The effect of moisture content, particle size and consolidation stress on flow properties of vermicompost

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Abstract: Physical properties of granular solids are essential to design appropriate, efficient, and economic bulk solids handling and storage equipment. Flow of vermicompost is often restricted by caking and bridging, which occurs during transportation and storage. This problem could be due to a number of factors including storage moisture, temperature, particle size, and consolidation stress. There is lack of study on the effect of the mention factors simultaneously on flow index, cohesive strength and angle of internal friction of vermicompost. The aims of this work were to discuss the primary factors affecting flowability of vermicompost as granular solids and powders, as well as using shear testing methodologies for this biomass material. The experiments were conducted on samples selected from a wormy culture farm, Karaj, Iran, by Jenike's shear cell technique. The data was statistically analyzed using the three factors completely randomized design to study the effects of particle size, moisture content and consolidation stress on vermicompost flow properties. The results showed that a significant difference between the flow index values at different stress levels. Greater moisture content and smaller particle size caused poor flowability of vermicompost. Increasing the moisture content and decreasing the particle size from 1.18 to 0.3 mm, the vermicompost reduced its flowability from free flowing at moisture content of 25% (w.b.) to cohesive at moisture content of 35% (w.b.).

Keywords: biomass flowability, flow index, shear test, vermicompost

Citation: Hadi Rahmanzadeh Bahram, Seyed Reza Hassan-Beygi, Mohammad Hossein Kianmehr, Iman Valaei, and Hossein Mohammadi Mazraeh. The effect of moisture content, particle size and consolidation stress on flow properties of vermicompost. Agric Eng Int: CIGR Journal, 16(1): 247−252.

1 Introduction

Urban organic waste can be processed in many different ways such as incineration, land filling and recycling. Some waste processing methods have high-cost operation and cause environmental problems. New methods of recycling can be effectively reduced pollution and converted waste materials to useful ones. One of the composting methods is vermicomposting, which involves utilizing various species of worms, usually red wigglers, white worms, and earthworms to create a vermicast from heterogeneous mixture of decomposing vegetable or food waste, and bedding materials. Vermicast, known as worm castings, worm humus or worm manure, is the end-product of the breakdown of organic matter by a species of earthworm (Puri, 2002). Therefore, by widespread vermicomposting technology, the low-cost production could be run with minimal facilities, so it brings many economical benefits.

To manage urban organic waste, powder flowability is important in handling and processing operations such as hoppers, silos flow, transportation, mixing, compression, and packaging. In other words,

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Received date: 2013-02-24 **Accepted date:** 2014-02-01

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knowledge of powder flow is essential in modifying existing bins, hoppers, feeders, determining of flow problems, and understanding the differences between the behavior of various bulk materials and grades of the same material (Colley et al., 2006). Flow properties of powder-like materials can be characterized with the flow index, cohesion strength and angle of internal friction (Colley et al., 2006; Jenike, 1964). The flow index is obtained by the inverse of the flow function. The flow function is the slope of the plot of unconfined yield stress versus the major consolidating stress and it was obtained when the material is sheared to failure in a shear cell (McGlinchey, 2005). Major principal stress in the steady-state flow is called the major consolidation stress (σ_1), acting on the critical consolidation condition and is determined by drawing the Mohr's circle (steady state Mohr's circle) passing through the point (σ, τ_c), which represents the consolidation conditions in the shear test (Figures 1 and 2). The φ (slope of yield locus) is the angle of internal friction in degree, τ is shear stress in kPa and σ_c is unconfined yield strength in kPa.

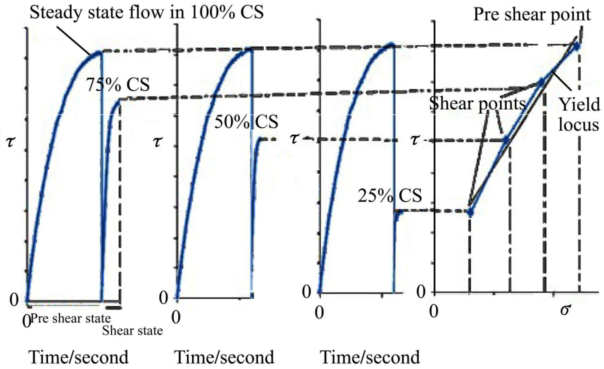

Figure 1 Shear test procedure of a ring shear tester in 100%, 75%, 50 %and 25% consolidation stress(CS) (Balasubramanian, 2001)

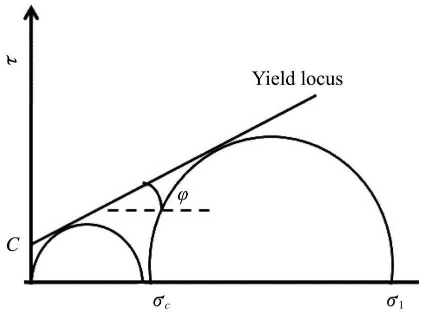

Figure 2 Yield locus, σ_1 (the major consolidation stress) and σ_c (unconfined yield strength) of the test

The classification of powder flowability by flow index (FI) is given in Table 1. The powder flowability is increased when flow index increased (Table 1). In the boundaries of the classifications listed in Table 1, the FI and the flowability of powder materials were changed with consolidation stress. In addition, it is generally assumed that materials with cohesion strength greater than 2 kPa and angle of internal friction smaller than 30° can be flowed by gravity (McNeill et al., 2004). Even a small change in moisture content and particle size may influence the powder flowability. Increasing moisture content reduced the powder flowability due to increasing liquid bridges and capillary forces acting between the powder particles (Horabik, 2001; Jenike, 1964; Kamath et al., 1993; Schulze, 1996). Shear cells are designed to condition powders under a known load and to measure forces needed to shear powder beds (Fitzpatrick et al., 2004, Knowlton et al., 1994). Shear measurement is able to provide useful indications of powder flow threshold, while the powder bed is being loaded. Therefore, if the forces applied on a powder were known during a given process, intrinsic information can be gathered regarding the frictional and cohesive nature of granular material. Several studies have been shown the effect of moisture content on the physical, compressibility and flow properties of biological materials (Balasubramanian, 2001; McNeill et al., 2004; Colley et al., 2006; Stasiak et al., 2009).

Table 1 Classification of powder flowability by flow index (FI) (Barbosa-Canovas et al., 2005)

Flowability	Hardened	Very cohesive	Cohesive	Easy flowing	Free flowing
Flow index (FI)	<1	<2	<4	<10	>10

The aims of this work were to discuss the primary factors affecting flowability of vermicompost as granular solids and powders, as well as using shear testing methodologies for this biomass material.

2 Materials and methods

The vermicompost samples were selected from wormy culture farm, College of Soil Science, Karaj, western north of Tehran, Iran. The samples produced from mixture of rotten dairy cow manure (80%) and the leaves of sycamore (20%), which was fermented during two months. The experiments were done at physical properties laboratory of Agro-technology Department, Abouraihan College, University of Tehran. The samples were ground using a hammer mill (Glen Mills Inc., NJ). The samples were sized by standard sieves to three particle mesh sizes numbers of 16, 30 and 50. The dimensions of each mesh sizes are given in Table 2.

Table 2 Dimensions of mesh sizes according to ASTM E 1170

Mesh size number	16	30	50
Diameter/mm	1.18	0.6	0.3

Moisture is a key environmental factor that affects many aspects of the vermicomposting process (Richard., et al., 2002). The moisture content of the vermicompost was determined using air convection oven method. The oven temperature was set at 105±3°C for 48 hours (ASAE Standards, 1998). The initial moisture content of the vermicompost sample was 15% (w.b.). In order to adjust the moisture content of the samples to the desired levels (25%, 30% and 35% w.b.), the vermicompost sample was either wetted by adding distilled water (Kingsly et al., 2006). The samples were stored in an air tight container at 4°C in a refrigerator for a minimum of 72 hours to allow moisture equilibration (Valaei et al., 2012). The amount of water needed to bring a sample to desired moisture content was calculated using the following equation:

$$m_w = \frac{m_i(M_{wf} - M_{wi})}{1 - M_{wf}} \qquad (1)$$

where, m_w = The amount of added water; M_i = Initial mass of the biomass; M_{wi} = Initial moisture content ; M_{wf} = Final moisture content.

All measurements were performed with a Jenike's shear cell, which was developed by Rahmanzadeh et al. (2011) (Figure 3). The three main components of this device including a steel shear ring (diameter of shear ring is 9.5 cm), a driving unit (AC electric motor, inverter and reduction unit) and a data acquisition (load cell with resolution of 0.2 N, indicator, PC interface and software). The steel ring was rested on a sample of wall material which was fixed to the base plate of the tester. For any flow function, four yield loci and four points for each yield locus were obtained. To construct a yield locus, the powder was critically consolidated under a known normal consolidating stress (σ_1), and the shear stress (τ), required to cause the powder to fail under 75%, 50%, 25% of consolidating stress (normal stress σ), and applied the load head began to twist the cell lid at a speed of 2.5 mm/min, thereby causing the sample to shear also the consolidating stress were measured. A yield locus is a plot of failure shear stress versus normal stress for a given consolidating stress. This is repeated for four different consolidating stresses to obtain four yield loci. Every point of the yield locus was repeated three times.

The liner Mohr-Coulomb equation (Equation (2)) was fitted to yield locus to estimate the cohesion and internal friction angle. Geometric methods were used to estimate σ_1 and σ_c (Puri, 2002). The flow function for the sample was then obtained from the slope of the plot of σ_1 (UYS) versus σ_c (MCS). The details of these calculations can be found in Puri (2002). The flow function therefore gives the stress needed to make an arch (formed when flow from a hopper stops) collapse as a function of the compacting stress under which it was formed (Williams, 1990). The ratio of the σ_1/σ_c is the flow function.

$$\tau = c + \sigma \tan(\varphi) \qquad (2)$$

where, τ is shear stress, kPa; σ is normal stress, kPa; φ is angle of internal friction,degreesand c is cohesion strength, kPa.

Figure 3 Jenike's shear tester used in this study, which was developed by Rahmanzadeh *et al.* (2011)

The data was statistically analyzed with SAS software using the three variables factorial experiments with completely randomized design to study the effects of consolidating stress, particle size and moisture content on flow index, cohesive strength and angle of internal friction of vermicompost.

3 Results and discussion

As shown in Table 3, the bulk density of vermicompost decreased from 0.854 to 0.658 g/cm^3 within the moisture content range of 25%–35% (w.b.) and particle size 0.3 mm to 1.18 mm. These mean that with increasing moisture content, the particle volume increasing rate of the vermicompost was faster than the particle mass increasing rate. Therefore, the amount of volume that will be required to store a unit mass of vermicompost would be increased with moisture increase. The bulk density reduction of vermicompost with moisture content increasing was similar to the reported bulk density-moisture content relationship for biomass materials (poultry litter- Bernhart and Fasina, 2009) and granular biological materials (cashew nut – Balasubramanian, 2001; soybean – Deshpande et al., 1993; alfalfa cubes and pellets – Fasina and Sokhansanj, 1992; green gram – Nimkar and Chattopadhyay, 2001). The measured bulk density of vermicompost (>0.658 g cm^{-3}) was also considerably greater than the values reported by Mani et al. (2006) for other bioenergy feedstock such as switch grass and peanut hulls (typically <0.2 g/cm^3).

Table 3 Physical properties of vermicompost

Moisture Content /(% w.b.)	Hammer mill screen size/mm	Geometric mean diameter/mm	Geometric standard deviation/mm	Bulk density /g cm^{-3}	Particle density /g cm^{-3}
25	0.3	0.174	0.214	0.854	1.652
	0.6	0.211	0.387	0.814	1.554
	1.18	0.246	0.312	0.732	1.493
30	0.3	0.232	0.362	0.771	1.587
	0.6	0.253	0.436	0.736	1.545
	1.18	0.274	0.364	0.689	1.466
35	0.3	0.237	0.394	0.743	1.543
	0.6	0.282	0.466	0.685	1.531
	1.18	0.288	0.412	0.658	1.443
p-value		0.043	0.038	0.028	0.042
CV/%		3.98	4.34	3.72	4.23

The particle density of vermicompost also decreased from 1.652 to 1.443 g/cm^3 with increasing moisture content from 25% to 35% (Table 3). This trend showed that with increasing moisture content of the vericompost, the volume of particles increased at a faster rate than the mass of particles. A similar trend was observed for various biological materials (soybean - Deshpande et al., 1993; poultry litter - Bernhart and Fasina, 2009; and green gram - Nimkar and Chattopadhyay, 2001).

The variations ultimate yield stress (UYL) versus the major stress consolidating (MSC) of the vermicompost at three moisture content and particle size levels are shown in Figure 4. The flow function (the slope of the plots in the figure) increased with moisture content. This indicated that the stress needed to make an arch (formed when flow from a hopper stops) to collapse increased with moisture content (Knowlton et al., 1994; Teunou and Fitzpartick, 2000). Using the classification given in Table 1, the flow index values (inverse of the flow function) indicate that the flowability of vermicompost reduced with increasing the moisture content (Figure 4).

Teunou and Fitzpatrick (1999) also found similar results when they compared the flow functions of flour (at 12.0% moisture content), tea (at 6.5% moisture content), and whey (at 4.0% moisture content). They concluded from their study that the flour with the highest moisture content had the most difficult flow.

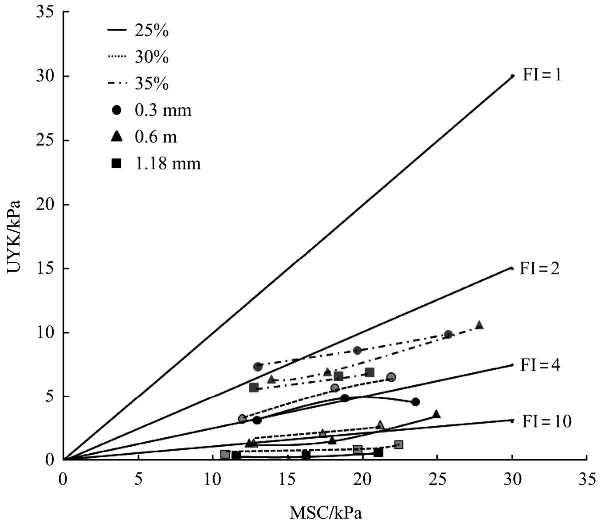

Figure 4 Classification of unconfined yield stress(UYS) versus major consolidating stress(MCS) (FI= UYS / MCS) according to Table 1 for the vermicompost at three levels of moisture content and particle size.

The effects of moisture content, consolidating pressure and particle sizes parameters on the cohesive strength and angle of internal friction of vericompost are given in Table 4. As expected, the cohesion was significantly affected by moisture content ($P<0.01$), particle size and applied pressure ($P\leq0.05$) for vermicompost. Also the angle of internal friction was significantly ($P\leq0.05$) affected by moisture content, particle size and applied pressure.

The previous researches showed that the cohesive strength data are generally lower than the values obtained for high-rising wheat flour (1.5–3.5 kPa) for fine tea powder (1.0–2.3 kPa) (Knowlton et al., 1994); poultry litter (0.41–3.26 kPa), and for chickpea flour and components (3.22–7.11 kPa) (Bernhart. 2007); but comparable to the values obtained for spray dried whey permeate powder (0.5–1.0 kPa) and for sugar and wheat flour (0.6–1.3 kPa) (Kamath et al., 1993).

Table 4 Cohesive strength and angle of internal friction of vermicompost on three consolidation stresses

Moisture content /(%, w.b.)	Consolidating pressure/kPa								
	7			13			17		
	Particle size/mm			Particle size/mm			Particle size/mm		
	0.3	0.6	1.18	0.3	0.6	1.18	0.3	0.6	1.18
	Cohesive strength/kPa								
25	1.16	1.16	0.22	0.81	0.41	0.16	0.23	0.16	0.08
30	2.23	2.08	1.12	1.67	1.55	1.01	1.30	1.41	0.48
35	2.88	2.11	0.97	1.61	1.63	1.12	1.06	0.86	0.74
p-value	0.0168	0.0168	0.0168	0.0168	0.0168	0.0168	0.0168	0.0168	0.0168
CV/%	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97	3.97
	Angle of internal friction/(°)								
25	31.4	33.1	32.1	29.7	33.7	35.9	32.7	28.7	26.6
30	35.1	33.6	34.8	34.8	34.8	35.4	29.0	34.3	34.3
35	37.2	33.3	31.8	36.0	35.7	28.6	30.1	25.3	27.7
p-value	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036	0.036
CV/%	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81

The measured angle of internal friction and cohesive strength in most cases were greater than the critical values of 30° and 2 kPa required for gravity discharge of bulk materials from storage bins and silos (Ndegwa et al 1998; Puri, 2002). Therefore, gravity discharge alone may not be used to unload vermicompost from storage bins and silos.

4 Conclusions

The results confirm the role of moisture content and particle size on the flow properties of vermicompost. Also the results showed increasing moisture content and decreasing particle size of vermicompost reduced the flowability. Higher angles of internal friction are mainly due to interlocking among particles during direct shear and depend very much on the normal stress. So according to the numerical results in cases where amount of angle of internal friction is lower than 30°; it is amenable using gravity alone for handling vermicompost. However, friction values are intrinsic and have the potential to be effectively used for bulk characterization.

Acknowledgements

The authors would like to thank the agro technology engineering department of Abouraihan College, Tehran University for their collaboration in this project.

Nomenclature

ff	Flow function (indicator of powder flowability)
FI	Flow index (σ_c/σ_1) (indicator of powder flowability)
M_w	Mass of Water that is added, g
m_i	The initial mass of fresh vermicompost, g
M_{wi}	Initial moisture content of vermicompost(w.b.), %
M_{wf}	Final moisture content of vermicompost(w.b.), %
φ	Angle of internal friction, degree
τ	Shear stress, kPa
σ_1	Major consolidation stress, kPa
σ_c	Unconfined yield strength, kPa

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