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Bulk density and compaction behavior of knife mill chopped switchgrass, wheat straw, and corn stover

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ABSTRACT

Bulk density of comminuted biomass significantly increased by vibration during handling and transportation, and by normal pressure during storage. Compaction characteristics affecting the bulk density of switchgrass, wheat straw, and corn stover chopped in a knife mill at different operating conditions and using four different classifying screens were studied. Mean loose-filled bulk densities were 67.5 ± 18.4 kg/m^3 for switchgrass, 36.1 ± 8.6 kg/m^3 for wheat straw, and 52.1 ± 10.8 kg/m^3 for corn stover. Mean tapped bulk densities were 81.8 ± 26.2 kg/m^3 for switchgrass, 42.8 ± 11.7 kg/m^3 for wheat straw, and 58.9 ± 13.4 kg/m^3 for corn stover. Percentage changes in compressibility due to variation in particle size obtained from a knife mill ranged from 64.3 to 173.6 for chopped switchgrass, 22.2–51.5 for chopped wheat straw and 42.1–117.7 for chopped corn stover within the tested consolidation pressure range of 5–120 kPa. Pressure and volume relationship of chopped biomass during compression with application of normal pressure can be characterized by the Walker model and Kawakita and Ludde model. Parameter of Walker model was correlated to the compressibility with Pearson correlation coefficient greater than 0.9. Relationship between volume reduction in chopped biomass with respect to number of tappings studied using Sone's model indicated that infinite compressibility was highest for chopped switchgrass followed by chopped wheat straw and corn stover. Degree of difficulty in packing measured using the parameters of Sone's model indicated that the chopped wheat straw particles compacted very rapidly by tapping compared to chopped switchgrass and corn stover. These results are very useful for solving obstacles in handling bulk biomass supply logistics issues for a biorefinery.

1. Introduction

Biomass is a sustainable source for energy production at an industrial scale (Ibsen et al., 2000). Switchgrass (*Panicum virgatum* L.) is a perennial grass with high yield potential and has been touted as a model dedicated energy crop. It adapts to marginal sites, and tolerates water deficit and low moisture content (Sanderson et al., 1999). Also, corn (*Zea mays* L.) stover, wheat (*Triticum aestivum* L.) straw and a number of other crop residues are abundant from the US agricultural production as candidate feedstock for energy production (Perlack et al., 2005). Many organizations are on the threshold of commercial-scale conversion of lignocellulosic biomass into ethanol (Bouton, 2007). Some engineering challenges often overlooked include development of harvesting, handling, transportation, storage, and processing of biomass feedstock for fuels (Wright et al., 2006; Knauf and Moniruzzaman, 2004; Sokhansanj et al., 2006).

Bulk density has significant effect on material handling and storage aspects in a biorefinery, and depends on material composition, particle size, shape and distribution, moisture content, specific density and applied pressure (Lam et al., 2007). Bulk density of biomass increases during transportation, handling, and storage which can be caused by compaction due to vibration, tapping, or normal load (Emami and Tabil, 2008). Hence, compaction behavior of biomass is very important for capacity sizing and supply logistics (Fasina, 2006).

Mathematical models are used for understanding the compaction behavior of particulate materials. In modeling, the relationship between physical state and compression pressure is linearized and parameters of the linear model are determined. These parameters are then used for characterizing the materials. Another important use of these models is to accurately predict the density of material at different consolidation pressures (Denny, 2002).

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The model developed by Sone (1969) has performed well for biomaterials (Peleg and Bagley, 1983) compared to other models used for understanding the compaction behavior caused by tapping. During initial stages of compression with normal pressure, the particles rearrange themselves to form a closely packed mass. At this stage, the particles retain most of the original properties. As compaction pressure increases, the particles are forced against each other undergoing elastic and plastic deformations. Brittle particles may fracture leading to mechanical interlocking that affects compaction characteristics (Gray, 1968). Adapa et al. (2005) observed that the linear model developed by Walker (1923) can be used for understanding the compression characteristics of chopped alfalfa grinds. Emami and Tabil (2008) also studied the compaction characteristics of chickpea flour using the models developed by Walker and used the parameters of model for characterizing the material. Mani et al. (2004a) studied the compaction behavior of ground swichgrass, wheat straw, corn stover, and barley in a hammer mill for making pellets. They studied the compression behavior of ground biomass using the models developed by Cooper and Eaton (1962), Heckel (1961), and Kawakita and Ludde (1971). Their results indicated that the parameters of Kawakita and Ludde model correlated well with porosity and yield strength of ground biomass. However, no work has been carried out on the compression characteristics of chopped biomass, which has larger particles than ground biomass.

The objectives of this research work are as follows: (a) determine the effect of particle size on the densities of biomass chopped in a knife mill, and (b) evaluate the compaction behavior of chopped biomass by tapping and with application of normal pressure.

2. Compaction models investigated

Compaction characteristics of chopped biomass with application of normal pressure was studied using the models developed by Kawakita and Ludde (1971) and Walker (1923). Walker (1923) proposed the following model for understanding the pressure–volume relationships of calcium carbonate and tetronitromethylamiline and subsequently various researchers used this model for biological materials:

$$V = a_1 - K_1 \ln P \tag{1}$$

where V is relative volume ratio, P is applied pressure (kPa), and a_1 and K_1 are constants. Another model widely used for understanding the pressure–volume relationships was that developed by Kawakita and Ludde (1971) which has the form

$$\frac{P}{C} = \frac{1}{a_2 b_2} + \frac{P}{a_2} \tag{2}$$

where P is applied pressure, a_2 and b_2 are constants, and C is relative volume decrease or engineering strain given by the equation

$$C = \frac{V_0 - V_p}{V_0} \tag{3}$$

where V_0 is the initial volume and V_p is volume measured at any given pressure. The model developed by Sone (1969) is used for understanding the compaction characteristics by tapping. Sone's model has close resemblance to the Kawakita and Ludde model, and the pressure term in the Kawakita and Ludde model is replaced with number of tappings. Eq. (3) can be rewritten in the form

$$\frac{n}{\gamma_n} = \frac{1}{a_3 b_3} + \frac{n}{a_3} \tag{4}$$

where γ_n is volume reduction ratio, n is number of tappings and a_3 and b_3 are constants. The volume reduction ratio γ_n is calculated using

$$\gamma_n = \frac{(V_0 - V_n)}{V_0} \tag{5}$$

where V_0 is initial volume, and V_n is volume after n taps.

3. Methods

3.1. Chopped biomass

Switchgrass, wheat straw, and corn stover were chopped in a knife mill (H.C. Davis Sons Mfg. Co., Inc., Bonner Springs, KS, USA) with rotor speeds between 250 and 500 rpm, mass feed rates from 1 to 11 kg/min, and classifying screen opening dimensions of 12.7, 19.0, 25.4 and 50.8 mm. Particle size distributions of the chopped biomass were classified using ASABE S424.1-specified sieves and horizontal sieving actuation (ASABE, 2006). Mass fractions retained on the sieves having diagonal opening dimensions of 1.65, 5.61, 8.98, 18.0, and 26.9 mm, and pan were used to determine the geometric mean length (X_{gm}) and standard deviation (S_{gm}).

3.2. Bulk density

Loose-filled bulk density of biomaterials such as grains, pellets and ground particles is typically determined using containers having a capacity of 500 cm^3 per standard methods (Chevanan et al. 2007). The container used to determine tapped bulk density per an ASTM standard and other standards have a capacity of only 250 cm^3. However, the chopped biomass particles in this study were large compared to these standardized container sizes and could not be filled to obtain representative density measurements (Chevanan et al., in press). Hence, the standard methods for determination of bulk density were not applicable in this experiment. Loose-filled bulk density was measured using a cylindrical aluminum container with 149 mm diameter and 143 mm height (~2500 cm^3). Biomass was filled in layers with approximately 10 mm thickness, and care was taken to avoid bridging of biomass particles. Mass of biomass in the container was determined using an electronic balance (±0.01 g accuracy). Loose-filled bulk density in kg/m^3 was determined as (Chevanan et al., 2008):

$$\text{Loose}-\text{filled bulk density } (\rho_L) = \frac{\text{Mass of the biomass}}{\text{Volume of the biomass}}. \tag{6}$$

The container with biomass was tapped on a wooden platform 50 times with an approximate amplitude of 20 mm. Reduction in height of the top biomass surface was measured using a vernier caliper (±0.01 mm). The settled distance was measured at a total of nine locations. Four locations were near the inside surface of the container wall, another four were at 50% of radius and one measure was taken at the center of the container. The reduction in volume of biomass was calculated as an imaginary cylindrical volume having inside diameter of the container and height of average settled distance. Tapped bulk density was calculated as

$$\text{Tapped bulk density } (\rho_T) = \frac{\text{Mass of the biomass}}{\text{Cylinder volume} - \text{settled volume reduction}} \tag{7}$$

Loose-filled and tapped bulk density measurements were conducted with three replications.

3.3. Compaction behavior with normal pressure

A compression cell was fabricated using mild steel to study the compression behavior of chopped biomass with application of normal pressure in a Universal Testing Machine (UTM). The compression cell consisted of a cylinder and a close fitting piston (Fig. 1).