

PHYSICAL AND RHEOLOGICAL PROPERTIES OF MANURE PRODUCTS

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ABSTRACT. Selected physical and rheological properties deemed to influence the performances of handling and land application equipment were quantified for different types of manure at different levels of total solids concentration (TS) ranging from 10% to 50% on a wet mass basis. The selected properties included total solids concentration, bulk density, particle size distribution, friction characteristics, and shearing behavior and were measured for dairy cattle, sheep, poultry, and pig manure. The bulk density of all manure products was found to increase with TS and the values for poultry and pig manure were not significantly different at the tested TS levels. The measured density values were in close agreement with ASAE D384. The proposed modified geometric mean length of the particles was found to significantly increase as TS became smaller. The static friction coefficients of all manure types with the exception of pig manure on the different surface materials [plywood, plastic, steel (bare and painted)] did not exhibit large differences and a single linear equation was suggested to predict the static friction coefficient as a function of TS. Animal manures were described as pseudoplastic fluids and the consistency coefficients were found to increase with TS for all manure types. The apparent viscosity of the tested manure products was well correlated to TS. The implications of the property results obtained in this study as well as future research are discussed.

Keywords. Handling, Land application, Manure, Physical properties, Rheological properties.

Proper recycling of animal manure is of paramount importance to increase the sustainability and social acceptance of intensive livestock production. As the environmental and agronomic requirements for effective and safe land application of manure products become more prescriptive, equipment used in manure management systems are subjected to higher performance expectations. Solid and semi-solid manure products represent potential alternatives to reduce some of the environmental and societal problems that may be associated with liquid manure management. Commercial equipment designed to handle and land apply solid and semi-solid manure do exhibit large coefficients of variation for both transversal and longitudinal product distribution (Bisang, 1987; Wilhoit et al., 1993; Frick et al., 2001; Thirion and Chabot, 2003). Appropriate knowledge of the physical and flow properties of the products to be handled is fundamental to the design and operation of efficient systems.

LITERATURE REVIEW

Published research results are readily available in the area of manure chemical properties. Much fewer journal articles have targeted the physical and flow properties of manure products and most of the manure characterization efforts have focused on liquid manure and slurry.

Kumar et al. (1972) studied the flow properties of animal waste slurries. They concluded that the viscosity of dairy cattle slurry decreased with an increase in dilution and an increase in temperature. They also noticed that the flow of slurry is Newtonian at solids contents below 5%. The addition of sawdust up to as much as 10% by weight of the amount of manure decreased the viscosity of a slurry having a total solids content of up to approximately 9%.

Hashimoto and Chen (1976) attempted to identify a parameter that would mathematically describe the rheological properties of aerated and fresh dairy cattle, poultry and swine waste slurries and that could be easily and precisely measured experimentally. They also tried to describe procedures to estimate the effect of rheological properties on pumping, mixing and aerating livestock waste slurries. Their study showed that the rheological consistency coefficient (K) and rheological behavior index (n) of livestock waste slurries can be expressed in terms of the equilibrium sludge volume fraction (Φ_L) as:

$$K = b_1 \phi_L^{b_2} \quad (1)$$

$$n = b_3 + b_4 \ln(\phi_L) \quad (2)$$

where b_1 to b_4 are constants.

Values of these constants were given for the tested animal manures and were found to be dependent on the range of Φ_L . Relationships have also been established to relate mixer power characteristics and pressure head loss in pipeline

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transport of slurries to K , n , the effective viscosity, and generalized Reynolds number. A method of determining Φ_L is also presented, but to the authors' knowledge, the equilibrium sludge volume fraction has never been widely used in manure characterization.

Rheological consistency index, flow behavior index, specific heat, and thermal conductivity of beef cattle manure were determined by Chen (1982). Density was also measured for solid contents ranging from 1% to 99%. The results suggested that the density of manure increased as the total solids concentration increased for manure with less than 16% TS. For manure with TS higher than 50%, the bulk density of the manure dropped much below the liquid manure density. The study also included rheological properties for TS ranging from 1% to 14%. Beef cattle slurries were described as non-Newtonian pseudoplastic fluids, the deviation from Newtonian behavior increasing with TS.

Using a constant temperature rotational viscometer, Chen and Shetler (1983) investigated the effect of temperature on the rheological properties of cattle manure having total solids concentrations ranging from 2.5% to 19.3%. The experimented shear rates ranged from 20 to 200 s^{-1} and temperatures varied from 14°C to 64°C. This study confirmed previous findings that beef cattle manure slurry is a non-Newtonian pseudoplastic fluid and a power-law equation could be used in this range of shear rates. The rheological behavior index (n) was found to decrease exponentially with TS, but was not affected by temperature while the rheological consistency index (K), in general, increased as TS increased. The apparent viscosity of the slurry decreased exponentially as temperature increased, and increased as TS increased. An equation relating the apparent viscosity to TS and to the absolute temperature was given.

Chen (1986) later proposed a rheological model for manure slurries and applied this model to experimental data of cattle manure slurry obtained using a rotational viscometer. He found that cattle manure slurry showed negligible yield stress and that the Bingham Plastic, Herschel-Bulkley and Casson models were not applicable. The power law model could be used only for sieved slurries with TS below 4.5%. He also observed a curvilinear relationship of shear stress and shear rate in the logarithmic plot for high TS slurries due to the existence of a limiting viscosity. He proposed the following rheological model for beef cattle manure slurry:

$$\tau = \eta_0 \dot{\gamma} + K'' \dot{\gamma}^{n''} \quad (3)$$

where τ is the shear stress, $\dot{\gamma}$ is the shear rate, η_0 is the limiting viscosity, and K'' and n'' are rheological parameters. Nonlinear least square regression was used to fit the proposed model to the experimental rheological data for slurries having TS above 4.5%. The results showed that the proposed model was well correlated to the experimental data. The value of n'' for sieved slurries did not vary with TS or temperature, having an average value of 0.307 with a standard deviation of 0.054. Equations expressing η_0 and K'' in terms of TS and temperature were also obtained. The values of η_0 and K'' were found to increase as TS increased and to decrease as temperature increased.

Achkari-Begdouri and Goodrich (1992) studied the rheological properties of Moroccan dairy cattle manure with total solids concentrations ranging from 2.5% to 12% at

temperatures between 20°C and 60°C. Their results showed that in the ranges of total solids and temperature of the study, Moroccan dairy cattle manure behaved as a pseudoplastic fluid. Two equations based on the total solids content and the temperature, one expressing the consistency coefficient and the other to predict the flow behavior index, were proposed.

Solid and semi-solid manures have not been studied as much as liquid manure and slurry in terms of physical properties. A few studies have mentioned the effect of manure properties on the performance of various mechanisms. In their study of spreader distribution patterns for poultry litter, Wilhoit et al. (1993) made observations on the effect of particle size on spreading distances. They concluded that large particles were distributed more evenly and on a larger width when compared to smaller particles that landed closer to the spreader. Wilhoit et al. (1994) also observed the effects of particle size distribution while developing a drop applicator for poultry litter. They concluded that their gravity flow metering system was not appropriate due to the presence of clumps blocking the flow of material from the hopper. Observations were made by Wilhoit and Ling (1996) to the effect that the nature of wood and fly ash caused the spreading uniformity to be inconsistent from trial to trial. In their design of an applicator for side dressing row crops with solid wastes, Glancey and Adams (1996) identified maximum lump size and moisture content as the physical properties presenting potential problems in raw manure conveying.

Glancey and Hoffman (1996) measured physical properties of poultry manure and compost under different management practices. They investigated trends in the measured properties to develop general guidelines for the design and analysis of material handling systems, transportation equipment and spreaders. They concluded that wet bulk density was dependent on moisture content for all the solid wastes evaluated and that knowledge of moisture content was therefore more important than the type or source of material. The static friction characteristics suggested that there was little practical difference between the different products. Another trend identified by the authors indicated that all unscreened waste materials contained large lumps. This presents potential design problems in developing conveying systems to handle unscreened materials.

Agnew et al. (2003) used an air pycnometer to measure the air volume and density of compost. The free air space (FAS) and bulk density of manure compost, municipal solid waste compost, and mixtures of biosolids and amendment materials were measured at various moisture contents and compressive loads. Their results indicated that the FAS decreased with loading and increasing moisture content while the wet bulk density increased with loading and increasing moisture content. A linear relationship was established between FAS and bulk density for all the materials tested under loads.

Malgeryd and Wetterberg (1996) reported the efforts of the Swedish National Machinery Testing Institute and the Swedish Institute of Agricultural Engineering to provide the necessary knowledge of how the physical properties of manures and slurries affect the spreading of different machines. They highlighted the fact that there is a lack of general knowledge about which properties are important in practice and how they should be measured. For manures that can be pumped, four properties were considered significant, namely, fluidity, separation tendency, risk of clogging and dry matter content. For manures that cannot be pumped, five

properties were deemed important: bulk density, stacking ability or consistency, comminuting resistance, heterogeneity and dry matter content. Methods were suggested for measuring those properties. Their results suggested that there is no clear relationship between the active angle of repose and the dry matter content for non-pumpable manures and that bulk density and the active angle of repose are closely related to each other. The active angle of repose could be estimated from the bulk density, which is easier to measure.

Thirion et al. (1998) experienced difficulties in trying to implement the test methods outlined by Malgeryd and Wetterberg (1996). They measured manure properties including normal stress, shear stress, bulk density, friction coefficient, straw content and dry matter content. They included numerous comments on the difficulty of obtaining reliable results and proposed a method for obtaining a numerical value of manure heterogeneity.

Landry and Laguë (1999) studied selected physical properties of papermill residues. They measured bulk density, moisture content, angle of repose, friction coefficient on different materials and particle size distribution. They concluded that while the values of the selected properties were relatively constant among samples that originated from the same papermill, there could also be large variations depending upon the specific origin of the products.

The literature review clearly demonstrates the variability that exists in manure properties and the lack of widely accepted and used methods to measure those physical and rheological properties. More data are required to highlight general trends and to develop design guidelines for manure handling and land application equipment.

OBJECTIVE

The objective of the work reported herein was to measure selected physical and rheological properties of different types of manure products at different levels of total solids concentration with an emphasis on the solid and semi-solid ranges.

MATERIALS AND METHODS

Based on the review of previous work, the properties that were deemed having the most influence on the performances of manure handling and land application equipment were identified as: (a) total solids concentration, (b) bulk density, (c) particle size distribution, (d) friction characteristics, and (e) shearing properties. Four types of manure were investigated: (1) dairy cattle, (2) sheep, (3) poultry, and (4) pig. Manure samples were collected from the facilities on the University of Saskatchewan farm (Saskatoon, Saskatchewan, Canada). The dairy, pig, and poultry (laying hens) barns all featured scrapers to move the manure out of the buildings. The dairy and poultry barns were scraped twice a day and the manure went directly into underground pits. The pig manure was stored in a room at the end of the barn and that room was periodically emptied. Fresh samples were collected after scraping, just before the manure entered the pits. In the case of sheep manure, the samples were collected from outside pens and contained a large proportion of straw. A small amount of chopped straw was used in the free stall barn where the dairy cattle manure samples were collected. No bedding material was used in the pig and poultry barns. With the

objective of characterizing the manure products in the state they would be when handled and/or land applied, the samples were not submitted to any treatment (e.g., separation, screening, etc.) prior to testing. Several large samples (approximately 150 L per sample) were collected for each type of manure to avoid using the same material more than once. In order to reach the targeted total solids concentrations, the raw samples were either dried outside or diluted with water. Based on the initial and targeted total solids concentrations, the amount of water to add was estimated by weighing the samples. The TS of the samples was measured daily during the preparation phase. The majority of the tested samples went through one wetting or drying cycle, two wetting phases were sometimes necessary to reach the desired TS level. The samples were stored and handled in 170-L barrels and were tested as soon as the targeted TS level was reached. All property measurements were replicated on four sub-samples.

TOTAL SOLIDS CONCENTRATION

The total solids (TS) concentration of the manure products was determined by drying the samples in an oven overnight at 103°C (ASAE Standards, 2002a). TS was the ratio of oven-dry weight to wet weight and was expressed as a percentage.

BULK DENSITY

The bulk density of manure products was measured in an uncompacted state by weighing large containers of known volume filled with manure according to the procedure described by Glancey and Hoffman (1996). A weighing apparatus was designed and built to accommodate large samples (i.e., 170-L barrels). The apparatus was made of a platform supported by two load cells (2224-N capacity; ± 1.11 N nonlinearity; ± 0.67 N hysteresis; Interface, Scottsdale, Ariz.) and allowed for easy placement of the barrels. The load cells with the data acquisition system were calibrated using a universal testing machine (Model 1011, Instron Corporation, Canton, Mass.). All the test apparatuses that required calibration featured load cells (weighing apparatus, shearbox and large-scale viscometer) and the universal testing machine was used. Observations were made by Thirion et al. (1998) and Frick et al. (2001) to the effect that density values are affected by the measurement method. The chosen method consisted of manually handling the samples to create a consistent state of compaction for the entire test series. Once the barrels were filled to the desired level, opposite sides of the barrels were alternately lifted and dropped twice on the ground from an approximately 300-mm height to compact and level the material.

PARTICLE SIZE DISTRIBUTION

A modified soil sieves shaker and a screen set were used to determine the particle size distribution of the manure samples using a procedure adapted from ASAE S424.1 (ASAE Standards, 2002b). The size openings of the screen set used in this study were 25.4, 16.4, 8.7, 5.2, and 1.2 mm. The samples were placed on the top screen (25.4-mm openings), shaken for 90 s, and the screens were finally weighed on a laboratory scale to determine the amount of manure retained on each screen.

FRICTION CHARACTERISTICS

The values of the static friction coefficient of manure products on different surface materials were measured using the inclined plane method (Mohsenin, 1986). Four different surfaces, representative of possible candidate materials for the construction of manure handling and land application equipment, were selected: steel (bare and painted), plastic (PVC), and plywood. An inclined plane apparatus was designed and built to measure the static coefficients of friction of manure products. The apparatus featured an electric motor giving a constant angular inclination velocity of 0.007 rad/s. For the static coefficient of friction experiments, the samples were placed and held in a fiberglass ring having a diameter of 300 mm and a height of 30 mm. The angle of repose of manure products was also measured according to the method described by Henderson et al. (1997) using an apparatus made of a cylinder that could be lifted from a base plane to let the sample flow out of it and form a pile. The radius of the pile was measured at four different locations 90 degrees apart on the base plane. The height of the pile was also measured and the angle of repose was calculated as the arc tangent of the ratio of the height to the average radius. Approximately 10 to 15 L of manure were used for each angle of repose measurement.

SHEARING PROPERTIES

Depending on the total solids concentration of the product that was tested, three different apparatuses were used to characterize the relation between shear stress and shear rate: the shearbox apparatus (Model No. 25301, Wykeham Ferrance Engineering Ltd., Slough, England), a laboratory rotational viscometer (DV-III+ Digital Rheometer, Brookfield, Middleboro, Mass.), and a large-scale rotational viscometer. The large-scale viscometer was designed and built to accommodate the 170-L barrels that were used in the study. It was also introduced to compare the results obtained with small and very large samples (0.5 L-samples were used with the laboratory viscometer compared to approximately 85 L-samples for the large-scale unit). The large-scale viscometer is illustrated in figure 1. The barrel was rotated through the 90-degree gearbox and the torque calculated from the force measured via a load cell located between a fixed back plate and a rigid member attached to the freewheeling spindle shaft. The rotational speeds varied from 0.3 to 100 rpm and 3 to 100 rpm for the laboratory and large-scale viscometer, respectively. The shear rate and shear stress were calculated using equations 4 and 5, respectively.

$$S = \frac{2\omega R_c^2 R_b^2}{R_b^2(R_c^2 - R_b^2)} \quad (4)$$

$$F' = \frac{M}{2\pi R_b^2 L} \quad (5)$$

where

- S = shear rate (s^{-1})
- W = angular velocity of spindle (lab) or container (large) (rad/s)
- R_c = radius of container (m)
- R_b = radius of spindle (m)
- F' = shear stress (Pa)

M = torque input by instrument (N-m)

L = effective length of spindle (m)

The appropriate values of R_c , R_b , and L were obtained from the Brookfield documentation in the case of the laboratory viscometer. For the large viscometer, the integration of the apparatus parameters into equation 4 gave a shear rate, in s^{-1} , equal to 0.239 times the rotational velocity of the barrel in revolutions per minute. The immersion depth of the spindle was used as the effective length for the large unit. Four normal loads were used for the direct shear tests (7.0, 22.5, 38.1, and 70.7 kPa) and the rate of shear was constant at 1.2 mm/min. The standard procedure ASTM D3080-98 (ASTM, 1998) was followed.

RESULTS AND DISCUSSION

Table 1 summarizes the results obtained for the total solids concentration of the tested animal manures. It can be seen that some of the tested samples exhibited variability, as assessed by the values of standard deviation. However, the ANOVA performed on the TS results indicated that the measured TS values are similar enough to proceed to comparisons between the different waste products based on the target TS level. The original total solids concentrations of the dairy cattle, sheep, and pig manure samples were around 15%, 30%, and 25%, respectively. For the poultry manure samples, two different initial levels of TS were observed (12% and 18% approximately) depending on the amount of water that got into the manure from leaking drinkers. Samples with a TS level corresponding to a target value were tested as is.

SOLID MANURE PRODUCTS

Solid manure products can be compared on the basis of the properties presented in table 2. As it can be seen from the bulk density results included in table 2, poultry and pig manure are similar products while dairy cattle and sheep manure show significant differences at most TS levels. Using the density

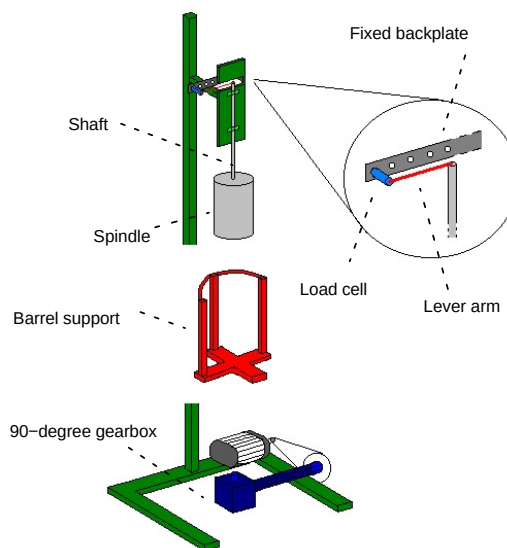


Figure 1. Schematic representation of the large-scale viscometer.

Table 1. Average total solids concentration for the manure products evaluated.

Target TS Level (%)	Measured TS (%)			
	Dairy Cattle	Sheep	Poultry	Pig
50	47.8 ^[a] _{(3.1)^[c]} ^[b]	53.0 a (3.1)	47.3 b (1.9)	48.0 ab (1.7)
40	44.4 a (4.7)	41.5 a (4.9)	41.5 a (0.9)	41.7 a (5.2)
30	33.5 a (1.6)	30.7 a (1.9)	34.5 a (0.6)	32.0 a (4.5)
20	23.4 a (1.7)	18.4 a (2.5)	21.2 a (4.2)	22.8 a (0.2)
15	14.2 ab (0.4)	13.8 a (0.1)	14.5 ab (0.6)	14.8 b (0.04)
10	8.9 a (0.2)	10.4 b (0.3)	10.3 b (0.3)	10.7 b (0.6)

[a] Average value.

[b] Values within each TS level row not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level.

[c] Standard deviation.

values obtained at the appropriate TS level, the results are very similar to those outlined in ASAE D384.1 (ASAE Standards, 2002c). According to the ASAE standard, the density in kg/m³ of fresh manure is 990 for dairy cattle (14.0%TS), 1000 for sheep (27.5%TS) and for layer (25.0%TS), and 990 for swine (13.1%TS). Using the TS level closest to the ASAE standard, the comparisons (ASAE vs.

current study) of density values in kg/m³ become dairy cattle (990 vs. 973); sheep (1000 vs. 521); layer (1000 vs. 1028); swine (990 vs. 1026). The only major difference is in sheep manure. This difference was due to the presence of a large proportion of straw in the sheep manure that was used in this study. The densities of all manure products were expected to become stable near the liquid density as TS becomes small.

Relationships between density and total solids concentration were obtained and are presented in figures 2 and 3. The following equations were obtained by polynomial regression analysis, using third order models and forcing the density at 0% TS to be 1000 (the density is in kg/m³):

Poultry and pig:

$$\text{Density} = -0.0235 \text{ TS}^3 + 1.19 \text{ TS}^2 - 11.2 \text{ TS} + 1000; \\ R^2 = 0.83 \quad (6)$$

Dairy cattle:

$$\text{Density} = 0.0367 \text{ TS}^3 - 2.38 \text{ TS}^2 + 14.6 \text{ TS} + 1000; \\ R^2 = 0.93 \quad (7)$$

Sheep:

$$\text{Density} = 0.00860 \text{ TS}^3 - 0.873 \text{ TS}^2 + 8.90 \text{ TS} + 1000; \\ R^2 = 0.91 \quad (8)$$

Equations 6, 7, and 8 can be used to obtain a reasonable approximation of the bulk density of poultry and pig, dairy cattle and sheep manure respectively. It can be seen on

Table 2. Density, static coefficients of friction, and angle of repose for the solid manure products evaluated.

Measured and Calculated Properties							
Target TS Level (%)	Manure Type	Density (kg/m ³)	Static Coefficient of Friction (dimensionless)				Angle of Repose (°)
			Plywood	Plastic	Painted Steel	Bare Steel	
50	Dairy cattle	238.4 ^[a] a ^[b] (20.1) ^[c]	0.88 a (0.042)	0.93 a (0.0082)	0.90 a (0.026)	0.80 a (0.0050)	n.a. ^[d]
	Sheep	332.3 b (20.3)	0.73 b (0.051)	0.79 b (0.048)	0.68 b (0.029)	0.66 b (0.028)	32.2 a (1.3)
	Poultry	607.5 c (75.3)	0.82 a (0.013)	0.88 a (0.022)	0.89 a (0.017)	0.79 a (0.018)	36.1 a (5.3)
	Pig	552.5 c (18.1)	0.83 a (0.029)	0.86 ab (0.052)	0.84 a (0.042)	0.89 c (0.045)	30.1 a (2.2)
40	Dairy cattle	198.6 a (7.9)	0.88 a (0.065)	0.88 a (0.029)	0.82 a (0.031)	0.79 a (0.021)	n.a
	Sheep	556.9 b (52.1)	0.81 a (0.057)	0.86 a (0.056)	0.83 a (0.021)	0.83 a (0.022)	48.0 a (6.8)
	Poultry	884.7 c (117.2)	0.90 a (0.047)	0.83 a (0.051)	0.89 a (0.039)	0.86 a (0.030)	40.3 a (2.9)
	Pig	948.7 c (30)	6.4 b (0.94)	2.3 b (0.43)	2.3 b (0.80)	1.5 b (0.22)	n.a
30	Dairy cattle	267.1 a (6.6)	0.91 a (0.051)	1.0 a (0.052)	1.0 a (0.027)	0.95 a (0.036)	n.a
	Sheep	520.8 b (34.9)	0.92 a (0.088)	0.93 a (0.021)	0.96 a (0.019)	0.91 a (0.055)	33.8 (0.9)
	Poultry	1028.2 c (45.5)	3.4 b (0.38)	0.87 a (0.062)	1.1 a (0.078)	1.0 a (0.20)	n.a.
	Pig	1140.9 c (112.3)	7.8 c (0.49)	0.95 a (0.12)	1.0 a (0.17)	0.80 a (0.080)	n.a
20	Dairy cattle	411.0 a (32.1)	1.0 (0.070)	1.2 (0.030)	1.1 (0.10)	1.1 (0.03)	n.a
	Sheep	1051.2 b (60.2)	These samples were not solid enough to measure the static coefficient of friction, the geometric mean length and the angle of repose.				
	Poultry	1091.8 b (63.9)					
	Pig	1090.0 b (77.3)					

[a] Average value.

[b] Values within each TS level row and property column not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level.

[c] Standard deviation.

[d] Data not available.

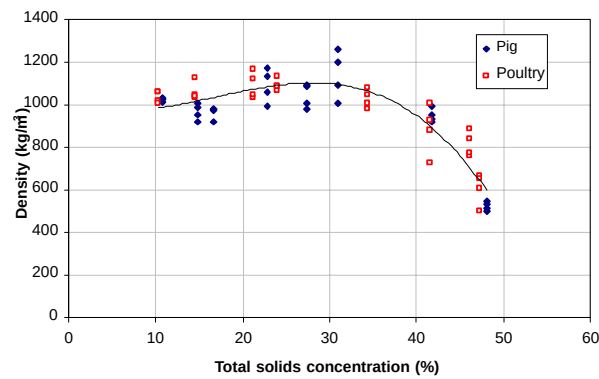


Figure 2. Bulk density values for poultry and pig manure and regression curve.

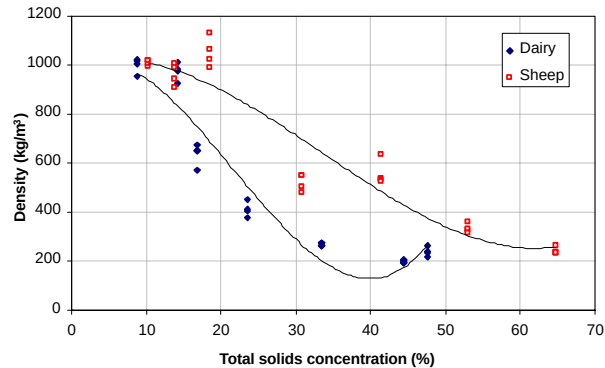


Figure 3. Bulk density values for dairy cattle and sheep manure and respective regression curves.

figures 2 and 3 that some density measurements yielded high values, up to 260 kg/m³ greater than the density of water (1000 kg/m³). Although density values above 1000 kg/m³ were also reported by Chen (1982), a bias induced by the initial tension/compression state of the load cells on the weighing apparatus as well as vibration during measurements are potential causes that may have yielded high density results.

Modified geometric mean lengths (Xgm') are presented in table 3. Large lumps were observed on the top screen (25.4-mm openings) yielding an overestimation of the particles' geometric mean length, as calculated according to ASAE S424.1 (ASAE Standards, 2002b). The calculations were then adapted using 16.4 mm as the largest size opening to obtain the modified value (Xgm'). Observations were made on the size of the lumps collected on the top screen. Their largest dimension was generally between 30 and 50 mm, but large 100- to 150-mm lumps were also observed, as mentioned by Glancey and Hoffman (1996). These lumps will affect the conveying behavior of the waste products, but it becomes difficult to predict how without prior knowledge of their mechanical strength. The data included in table 3 allow seeing the effect of total solids concentration on the characteristic dimensions of the particles for each manure type. It can be seen that as the total solids concentration decreased, or as the manure products became wetter, the modified geometric mean length became significantly higher. This was due to the increased aggregation ability of the animal wastes as the proportion of water in the manure increased. The data of table 3 also indicate there was no

Table 3. Average modified geometric mean length and standard deviation for dairy cattle, sheep, poultry and pig manure.

	Average TS (%)	Average Xgm' ^[a] (mm)	Standard Deviation (mm)
Dairy cattle (a ^[b])	16.8	14.0 a	1.7
	23.4	12.6 ab	0.27
	33.5	11.2 bc	0.46
	44.4	9.6 c	1.3
	47.7	9.5 c	1.1
Sheep (b)	18.4	11.6 a	0.29
	30.7	11.1 a	0.77
	41.5	10.1 b	0.34
	53.0	6.5 c	0.12
	64.8	5.4 d	0.53
Poultry (c)	34.5	18.9 a	0.95
	41.5	14.2 b	0.41
	46.2	13.4 b	0.45
	47.3	10.9 c	0.36
Pig (c)	27.4	18.6 a	1.0
	31.0	19.7 a	0.25
	41.7	12.6 b	0.0
	44.5	11.3 b	0.17
	48.1	12.0 b	0.96

[a] Modified geometric mean length.

[b] Values within each manure type group (rows) and manure type column not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level.

significant difference in the overall average modified geometric mean length of poultry and pig manure. Also, the difference between dairy cattle manure and sheep manure in terms of modified geometric mean length was not very important, as suggested by the values of table 3. Predictive equations 9 and 10 for the modified geometric mean length of dairy cattle and sheep manure as well as for poultry and pig manure were obtained (fig. 4).

Dairy cattle and sheep:

$$Xgm' [mm] = 16.1 - 0.16 TS; R^2 = 0.83 \quad (9)$$

Poultry and pig:

$$Xgm' [mm] = 31.9 - 0.43 TS; R^2 = 0.84 \quad (10)$$

The results obtained for the static friction coefficients indicate that while a fair amount of variability could be observed, similar values of friction coefficient were also present in the database. The large values of static coefficient

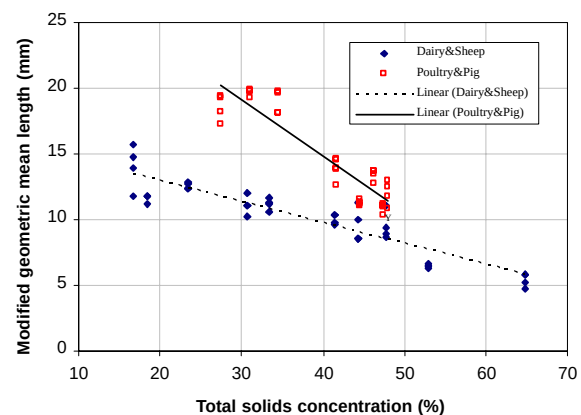


Figure 4. Modified geometric mean length of dairy cattle, sheep, poultry, and pig manure as a function of total solids concentration.

of friction for pig manure could not be explained. More measurements would be required to see if pig manure really exhibits such large friction coefficients or if the values obtained were marginal. When all the coefficient of friction data were analyzed together, no significant differences were found between materials except for plywood, which had significantly higher coefficients of friction. It was observed during the experiments that some products had a different behavior on the inclined plane when they had a paste-like consistency or when seepage occurred. The tested poultry and pig manures exhibited a paste-like consistency at TS between 20% and 30%. It is difficult to define the limits of the solid or liquid states since small TS increments have not been studied in the suspected transition zone. The dairy cattle and sheep manure samples did not seem to have a solid to liquid transition zone as defined as the poultry and pig samples. The coefficient of friction results were further analyzed without the results obtained for these particular cases. The resulting linear regression equation is (fig. 5):

$$\text{Static friction coefficient [dimensionless]} = 1.34 - 0.011 \text{ TS}; \\ R^2 = 0.71 \quad (11)$$

Equation 11 can be used to predict the static friction coefficient of the tested manure products on the selected surface materials. For the design and analysis of handling and land application systems, the choice of appropriate safety factors should compensate for the lack of fit of the equation. More data would be required to deepen the observations made on the friction behavior of pasty products. The coefficients of friction measured in this study are consistent with those reported by Glancey and Hoffman (1996) and with their conclusion that there is little practical difference between the coefficients measured on the various surfaces and for the manure products tested.

The angle of repose results included in table 2 demonstrate that there was no significant difference between the angles measured for all manure types at a given level of total solids concentration. The missing data for this property were due to problems encountered with the apparatus. Some products would also keep the shape of the cylinder they were confined in after it had been lifted from the base plane. However, the results indicate there was little practical difference between

the angles of repose of the tested animal manures. The average of all angle of repose measurements was 38°, which was in agreement with what was presented by Glancey and Hoffman (1996) (average of 37°) and also close to the values reported by Moysey and Hiltz (1985) for commercial fertilizers that had angles of repose between 33° and 36°. The average value of the current study is greater than what was measured by Landry and Laguë (1999) for papermill residues (average of 30°).

The results obtained for the direct shear test were highly variable, as revealed by the large values of standard deviation presented in table 4. General trends could not be observed for the angle of internal friction or the apparent cohesion. The direct shear tests were carried out using a 190.5- × 101.6- × 63.5-mm box and the samples were not screened prior to the experiments. The large aggregates present in most of the tested samples may have been responsible for the inconclusive results, although observations made while testing samples free of large lumps did not show major differences in the recorded data. The direct shear test was difficult to

Table 4. Angle of internal friction and apparent cohesion for the manure products tested.

	Average TS (%)	Angle of Internal Friction (°)		Cohesion (kPa)	
		Average	Standard Deviation	Average	Standard Deviation
Dairy cattle	16.8	36.3 a ^[a]	3.1	3.0 a	0.7
	23.4	35.6 a	1.1	2.8 a	1.0
	33.5	37.3 ab	1.5	2.1 a	1.4
	44.4	37.6 ab	0.8	3.7 a	0.4
	47.7	40.7 b	1.0	3.1 a	0.9
Sheep	18.4	26.5 a	1.0	7.2 a	1.5
	30.7	23.9 a	0.4	7.4 a	0.9
	41.5	25.9 a	0.8	7.5 a	0.1
	53.0	38.3 b	3.3	1.7 b	1.9
Poultry	34.5	12.4 a	0.2	7.3 a	0.6
	41.5	28.1 b	0.8	11.9 b	0.3
	47.3	22.4 c	3.7	12.0 b	1.2
Pig	31.0	19.2 a	4.0	0.5 a	0.9
	41.7	9.2 b	2.4	9.3 b	0.8
	48.1	24.2 a	1.7	15.6 c	1.4

^[a] Values within each manure type row and property column not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level.

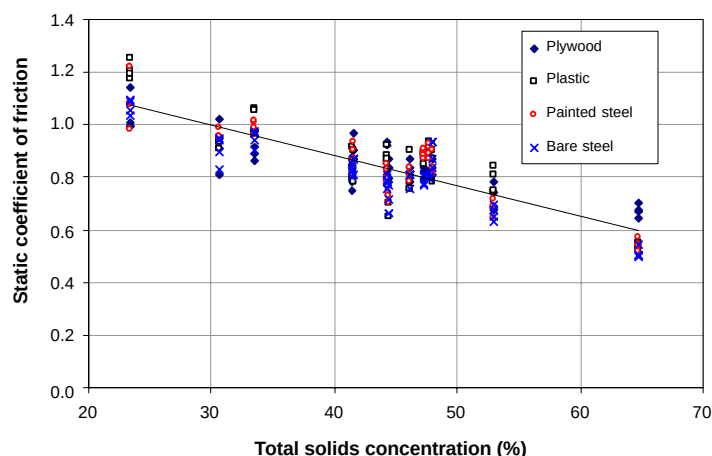


Figure 5. Static coefficient of friction of dairy cattle, sheep, poultry, and pig manure as a function of total solids concentration.

carry out due to the lumpy and heterogeneous nature of manure products. A larger split box could be used to attempt investigating the shearing behavior of manure products with the aggregates. Another option would be to carry out the test on screened samples. Other tests should also be explored, as they may be more suitable to characterize the shear stress – shear rate behavior of organic wastes.

LIQUID AND SEMI-SOLID PRODUCTS

For manure products that could not be tested in the direct shearbox and for which static friction coefficients were irrelevant, the focus was on the density and on the shear stress – shear strain behavior as determined by rotational viscometry. The tested manure products generally displayed a decreasing viscosity with an increasing shear rate, which corresponds to the typical behavior of non-Newtonian pseudoplastic fluids. It was found that the power law $\tau = K\dot{\gamma}^n$ (where τ is the shear stress, K the consistency coefficient, $\dot{\gamma}$ the shear rate, and n the flow behavior index) could be used to describe the relation between shear stress and shear rate for the animal waste products tested. The values of the consistency coefficient K and of the flow behavior index n are presented in table 5 for both the laboratory and the large-scale viscometers. The density results have been previously discussed and included in predictive equations 6, 7, and 8. Comparisons between the results obtained using the large-scale viscometer and the laboratory unit showed there was in most cases no significant difference between the two apparatuses, for both the consistency coefficient K and the

flow behavior index n . The high variability of the results obtained using the large-scale viscometer, with an average coefficient of variation of 20% for all groups of measured data, combined with the rather severe statistical test used, is one factor explaining the similarities between the two viscometers. Results obtained using the laboratory viscometer also exhibited a fair amount of variability, but this could be expected when very small quantities, to fill a 600-mL beaker, are taken from large 150-L samples. To reduce the variability of the results obtained with the large-scale viscometer, two issues must be addressed. The mechanical vibration coming from the motor and the gearbox were substantial and should be damped or reduced to ensure the torque measured is mainly related to the shearing of the fluid. Also, the sensitivity of the torque-measuring load cell should be increased by using a combination of smaller capacity (the load cell used had a capacity of 222 N) and variable lever arm length. More conclusive results might be obtained with an improved large-scale viscometer.

Many similarities between products having the same level of total solids were detected by the statistical analysis. The rather large standard deviations are partly responsible for those conclusions. Figures 6, 7, and 8 allow for a visual appreciation of the shear stress – shear strain relationships for animal waste products. They also illustrate the effect of TS on the consistency coefficient and on the flow behavior index for the various types of manure tested. It should be noted that these charts were plotted using the average experimental values of K and n to calculate the shear stress at the minimum

Table 5. Bulk density, consistency coefficient (K) and flow behavior index (n) for the animal manure products tested.^[a]

Table 3. Bulk density, consistency coefficient (K) and flow behavior index (n) for the animal manure products tested.								
		Measured and Calculated Properties					Shear Rate Range (s ⁻¹)	
Total Solids Concentration (%)	Manure Type	Density (kg/m ³)	Lab Viscometer		Large Viscometer		Viscometer Type	
			K (Pa·s ⁿ)	n (—)	K (Pa·s ⁿ)	n (—)	Lab	Large
20	Dairy cattle	411.0 ^[b] a ^[c] (32.1) ^[d]	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Sheep	1051.2 b (60.2)	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
	Poultry	1091.8 b (63.9)	9.9 a (1.4)	0.43 a (0.078)	35.4 a (2.7)	0.29 a (0.083)	[0.07 – 22.10]	[0.64 – 24.14]
	Pig	1090.0 b (77.3)	41.1 b (4.7)	0.34 a (0.018)	56.8 a (14.8)	0.35 a (0.074)	[0.08 – 25.38]	[0.24 – 23.90]
15	Dairy cattle	973.0 a (33.9)	22.9 a (8.3)	0.41 a (0.042)	31.3 a (7.2)	0.30 a (0.12)	[0.07 – 21.61]	[0.61 – 24.37]
	Sheep	961.5 a (44.8)	26.9 a (11.5)	0.36 a (0.076)	19.4 a (8.4)	0.29 a (0.035)	[0.07 – 22.07]	[0.70 – 23.90]
	Poultry	1063.6 b (42.4)	1.7 b (0.06)	0.41 a (0.012)	2.4 b (0.3)	0.38 a (0.018)	[0.07 – 22.00]	[0.80 – 23.90]
	Pig	967.7 a (39.5)	3.4 b (0.2)	0.42 a (0.0058)	2.4 b (0.3)	0.38 a (0.018)	[0.07 – 22.00]	[0.96 – 23.90]
10	Dairy cattle	999.6 a (30.7)	2.6 a (0.3)	0.42 a (0.026)	5.3 a (2.1)	0.11 a (0.10)	[0.07 – 22.00]	[0.90 – 23.90]
	Sheep	1008.3 a (11.1)	3.7 b (0.5)	0.42 a (0.029)	2.7 a (0.9)	0.33 b (0.084)	[0.07 – 22.00]	[0.90 – 23.90]
	Poultry	1036.5 a (26.6)	1.2 c (0.07)	0.37 a (0.022)	8.9 b (2.3)	0.29 ab (0.11)	[0.12 – 30.79]	[0.96 – 24.14]
	Pig	1025.7 a (7.1)	1.0 c (0.04)	0.55 b (0.018)	2.2 a (0.8)	0.21 ab (0.041)	[0.12 – 38.75]	[0.90 – 23.90]

^[a] For the viscometry tests, the temperature of the manure samples was between 17°C and 24°C.

^[b] Average value.

^[c] Values within each total solids concentration level row and property column not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level (a T-test was used when only two means were available).

^[d] Standard deviation.

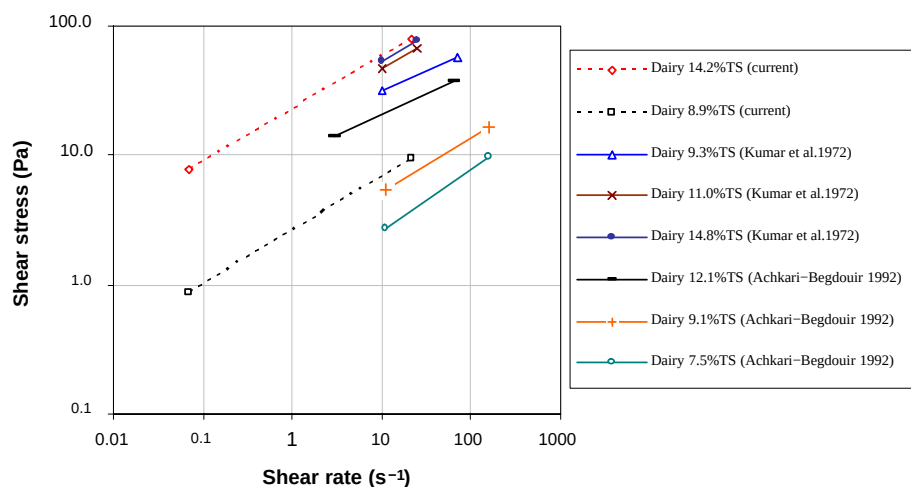


Figure 6. Shear stress – shear rate curves for dairy cattle manure (current study and other published results).

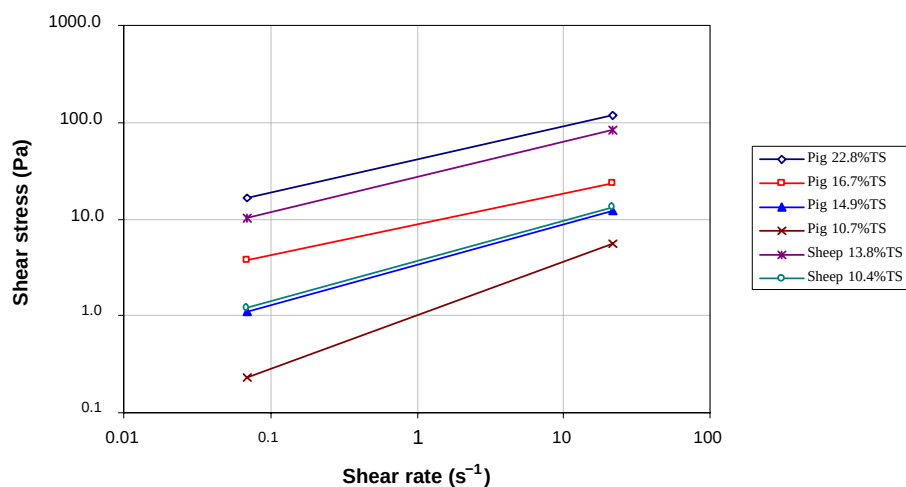


Figure 7. Shear stress – shear rate curves for sheep and pig manure.

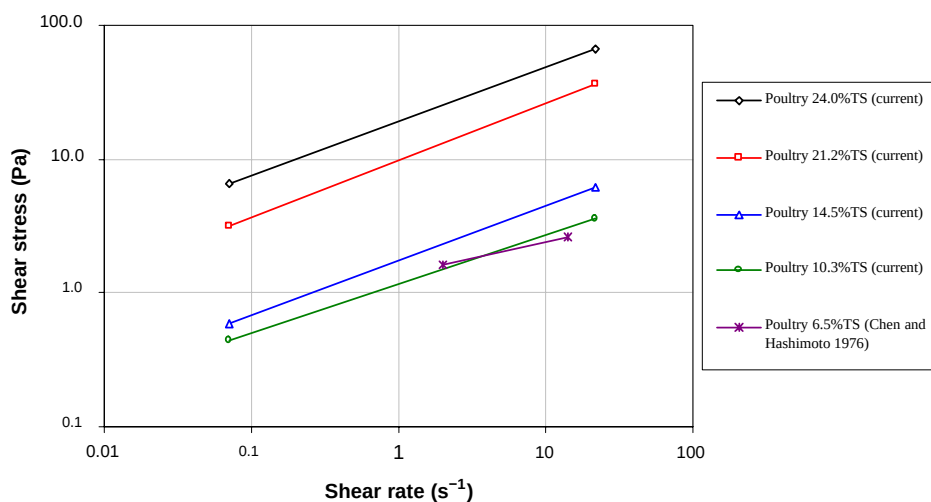


Figure 8. Shear stress – shear rate curves for poultry manure (current study and other published results).

and maximum shear rate values. Results from other studies (Kumar et al., 1972; Chen and Hashimoto, 1976; Achkar-

Begdour and Goodrich, 1992) have been included, using the same plotting method, to illustrate the similarities and

differences among results obtained for manure products originating from very similar sources.

If the viscometry results are further analyzed to evaluate the effect of total solids concentration on the consistency coefficient and flow behavior index using the results obtained with the laboratory viscometer, it can be seen that the value of K became significantly smaller with an increase in TS (table 6). The values of n, however, were not significantly different at various levels of total solids concentration except for pig manure for which the value of the flow behavior index was significantly higher for lower values of TS. This is consistent with the conclusions of Chen and Shetler (1983), but the relationship was not generalized enough to make this observation a conclusion. These observations can also be visualized on figures 6, 7, and 8. Even though a limited number of data were available, a relationship was identified between the consistency coefficient and the total solids concentration for poultry and pig manure. Similar relationships could be established using data obtained by Chen and Shetler (1983). Equations 12 and 13 can be used to predict the consistency coefficient for poultry and pig manure respectively within the ranges of total solids concentration (10% to 25%), temperature (17°C to 24°C), and shear rate (approximately 0.07 to 30 s⁻¹) of this study (where K is in Pa·sⁿ):

Table 6. Consistency coefficient (K) and flow behavior index (n) obtained using the laboratory viscometer.

	Total Solids Concentration (%)	Laboratory Viscometer	
		K (Pa·s ⁿ)	n (—)
Dairy cattle	14.2	22.9 [a] a [b]	0.41 a
		(8.3) [c]	(0.042)
	8.9	2.6 b	0.42 a
		(0.3)	(0.026)
Sheep	13.8	26.9 a	0.36 a
		(11.5)	(0.076)
	10.4	3.7 b	0.42 a
		(0.5)	(0.029)
Poultry	24.0	19.1 a	0.40 a
		(3.5)	(0.071)
	21.2	9.9 b	0.43 a
		(1.4)	(0.078)
	14.5	1.7 c	0.41 a
		(0.06)	(0.012)
Pig	10.3	1.2 c	0.37 a
		(0.07)	(0.022)
	22.8	41.1 a	0.34 a
		(4.7)	(0.018)
	16.7	8.9 b	0.32 a
		(0.9)	(0.036)
Pig	14.9	3.4 c	0.42 b
		(0.2)	(0.0058)
	10.7	1.0 c	0.55 c
		(0.04)	(0.018)

[a] Average value.

[b] Values within each manure type row and property column not followed by the same letter are significantly different as determined by Fisher's LSD test at the 1% level (a T-test was used when only two means were available).

[c] Standard deviation.

Consistency coefficient for poultry manure:

$$K = 0.14 TS^2 - 3.52 TS + 22.93; R^2 = 0.95 \quad (12)$$

Consistency coefficient for pig manure:

$$K = 0.33 TS^2 - 7.87 TS + 46.91; R^2 = 0.98 \quad (13)$$

To obtain a parameter that may be more useful for design purposes, it was possible to calculate the apparent viscosity (η_{app}) using equation (14) (Chen and Shetler, 1983):

$$\eta_{app} = K S^{(n-1)} \quad (14)$$

Plotting the apparent viscosity at a shear rate of 10 s⁻¹ against the total solids concentration on a log-log chart gave predictive equations 15, 16, and 17 (where η_{app} is in Pa·s):

$$\text{Dairy cattle: } \eta_{app} = 4E-05 TS^{4.4671}; R^2 = 0.95 \quad (15)$$

$$\text{Poultry: } \eta_{app} = 6E-05 TS^{3.4721}; R^2 = 0.94 \quad (16)$$

$$\text{Pig: } \eta_{app} = 4E-06 TS^{4.6432}; R^2 = 0.95 \quad (17)$$

The observed relationships between the apparent viscosity and the total solids concentration are in agreement with the relationship obtained by Chen and Shetler (1983). An analysis of the results obtained by several authors (Kumar et al., 1972; Chen and Hashimoto, 1976; Chen, 1982; Chen and Shetler, 1983; Achkari-Begdour and Goodrich, 1992) have demonstrated the heterogeneity of viscometry results highlighting the fact that the focus should be on determining ranges of acceptable values for manure properties. These results also showed that data obtained at several different times and locations still show similarities. The results of this study also suggested that processing animal manures to produce more homogeneous products in terms of physical and rheological properties may be the only effective way of making handling and land application equipment more efficient in terms of power requirement and uniformity of distribution. With the wide range of animal diets, management practices, and climates that can affect the properties of animal manures combined with differences between animal herds, as well as between individual animals, it is very difficult to design and operate machines with the objective of obtaining optimal performances. However, ranges of values for manure physical and rheological properties, such as the ones obtained in this study, should be the basis of any machinery design or optimization effort. Along with the judgment of the designing engineers, the knowledge base developed in the literature and in this study should allow for improved design and operation of manure handling and land application equipment, within the limits imposed by the inherent variability in the properties of animal manures.

CONCLUSIONS

Physical and flow properties of manure products were measured over a wide range of total solids concentration. Based on the results obtained, the major findings are:

- The density of dairy cattle, poultry, and pig manure was in agreement with ASAE D384.1 and other published results. Predictive equations based on total solids concentration were obtained.
- A method was proposed to calculate a modified value of the geometric mean length obtained by screening. Signifi-

cantly larger modified geometric mean lengths were observed as the total solids concentrations of the products decreased.

- Static friction coefficients were measured on different surface materials. For design purposes, the observation of similar values for most of the manure products over the majority of the tested surfaces led to a unique equation to predict the static friction coefficient as a function of total solids concentration.
- The animal manures studied were non-Newtonian pseudoplastic fluids and the power law could be used to relate shear stress and shear rate. The value of the consistency coefficient increased with the total solids concentration. The apparent viscosity was well correlated to TS for dairy cattle, poultry, and pig manure.
- For the design and analysis of manure handling and land application systems, the ranges of values presented can be used with proper care. Poultry and pig manure generally exhibited similar behaviors while dairy cattle and sheep manure showed similarities, though not as strong as the former due to the straw content of the tested sheep manure. The density values and friction characteristics of manure products were found to be consistent with other published results. The shear stress – shear strain relationships seemed however to be study-specific, but published values still showed similarities.

RECOMMENDATIONS

The lack of standard methods to measure the physical and rheological properties of organic by-products made the characterization of manure products more challenging. Some methods have successfully been used in this study and by other authors. For example, the oven method used to determine total solids concentration of the samples poses no difficulties. The inclined plane method is also a relatively simple means of measuring the static coefficient of friction. Other methods have proven to be more difficult to implement in a manure-testing program. The angle of repose, with a rather simple apparatus, did not give consistent results. The screening method presented in this study gave good results when the calculations were based on the bottom five screens of the six-screen set. It was, however, very labor-intensive to screen adhesive manure products. The results must also be interpreted with care, as the calculated characteristic dimension can become a measure of the aggregation ability of the tested sample. The change in particle size distribution from one TS level to another also includes the effect of the mechanical disturbances induced by the samples preparation. Different screening approaches should be suggested to enhance the potential information that such tests can yield. Innovative tests such as the triaxial test, the slump test, non-rotational viscometry or a test to measure the dynamic coefficient of friction should also be attempted. The pycnometer method used by Agnew et al. (2003) to measure the density of compost gave good results and would certainly be worth trying with other organic fertilizers. These new tests could deepen the knowledge of the engineering properties of manure products, potentially leading to improved ways of handling and land-applying organic by-products.

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