CHARACTERIZATION OF POULTRY LITTER

FOR STORAGE AND PROCESS DESIGN

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CHARACTERIZATION OF POULTRY LITTER

FOR STORAGE AND PROCESS DESIGN

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CHARACTERIZATION OF POULTRY LITTER FOR STORAGE AND PROCESS DESIGN

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THESIS ABSTRACT

THE CHARACTERIZATION OF POULTRY LITTER FOR STORAGE AND PROCESS DESIGN

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Concern over the world's dependence on nonrenewable fossil fuels as the primary source of energy is continually increasing. This has led researchers, industry officials and government agencies to begin to aggressively investigate the use of alternative and renewable energy resources such as biomass. Poultry litter, a combination of accumulated chicken manure, feathers, and bedding materials (obtained from broiler houses), is a potential biomass feedstock. In this study some of the characteristics of poultry litter (such as bulk density, particle density, compressibility, compaction and flowability) that are important for its storage and process design were examined. It was found that moisture content significantly affected the bulk density, particle density, and porosity of poultry litter. An average tap bulk density of 0.580 g/ml and Hausner ratio of

1.070 were obtained and were not affected by moisture content. Based on compressibility results, poultry litter was found to have good or excellent flow when pressures less than 12 kPa were applied to poultry litter samples at moisture contents of 26.0% (w.b.) and below. The fit of the GAB equation to poultry litter's equilibrium moisture isotherm (at 25°C) indicated that the monolayer moisture content for poultry litter is 5.8% (d.b.), implying that biochemical degradation occurs when the litter is stored at a moisture content greater than 5.8% (d.b.) or 5.5% (w.b.). To enhance storage and transportation, the effect of moisture content and pressure on the compaction of poultry litter was investigated. The initial density of the compacts, the energy required for compaction and the strength of the resulting compacts (after two months storage) were significantly affected by the moisture content of the samples and the pressure applied during compaction. However, the density of the compacts after two months storage was only significantly affected by the pressure applied during compaction. Increasing the moisture content of the poultry litter reduced its flowability (hence increased particle cohesion) from easy flowing (flow index of 6.369) at a moisture content of 10.3% (w.b.) to very cohesive/non-flowing (flow index of 1.871) at a moisture content of 30.9% (w.b.). The adhesion of poultry litter to the milled steel surface was reduced when the surface was modified. The carbon coated steel surface had the least adhesion in comparison to the aluminum surfaces and mirror finished steel surface. The findings from this study can be used to design and/or select optimal equipment and facilities to handle, store and transport poultry litter for value-added utilization.

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CHAPTER 1. INTRODUCTION

A significant amount of companies, businesses, governmental agencies, and institutions are beginning to invest in alternative energy because of the current high cost of energy obtained from fossil fuels. Energy production through biomass, which is abundant in this country and can be used as a carbon based fuel, is one of the promising renewable energy options being vigorously pursued in the US because of its positive environmental implications. In order for the large scale use of biomass as an alternative energy source to be realized in the US, more research must be done to characterize its physical properties. Without the knowledge of these properties, optimal design and selection of equipment and facilities to handle, store, and transport biomass cannot be achieved.

Poultry litter is one of the biomass feedstocks that can be utilized as a renewable resource for bioenergy production in the US. Poultry litter is a combination of accumulated chicken manure, feathers, and bedding materials found in broiler houses. The bedding materials are often made up of wood shavings, sawdust, wheat (*Triticum aestivum L.*) straw, peanut (*Arachis hypogaea L.*) hulls, or rice (*Oryza Sativa L.*) hulls (Edwards and Daniels, 1992). These broiler houses are located in concentrated areas across the country. Estimates indicate that about 11 million tons of poultry litter is generated in the country annually (Gollehon et al, 2001).

Poultry litter has a calorific value of 13.5 GJ/ton, about half that of coal (Abelha et al, 2002). Because of this there are plans around the world (e.g. Western Australia, Ireland, Britain) and in the U.S. to build large scale powerstations that use poultry litter as its feedstock (http://www.eprl.co.uk/profile; http://www.fibrowattusa.com). Poultry litter also has the potential to be used for the production of methane and the production of activated carbon for water purification purposes (Hills and Ravishanker, 1984; Safley et al, 1987; Lima and Marshall, 2004).

Poultry litter is, however, a bulk solid. The effective design and selection of storage, transportation and processing facilities and equipment of bulk solid materials requires information on its physical and flow properties and the effects of moisture on these properties. This information is currently lacking for poultry litter.

Traditionally, poultry litter is utilized in places of production as a fertilizer partly because of the expensive cost of transporting the low-density litter. The utilization of poultry litter for bioenergy and other value added applications will require that the litter be transported over long distances. Compaction or agglomeration of the litter will significantly reduce the cost of transportation. Other benefits such as low dust generation, minimal spread of pathogens, and a more uniform product can also be realized by compacting the litter.

Therefore, the main objective of this study is to investigate some of the properties of poultry litter that are crucial for process design and value added utilization. To achieve this, the following specific tasks were carried out:

(1) Characterization of the physical properties (particle size distribution, bulk density, tap bulk density, particle density, porosity, Hausner ratio,

compressibility, and equilibrium moisture relations) of poultry litter and the effect of moisture content on these properties,

(2) Optimization of the compaction of poultry litter for effective transportation for off-site utilization, and

(3) Characterization of the flow properties (flow function, cohesion, internal angle of friction, wall friction flow function, and angle of wall friction) of poultry litter and the effect of moisture content on these properties.

Chapters 3, 4, and 5 of this thesis each contain separate studies corresponding to the three tasks above: chapter 3 is on the moisture dependent physical properties of poultry litter; chapter 4 is on the compaction of poultry litter; and chapter 5 is on the flowability of poultry litter. Each chapter has a separate set of sections (introduction, set of objectives, methods and materials, results and discussion, conclusion, and references).

CHAPTER 2. LITERATURE REVIEW

2.1 Bioenergy

The need to obtain energy from sources other than fossil fuels is becoming more apparent everyday. Oil prices hit record highs in April 2006 (rising to over $74 per barrel in New York trading) and are expected to increase. In 2002, the price of oil was roughly $28 per barrel (www.washingtonpost.com). These prices already far exceed projections from the Department of Energy, which only predict the price of petroleum in 2010 to be $48.24 per barrel. These increases in price make research into the use of biomass as an alternative energy source a necessity. In addition to this, the total renewable energy generation in the United States is projected to grow by 1.7% per year due to expected improvements in technology, higher prices of fossil fuels, and extended tax credits provided by both the federal government's Energy Policy Act of 2005 and other state renewable energy programs (http://www.eia.doe.gov/oiaf/aeo/index.html). Because of all these factors, bioenergy has future economic potential.

Bioenergy is defined as energy derived from biomass. This includes biopower (electricity or industrial process heat or steam generated from biomass or intermediate byproducts), energy from biobased transportation fuels, and energy from biomass materials that are used for process or space heating. Biomass is defined as organic materials that are plant or animal based, including but not limited to dedicated energy crops, agricultural crops and trees, food, feed and fiber crop residues, aquatic plants, forestry and wood residues, agricultural wastes, biobased segments of industrial and municipal wastes, processing by-products and other non-fossil organic materials (ASABE Standard S593, 2006).

Biomass is a renewable energy source and is very friendly to the environment especially when compared to fossil fuels. The combustion and regrowth of biomass is a process which recycles atmospheric carbon. As a result, biomass power contributes virtually zero net emissions of CO_2. Fossil fuels on the other hand contribute over 600,000 kg (or 660 tons) of CO_2 for every gigawatt-hour of energy produced (Easterly and Burnham, 1996).

2.2 Poultry Litter

Poultry litter is a combination of accumulated chicken manure, feathers, and bedding materials. The bedding materials are often made up of wood shavings, sawdust, wheat (*Triticum aestivum L.*) straw, peanut (*Arachis hypogaea L.*) hulls, or rice (*Oryza Sativa L.*) hulls (Edwards and Daniels, 1992). In the United States close to 11 million tons of poultry litter is produced annually (Gollehon et al, 2001). Approximately, 2.7 million tons of broiler litter were produced in the state of Alabama in 2004. The production of broilers has continued to increase every year. Between 2002 and 2005 the number of broilers in the US increased from 8.59 billion to 8.87 billion (http://usda.mannlib.cornell.edu). This implies that the production of poultry litter will continue to rise. Therefore, it is urgent that value added utilization methods are identified for poultry litter.

2.2.1 Poultry litter as a fertilizer

Poultry litter is nutrient rich with typical N:P:K ratios of 6:2:3, which make it an excellent fertilizer (Nicholson et al, 1996). Unfortunately, in broiler producing states such as Alabama, Arkansas, Delaware, Georgia, Maryland, Mississippi, North Carolina, West Virginia, and Virginia, broiler houses are typically found in small concentrated areas. Large amounts of poultry litter are therefore produced in these areas that are beyond the fertilizer requirements of the neighboring agricultural areas (Ndegwa et al, 1991). The result is excessive use of poultry litter in some cropping systems that has resulted in reports of nitrate contamination of ground water in some of these areas (Bitzer and Sims, 1988). Improperly dispensed poultry litter can contribute to air pollution with the release of CH_4, NH_3, H_2S, amides, volatile organic acids, mercaptans, esters, and other compounds (Sweeten et al, 2003).

As a result of the problems mentioned in the previous paragraph regarding the disposal of poultry litter, the environmental regulation agencies in these areas are beginning to examine the methods being used to dispose poultry litter more carefully. In the state of Alabama the application of manure on pastureland and cropland in north Alabama is prohibited by ADEM (Alabama Department of Environmental Management) for most of the fall and winter months of the year (November 15 to February 15) (Mitchell and Tyson, 2002). In Maryland, the Quality Improvement Act was passed in 1998. It contains regulations concerning the application of manures and inorganic fertilizers to crops. This has already caused some Delmarva counties in the state of Maryland to realize the need to investigate alternative uses of broiler litter due to the excessive amounts they produce (Carr, 1998).

2.2.2 Poultry litter as an energy source

Air-dried poultry litter samples have a typical calorific value of 13.5 GJ/ton about half that of coal (Abelha et al, 2002). Despite this, several countries around the world have started utilizing poultry litter as a renewable energy resource. For example in Ireland, a small scale fluidized bed combustor that uses poultry litter or a poultry litter and peat mixture (50% of each) as feedstock is being installed to heat poultry houses (Abelha et al, 2002). Energy Power Resources Limited in the United Kingdom is currently operating three large scale power stations that are run on the combustion of poultry litter as the primary biomass. Each of these plants also produces ash which is sold as a safe alternative to super phosphate fertilizers. The plant in Eye, UK consumes 140,000 tonnes of poultry litter to produce 12.7 MW of power annually. The plant in Westfield, UK consumes 110,000 tonnes of poultry litter to produce 9.8 MW of power annually. The plant in Thetfield, UK consumes 420,000 tonnes of poultry litter to produce 38.5 MW of power annually (http://www.eprl.co.uk/profile).

Fibrowatt LLC, which runs Energy Power Resources Limited in the UK, is planning more litter powered plants to the US. In early 2007, it plans to launch a power plant run on turkey litter in Minnesota. This will be the first plant of its kind in the US and it will consume 700,000 tons of turkey litter to produce 55 MW of power annually. Plans to build similar plants that are run on poultry litter and forest residue mixtures (approximately 2:1) are being developed in Mississippi, and Maryland with an annual poultry litter consumption and power production estimates of 200,000-300,000 tons and 40 MW, and 200,000-300,000 tons and 30-40MW (http://www.fibrowattusa.com).

The major benefit of poultry litter as an energy source is the low amount of emissions it produces when combusted. As stated earlier there are no net CO_2 emissions in its use (Easterely and Burnham, 1996). Furthermore, with proper optimization of the combustion process CO emission levels can be controlled and lowered to permissible levels (Abelha et al, 2002; Henihan et al, 2003; Zhu and Lee, 2004). It is also recognized that SO_2 emissions always remain low because poultry litter has a low sulfur content. These emissions are even further lowered as ash is produced because the Ca in it acts to retain the small amounts of SO_2 that are released in the process (Abelha et al, 2002). Whenever poultry litter was used by itself or in conjunction with other energy sources, NO_x emissions were always considered low in comparison to other methods of energy production (Sweeeten et al, 2003; Sami et al, 2000; Zhu et al, 2004; Albeha et al, 2002; Henihan et al, 2003).

Coal produced 32% of the nation's energy in 2004, and is projected to continue to increase its production to 38% of the nation's energy by 2030 (http://www.eia.doe.gov/oiaf/aeo/index.html). Using poultry litter in conjunction with coal appears to be a very attractive option. The co-firing of coal and biomass is advantageous for many reasons. It reduces fossil fuel based CO_2 and it reduces NO_x. Biomass can be cheaper than coal. It can also potentially reduce the soil, water, and air pollution that may be associated with excess amounts of waste by creating an economic method for waste disposal (Sweeten et al, 2003). The majority of NO_x emissions from coal-fired plants come from fuel N_2 reacting with oxygen at high temperatures. Poultry litter when optimally used with the coal in staged co-combustion can drastically reduce these emissions by avoiding this reaction (Sami et al, 2000).

The co-combustion of poultry litter with other energy sources, such as natural gas, has also been explored. At optimal operating conditions, the co-combustion of poultry litter with natural gas in an advanced swirling fluidized bed combustor can have a carbon combustion efficiency of 89%, providing a cost effective disposal system for farmers with excess waste. This was also shown to be another low emission environmental friendly system for the production energy (Zhu and Lee, 2004).

Poultry litter can also be used to make energy by converting it into methane, which is a gas that can be used as a fuel. Putting poultry litter through an anaerobic digester in order to form methane gas has been a well established process (Hills and Ravishanker, 1984; Safley et al, 1987). Kinetic models have been created for this process relating gas yield to influent concentration and retention time of the digester (Webb and Hawkes, 1985). The economic analysis for anaerobic digestion of poultry litter done by Collins et al (2002), suggests that areas with large concentrations of broilers could possibly support a commercial size operation for the production methane, provided that a disposal fee for the poultry wastes brought to a facility was put in place, or if the digested solid effluent could be sold as a fertilizer (market value above that of the original poultry litter).

Combustion of only poultry litter can also be carried out, provided that the moisture content of the litter is less than 25%. A fluidized bed was used by Abelha et al (2002) to combust poultry litter. As with the co-combustion methods, the pure poultry litter combustion method resulted in the formation of NO_x well below EU standards and all heavy metals in the ash were also below EU standards. Through process optimization CO emissions were also reduced to acceptable levels. Henihan et al (2003) further reported that the same fluidized bed system can be used for poultry litter with moisture contents greater than 25% if the poultry litter was mixed (1:1 ratio) with peat.

2.2.3 Poultry litter for use as activated carbon

Another example of a value added product that can be obtained from poultry litter is activated carbon. Activated carbon is obtained by charring the litter to at least 700^{o} C resulting in the formation of a lattice-like carbon particle structure in the poultry litter. The activated carbon produced can then used for the adsorption of impurities in wastewater (Lima and Marshall, 2004). The present demand for activated carbon in the US is 420 million lbs a year and the demand has been growing by 3% yearly. Activated carbon for the adsorption of impurities in wastewater is currently being manufactured with bituminous coal and coconut shells. Coal is an expensive non-renewable resource and coconut shells are not readily available in the US. Poultry litter is an inexpensive renewable resource that is produced in mass quantities in the US making its use a viable option (Lima and Marshall, 2004).

2.2.4 Composition analysis

The exact elemental composition of poultry litter can vary depending on the management style in the poultry house. The major elements found in poultry litter are carbon, nitrogen, phosphorus, and potassium. In addition to these elements, lesser amounts of Ca, Mg, Cu, Fe, Mn, and Zn have also been detected in poultry litter (Sistani et al, 2003). Since poultry litter is traditionally used as a fertilizer, research regarding the compositional make up of poultry litter has mainly focused on its fertilizing nutrients:

nitrogen, phosphorus, and potassium. The typical N:P:K ratios of poultry litter are 6:2:3 (Nicholson et al., 1996).

The concentration of carbon in poultry litter will however become much more important if litter is to be used as a renewable fuel. This is because its combustion involves the exothermic chemical reaction of a fuel or organics, which by definition contain carbon, with oxygen. The reaction usually produces heat, CO_2, H_2O, and NO_x, along with lesser amounts of by products depending on the fuel being combusted (Zumdahl and Zumdahl, 2007). Furthermore, the amount of methane and activated carbon that can be produced using poultry litter is also dependent on the amount of carbon present. Zhu and Lee (2004) reported that the poultry litter used in their combustion was 13.71 weight percent fixed carbon. They also reported a moisture, volatile, and ash contents of 15.02, 40.35, and 30.92 weight percents, respectively.

It should also be noted that the elements observed in the poultry litter may be distributed with different concentrations depending on the areas throughout the material that are sampled. A study of the concentration of nitrogen, phosphorus, and potassium according to particle size revealed that, while the phosphorous and potassium had relatively the same concentration throughout, the nitrogen did not. The fine particulate was found to contain a higher concentration of nitrogen (Ndegwa et al, 1991). Unfortunately, there was no mention of how carbon varied with particulate size.

As one might expect, fecal coliforms (bacteria that inhabit the intestinal tract of warm-blooded animals and indicate the presence of bacterial pathogens), such as *Escherichia coli, Enterobacter aerogenes, Klebsiella pneumoniae,* and *Citrobacter freundii*, have been found in poultry litter. The levels of fecal bacteria are primarily affected by moisture, temperature, and pH. In order to decrease the amount of fecal bacteria in poultry litter, it is recommended that the poultry litter be stacked and aged. Within 8 days it was observed that the fecal coliforms reduced to below detectable levels (Hartel et al, 2000). An evaluation of broiler litter microbial composition did not detect the presence of pathogens, such as *Salmonella*, *Escherichia coli*, *Compylobacter* spp., *Yerersinia* spp., *Listeria* spp., or toxigenic *staphylococci*. However, bacteria associated with the degradation of wood and the cycling of nitrogen and sulfur, such as *Globicatella sulfidofaciens, Corynebacterium ammoniagenes, Corynebacterium urealyticum, Clostridium aminovalericum, Arthrobacter* sp., and *Denitrobacter permanens,* were found (Lu et al, 2003).

2.3 Physical Properties

Poultry litter is a bulk solid. Bulk solids are composed of many particles of varying sizes (and possibly slightly varying shape), chemical composition, and densities, that are randomly grouped together in order to form a bulk (Woodcock and Mason, 1987). Therefore, the characterization of bulk solid behavior will involve characterizing the individual particles that comprise the bulk material. Individual particle properties of interest include particulate size, shape, particle density, particle size distribution, and particle surface area, while the bulk properties needed to characterize poultry litter include bulk density, porosity, flow properties, compressibility, strength properties, moisture content, and water activity. Knowledge of these properties is needed to optimize the conditions required to process, store, and handle bulk materials. This will in turn result into saving in handling costs, improved utilization of men, machines, and space, and reduced amounts of material wastage (Shamlou, 1988).

2.3.1 Size

Size is considered the most important characteristic of particulates. This is because it is directly used to calculate properties such as surface area, and volume. It should be mentioned that size is always represented as a distribution because the shape and size of the particulates vary throughout a bulk solid. Methods that are used to measure the size of bulk biological materials include sieving, digital imagery analysis and a laser based system. Sieving is the simplest and the cheapest and is therefore mostly used for size determination. ASABE standard S319.3 (ASABE, 2003) is often used to estimate the average size and distribution of agricultural materials.

Ndegwa et al (1991) reported that the chemical composition of poultry litter varied with particle size. Their experiment divided the poultry litter into three distinct fractions: the fine fraction, the middle fraction, and the coarse fraction. They had a fine fraction that was made up of particulate that had particle sizes less than #20 mesh screen (0.83 mm). This portion of the material was a uniform brown powdery material that had the ability to clump together when squeezed. Manure, small amounts of split feeds, and saw dust were believed to be the contents. The middle fraction consisted of particulate that had particle sizes between the #20 (0.83mm) and the #6 (3.3 mm) mesh screens. This fraction was largely made up of small wood chips, saw dust, and some unidentified small flaky materials. The largest particulate in the poultry litter was found in the coarse fraction. These particles were too large to fit through the #6 (3.3 mm) mesh screen.

2.3.2 Bulk density

In general bulk density is obtained by measuring the mass of a material that occupies a container of known volume. The method of filling the sample container will determine the type of bulk density that is measured and the qualifier used when discussing the measurement (Woodcock and Mason, 1987). Traditionally, there are three different types of bulk densities. These are aerated, poured, and tap (Barbosa et al, 2005).

Aerated bulk density is a measure of the material's density when its particulates are in their most loosely packed form. The complicated approach used to obtain aerated bulk density can be found in Barbosa et al (2005). Because of the amount of complication involved most researchers do not measure the aerated bulk density of particulates.

The poured bulk density is the most common type of bulk density that is measured. This is obtained by pouring a sample into a container of known volume. The ratio of the mass of the material that filled the container to the size of the container is taken as the poured bulk density (Barbosa et al, 2005).

The tap bulk density is the ratio of the mass of the material to its volume after it has been closely packed together. Packing is achieved by repeatedly dropping the sample from a height of 14mm according to ASTM Standard B527 (ASTM 2005).

Quantifying the effect of moisture content on the poured and tapped bulk density is crucial to the behavious of biological materials during storage, handling and transportation (Barbosa et al, 2005).

2.3.3 Particle density

There are two types of particle density- apparent and true. True particle density is the mass of the particulate divided by its volume excluding open and closed pores. Apparent particle density is different only in that it includes the volume of closed pore within its calculation of the particulate volume (Woodcock and Mason, 1987). Measurement of the true density is often achieved by means of a helium pycnometer (Vianna et al, 2002). Apparent particle density is best obtained from size measurements of the particles.

2.3.4 Porosity

Porosity is a function of the poured bulk density and the true particle density. It is the amount of space in a bulk solid that is not occupied by a particulate and it is sometimes referred to as voidage. Porosity can be a good prediction of the sphericity or irregularity of the particles in a bulk solid. If particles are spherical, their porosity is on average around 0.4, while more irregular shapes have higher porosity values (Woodcock and Mason, 1987).

2.3.5 Hausner ratio

The Hausner ratio is a function of the tap and poured bulk density (Equation 2.1). The Hausner ratio is often used to indicate how easily a powder is fluidized (Geldart et al, 1984).

$$H_R = \frac{\rho_n}{\rho_o} \tag{2.1}$$

Where the ρ_n is the tap bulk density after n number of taps and the ρ_0 is the poured bulk density (Hayes, 1987). Powders that are easily fluidized have Hausner ratios less than 1.25, while those that have fluidization problems have Hausner ratios greater than 1.4 (Geldart et al, 1984). The Hausner ratio is affected by particle shape and size. Attempts have therefore been made to develop equations that relate the Hausner ratio as a function of the deviation of particulates from ideal spheres (Guo et al, 1980) including an index of powder shape based on the Hausner ratio (Kostelnik and Beddow, 1970).

2.3.6 Compressibility

Unintentional compression of bulk solids is undesirable during their storage, handling and transportation, because it often leads to flow problems. The compression of bulk solids may be due to vibrations (e.g. during transportation), due to the weight above it (sometimes called mechanical compression) (e.g. during storage), or a combination of both. Tap bulk density is often used to quantify the vibrational compressibility of a material. The mechanical compressibility of a material is usually quantified from the results obtained from a piston cylinder arrangement that is attached to the cross head of a universal testing machine such as a texture analyzer. A known force is applied to the bulk powder and the mechanical compressibility of the powder is obtained from the resulting data (Barbosa et al, 2005).

2.3.7 Equilibrium moisture relationships

Biomass materials such as poultry litter are hygroscopic in nature and will therefore exchange moisture with their surrounding environment. Knowledge of equilibrium moisture behavior is needed to prevent the spoilage of poultry litter during storage, which may reduce the fuel value and quality of the litter (Jenkins, 1989).

There are at least 77 different equations that have been developed to model moisture sorption isotherms (Bruin and Luyben, 1980). One of the most commonly used models is the Guggenheim-Anderson-de Boer or GAB equation (Equation 2.2) (Rao and Rizvi, 1986).

$$EMC = \frac{M_o * C * K * RH}{(1 - K * ERH)(1 + (C - 1) * K * ERH)} \tag{2.2}$$

where EMC is the equilibrium moisture content (g water/g solids), ERH is the equilibrium relative humidity (decimal), M_o is the monolayer moisture content (%), C is the constant related to monolayer sorption heat, and K is the constant related to multilayer sorption heat (ASAE Standard D245.5, 2000).

The GAB equation is a refinement of Brunauer-Emmett-Teller (BET) equation. It assumes layered localized physical adsorption of moisture with no lateral interaction just as the BET equation does. It differs from the BET equation in that the added third parameter assumes that the multilayer molecules interact with the sorbent with an energy level range somewhere between the monolayer molecules of the solid and the bulk liquid. When the third parameter is unity, the GAB equation simplifies to the BET equation. In addition, instead of being limited to water activities between 0.05 and 0.45 as is the case with the BET equation, the GAB equation can be used for water activities between zero and 0.9 (Rao and Rizvi, 1986). As stated by Van den Berg (1984), the GAB equation's major advantages are its theoretical background, its accuracy for describing sorption rates over almost the entire range of water activities, its simplicity in only using three parameters, its constants have physical meaning, and the fact that its parameters can be broken down into Arrhenius style equations when temperature effects are to be included in the model.

2.4 Compaction of Poultry Litter

Agglomeration is the process of using short range physical forces to form larger entities from smaller particulate (Pietsch, 2002). For agglomeration to be effective, the bonds formed between the particulates must be strong enough to prevent breakage during storage, handling and transportation of the agglomerate. Some of the advantages of a agglomerated or compacted material include

(a) Improving storage and handling characteristics (Colley et al, 2005),

(b) Handling a material with a lower dust content, thereby reducing primary and secondary pollution. Biosecurity is also important to poultry litter during transportation. Poultry litter that is transported from a place of production to a place of utilization might result in exposure in pathogen contamination in communities between these two areas (Fasina et al, 2006).

(c) Increasing bulk density and lowering bulk volume thus reducing the cost required to store and transport poultry litter,

(d) Handling a material of defined size, shape and weight, and

(e) Improving product appeal.

There have been several efforts to densify poultry litter by pelletization (McMullen et al, 2005; Lichtenberg et al, 2002). McMullen et al. (2005) reported that pelleting can be used to increase the density (hence decrease the amount of space required for storage and /or transportation) by more than three fold. Pelletizing is however an expensive process (about \$50-\$60 per ton) because of the high amount of energy required for the processing. Pelleting is therefore not economical for compacting agricultural wastes. Moreover due to the energy requirements of the pellet mill and the complexity involved in operating a pellet mill, it is not feasible for every broiler farmer to own a pellet mill. Colley et al (2005) reported that the pressure required to pelletize (4.9 to 7.9 mm diameter) poultry litter ranged from 8 to 22 MPa (1172 to 3256 psi). This resulted in pellets with particle densities of 1350 kg/m^3 to 1450 kg/m^3 (84.2 lb/ft^3 to 93.7 lb/ft^3).

Densification methods such as baling and cubing are less costly and less energy intensive when compared to pelleting. In general, cubes and bales have smaller densities than pellets. Bales and cubes typically have densities of 161 kg/m^3 and 870 kg/m^3 (10 lb/ft^3 and 54 lb/ft^3), respectively (Sokhansanj and Turhollow, 2004).

Cubing is a volume reduction agglomeration process that uses pressure, it is similar to pelleting except that lower pressures are applied. As the name implies, cubes are formed with a square cross section of chopped biomass, typically varying from 12.7 to 38.1 mm (Sokhansanj and Turhollow, 2004).

Baling is a process that combines compression and packing (tying with ropes or wrapping) operations, it is typically used for grassy or fibrous-like materials that are stringy in nature (Badger, 2003). The property of compaction is therefore crucial to the development and design of baling equipment. Poultry litter is not stringy and therefore the low-cost volume reduction method that can be developed is limited to pressure agglomeration. Bale dimensions are roughly 44 in by 49 in (Badger, 2003).

2.5 Flowability

Flowability of poultry litter is also very important to the efficient design of large-scale storage and conveying systems for poultry litter. Flowability is influenced by other bulk properties such as bulk density, porosity, and compressibility. Flowability is a measure of the cohesiveness and adhesiveness of bulk solids. Bulk solids with strong cohesion have particles that have a tendency to “stick” to one another due to strong attractive forces between the particles. Bulk solids with strong adhesion have particles that have a tendency to “stick” to the walls of storage containers. The cohesiveness and adhesiveness of a bulk material are obtained from flowability tests. In general, moisture content significantly influences the cohesiveness and the adhesiveness of bulk solid materials (Woodcock and Mason, 1987).

Bulk solids that are stockpiled in silos for storage purposes are often gravity discharged from the bottom of the silo at the time of use. The two types of flow that occur in the silo are mass flow and funnel flow. During mass flow, all the particles move when the outlet is opened thereby resulting in uniform flow. In funnel flow only some of the material moves when the outlet is opened while the rest remains stagnant. This may lead to problems such as rat holing, increased segregation, and a tendency of degradation over time of the stationary region. Therefore funnel flow is only desired during the storage and discharge of coarse, free-flowing non-degrading bulk solids. Mass flow bulk solids can also develop problems such as arches. When arches form within silos flow is halted. There are two types of arches mechanical and cohesive. Mechanical arches form when large particles interlock with one another. Cohesive arches form when small particles consolidate due attractive forces and become stable. Flow problems such as ratholing and arching can result in structural failure and damaging of silos. These flow problems can be avoided if results from the material's flowability test is taken into account during the design and selection of silos, bins, and hoppers (Shamlou, 1988).

Although properties such as particle size and moisture content do affect flowability, there is no strong mathematical relationship between these properties and cohesiveness and adhesiveness. Wall friction is one of the most important parameters in determining whether mass flow or funnel flow will occur. Jenike's mathematical analyses that uses data from wall friction tests is often used to determine the minimum hopper angle and the opening size for a mass flow system (Fitzpatrick et al, 2004).

In order to quantify the flowability and the cohesiveness of bulk solids, measurements of a material's shear strength is normally carried out. This test was developed by Jenike in 1964 and it involves a tangential shear cell (Figure 2.1) that measures the shear stress (τ) of a material while varying the pressure (σ) applied to the top of the material. At a given normal force (V = Aσ), the tangential force (S = Aτ) would increase until the material would fail or shear. The shear strength was obtained from the tangential force required to fail the material.

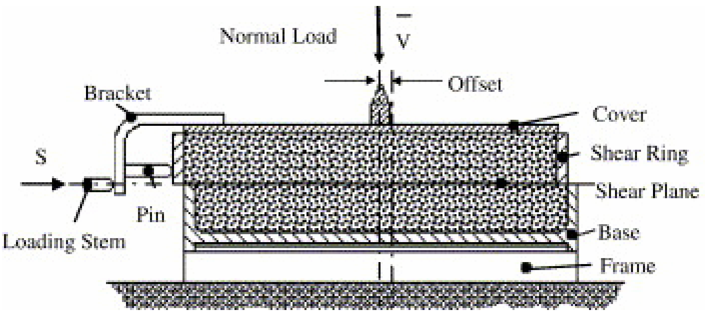

Figure 2.1 Jenike shear cell (Zulfiqar et al, 2006)

The yield locus is obtained from the plot of the normal force vs. the shear force. The flowability of a material is then obtained from the yield locus graph (Figure 2.2).

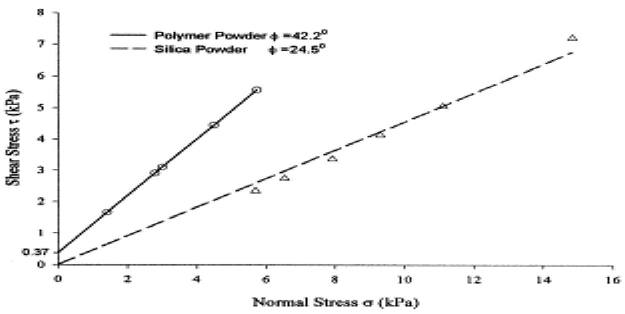

Figure 2.2 Yield locus plot (Klausner et al, 2000)

For any shearing to take place the angle of internal friction (ϕ) for that material must be overcome. Graphically the angle of internal friction is equal to the angle of the yield locus. No deformation or flow of the material can occur as long as $S < V \tan \phi$, but once $S = V \tan \phi$, slip takes place. If a material is free flowing, the plot of the graph intersects at the origin. If the material is cohesive the graph begins at a point where $S > 0$ when $V = 0$ (Jenike, 1964). For example, Figure 2.2 shows that the polymer powder is cohesive. The silica powder is free flowing in nature. Its angle of internal friction is smaller than that of the polymer powder.

The flow function graph is obtained by plotting the ultimate yield stress (UYS; Equation 2.3) vs. major consolidating stress (MCS; Equation 2.4) of a material (Figure 2.3). The UYS and MCS are calculated by using the data in a series of yield locus plots. This type of graph is very good at characterizing flow and the inverse of the slope of this line is a materials flow index (Fitzpatrick et al, 2004; Teunou et al, 1999). These values are mathematically defined as follows:

$$UYS = \frac{2c(1+\sin\phi)}{\cos\phi} \tag{2.3}$$

$$MCS = \left[\frac{A-\sqrt{A^2\sin^2\phi-\tau^2\cos^2\phi}}{\cos^2\phi}\right](1+\sin\phi)-\frac{c}{\tan\phi} \tag{2.4}$$

Where $A = \sigma + \frac{c}{\tan\phi}$

and c is cohesion defined as τ at $\sigma = 0$.

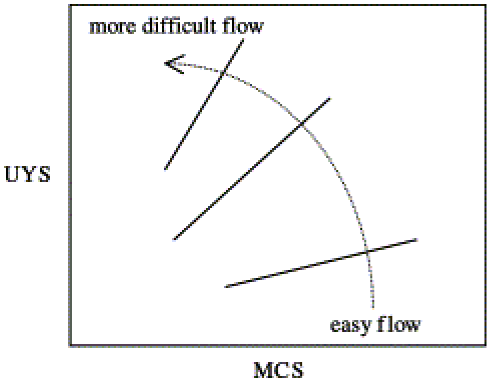

Figure 2.3 Flow function graph (Fitzpatrick et al, 2004)

By replacing the base container of the shear cell with a sample of the wall (Figure 2.4) that will be used for storage container and then applying the same method, Jenike (1964) was also able to find the wall yield locus (WYL) and the kinematic angle of friction between a bulk solid and a channel wall (ϕ’).

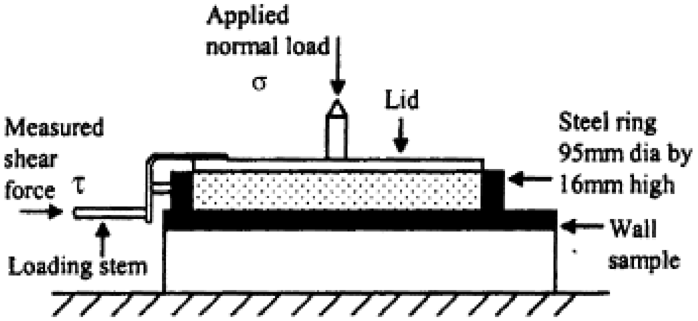

Figure 2.4 Jenike shear cell with wall sample (Iqbal and Fitzpatrick, 2006)

From his research, Jenike (1964) also found some general trends regarding the flowability of bulk solids. He discovered that bulk solids in silos tended to gain strength over time i.e. the value of S at V = 0 is increased. He attributed this to the compaction of the material increasing with moisture content. The compaction of the material was attributed to an escape of entrained air, external vibrations that cause the rearrangement of particles, the break up and softening of particles resulting in an increase of cohesiveness. While the migration of water and evaporation of water led to changes in moisture content over time, he also found that bulk solids which contained a range of sieve sizes including fine and coarse, such as poultry litter, generally had their flow properties governed by the fine fraction.

Jenike's work culminated with the development of equations for calculating the minimum outlet dimension of a channel (B in meters; Equation 2.6) and the diameter needed for a pipe to carry a given bulk solid (D in meters; Equation 2.7) as follows:

$$B = \frac{H(\theta')V}{A\gamma} \tag{2.6}$$

Where H(θ') (kg) is found within graphs he developed based on the slope of the angle of the channel, V (m^3) is the normal load, A is the area (m^2), and γ is the bulk weight (kg).

$$D = \frac{G(\phi)V}{A\gamma} \qquad (2.7)$$

Where G(ϕ_t) (kg) is found within graphs he developed based on the angle (^{o}) of friction between the bulk solid and the wall, V is the normal load (Pa), A is the area (m^2), and γ is the bulk weight (kg) (Jenike, 1964).

Although the use of Jenike's shear cell is well established its limitation is that the tests cannot be automated. Therefore this has led to the development of the rotational shear testers (Figure 2.5).

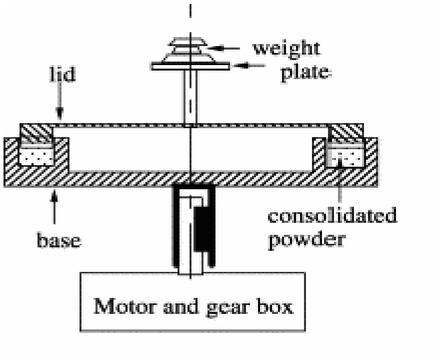

Figure 2.5 Annular shear cell tester (Fitzpatrick et al, 2004)

2.6 Summary

New uses of poultry litter as a renewable energy source through many different processes are currently being investigated and appear to be environmentally safe methods for energy production. Poultry litter also has the potential to be digested into methane and to be carbonized into activated carbon for adsorption of impurities in wastewater. By understanding the physical properties and the flowability of poultry litter efficient materials handling can be achieved and optimal storage and process facilities can be developed. This, in turn, will cause savings to handling costs, improved utilization of manpower, machines and storage space, and reduced amounts of material wastage. Furthermore, the development of an economical large scale agglomeration procedure for poultry litter will be crucial to its value-added utilization in the bioenergy economy.

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CHAPTER 3. MOISTURE DEPENDENT PHYSICAL PROPERTIES OF POULTRY LITTER

3.1 Introduction

Poultry litter is a combination of accumulated chicken manure, feathers, and bedding materials found in broiler houses. The bedding materials are often made up of wood shavings, sawdust, wheat (*Triticum aestivum L.*) straw, peanut (*Arachis hypogaea L.*) hulls, or rice (*Oryza Sativa L.*) hulls (Edwards and Daniels, 1992). In the United States, close to 11 million tons of poultry litter is produced annually (Gollehon et al, 2001). Unfortunately, the production of poultry litter occurs in concentrated areas in the states that are noted for broiler production (Alabama, Arkansas, Delaware, Georgia, Maryland, Mississippi, North Carolina, West Virginia, and Virginia; Ndegwa et al, 1991).

Presently, the most common use for poultry litter is application to cropland as a fertilizer because of its typical N:P:K ratios of 6:2:3 (Nicholson et al, 1996). However, the large amounts of poultry litter created in small areas are beyond the fertilizing needs of the neighboring agricultural areas (Ndegwa et al, 1991). The result is the excessive use of poultry litter on these lands that has resulted in ground water and surface water problems as excess nutrients run off of the land or leach into the ground water supplies, respectively (Moore et al, 1998; Wood et al, 1999). Therefore, environmental regulating agencies in these states are beginning to examine the methods used for the disposal and the utilization of poultry litter. For example, in the state of Alabama, the application of manure on pasture land and crop land in north Alabama (a large broiler producing region) is prohibited by ADEM (Alabama Department of Environmental Management) between November 15 and February 15 (Mitchell and Tyson, 2002).

The environmental implications of the prolonged use of poultry litter as a fertilizer has led to various studies into the non-fertilizing value-added utilization of poultry litter such as bioenergy feedstocks (Abelha et al, 2002), methane production (Safley et al, 1987) and activated carbon production (Lima and Marshall, 2004). These value added uses will require that appropriate equipment and facilities be designed and selected to store, handle, and transport poultry litter, hence the need to quantify the physical properties of poultry litter (Shamlou, 1988). Several studies have shown that moisture content has a significant affect on the physical properties of biological materials (Balasubramanina, 2001; Nimkar and Chattopadhyay, 2002; Barbosa et al, 2005). Therefore the objectives of this study were to:

(1) Quantify the effect of moisture on bulk density, particle density, tap density, Hausner ratio, and porosity of poultry litter,

(2) Quantify the effect of moisture and applied pressure on the compressibility of poultry litter, and

(3) Determine the equilibrium moisture isotherm of poultry litter at a temperature of $25^{o}C$.

3.2 Methods and Materials

3.2.1 Preparation

The poultry litter sample (with a hard wood shaving bedding) used in this study was obtained from a local poultry farmer in Lee County, Alabama. The litter was stored in the laboratory at 25^oC before use. Physical property tests were carried out on poultry litter samples within the moisture content range of 10% to 30%. To adjust the moisture content of a sample to the desired level, the poultry litter was either dried in an oven set to 60^oC (to reduce the moisture content of the sample), or a known quantity of water was added and mixed with the poultry litter in a mixer for 15 minutes. In both cases the samples were stored in an air tight container for 24 hours to allow moisture equilibration to take place. The moisture content of each sample was then verified by a moisture analyzer (Model IR-200, Denver Instruments, Arvada CO). The actual moisture content values used for the physical property tests can be found in section 3.3.1. All moisture contents are reported in wet basis unless otherwise noted.

3.2.2 Particle size distribution

Particle size distribution was determined according to ASABE Standard S319.3 (ASABE, 2003). This procedure involved placing 100 grams of material on the top sieve of a nest of successively smaller sieves and recording the weight of material retained on each sieve after the test was complete. For this analysis, 7 U.S. Series test sieves plus a pan with aperture sizes ranging from 1.700 to 0.212 mm were used. The nest of test sieves was shaken for ten minutes in a Sieve shaker (Model CL 340, Soil Test Engineering Test Equipment Co., Evanston, IL), after which, the nest of sieves were removed from the sieve shaker. The mass of material retained on each sieve was then recorded. This procedure was done in triplicate. The determination of the geometric mean diameter (d_{gw}) of the sample and the geometric standard deviation of particle diameter (S_{gw}) was carried out according to the ASABE Standard S319.3 (ASABE, 2003) (Equations 3.1 – 3.3):

$$d_{gw} = \log^{-1}\left[\frac{\sum_{i=1}^{n}(W_i \log \bar{d}_i)}{\sum_{i=1}^{n} W_i}\right] \tag{3.1}$$

$$S_{\log} = \left[\frac{\sum_{i=1}^{n} W_i (\log \bar{d}_i - \log d_{gw})^2}{\sum_{i=1}^{n} W_i}\right]^{1/2} \tag{3.2}$$

$$S_{gw} = \frac{1}{2} d_{gw}\left[\log^{-1} S_{\log} - \left(\log^{-1} S_{\log}\right)^{-1}\right] \tag{3.3}$$

Where, d_{gw} = geometric mean diameter or median size of particles by mass (mm)

$S_{\log}$ = geometric standard deviation of log normal distribution by mass in ten bases logarithm (dimensionless)

S_{gw} = geometric standard deviation of particle diameter by mass (mm)

W_i = mass on ith sieve (g)

n = number of sieves plus one pan

$\bar{d}_i$ = nominal sieve aperture size of the ith sieve (mm)

3.2.3 Poured bulk density

Bulk density was determined by a bulk density measurement apparatus (Burrows Co., Evanston, IL) and according to ASABE Standard S269.4 (2002). This method involves pouring the bulk solid into a container (volume of 947 mm^3) from a funnel. The material was leveled across the top of the surface of the container and weighed. The bulk density (ρ_b) of the poultry litter was taken as the mass of sample in the container (m_c) divided by the volume of the container (V_c) (Equation 3.4). This procedure was performed in triplicate.

$$\rho_b = \frac{m_c}{V_c} \tag{3.4}$$

3.2.4 Tap bulk density

The tap bulk density of the material was measured using an automated tap density tester (Model TD-12, Pharma Alliance Group Inc., Vencia, CA) according to the ASTM Standard B 527 (ASTM, 2005). A 250 ml graduated cylinder was filled with poultry litter and weighed using a balance accurate to 0.01 g (Model PE3600 DeltaRange, Mettler-Toledo, Heightstown). The cylinder was then placed in the tap density tester. For each run, the cylinder was initially tapped 500 times at a rate of 300 taps per minute. Each tap consisted of the cylinder being raised by 14 mm and then dropped under its own weight. After the first 500 taps, the new volume was entered into the machine. The cylinder was then tapped 750 times, and the new volume was recorded. If the difference in volume after the 500 taps and after 750 taps was greater then 2%, the process was repeated, otherwise the experiment was completed and the new sample volume was recorded. The tap bulk density (ρ_t) of the poultry litter was taken as the mass of sample in the container (m_c) divided by the volume of the sample after the completion of the tapping (V_t) (Equation 3.5). This procedure was performed in triplicate.

$$\rho_t = \frac{m_c}{V_t} \tag{3.5}$$

3.2.5 Particle density

The particle density of the poultry litter was measured by gas comparison pycnometry (Model AccuPyc 1330, Micromeritics Instrument Corp, Norcross, GA) where a known quantity of helium under pressure was allowed to flow from a previously known reference volume into a cell containing a sample of the material. By applying the ideal gas law to the pressure change from the reference cell to the sample cell, the pycnometer calculates the volume of the material in the sample cell. Particle density (ρ_p) was taken as the ratio of the mass of material in the sample cell (m_p) to the volume (V_p) measured by the pycnometer (Equation 3.6). Sample mass was obtained with a digital balance accurate to 0.001 grams (Model AR3130, Ohaus Corp., Pinebrook, NJ). This procedure was performed in triplicate.

$$\rho_p = \frac{m_p}{V_p} \tag{3.6}$$

3.2.6 Porosity

Porosity is the percentage of the total container volume occupied by air spaces when a bulk solid is placed in a container (Woodcock and Mason, 1987). Porosity is mathematically defined by Equation 3.7 and was calculated using the average bulk and particle densities that were obtained for each sample.

$$\varepsilon = 1 - \frac{\rho_b}{\rho_p} \tag{3.7}$$

3.2.7 Hausner ratio

Hausner ratio quantifies the change in the volume of a sample subjected to the tap bulk density test described in Section 3.2.4. It is mathematically defined by Equation 3.8 and was calculated as the ratio of the average tap bulk density to the poured bulk density at each moisture content.

$$H_r = \frac{\rho_t}{\rho_b} \tag{3.8}$$

3.2.8 Mechanical compressibility

A texture analyzer (Model TA-HD, Stable MicroSystems, Surrey, UK) was used to measure the mechanical compressibility of poultry litter. The measurement system consisted of a compression cell (internal diameter of 49.55 mm and height of 101.83 mm) and a close-fitting piston (49.00 mm in diameter) that was attached to the crosshead of the texture analyzer (see Appendix D Figure D.1). Before each test, a sample of known weight (using a balance accurate to 0.01 g (Model PM4600, DeltaRange, Mettler-Toledo, Heightstown) was loaded into the compression cell. The piston was used to compress the sample within the cell at a speed of 1 mm/s until a consolidating pressure of 1.5, 3, 6, 9, 12, or 15 kPa was achieved. This procedure was done in duplicate. The force (hence the pressure) impacted on the sample by the moving crosshead of the texture analyzer and the distance traveled (hence the compression of the sample) were automatically recorded by the software supplied by the manufacture of the texture analyzer. Mechanical compressibility (in percent; Equation 3.9) was calculated.

$$Cm = 100\left(\frac{V_i - V_f}{V_i}\right) = 100\left(1 - \frac{\rho_{bi}}{\rho_{bf}}\right) \tag{3.9}$$

3.2.9 Equilibrium moisture isotherm

A water activity instrument (HygroLab 2 - H3, Rotronic Instrument Corp., Huntington, NY) was used to obtain the equilibrium moisture isotherm of poultry litter at a temperature of 25^{o}C. To conduct a test, each sample (about 20g) was placed in the sample holder of the water activity instrument. The water activity probe was placed on top of the sample holder thereby forming a sealed measurement system. The probe was equipped with a small fan that circulates air within the sample container, a thin film capacitance sensor that was capable of measuring relative humidity from 0 to 100% (with an accuracy of ± 1.5%) and a platinum RTD (resistance temperature detector) temperature probe (with an accuracy of ±0.3°C). The measurement system was then transferred to a temperature controlled-chamber (Model ESL-2CA, ESPEC North America, Inc., Hudsonville, MI) set at 25˚C to ensure a constant environmental temperature during the measurement process. The relative humidity and dry bulb temperature output from the water activity meter was continuously recorded on a personal computer until equilibrium was reached (usually less than 4 hrs). The moisture content of a sample at a measured ERH (or water activity) was taken as the equilibrium moisture content of that sample. The equilibrium moisture isotherm experiment was carried out in triplicate.

3.2.10 Data analysis

Regression analysis was performed on poured bulk density, tap bulk density, particle density, porosity, Hausner ratio, and compressibility data sets using the proc reg function in SAS statistical software package (Version 9.1, SAS Institute Inc., Cary, NC, 2002-2003) and plotted with the experimental data using Microsoft Excel (Microsoft Office XP Professional, 2005). A nonlinear regression was performed on the water activity data set using PolyMath statistical software package (Version 5.1 build 230, Mordechai Shacham, Michael B. Cutlip, Michael Elly, 2007) and then plotted with the experimental data using Microsoft Excel (Microsoft Office XP Professional, 2005).

3.3 Results and Discussion

3.3.1 Moisture contents

The original intention of this study was to measure the physical properties of poultry litter at moisture contents of 10%, 14%, 18%, 22%, 26%, and 30% (w.b.). However, it was found that these exact moisture contents are practically impossible to obtain. Because of this, the moisture content of the sample at the time of measuring a physical property was recorded. It should be mentioned that none of the actual moisture contents vary more than 2% from the target moisture contents. The moisture contents used for each of the physical property measurements is summarized in Table 3.1.

Table 3.1 Summary of moisture contents used for various physical property tests

Physical Property	Moisture Contents (%, w.b.)					
Bulk Density	30.6	26.1	22.0	18.1	14.2	10.3
Tap Bulk Density	29.6	26.1	22.0	18.4	14.2	10.3
Particle Density	30.9	26.0	22.1	18.0	13.8	10.3
Porosity	30.7	26.1	22.0	18.0	14.0	10.3
Hausner Ratio	30.1	26.1	22.0	18.2	14.2	10.3
Compressibility	30.9	26.0	22.1	18.0	13.8	10.3
Water Activity	30.6	26.7	23.6	17.7	13.4	10.1

3.3.2 Particle Size Distribution

The particle size distribution of poultry litter is shown in Table 3.2 and Figure 3.1. Most of the particles (24.14 % and 20.19%) were retained on the bottom pan and on the sieve with an aperture of 0.850 mm, respectively. The geometric mean diameter (d_{gw}) and the geometric standard deviation (S_{gw}) of poultry litter were calculated to be 0.841 mm and 0.251 mm, respectively (Equations 3.1-3.3). Particle sizes below 0.400 mm (40% of the poultry litter) are considered fine and highly compressible. Fine particles are also associated with decreased flowability because of their increased compressibility (Tabil and Sokhansanj, 1997; Mani et al 2003).

Table 3.2 Particle size distribution of poultry litter

U.S. Sieve No.	Sieve Aperture Size (mm)	Distribution (%)
12	1.700	16.41
20	0.850	20.19
30	0.595	15.39
40	0.425	8.08
50	0.297	9.01
60	0.250	3.80
70	0.212	2.98
Pan	0.000	24.14

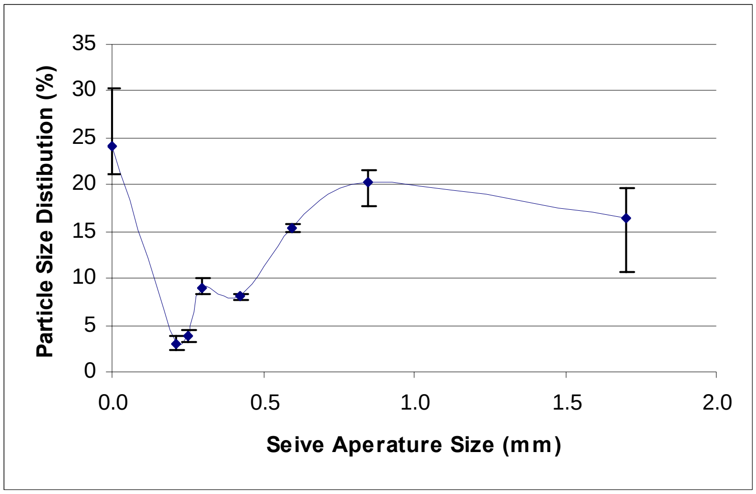

Figure 3.1 Particle size distribution of poultry litter at various sieve apertures

3.3.3 Poured bulk density

The poured bulk density of poultry litter ranged from 0.550 g/ml to 0.533 g/ml within the moisture content range of 10.3% and 30.6% (Figure 3.2). In general, the poured bulk density decreased with increases in the moisture content. This implies the bulk poultry litter volumetrically expands faster than the increased weight when the moisture content of the litter is increased. The implication of this is that in process design applications, the amount of volume that will be required to store poultry litter will increase as moisture increases. The following equation (Equation 3.10) describes the relationship between bulk density (g/ml) and moisture content (%, w.b.).

$$\rho_b = 0.540 + 0.000919M - 0.0000373M^2 \quad R^2 = 0.875 \qquad (3.10)$$

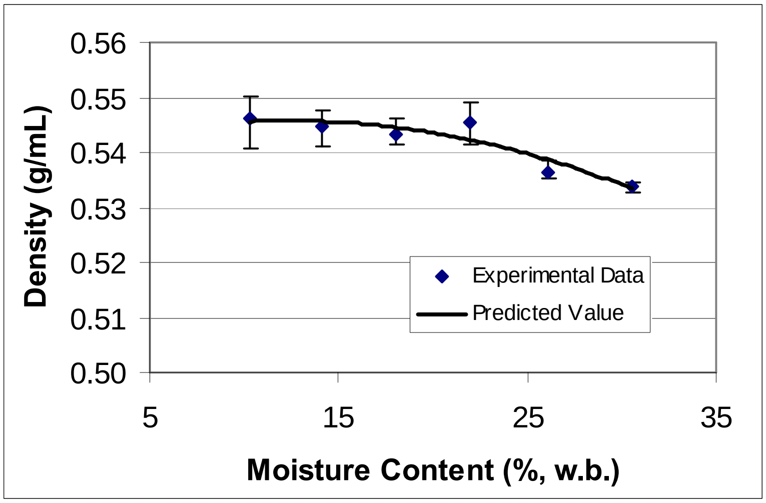

Figure 3.2 Effect of moisture content on the poured bulk density of poultry litter

It should be mentioned that the poured bulk density of poultry litter (0.50 g/ml) is significantly higher than the values that are typically obtained for agricultural materials (less than 0.20 g/ml) (Balasubramanian, 2001; Deshpande et al, 1993; Fasina and

Sokhansanj, 1992; Nimkar and Chattopadhyay, 2001). This is because of the relatively high amount of minerals present in poultry litter. The response of poultry litter's bulk density to moisture content was also similar to those documented for the poured bulk density of other biological materials (Balasubramanian, 2001; Deshpande et al, 1993; Fasina and Sokhansanj, 1992; Nimkar and Chattopadhyay, 2001).

3.3.4 Tap bulk density

Statistical analysis showed that there was no significant ($P<0.05$) effect of moisture content on the tap bulk density of poultry litter. The average tap bulk density of poultry litter was 0.580 g/ml.

3.3.5 Particle density

The particle density of poultry litter decreased from 1.623 g/ml to 1.434 g/ml as moisture content increased from 10.3% to 30.9%, respectively (Figure 3.3). It is postulated that the volume of the particles of the litter increased at a higher rate than the increase in mass due to the saturation of the particles with moisture. This trend has also been observed in various other biological materials (Deshpande et al, 1993; Joshi et al., 1993; Nimkar and Chattopadhyay, 2001). Equation 3.11 was used to describe the relationship between the particle density (g/ml) and the moisture content (%, w.b.) of poultry litter.

$$\rho_p = 1.627 + 0.0000658\mathrm{M} - 0.000177\mathrm{M}^2 , \mathrm{R}^2 = 0.970 \qquad (3.11)$$

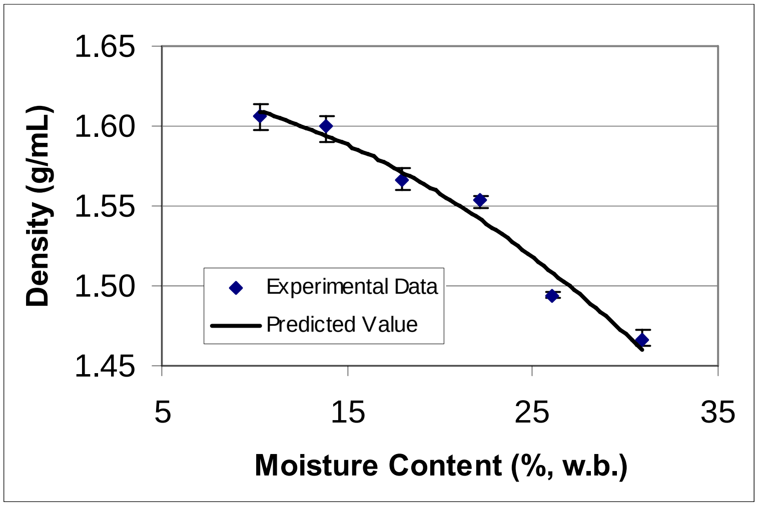

Figure 3.3 Effect of moisture content on the particle density of poultry litter

3.3.6 Porosity

The average porosity of poultry litter ranged from 0.63 to 0.67 at moisture contents of 30.7% and 10.2%, respectively (Figure 3.4). The average porosity of spherical particles is 0.4, while irregular shaped particles have higher porosity values (Woodcock and Mason, 1987). The porosity values obtained in this study were indicative of the irregular and non-spherical nature of the particulates that constitute poultry litter. In general, the porosity of the poultry litter increased with a decrease in moisture content. Results presented earlier on the poured bulk density and particle density showed that the bulk and individual particulates of poultry litter were expanding volumetrically at a faster rate than it was gaining weight as it absorbed moisture. This resulted in less air space between the particulates, thus the general decrease in porosity as the moisture increased. A similar trend was also observed with other biological materials (Joshi et al, 1993;

Deshpande et al, 1993). Equation 3.12 was used to describe the relationship between the porosity (decimal) and moisture content (%, w.b.) of poultry litter.

$$\varepsilon = 0.666 - 0.000270\text{M} - 0.0000244\text{M}^2 \text{, R}^2 = 0.982 \tag{3.12}$$

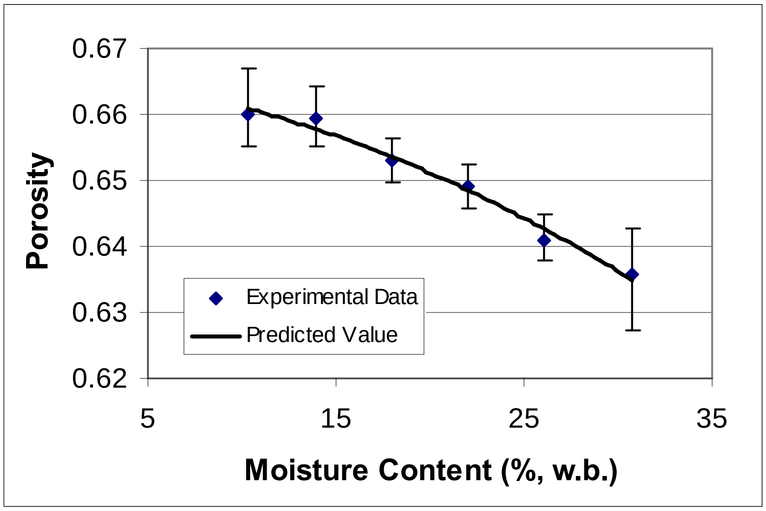

Figure 3.4 Effect of moisture content on the porosity of poultry litter

3.3.7 Hausner ratio

Statistical analysis showed that there was no significant effect ($P < 0.05$) of moisture content on the Hausner ratio of poultry litter. The average Hausner ratio of poultry litter was 1.070. This value was less than the critical value of 1.25 thereby indicating that poultry litter can be easily fluidized.

3.3.8 Compressibility

The percent compressibility of poultry litter ranged from 2.4% to 18.1%, with sample moisture contents and applied pressures of 10.2% and 1.5kPa, and 30.9% and 15kPa, respectively (Figure 3.5). The percent compressibility increased with moisture content and applied pressure. Similar trends have been documented for other biological materials (Barbosa et al, 2005). Fayed and Skocir (1997) used compressibility values to classify the flowability of a material. Percent compressibility values between 5-15% indicated excellent flow, and 12-16% indicated fair to passable flow. Based on this classification, except for poultry litter samples of 30.9% moisture content compressed to pressures of 12 and 15 kPa, poultry litter has good or excellent flow. Equation 3.13 was developed to relate the mechanical compressibility (%) to the moisture content (%, w.b.) and pressure (kPa) of poultry litter.

$$Cm = -3.312 + 0.164\mathrm{M} + 0.00568\mathrm{M}^2 + 3.3821\log(\sigma)\,,\ \mathrm{R}^2 = 0.948 \qquad (3.13)$$

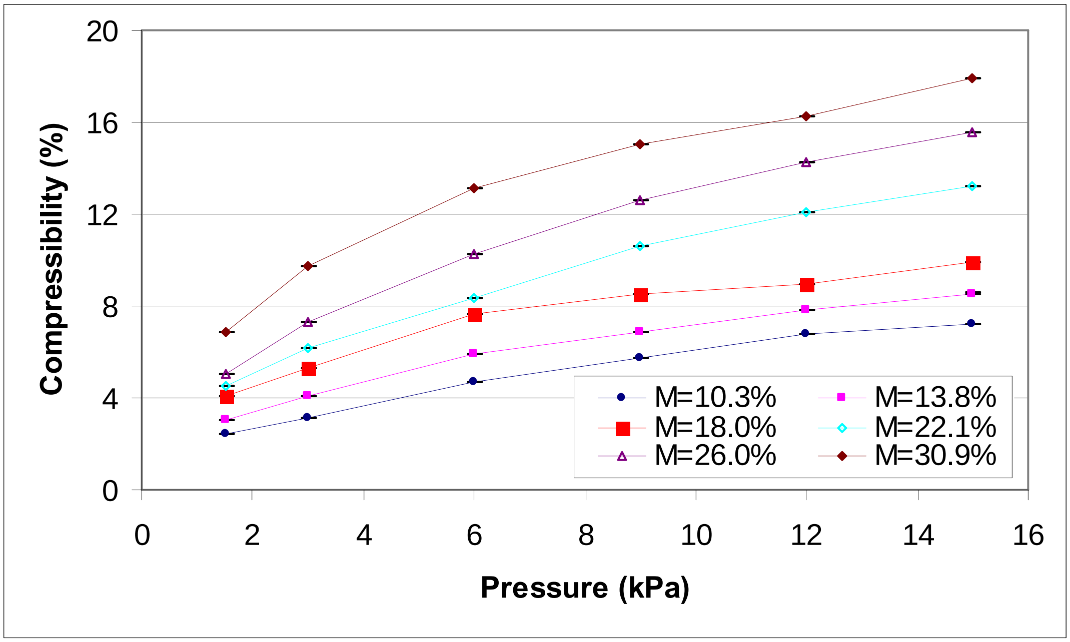

Figure 3.5 Effect of moisture content and pressure on the mechanical compressibility of poultry litter

3.3.9 Equilibrium moisture isotherm

Since equilibrium relations for biological materials are often represented in dry basis moisture contents, Equation 3.14 was used to convert the wet basis moisture content values to dry basis moisture contents values (ASAE Standard D245.5, 2000).

$$MC_D = \frac{100 * MC_W}{(100 - MC_W)} \qquad (3.14)$$

Where MC_D is the percent dry basis moisture content and MC_W is the percent wet basis moisture content.

Figure 3.6 shows that the equilibrium moisture relation curve for poultry litter is type II (sigmoidal in shape). This is typically obtained for biological materials (Labuza, 1984; Erbas et al., 2005). The ERH (on the x axis) is often used to determine the amount of moisture that is available for microbial activity, enzymatic activity and chemical reaction. When the ERH is above 0.8, there is sufficient moisture in the material to promote mold growth (30% moisture content dry basis or 24% moisture content wet basis for poultry litter). Bacterial growth is often associated with materials stored at moisture contents that are at equilibrium with relative humidity of 90% and above (corresponding to 30% moisture content wet basis or 43% moisture content dry basis for poultry litter) (Wilhelm et al, 2004).

The GAB equation (Equation 3.15, ASAE Standard D245.5, 2000) was fitted (using the non-linear regression procedure in PolyMath 5.1 Software) to the experimental equilibrium moisture sorption isotherm data.

$$EMC = \frac{M_o * C * K * ERH}{(1 - K * ERH)(1 + (C - 1) * K * ERH)} \qquad (3.15)$$

Where EMC (MC_D) is the equilibrium moisture content (g water/g solids), ERH is the equilibrium relative humidity (decimal), M_o is the monolayer moisture content (g water/g solids), C is the constant related to monolayer sorption heat, and K is the constant related to multilayer sorption heat. A good fit of the GAB equation to the experimental data was obtained with R^2 value of 0.917. The estimated values of M_o, C, and K were 0.0583, 3031, and 0.955, respectively. These values illustrated the presence of a monolayer (at a moisture content 5.8% dry basis), with strongly bound water molecules (C>>1), and a multilayer that had characteristics comparable to bulk liquid (K~1) (Quirijns et al, 2005). The monolayer moisture content is the moisture content that is optimal for the stability of the biological materials during storage (Moraga et al, 2006). The equilibrium relative humidity that was calculated to be in equilibrium with the monolayer moisture content is 1.9%. Beyond this value, deteriorative reactions are accelerated in the product. Therefore the maximum stability for poultry litter stored at 25°C will be obtained at a moisture content of 5.8% (d.b.) or 5.5% (w.b.).

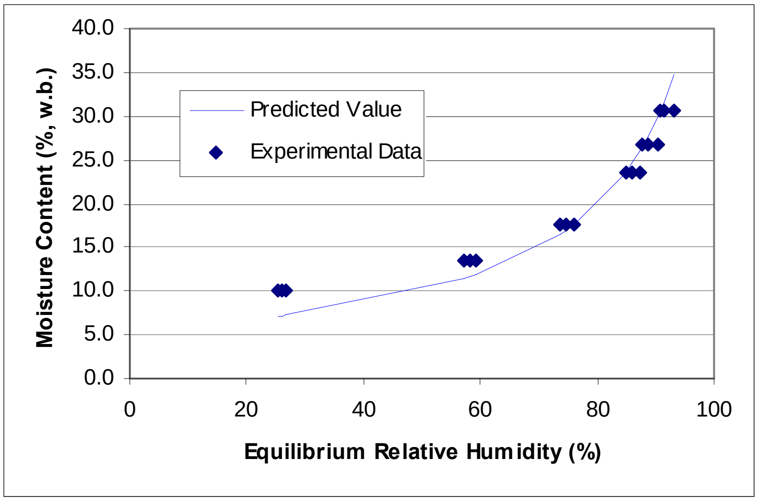

Figure 3.6 Effect of moisture content on the relative humidity of poultry litter (25°C)

3.4 Conclusion

It can be concluded from this study that moisture content significantly affects the physical properties of poultry litter. Based on particle size analysis, 40% of the poultry litter was considered to be fine and highly compressible. Other physical properties such as the poured bulk density, particle density and porosity decreased while the compressibility increased with increases in moisture content. The porosity indicated that poultry litter's particles were irregular and non-spherical in shape. The average tap bulk density and Hausner ratio were not affected by moisture content and had average values of 0.580 g/ml and 1.070, respectively (which indicated easy fluidization).

The compressibility of poultry litter was affected by both pressure and moisture content with a maximum compressibility percent of 18.0% obtained at a moisture content of 30.8% and a pressure 15 kPa. As moisture content increased the compressibility was found to increase.

The equilibrium moisture isotherm data was found to follow the model used in the GAB equation, where constants M_o, C, and K were found to be 0.0583, 3031, and 0.955, respectively, with a R^2 value of 0.917. Based on the estimated monolayer moisture content, it was found that when poultry litter was stored at a temperature of 25^oC, minimum biochemical degradation of the litter will occur when the relative humidity of the environment is about 1.9%.

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CHAPTER 4. COMPACTION OF POULTRY LITTER

4.1 Introduction

Compactibility is defined as the ability of a bulk solid to be agglomerated into a tablet of specified strength. This differs from compressibility in that compressibility involves the ability of a bulk material to decrease in volume under pressure (Leunberger and Jetzer, 1984). Compressibility studies are therefore useful in diagnosing flow problems in bulk solids while the main focus of compactibility studies is to enhance storage and handling properties of bulk solids through increased density of the material (Demirbas, 1999).

Poultry litter is a lightly dense material (bulk density is less than 500 kg/m^3 – see results in section 3.3.3 of this thesis). This makes it costly to transport poultry litter from production sites to areas where it could be effectively utilized for value-added applications such as in bioenergy and bioproduct applications (Colley et al, 2005). Biosecurity is also a concern when poultry litter is to be transported over long distances. Poultry litter is dusty, and is known to contain pathogens such as *E. Coli* (Nandi et al, 2004). Thus, during transportation, pathogen infected dust maybe released into the atmosphere. This in turn could lead to the spreading of poultry-related diseases in locations where the litter is transported through. This biosecurity problem could be considerably minimized if the poultry litter is densified because this would reduce the dispersion of dust and dust-laden microbes during transportation (Fasina et al, 2006).

Traditionally, agricultural materials are densified into pellets, cubes, and bales. Pellets are the densest of these agglomerates and therefore require the maximum amount of energy input. This high energy input translates into high costs ($50-$60 per ton), which prevent the process from being economical and practical for every broiler farmer to purchase and operate a pellet mill (Fasina et al, 2006). Similar to the production of pellets, pressure agglomeration is used to manufacture cubes except that lower pressures are used. Production of cubes is presently limited to forage crops such as alfalfa. As the name implies, cubes are usually in the forms of a square cross section of chopped biomass (Sokhansanj and Turhollow, 2004), and typically vary from 12.7 to 38.1 mm dimensionally.

Baling is a process that combines compression and packing (tying with ropes or wrapping) operations, it is typically used for grassy or fibrous-like materials that are stringy in nature (Badger, 2003). Poultry litter is not stringy and therefore the low-cost volume reduction method that can be developed for poultry litter is limited to pressure agglomeration. Bale dimensions are roughly 44 in by 49 in (1026mm x 1040mm; Badger, 2003).

The objective of this study is to optimize the compaction of poultry litter for efficient transportation and off-site utilization. This will be achieved by

(1) Determining the effect of moisture content on the minimum pressure required to compact poultry litter, and

(2) Determining the energy required to compact poultry litter.

4.2 Methods and Materials

4.2.1 Preparation

This experiment was conducted with fresh poultry litter that was obtained from a local poultry farmer in Lee County, Alabama. The methodology described in section 3.2.1 for adjusting the moisture contents of poultry litter was also used in this study. Compaction of poultry litter was carried out on samples conditioned to the following moisture contents: 16.5%, 21.7%, 24.2%, 26.1%, 29.0%, 31.7%, 35.1%, 37.7%, and 41.4%, wet basis.

4.2.2 Compaction

The compaction apparatus consisted of a 27.3 mm diameter die. The die had a length of 135.2 mm and was composed of two semicircular halves that were bound together by three to eight clamps depending on the pressure applied. Before each test, the inside of each half was lubricated with vegetable oil to minimize the amount friction between the poultry litter and the die. The two halves were then clamped together and the die was filled with poultry litter. A plunger (25.6 mm diameter, 124.6 mm length) attached to the crosshead of the texture analyzer (model TA-HDi, Stable Microsystems, Surrey, UK) was used to compress the sample at a speed of 1 mm/s until the desired force was reached (see Appendix D Figure D.2). The compacted sample was held in a creep mode (i.e. constant force) for a period of 60s after the desired force was reached. Compaction forces of 50 kg, 100 kg, 150 kg, 200 kg, 250 kg, 300 kg, 350 kg, 400 kg, 450 kg, and 500 kg (corresponding to pressures of 0.84, 1.7, 2.5, 3.4, 4.2, 5.0, 5.9, 6.7, 7.5, and 8.4 MPa) were applied on the samples at the various moisture contents. Force and deformation data were automatically acquired and stored by the software provided by the manufacturer of the texture analyzer. The force-deformation data was used to calculate the energy expended during the compaction process. Once compaction was completed, the agglomerated sample was removed from the die (see Appendix D Figure D.3) and stored in the laboratory (temperature of 22^{o}C and a relative humidity of 45%) for a period of 2 months.

A digital vernier caliper (Solar ABSOLUTE Digimatic Caliper, Model CD-S6”C, Mitutoyo Corporation, Japan) was used to measure the length and the diameter, while a digital balance accurate to 0.001 grams (Model AR3130, Ohaus Corp., Pinebrook, NJ) was used to measure the mass of freshly made and stored compacts. The density of the samples were calculated from the ratio of mass to volume (obtained from length and diameter measurements). In addition, the strength of some compact samples (those that were adjusted to moisture contents of 31.7% to 41.4%) was also obtained by means of a 12.7 mm diameter round probe (Model TA-23, Texture Technologies, Scarsdale, NY). The compact was placed on a flat plate in its natural position (i.e. radial dimension was in the same direction as that of the compressive force). The probe (attached to the crosshead of the texture analyzer) was then used to compress the compact at a speed of 1 mm/s. The force required to rupture the compacts was obtained from the maximum force in the force deformation curve. All of the procedures outlined above were carried out in duplicate.

4.2.3 Data analysis

Regression analysis was performed using the proc reg function in SAS statistical software package (Version 9.1, SAS Institute Inc., Cary, NC, 2002-2003) and plotted with the experimental data using Microsoft Excel (Microsoft Office XP Professional, 2005).

4.3 Results and Discussion

4.3.1 Density of poultry litter compacts

Initially, compaction was carried out on samples with moisture contents ranging from 16.5% to 29.0 % (w.b.) with a pressure range of 5.0 to 8.4 MPa. A preliminary evaluation showed that:

(a) The agglomeration of poultry litter was not achieved at applied pressures less than 5.0 MPa,

(b) Poultry litter has to be compacted to a minimum density of 765.6 kg/m^3 (Figure 4.1), and

(c) The density of agglomeration after compaction increased with moisture content.

Regression analysis showed that within the moisture content range of 16.5% to 29.0% (w.b.) and the pressure range of 5.0 to 8.4 Mpa, the following relationship (Equation 4.1) can be used to predict the density (kg/m^3) of compacts as a function of moisture content (%, w.b.) and pressure (MPa).

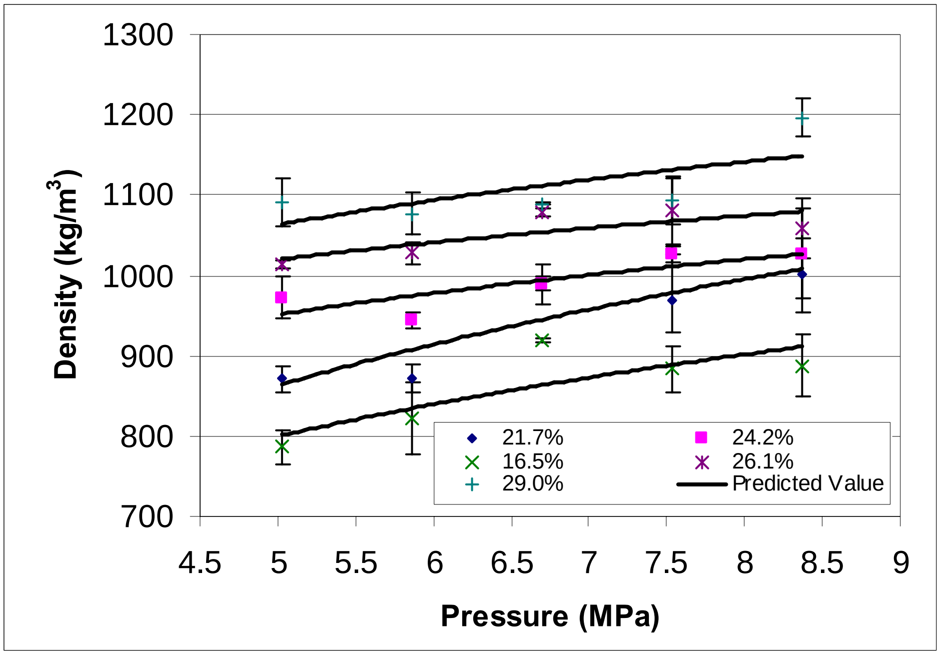

Figure 4.1 Effect of moisture content and pressure on the density of poultry litter compacts

$$\rho_{compact} = 159.994 + 20.343 * \mathrm{M} + 187.075 * \log(\sigma)\text{, } \mathrm{R}^2 = 0.907 \qquad (4.1)$$

Similar plots were obtained by Demirbas (1999) and Mani et al (2006) for biomass feedstocks.

Based on the above results a second set of compaction tests was conducted at higher moisture values (31.7% to 41.4%, w.b.) with the hypothesis that less energy would be required to compact poultry litter at higher moisture contents, since moisture is acting as a binder during the compaction process. Statistical analysis (P<0.05) showed that the densities from the second set of experiments were not significantly different from those obtained by the first set of experiments. However, the following observations were made from the second set of compaction tests:

(a) It was possible to produce poultry litter compacts at pressures less than 5 MPa. Successful agglomeration occurred at pressures as low as 0.84 MPa. It should be recalled that compaction was not possible below 5 MPa for samples with moisture contents less than 29.0%.

(b) At moisture contents greater than 37.6% and pressures greater than 5 MPa, it was extremely difficult to compact poultry litter. This is because the samples began to exhibit fluid like (or slurry) behavior at these higher pressures and therefore could not be contained within the die.

(c) Within the pressure range of 0.84 to 5.9 MPa the density (kg/m^3) of the compacts increased logarithmically with increases in applied pressure (MPa) and increased linearly with increases in the moisture content (%, w.b.) of the samples (Figure 4.2 & Equation 4.2).

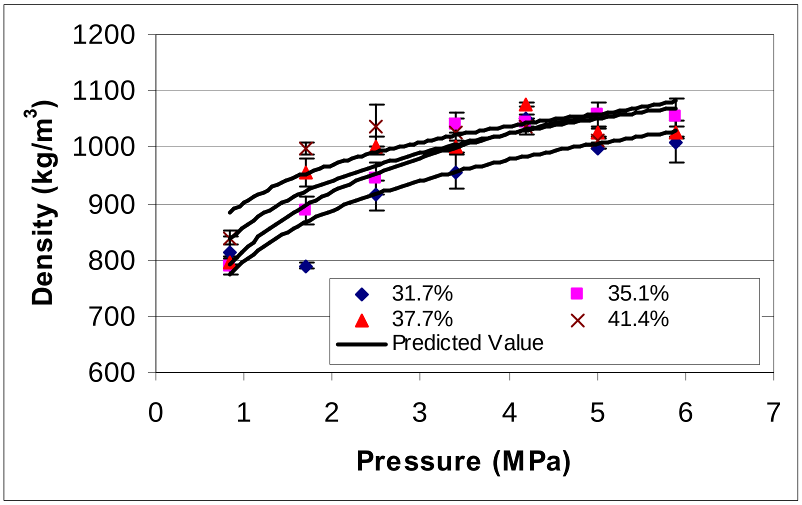

Figure 4.2 Effect of moisture content and pressure on the density of poultry litter compacts

$$\rho_{compact} = 574.570 + 7.363 * \mathrm{M} + 125.778 * \log(\sigma)\,,\ \mathrm{R}^2 = 0.831 \qquad (4.2)$$

4.3.2 Density of poultry litter compacts after 2 months

After two months of storage the compacts equilibrated to the environment and each had an equal moisture content of 9.4% (w.b.). Figure 4.3 shows the density of all the compacts (set 1 & 2) after two months of storage.

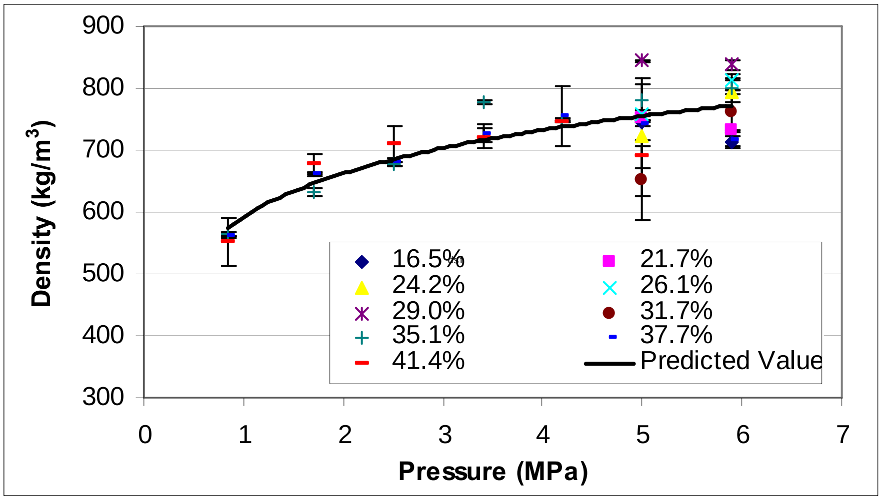

Figure 4.3 Effect of moisture content and pressure on the density of poultry litter compacts after 2 months storage

Despite the fact that moisture content and pressure significantly affect the density to which the compacts can be made (Figure 4.1 & 4.2), this was not the case for compacts that have been stored for two months under laboratory conditions. Statistical testing ($P<0.05$) showed that within the moisture range of 16.5 to 41.4% (w.b.) only pressure had a significant affect on the density of the stored compacts. The average density values obtained at the various moisture contents were therefore averaged, and an exponential relationship was obtained between the compact density (kg/m^3) and the applied pressure (MPa) (Equation 4.3).

$$\rho_{compact} = 592.190 + 101.241 * \log(\sigma)\text{, } R^2 = 0.710 \qquad (4.3)$$

The density of the compacts decreased by an average of 23.5% during the two month period. This is because of two reasons:

(a) The samples equilibrated with the laboratory conditions to an average moisture content of 9.4% (w.b.).

(b) The compacts relaxed (or expanded in size) over the two month period.

4.3.3 Breakage force of poultry litter compacts

Figure 4.4 shows that the average force required to rupture the compacts (after 2 months of storage) vary from 16.6 N to 357.0 N.

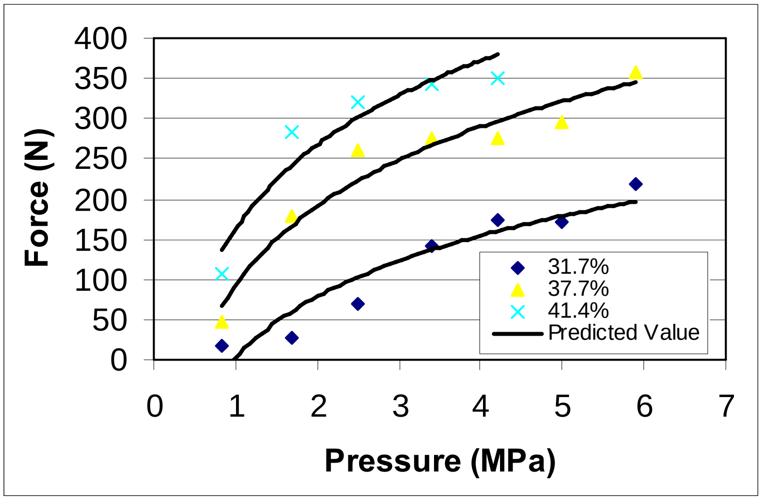

Figure 4.4 Effect of moisture content and pressure on poultry litter compact's breakage force after two months storage

Despite the fact that the moisture had no significant effect on density of the compacts after 2 months of storage, the force (N) required to rupture the compacts was significantly influenced by moisture content (%, w.b.) in a linear fashion and by pressure (MPa) in an logarithmic fashion (Equation 4.4).

$$F_{breakage} = 50.917 + 0.462 * \mathrm{M} + 108.220 * \log(\sigma) \text{ , } \mathrm{R}^2 = 0.707 \qquad (4.4)$$

It is well known in the field of agglomeration that moisture can act as a film and bridge forming binder by coating particles thereby improving the natural adhesion of the particles to each other (Pietsch, 2002).

4.3.4 Specific energy for poultry litter compaction

The specific energy required to form agglomerates of poultry litter ranged from 0.190 kJ/kg to 1.763 kJ/kg within the moisture content range of 16.5% to 41.4% (w.b.) and applied pressure range of 0.84 MPa to 5.9 MPa (Figure 4.5).

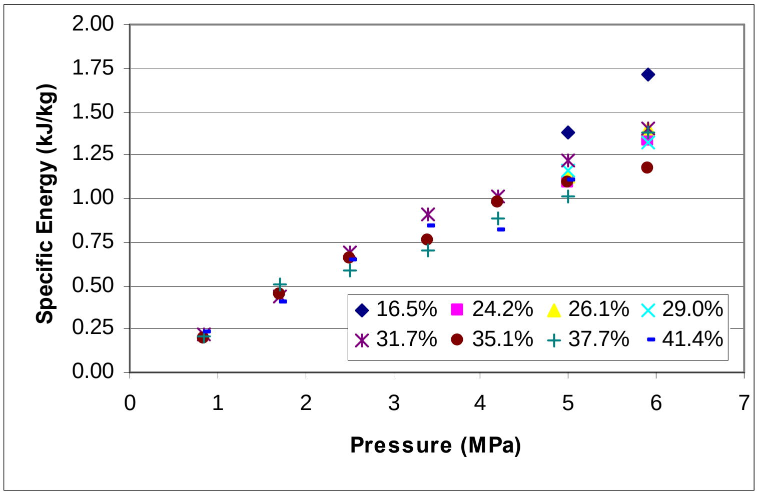

Figure 4.5 Effect of moisture content and pressure on the specific energy required for the compaction of poultry litter

This is significantly lower than the specific energy required to produce pellets from biomass feedstocks (typically 19 kJ/kg to 90kJ/kg; Colley et al, 2005). By substantially increasing the moisture content, it is therefore feasible to reduce the energy required to compact biomass feedstocks by nine fold. The required energy (kJ/kg) increased with applied pressure (MPa) and decreased with moisture content (%) in a linear fashion as follows (Equation 4.5):

$$E = 0.479 - 0.0108 * \mathrm{M} + 0.204 * \sigma \tag{4.5}$$

4.4 Conclusion

It can be concluded that both the pressure applied and the moisture content of the poultry litter at the time of compaction significantly affect the density of the compact and the energy required for the compaction. After two months of storage, the density of the compacts were only significantly affected by the amount of pressure applied during compaction while the moisture content no longer had any significant affect. However, the force required to rupture the compacts after 2 months of storage was significantly affected by both the moisture content and the pressure applied. It was found that when the moisture content of poultry litter was increased to as high as 37.7% the energy required to compact the litter in comparison to the energy required for pelleting was reduced by nine fold. Based on the results from this study, it is recommended that poultry litter be compacted at a moisture content of 37.7% and a pressure of 5.0 MPa.

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CHAPTER 5. FLOWABILITY OF POULTRY LITTER

5.1 Introduction

Flowability is the mathematical representation of a material's cohesiveness and adhesiveness. Cohesiveness refers to the material's internal friction within itself and adhesiveness refers to the material's friction against surfaces it may be touching. Each of these characteristics determine how easy or difficult a material will flow when handled, stored, and/or transported (Woodcock and Mason, 1987).

Most bulk solids are stored in bins or silos. Poultry litter may have to be stored in these types of equipment if it is going to be utilized at off-production sites. This will require the proper design and selection of bins and silos that will enable poultry litter to be easily unloaded from them (Shamlou, 1988). The Jenike Shear cell is the best known machine that is used to measure material's flowability. Flowability data provides information that are applied to strength and flow, feeder loads and power requirements, gravity flow blenders, purge bins, and pneumatic dense-phase conveying, all of which are required for proper storage silo design (Wilms, 1999). Improper flow and design such as rat holing and arches can be avoided, when storage bins and silos are properly designed.

The objectives of this study were to:

(1) Measure the flowability, cohesion, and internal angle of friction of poultry litter at moisture contents (w.b.) of 10%, 18%, 22%, 26%, and 30%, and

(2) Measure the wall friction and the wall angle of friction of poultry litter on milled aluminum, mirror finished aluminum, milled steel, mirror finished steel, and carbon coated steel.

5.2 Methods and Materials

5.2.1 Preparation

The methodology described in Section 3.2.1 to adjust the moisture contents of samples was used.

5.2.2 Flowability

An automated shear tester (ShearScan TS12, Sci-Tec Inc., Worthington, Ohio) was used to quantify the flow behavior of the samples. The shear cell was of the annular split cell type that consisted of a base ring with attached inner and outer sides, upper floating inner and outer rings, and a twisting lid (see Appendix D Figure D.4). The diameters of the outer and inner rings were 110 mm and 55 mm, respectively. The height of the upper and bottom rings were 18 mm and 12 mm, respectively. To run a sample, the space between the outer and inner rings of the shear cell was loaded with the sample to be tested. The cell containing the poultry litter was then placed on the base of the shear tester, and the cell lid was placed carefully on top of the sample.

The software provided by the manufacturer of the shear tester was then activated. This caused the load head, which houses the normal load cell, to move down until it made contact with the cell lid. A compression load was then applied at a rate of 7.5 mm/min until the preset normal load was reached (consolidating stress). With the normal (or consolidating) stress applied, the load head began to twist the cell lid at a speed of 2.5 mm/min. This motion caused the sample to shear. The shear stress was measured by the shear load cell and continued to increase until it reached the steady-state point. When the steady-state point was reached, the load head lifted to reduce the load to a preset point.

The shear motor then started, and the maximum shear stress required for the sample to fail was monitored and recorded. The maximum shear stress was measured for multiple loads (25%, 35%, 45%, 55%, 65%, and 75% of the consolidating stress). A plot of the maximum shear stress versus normal stress produces a line called the yield locus at that consolidating stress. Consolidating stresses of 1.5, 3, 6, 9, and 12 kPa were used for all the samples. The Mohr-Coulomb equation (Equation 5.1) was used to estimate the cohesion and angle of internal friction:

$$\tau = c + \tan(\phi)\sigma \tag{5.1}$$

Where τ = shear stress (kPa)

σ = normal stress (kPa)

ϕ = angle of internal friction (^{o})

c = cohesion strength (kPa).

Using the software provided by the manufacturer of the shear tester, each yield locus was used to calculate the unconfined yield stress (UYS; Equation 5.2) and the major consolidating stress (MCS; Equation 5.3) of each sample. Two yield loci for each consolidating stress (10 yield loci for each sample) were used to make a flow function (a plot of the UYS vs. MCS) for each sample. This was used to obtain the flow index of the poultry litter samples.

$$UYS = \frac{2c(1+\sin\phi)}{\cos\phi} \tag{5.2}$$

$$MCS = \left[\frac{A - \sqrt{A^2 \sin^2\phi - \tau^2 \cos^2\phi}}{\cos^2\phi}\right](1+\sin\phi) - \frac{c}{\tan\phi} \tag{5.3}$$

Where $A = \sigma + \frac{c}{\tan \phi}$, and c is the cohesion defined as τ at $\sigma = 0$.

5.2.3 Wall friction

The methodology and equipment described in the previous section to quantify the flowability of poultry litter were used in this section for the wall friction and the wall angle of friction determination except that the bottom section of the shear cell that previously contained poultry litter was replaced with a solid material that was manufactured for a given wall material of interest (i.e. milled aluminum, mirror finished aluminum, milled steel, mirror finished steel, and carbon coated steel; see Appendix D Figure D.4).

Therefore instead of developing the yield locus, the wall yield locus was developed from the normal load-shear stress data. Further analysis was carried in the fashion described in the previous section.

5.2.4 Data Analysis

All of the regression analysis and plots of the data were created using Microsoft Excel (Microsoft Office XP Professional, 2005).

5.3 Results and Discussion

5.3.1 Moisture contents

The flowability tests for poultry litter were carried out on samples of the following moisture contents: 10.3%, 18.0%, 22.1%, 26.0%, and 30.9%, wet basis. While the wall friction test was carried out on a sample of 20.0% moisture content, wet basis.

5.3.2 Flowability

The flow function plots (Figure 5.1) or the plots of the ultimate yield stress (UYL) vs. the major consolidating stress (MCS) at different moisture contents indicate that the flowability of poultry litter reduces as moisture content increases.

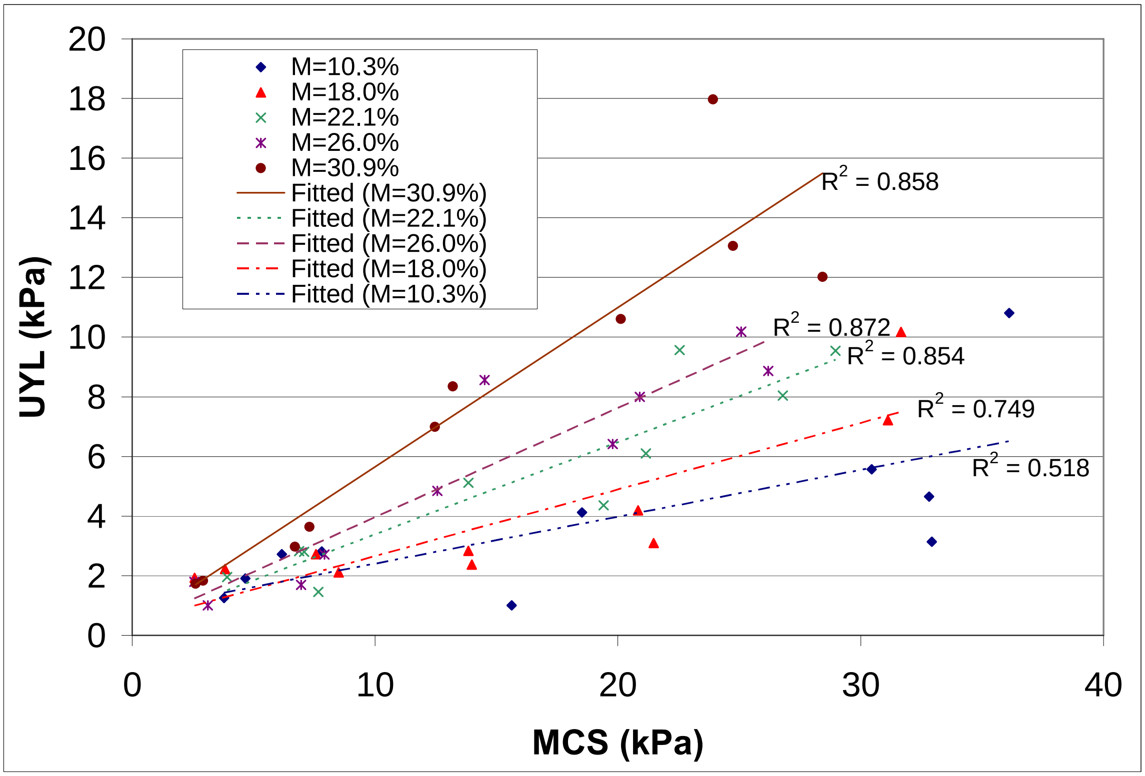

Figure 5.1 Flow function graph of poultry litter

This is confirmed from the values of the flow index (obtained from the inverse of the slope of the linear fit of the UYL vs. MCS plot; Table 5.1).

Table 5.1 Flow index of poultry litter at various moisture contents

M.C. % (w.b.)	Flow Function (FF)	Flow Index (FI)	Characteristic Flow
30.9	0.535	1.871	Very cohesive/non-flowing
26.0	0.367	2.727	Cohesive
22.1	0.309	3.239	Cohesive
18.0	0.224	4.474	Easy flowing
10.3	0.157	6.369	Easy flowing

Based on the flow index values, poultry litter conditioned to moisture contents of 18.0% and below can be classified as easily flowing materials, while poultry litter at a moisture content of 30.9% and above are considered very cohesive and non-flowing. This implies that flow aids will be required to discharge high moisture content poultry litter from storage bins, silos, or hoppers.

This is not surprising since the results reported in section 3.3.8 of this thesis showed that poultry becomes more compressible with increased moisture contents. Thus when the same load is applied to samples of high and low moisture contents, the high moisture content sample compresses more than the lower moisture content sample. The result is that more force is required to shear the high moisture content sample. 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% MC), and whey (at 4.0%MC). They concluded from their study that the flour with the highest moisture content had the most difficult flow and that whey with the lowest moisture content had the easiest flow.

The cohesion and internal angle of friction of poultry litter was not significantly affected by the moisture content of the samples. The average cohesion of poultry litter at normal stresses of 1.5, 3, 6, 9, and 12 kPa were 0.4, 0.6, 1.1, 1.7, and 2.1 kPa, respectively. These values are similar to some agricultural materials. Teaunou and Fitzpatrick (2000) measured approximately the same range of cohesion values in whey. Pressure did not have a significant affect on the internal angle of friction. The average internal angle of friction was 42.1^{o}.

5.3.3 Wall friction

For the wall friction tests a poultry litter sample of 20.0% moisture content was tested on milled aluminum, mirror finished aluminum, milled steel, mirror finished steel, and carbon coated steel. Wall friction flow function graphs for each of the materials were developed through an excel spreadsheet (Figure 5.2).

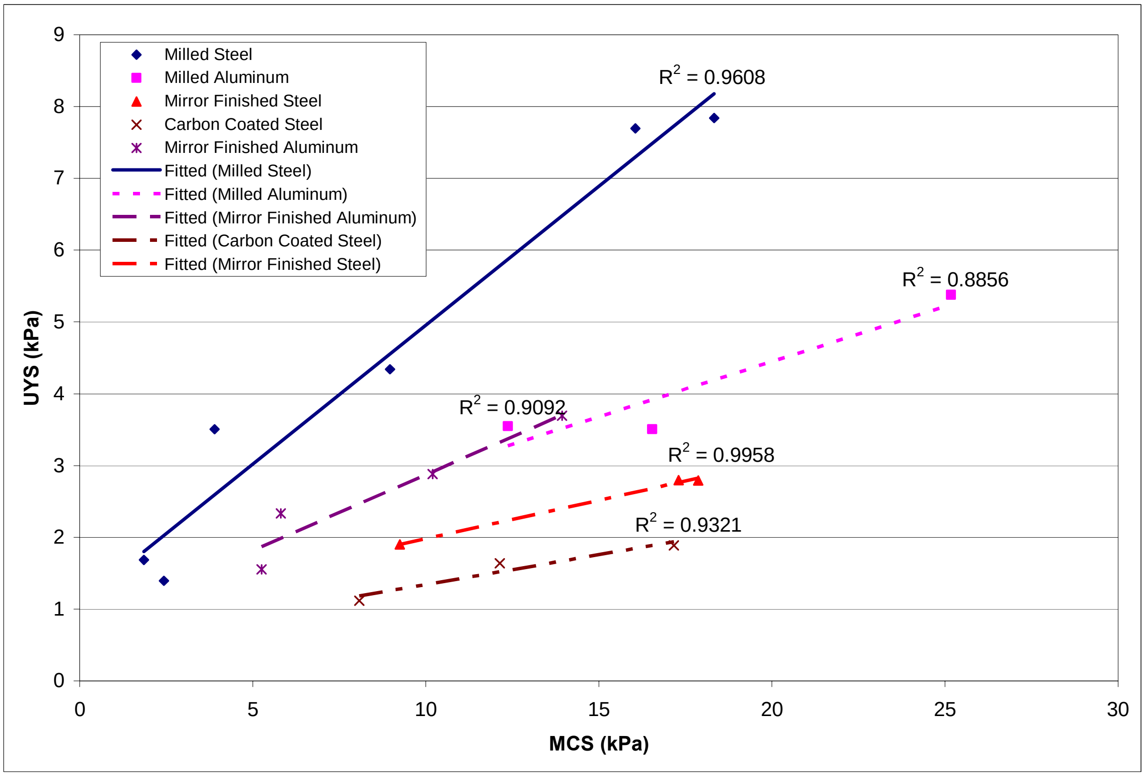

Figure 5.2 Wall friction flow functions of 20.0% moisture content (w.b.) poultry litter

The worst flow for poultry litter was obtained on the milled steel surface. However, the flow of poultry litter significantly improved when the steel surface was modified by either carbon coating or by mirror finishing. A better response to improve flow was obtained by the carbon coating the steel rather then mirror finishing it. A study looking at the flow properties of biomass and coal blends also reported having better flow after modifying the steel surfaces tested. In the study conducted the worst flow occurred on a milled mild steel surface and improved flow was observed on a stainless steel 304 with 2B finish surface (Zulfiqar et al, 2004).

Figure 5.1 also shows that poultry litter flows better on a milled aluminum surface in comparison to a milled steel surface. However, modifying the milled aluminum surface by mirror finishing did not improve the flow of poultry litter. This may be because thin aluminum oxide films are known to readily form on the metal's surface (Kresse et al, 2005). Each sample was made from the same aluminum and only differed in finish. It is hypothesized that the data is indicating that the type of finish has no effect on the wall friction because an aluminum oxide film of uniform friction has been formed on the surface of each sample. This may explain why these findings are in contrast to the significant improvement in the flow of poultry litter on the modified steel surfaces explained in the previous paragraph.

The average angle of wall friction for each of the materials, milled aluminum (37.9°), mirror finished aluminum (32.5°), milled steel (26.6°), mirror finished steel (35.1°), and carbon coated steel (30.7°), was calculated. These angles can be used to insure mass flow out of gravity flow devices, such as silos and hoppers.

The results above were confirmed by the flow index (obtained from the inverse of the slope of the linear fit of the UYL vs. MCS plot; Table 5.2). The flow index data indicated that all of the materials appear to have low adhesion with poultry litter. Milled steel was the only material with some adhesion but it was not close to being non-flowing. The optimal material appears to be the carbon coated steel because it allowed the easiest flow to occur.

Table 5.2 Wall friction flow index of 20.0% moisture content (w.b.) poultry litter

Material	Flow Function (FF)	Flow Index (FI)	Characteristic Flow
Milled steel	0.387	2.584	Adhesive
Mirror finished aluminum	0.211	4.739	Easy flowing
Milled aluminum	0.154	6.494	Easy flowing
Mirror finished steel	0.107	9.346	Easy flowing
Carbon coated steel	0.083	12.048	Free flowing

5.4 Conclusion

This study found that poultry litter’s moisture content greatly affected its flowability. Flowability reduced with increases in moisture content. The carbon coated steel surface gave the least resistance to flow, while the milled steel gave the greatest resistance. Modifying the milled aluminum surface by mirror finishing did not change the flowability of poultry litter on that surface.

5.5 References

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CHAPTER 6. CONCLUSION

It can be concluded from this study that moisture content significantly affects the physical properties, compaction and flowability of poultry litter. According to particle size analysis, 40% of the poultry litter can be considered to be fine and highly compressible. Physical properties such as the poured bulk density, particle density and porosity decreased with increases in moisture content. The porosity values indicated that poultry litter's particles were irregular and non-spherical in shape. The average tap bulk density and Hausner ratio were not affected by moisture content and had average values of 0.580 g/ml and 1.070, respectively (which indicated easy fluidization).

The compressibility of poultry litter was affected by both pressure and moisture content with a maximum compressibility percent of 18.0% obtained at a moisture content of 30.8% and a pressure 15 kPa.

The equilibrium moisture isotherm data was modeled with the GAB equation, where constants M_o, C, and K were found to be 0.0583, 3031, and 0.955, respectively, with a R^2 value of 0.917. The estimated monolayer moisture content of poultry litter indicated that biochemical degradation of the litter will occur when the relative humidity and temperature of the environment were 1.9% and 25°C, respectively.

Both the pressure applied and the moisture content of the poultry litter at the time of compaction significantly affected the density of the compact and the energy required for the compaction. Increase in moisture content resulted in an increase in the density of the compacts and a decrease in the energy expended during compaction. After two months of storage, the density of the compacts were only significantly affected by the amount of pressure applied during compaction while the original moisture content no longer had any significant affect. However, the force required to rupture the compacts after 2 months of storage was significantly affected by both the moisture content and the pressure applied. Based on the results from this study, it is recommended that poultry litter be compacted at a moisture content of 37.7% (w.b.) and a pressure of 5.0 MPa.

Poultry litter's moisture content significantly affected its flowability. Flowability reduced with increases in moisture content. The carbon coated steel surface gave the least resistance to flow, while the milled steel gave the greatest resistance. Modifying the milled aluminum surface by mirror finishing did not change the flowability of poultry litter on that surface.

CHAPTER 7. FUTURE WORK

This study provides useful information about the physical properties, compaction and flowability of poultry litter that will aid in the design or selection of optimal equipment and facilities to handle, store and transport poultry litter. Still, more research can be done to better understand the material.

More information on poultry litter's particle size distribution is needed. The sieve analysis completed in this study found that the largest percentage of the particles (24.14%) was retained on the bottom pan. Additional sieve analysis should be done to get a distribution of the particles smaller than 0.212 mm. The top sieve (with an aperture of 1.700 mm) also retained a large percentage (16.41%) of the poultry litter. This indicates that additional sieve analysis should be done on particles bigger than 1.700 mm. If this additional sieve analysis was carried out the error bars on the Figure 3.1 could considerably decrease and a more thorough size distribution could be provided.

The data provided in the Chapter 4 on the compaction of poultry litter should be taken into consideration and applied to a larger compaction process in order to produce larger agglomerates, such as cubes. The process of cubing poultry litter should be looked at rather than baling because poultry litter is not stringy in nature, and therefore would not benefit from baling. Research into the optimal compaction of poultry litter through cubing would allow for the densification of more material per process making it a more economical and efficient method for large scale compaction.

Additional tests on the flowability of poultry litter should also be completed. These tests should be done on samples with moisture contents (w.b.) between 18% and 22%, and between 26% and 30%. These additional tests could be used to find the exact moisture contents where the flow of the poultry litter changes from easy to cohesive, and from cohesive to very cohesive/non-flowing, respectively. With additional research a more complete understanding of poultry litter's physical properties, compaction and flowability could be obtained.

Therefore, future research objectives could include:

(1) Developing a more complete particle size distribution of poultry litter through further sieve analysis,

(2) Applying the small scale compaction data provided here to optimize the large scale compaction of poultry litter through cubing, and

(3) Measuring the flowability of poultry litter at smaller moisture content increments between 18% and 22%, and between 26% and 30%, in order to find the exact point where the flow of poultry litter transitions from easy to cohesive, and from cohesive to very cohesive/non-flowing, respectively.

APPENDICES

Appendix A. Physical Property Data

Table A.1 Particle size distribution of poultry litter

US Seive No.	Aperture (mm)	Run 1 (%)	Run 2 (%)	Run 3 (%)
12	1.700	10.66	19.64	18.94
20	0.850	17.72	21.49	21.36
30	0.595	14.87	15.50	15.81
40	0.425	8.21	8.34	7.68
50	0.297	9.98	8.36	8.69
60	0.250	4.48	3.31	3.61
70	0.212	3.85	2.38	2.70
Pan	0.000	30.23	20.96	21.21

Table A.2
Bulk density

M (%, w.b.)	ρ_b (g/ml)
10.3	0.550
10.3	0.547
10.3	0.541
14.2	0.541
14.2	0.548
14.2	0.546
18.1	0.546
18.1	0.542
18.1	0.542
22.0	0.546
22.0	0.549
22.0	0.542
26.1	0.538
26.1	0.535
26.1	0.536
30.6	0.534
30.6	0.534
30.6	0.533

Table A.3
Particle density

M (%, w.b.)	ρ_p (g/ml)
10.3	1.623
10.3	1.596
10.3	1.597
13.8	1.601
13.8	1.612
13.8	1.588
18.0	1.567
18.0	1.562
18.0	1.570
22.1	1.550
22.1	1.559
22.1	1.554
26.0	1.488
26.0	1.507
26.0	1.487
30.9	1.491
30.9	1.473
30.9	1.434

Table A.4
Tap bulk density

M (%, w.b.)	ρ_T (g/ml)
10.3	0.591
10.3	0.589
10.3	0.589
14.2	0.595
14.2	0.587
14.2	0.564
18.4	0.561
18.4	0.581
18.4	0.584
22.0	0.586
22.0	0.579
22.0	0.565
26.1	0.581
26.1	0.576
26.1	0.574
29.6	0.578
29.6	0.577
29.6	0.581

Table A.5 Porosity of poultry litter

M (%, w.b.)	ε	M (%, w.b.)	ε	M (%, w.b.)	ε
10.3	0.661	18.0	0.652	26.1	0.638
10.3	0.663	18.0	0.650	26.1	0.640
10.3	0.667	18.0	0.654	26.1	0.640
10.3	0.655	18.0	0.651	26.1	0.643
10.3	0.657	18.0	0.648	26.1	0.645
10.3	0.661	18.0	0.653	26.1	0.644
10.3	0.656	18.0	0.652	26.1	0.638
10.3	0.657	18.0	0.650	26.1	0.640
10.3	0.661	18.0	0.655	26.1	0.640
14.0	0.662	22.0	0.648	30.7	0.642
14.0	0.658	22.0	0.646	30.7	0.642
14.0	0.659	22.0	0.651	30.7	0.643
14.0	0.664	22.0	0.650	30.7	0.637
14.0	0.660	22.0	0.648	30.7	0.637
14.0	0.662	22.0	0.653	30.7	0.638
14.0	0.659	22.0	0.649	30.7	0.627
14.0	0.655	22.0	0.647	30.7	0.627
14.0	0.657	22.0	0.651	30.7	0.628

Table A.6 Hausner ratio of poultry litter

M (%, w.b.)	H_R	M (%, w.b.)	H_R	M (%, w.b.)	H_R
10.3	1.074	18.2	1.028	26.1	1.079
10.3	1.080	18.2	1.022	26.1	1.086
10.3	1.093	18.2	1.036	26.1	1.084
10.3	1.070	18.2	1.065	26.1	1.070
10.3	1.076	18.2	1.058	26.1	1.076
10.3	1.089	18.2	1.073	26.1	1.075
10.3	1.070	18.2	1.070	26.1	1.066
10.3	1.076	18.2	1.064	26.1	1.073
10.3	1.089	18.2	1.078	26.1	1.071
14.2	1.099	22.1	1.074	30.1	1.082
14.2	1.086	22.1	1.067	30.1	1.082
14.2	1.091	22.1	1.082	30.1	1.085
14.2	1.085	22.1	1.061	30.1	1.080
14.2	1.072	22.1	1.055	30.1	1.080
14.2	1.076	22.1	1.069	30.1	1.083
14.2	1.042	22.1	1.035	30.1	1.087
14.2	1.030	22.1	1.029	30.1	1.087
14.2	1.034	22.1	1.043	30.1	1.091

Table A.7 Compressibility of poultry litter

M (%, w.b.)	P (kPa)	C (%)	M (%, w.b.)	P (kPa)	C (%)
10.3	1.5	2.44	22.1	1.5	4.37
10.3	1.5	2.48	22.1	1.5	4.63
10.3	3	3.05	22.1	3	6.31
10.3	3	3.22	22.1	3	5.98
10.3	6	4.60	22.1	6	8.46
10.3	6	4.76	22.1	6	8.18
10.3	9	5.77	22.1	9	10.71
10.3	9	5.71	22.1	9	10.56
10.3	12	6.62	22.1	12	12.03
10.3	12	6.87	22.1	12	12.20
10.3	15	7.20	22.1	15	13.11
10.3	15	7.25	22.1	15	13.34
13.8	1.5	2.87	26.0	1.5	4.80
13.8	1.5	3.26	26.0	1.5	5.21
13.8	3	4.05	26.0	3	7.20
13.8	3	4.19	26.0	3	7.47
13.8	6	6.13	26.0	6	10.18
13.8	6	5.74	26.0	6	10.32
13.8	9	7.03	26.0	9	12.43
13.8	9	6.74	26.0	9	12.79
13.8	12	7.92	26.0	12	14.19
13.8	12	7.70	26.0	12	14.31
13.8	15	8.48	26.0	15	15.63
13.8	15	8.65	26.0	15	15.54
18.0	1.5	3.96	30.9	1.5	6.99
18.0	1.5	4.16	30.9	1.5	6.80
18.0	3	4.95	30.9	3	9.49
18.0	3	5.59	30.9	3	9.97
18.0	6	7.57	30.9	6	12.97
18.0	6	7.75	30.9	6	13.31
18.0	9	8.28	30.9	9	15.19
18.0	9	8.71	30.9	9	14.83
18.0	12	8.83	30.9	12	16.39
18.0	12	9.15	30.9	12	16.13
18.0	15	9.64	30.9	15	17.69
18.0	15	10.23	30.9	15	18.10

Table A.8 Equilibrium moisture isotherm (25^{o}C) raw data for poultry litter

M (%)	EMC (%, d.b.)	ERH (%)
10.09	11.22	25.51
10.09	11.22	25.86
10.09	11.22	26.76
13.42	15.50	57.25
13.42	15.50	58.10
13.42	15.50	59.24
17.68	21.48	73.79
17.68	21.48	74.57
17.68	21.48	76.01
23.64	30.96	84.87
23.64	30.96	86.07
23.64	30.96	87.41
26.70	36.43	87.73
26.70	36.43	88.72
26.70	36.43	90.37
30.58	44.05	90.84
30.58	44.05	91.51
30.58	44.05	93.21

Appendix B. Compaction Data

Table B.1 Poultry litter compaction data set 1

M (%, w.b.)	P (Mpa)	ρ (kg/m^3)	M (%, w.b.)	P (Mpa)	ρ (kg/m^3)
16.5	5.0	765.55	24.2	6.7	963.63
16.5	5.0	807.43	24.2	6.7	1014.47
16.5	5.9	867.90	24.2	7.5	1016.24
16.5	5.9	776.69	24.2	7.5	1036.57
16.5	6.7	920.44	24.2	8.4	1082.56
16.5	6.7	915.96	24.2	8.4	971.02
16.5	7.5	855.58	26.1	5.0	1019.47
16.5	7.5	912.78	26.1	5.0	1008.09
16.5	8.4	927.12	26.1	5.9	1041.50
16.5	8.4	848.59	26.1	5.9	1013.81
21.7	5.0	855.05	26.1	6.7	1084.50
21.7	5.0	887.21	26.1	6.7	1072.47
21.7	5.9	888.99	26.1	7.5	1123.85
21.7	5.9	853.63	26.1	7.5	1038.78
21.7	6.7	982.33	26.1	8.4	1020.24
21.7	6.7	999.23	26.1	8.4	1095.60
21.7	6.7	992.79	29.0	5.0	1120.45
21.7	7.5	1027.08	29.0	5.0	1061.42
21.7	7.5	930.23	29.0	5.9	1102.36
21.7	7.5	948.78	29.0	5.9	1050.14
21.7	8.4	955.10	29.0	6.7	1087.83
21.7	8.4	1046.03	29.0	6.7	1090.94
24.2	5.0	946.72	29.0	7.5	1064.28
24.2	5.0	998.21	29.0	7.5	1121.67
24.2	5.9	934.24	29.0	8.4	1172.17
24.2	5.9	953.57	29.0	8.4	1220.05

Table B.2 Poultry litter compaction data set 2

M (%, w.b.)	P (Mpa)	ρ (kg/m^3)	M (%, w.b.)	P (Mpa)	ρ (kg/m^3)
31.7	0.84	842.28	37.7	0.84	791.51
31.7	0.84	786.97	37.7	0.84	801.85
31.7	1.7	795.44	37.7	1.7	928.49
31.7	1.7	783.65	37.7	1.7	980.06
31.7	2.5	942.46	37.7	2.5	1017.29
31.7	2.5	887.58	37.7	2.5	985.77
31.7	3.4	986.02	37.7	3.4	990.04
31.7	3.4	927.19	37.7	3.4	1010.57
31.7	4.2	1058.98	37.7	4.2	1080.79
31.7	4.2	1045.87	37.7	4.2	1072.55
31.7	5.0	996.70	37.7	5.0	1020.63
31.7	5.0	996.15	37.7	5.0	1032.45
31.7	5.9	1047.41	37.7	5.9	1015.22
31.7	5.9	972.67	37.7	5.9	1036.84
31.7	6.7	1012.72	37.7	6.7	958.99
31.7	6.7	1019.09	37.7	6.7	1017.64
31.7	7.5	1115.38	41.4	0.84	851.57
31.7	7.5	1050.46	41.4	0.84	826.29
31.7	8.4	999.57	41.4	1.7	985.38
31.7	8.4	947.63	41.4	1.7	1007.57
35.1	0.84	772.76	41.4	2.5	1002.05
35.1	0.84	805.33	41.4	2.5	1074.68
35.1	1.7	863.17	41.4	3.4	1061.84
35.1	1.7	910.75	41.4	3.4	991.68
35.1	2.5	972.46	41.4	4.2	1024.17
35.1	2.5	916.53	41.4	4.2	1052.26
35.1	3.4	1049.62	41.4	5.0	1015.59
35.1	3.4	1027.69	41.4	5.0	1009.27
35.1	4.2	1050.46			
35.1	4.2	1035.94			
35.1	5.0	1077.80			
35.1	5.0	1036.57			
35.1	5.9	1087.27			
35.1	5.9	1018.84			
35.1	6.7	1053.00			
35.1	6.7	1079.95			
35.1	7.5	1084.75			
35.1	7.5	1103.66			
35.1	8.4	1159.60			
35.1	8.4	1139.94			

Table B.3 Poultry litter compaction data set 1 after 2 months storage

M (%, w.b.)	P (Mpa)	ρ (kg/m^3)	M (%, w.b.)	P (Mpa)	ρ (kg/m^3)
16.5	5.0	746.93	24.2	6.7	751.44
16.5	5.0	744.41	24.2	6.7	871.20
16.5	5.9	722.01	24.2	7.5	793.18
16.5	5.9	705.69	24.2	7.5	805.92
16.5	6.7	914.17	24.2	8.4	874.47
16.5	6.7	906.56	24.2	8.4	773.11
16.5	7.5	844.94	26.1	5.0	766.01
16.5	7.5	839.58	26.1	5.0	747.51
16.5	8.4	859.65	26.1	5.9	811.34
16.5	8.4	728.60	26.1	5.9	815.56
21.7	5.0	707.08	26.1	6.7	858.88
21.7	5.0	797.53	26.1	6.7	844.34
21.7	5.9	638.44	26.1	7.5	908.81
21.7	5.9	824.18	26.1	7.5	873.15
21.7	6.7	834.39	26.1	8.4	854.79
21.7	6.7	776.13	26.1	8.4	869.34
21.7	6.7	824.20	29.0	5.0	846.31
21.7	7.5	873.85	29.0	5.0	842.12
21.7	7.5	790.77	29.0	5.9	846.23
21.7	7.5	728.17	29.0	5.9	829.94
21.7	8.4	813.17	29.0	6.7	927.06
21.7	8.4	808.52	29.0	6.7	892.15
24.2	5.0	817.08	29.0	7.5	864.01
24.2	5.0	626.24	29.0	7.5	865.25
24.2	5.9	795.28	29.0	8.4	917.68
24.2	5.9	788.98	29.0	8.4	922.35

Table B.4 Poultry litter compaction data Set 2 after 2 months storage

M (%, w.b.)	P (Mpa)	ρ (kg/m^3)
31.7	5.0	588.43
31.7	5.0	716.26
31.7	5.9	796.31
31.7	5.9	728.76
31.7	6.7	731.83
31.7	6.7	759.10
31.7	7.5	704.84
31.7	7.5	820.86
31.7	8.4	706.11
31.7	8.4	654.03
35.1	0.84	561.33
35.1	0.84	568.15
35.1	1.7	637.39
35.1	1.7	625.43
35.1	2.5	679.17
35.1	2.5	672.94
35.1	3.4	775.28
35.1	3.4	781.47
35.1	4.2	750.52
35.1	4.2	744.84
35.1	5.0	807.39
35.1	5.0	755.94
35.1	5.9	821.91
35.1	5.9	778.71
35.1	6.7	874.36
35.1	6.7	777.82
35.1	7.5	813.69
35.1	7.5	804.19
35.1	8.4	767.92
35.1	8.4	803.27
37.7	0.84	562.75
37.7	0.84	559.28
37.7	1.7	658.59
37.7	1.7	665.26
37.7	2.5	674.38
37.7	2.5	688.53
37.7	3.4	711.92
37.7	3.4	740.94
37.7	4.2	707.52
37.7	4.2	804.21
37.7	5.0	737.74
37.7	5.0	748.91
37.7	5.9	731.15
37.7	5.9	703.71
37.7	6.7	717.43
37.7	6.7	702.64
41.4	0.84	588.90
41.4	0.84	513.86
41.4	1.7	662.88
41.4	1.7	694.99
41.4	2.5	681.26
41.4	2.5	738.95
41.4	3.4	736.74
41.4	3.4	701.75
41.4	4.2	743.91
41.4	4.2	749.32
41.4	5.0	672.36
41.4	5.0	707.39

Table B.5 Poultry litter compact's percent decrease in density after 2 months

M (%, w.b.)	P (Mpa)	$\rho_{decrease}$ (%)	M (%, w.b.)	P (Mpa)	$\rho_{decrease}$ (%)
16.5	5.0	5.2	31.7	6.7	26.6
16.5	5.9	13.2	31.7	7.5	29.6
16.5	6.7	0.9	31.7	8.4	30.1
16.5	7.5	4.7	35.1	0.84	28.4
16.5	8.4	10.6	35.1	1.7	28.8
21.7	5.0	13.6	35.1	2.5	28.4
21.7	5.9	16.1	35.1	3.4	25.1
21.7	6.7	18.1	35.1	4.2	28.3
21.7	7.5	17.7	35.1	5.0	26.1
21.7	8.4	19.0	35.1	5.9	24.0
24.2	5.0	25.8	35.1	6.7	22.5
24.2	5.9	16.1	35.1	7.5	26.1
24.2	6.7	18.0	35.1	8.4	31.7
24.2	7.5	22.1	37.7	0.84	29.6
24.2	8.4	19.8	37.7	1.7	30.6
26.1	5.0	25.4	37.7	2.5	32.0
26.1	5.9	20.8	37.7	3.4	27.4
26.1	6.7	21.0	37.7	4.2	29.8
26.1	7.5	17.6	37.7	5.0	27.6
26.1	8.4	18.5	37.7	5.9	30.1
29.0	5.0	22.6	37.7	6.7	28.2
29.0	5.9	22.1	41.4	0.84	34.3
29.0	6.7	16.5	41.4	1.7	31.9
29.0	7.5	20.9	41.4	2.5	31.6
29.0	8.4	23.1	41.4	3.4	30.0
31.7	5.0	34.5	41.4	4.2	28.1
31.7	5.9	24.5	41.4	5.0	31.9

Table B.6 Breakage force of compacts after 2 months storage

M (%, w.b.)	P (Mpa)	F (N)	M (%, w.b.)	P (Mpa)	F (N)
31.7	0.84	9.8	37.7	3.4	259.3
31.7	0.84	23.5	37.7	4.2	277.0
31.7	1.7	26.6	37.7	4.2	273.3
31.7	2.5	74.6	37.7	5.0	319.7
31.7	2.5	65.6	37.7	5.0	269.6
31.7	3.4	141.7	37.7	5.9	344.1
31.7	4.2	179.0	37.7	5.9	370.5
31.7	4.2	168.2	41.4	0.84	127.7
31.7	5.0	160.5	41.4	0.84	86.9
31.7	5.0	183.5	41.4	1.7	260.4
31.7	5.9	213.6	41.4	1.7	308.5
31.7	5.9	225.1	41.4	2.5	272.2
37.7	0.84	44.4	41.4	2.5	370.0
37.7	0.84	50.9	41.4	3.4	414.8
37.7	1.7	155.5	41.4	3.4	272.9
37.7	1.7	200.0	41.4	4.2	366.6
37.7	2.5	266.0	41.4	4.2	336.1
37.7	2.5	255.6	41.4	5.0	257.2
37.7	3.4	291.6	41.4	5.0	334.6

Table B.7 Specific energy required for compaction of poultry litter

M (%, w.b.)	P (Mpa)	E (KJ/kg)	M (%, w.b.)	P (Mpa)	E (KJ/kg)
16.5	5.0	1.380	35.1	3.4	0.763
16.5	5.9	1.710	35.1	4.2	0.972
24.2	5.0	1.091	35.1	5.0	1.086
24.2	5.9	1.335	35.1	5.9	1.168
26.1	5.0	1.124	37.7	0.84	0.205
26.1	5.9	1.398	37.7	1.7	0.504
29.0	5.0	1.161	37.7	2.5	0.590
29.0	5.9	1.318	37.7	3.4	0.698
31.7	0.84	0.216	37.7	4.2	0.889
31.7	1.7	0.440	37.7	5.0	1.011
31.7	2.5	0.686	37.7	5.9	1.374
31.7	3.4	0.913	41.4	0.84	0.233
31.7	4.2	1.012	41.4	1.7	0.404
31.7	5.0	1.216	41.4	2.5	0.645
31.7	5.9	1.407	41.4	3.4	0.837
35.1	0.84	0.190	41.4	4.2	0.812
35.1	1.7	0.452	41.4	5.0	1.106
35.1	2.5	0.651			

Appendix C. Flowability Data

Table C.1 Flow function data for poultry litter

M (%, w.b.)	10.3		18.0		22.1	
σ (kPa)	UYS (kPa)	MCS (kPa)	UYS (kPa)	MCS (kPa)	UYS (kPa)	MCS (kPa)
1.5	1.25	3.79	1.93	2.58	1.95	3.91
1.5	1.91	4.66	2.22	3.83	2.82	6.87
3	1.00	15.63	2.72	7.57	2.80	7.09
3	2.81	7.81	2.11	8.51	1.46	7.67
6	2.72	6.17	2.84	13.85	5.12	13.85
6	3.14	32.93	2.37	13.99	4.36	19.41
9	4.65	32.82	4.19	20.83	6.10	21.15
9	4.12	18.53	3.09	21.48	9.57	22.55
12	5.57	30.45	7.22	31.12	8.04	26.79
12	10.81	36.11	10.18	31.67	9.54	28.97

M (%, w.b.)	26.0		30.9	
σ (kPa)	UYS (kPa)	MCS (kPa)	UYS (kPa)	MCS (kPa)
1.5	1.79	2.56	1.73	2.62
1.5	1.00	3.12	1.83	2.92
3	1.69	6.96	2.97	6.71
3	2.71	7.92	3.64	7.30
6	4.84	12.57	6.99	12.47
6	8.56	14.51	8.35	13.21
9	6.42	19.79	10.60	20.13
9	8.00	20.91	17.97	23.92
12	10.19	25.08	13.05	24.74
12	8.87	26.19	12.02	28.43

Table C.2 Cohesion and angle of internal friction of poultry litter

σ (kPa)	1.5		3		6		9		12	
M (%, w.b.)	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**φ (°)**	**c (kPa)**	**Φ (°)**	**c (kPa)**	**Φ (°)**
10	0.51	33.74	0.61	41.66	0.84	45.65	0.98	44.30	2.08	47.90
10	0.30	38.55	0.59	44.49	0.20	46.24	1.22	42.69	0.52	53.36
18			0.57	44.56	0.62	42.89	0.93	42.13	2.37	40.07
18	0.72	24.06	0.45	43.88	0.52	42.70	0.65	44.38	1.55	43.50
22	0.27	49.52	0.61	43.16	1.18	40.53	1.30	43.82	1.88	39.89
22	0.49	36.69	0.61	42.84	0.69	54.89	2.07	43.22	2.05	43.47
26	0.49	32.49	0.33	47.25	1.98	40.35	1.84	40.61	1.99	41.67
26	0.20	46.51	0.50	49.44	1.17	38.40	1.43	41.98	2.48	38.07
30	0.37	46.00	0.65	42.65	2.21	34.22	3.94	42.64	2.53	44.35
30	0.44	36.15	0.73	46.28	1.77	36.28	2.57	38.25	3.32	36.06

Table C.3 Wall friction flow function data and angle of wall friction for poultry litter with milled steel

σ (kPa)	UYS (kPa)	MCS (kPa)	φ (°)
12	7.84	18.33	27.27
9	7.70	16.05	32.07
6	4.34	8.96	35.43
3	3.51	3.90	21.66
1.5	1.68	1.86	8.95
1.5	1.39	2.43	33.99

Table C. 4 Wall friction flow function data and angle of wall friction for poultry litter with milled aluminum

σ (kPa)	UYS (kPa)	MCS (kPa)	φ (°)
12	5.38	25.17	32.66
9	3.51	16.55	35.66
6	3.55	12.38	45.28

Table C. 5 Wall friction flow function data and angle of wall friction for poultry litter with mirror finished aluminum

σ (kPa)	UYS (kPa)	MCS (kPa)	φ (°)
12	2.24	16.19	28.13
9	3.70	13.93	34.60
6	2.88	10.19	30.67
3	1.55	5.26	40.24
3	2.33	5.81	28.81

Table C. 6 Wall friction flow function data and angle of wall friction for poultry litter with carbon coated steel

σ (kPa)	UYS (kPa)	MCS (kPa)	φ (°)
12	1.88	17.17	36.97
9	1.64	12.14	29.20
6	1.12	8.07	25.80

Table C.7 Wall friction flow function data and angle of wall friction for poultry litter with mirror finished steel

σ (kPa)	UYS (kPa)	MCS (kPa)	φ (°)
12	2.79	17.87	32.86
12	2.80	17.30	36.17
6	1.90	9.25	36.39

Appendix D. Equipment Photos

Figure D.1 Texture analyzer with compression cell and tight fitted piston

Figure D.2 Clamped compaction die filled with poultry litter below a plunger attached to the crosshead of the texture analyzer before compaction

Figure D.3 Poultry litter compact removed from compaction die

Figure D.4 Annular shear cell

Figure D.5 Wall friction samples
(Top row, left to right: milled aluminum, mirror finished aluminum;
Bottom row, left to right: milled steel, mirror finished steel, and carbon coated steel)