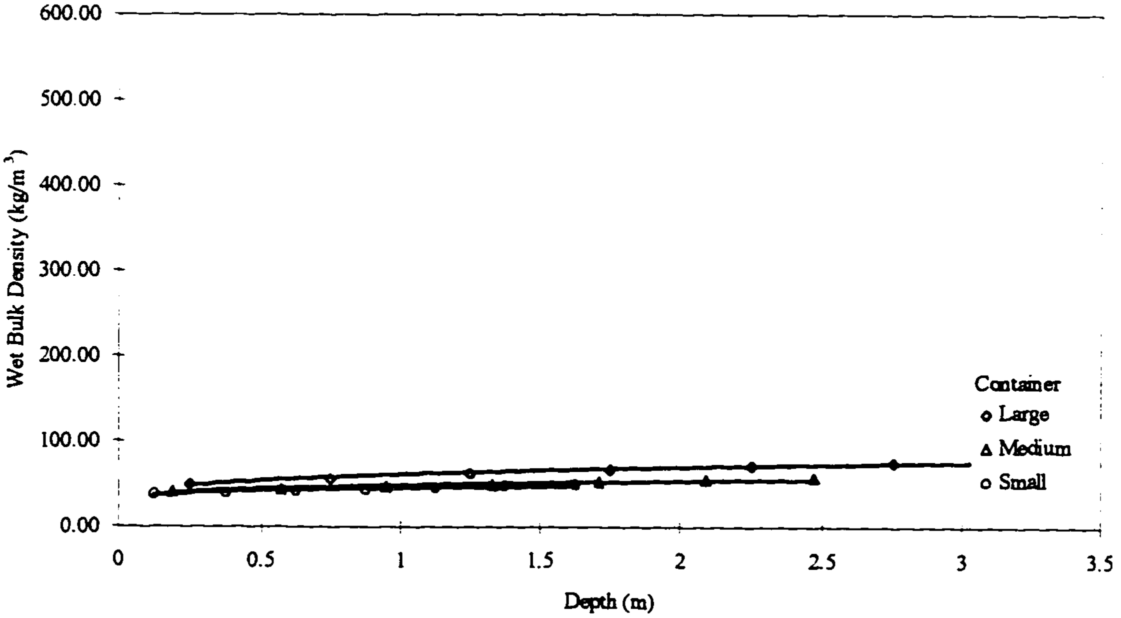

Figure B.6 Power function curves for straw.

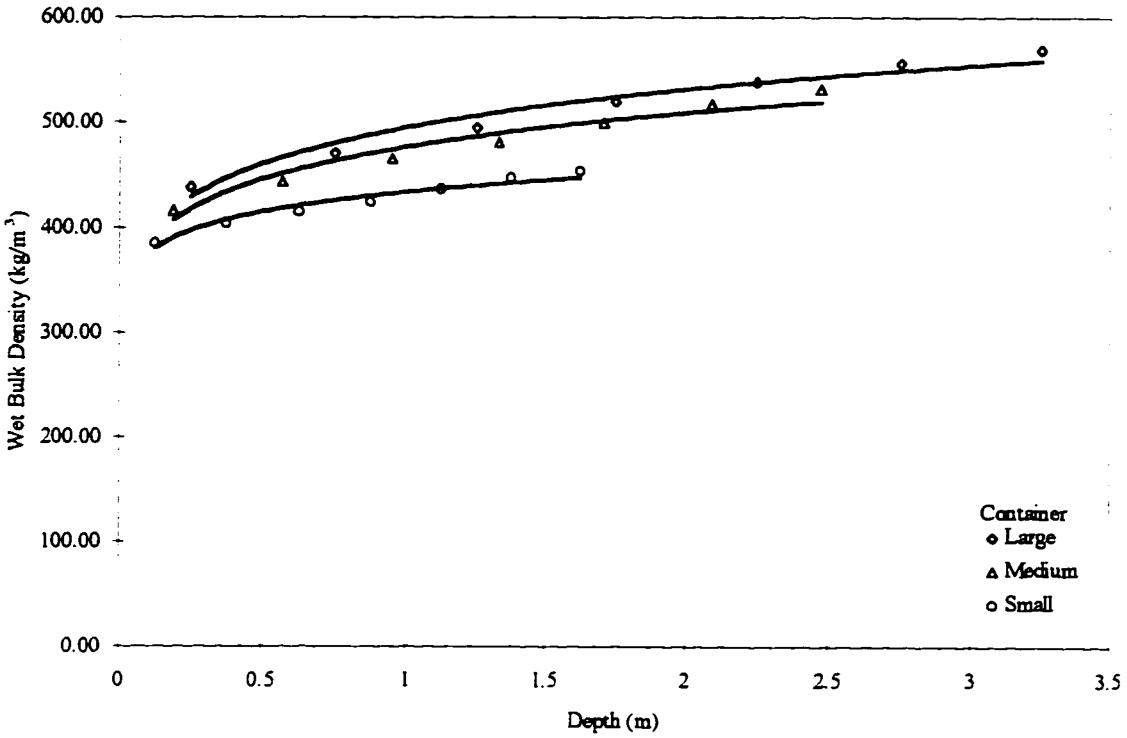

Figure B-7. Power function curves for in-vessel compost.

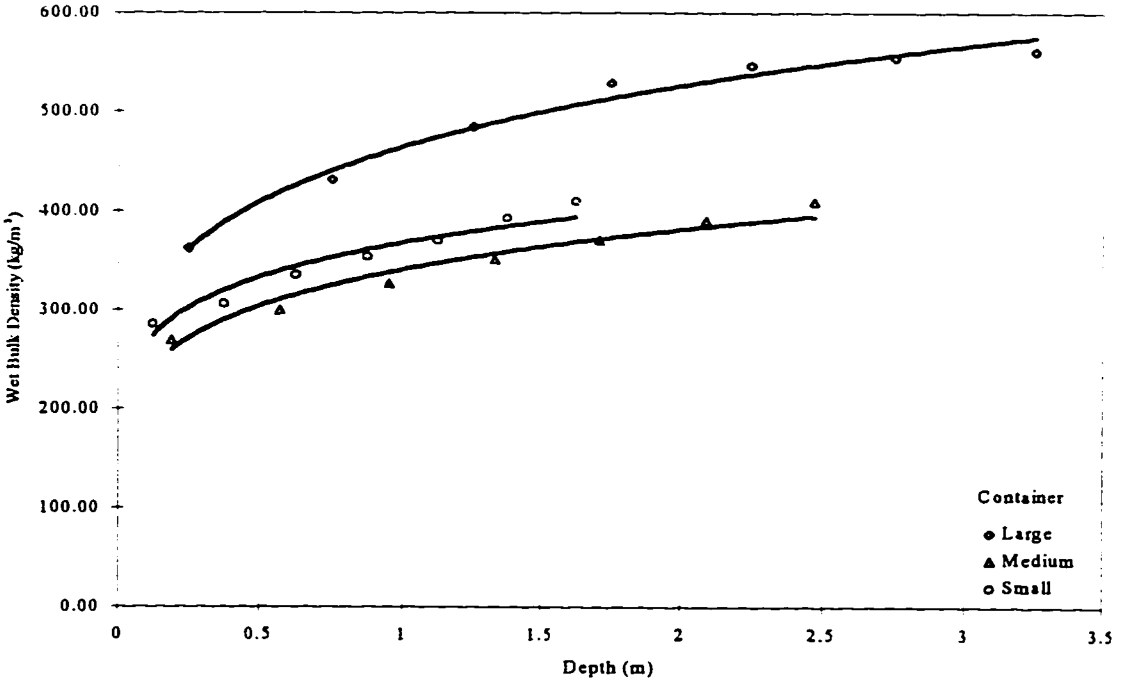

Figure B-8. Power function curves for peat at the wet moisture level.

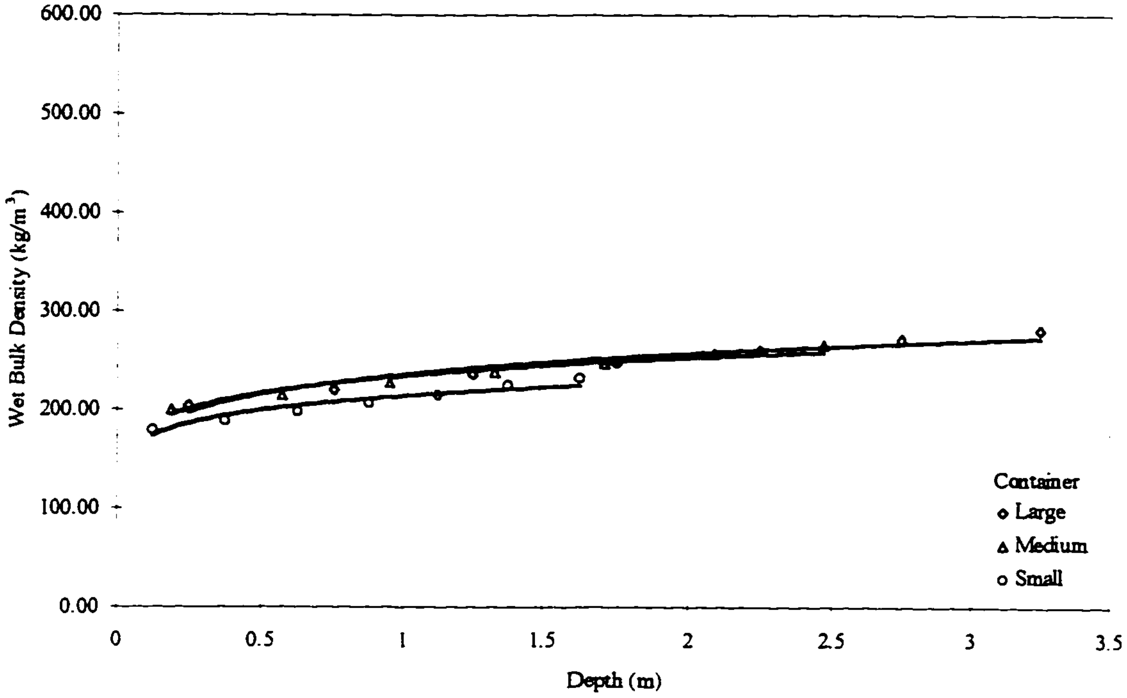

Figure B-9. Power function curves for peat at the intermediate moisture level.

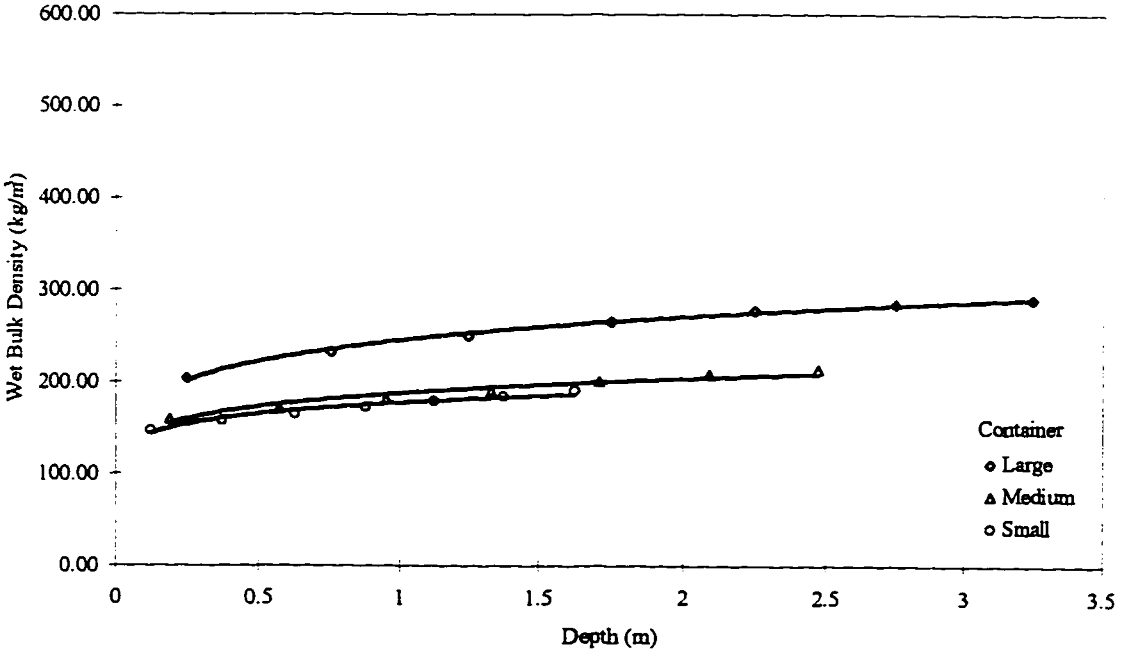

Figure B-10. Power function curves for peat at the dry moisture level.