Bioresource Technology 101 (2010) 207–214

Contents lists available at ScienceDirect

Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

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

Nehru Chevanan [a], Alvin R. Womac [a,*], Venkata S.P. Bitra [a], C. Igathinathane [b], Yuechuan T. Yang [a], Petre I. Miu [a], Shahab Sokhansanj [c]

[a] Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, TN, USA
[b] Agricultural and Biological Engineering, Mississippi State University, MS, USA
[c] Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, TN, USA

ARTICLE INFO

Article history:
Received 28 August 2008
Received in revised form 26 March 2009
Accepted 29 July 2009
Available online 21 August 2009

Keywords:
Chopped biomass
Knife mill
Bulk density
Tapped bulk density
Compaction models

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).

* Corresponding author. Tel.: +1 865 974 7104; fax: +1 865 974 4514.
E-mail address: awomac@utk.edu (A.R. Womac).

0960-8524/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.biortech.2009.07.083

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):

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

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).

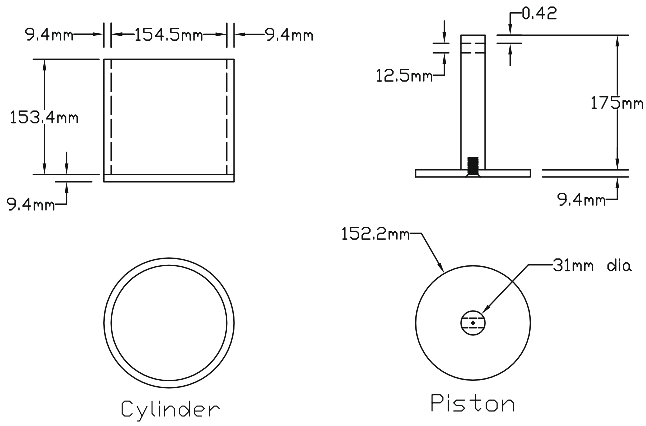

Fig. 1. Compression cell.

The cylinder had an internal diameter of 154.5 mm and height of 153.4 mm. The piston had an outer diameter of 152.2 mm and stem length of 175 mm. The stem of the piston was connected to the load cell (30 kN capacity) of UTM (MTS System Corporation, Eden Prairie, MN, USA). The compression cell was filled with biomass in layers of approximately 10 mm thickness up to the rim of the cylinder and weight of the biomass was recorded using an electronic balance (±0.01 g accuracy). Test works software (MTS System Corporation, Eden Prairie, MN, USA) recorded force–displacement data (10 Hz frequency) at a compression rate of 1 mm/s. Pressure, volume, and density were calculated from displacement, cylinder physical dimensions and sample mass.

Compressibility of biomass (C_m) with normal pressure was determined using the following equation (Fayed and Skocir, 1997):

$$C_m = \left(\frac{V_i - V_f}{V_i}\right) * 100 = \left(1 - \frac{\rho_{bi}}{\rho_{bf}}\right) * 100 \tag{8}$$

where V_i is initial volume of biomass (m^3), V_f is final volume of biomass at desired consolidating pressure (m^3), ρ_{bi} is initial bulk density of the biomass (kg/m^3), and ρ_{bf} is final bulk density of the biomass at desired consolidating pressure (kg/m^3).

Volume of biomass at 0, 2.5, 5, 10, 20, 40, 60, 80, 100, and 120 kPa consolidation pressures were used to determine the parameters of Walkers model and Kawakita and Ludde model. The constants a_1 and K_1 of Walker model were determined as intercept and slope respectively, of linear relationship between volume ratio and ln P, as per Eq. (1). Parameters a_2 and b_2 of Kawakita and Ludde model were determined by linear regression of P/C and P values, as per Eq. (2).

3.4. Compaction behavior with tapping

Two samples of chopped switchgrass having X_{gm} of 3.30 and 14.06 mm, two samples of chopped wheat straw having X_{gm} of 3.69 and 10.68 mm and two samples of chopped corn stover having X_{gm} of 3.22 and 12.79 mm were selected for contrasting particle sizes for understanding the compaction behavior during tapping. The three coarse samples were chopped using similar operating conditions with 50.8 mm classifying screen in the knife mill, while the three finer samples were chopped using 12.7 mm classifying screen in knife mill with similar operating conditions. Chopped biomass samples were filled in the previously-described $\sim$2500 cm^3 – aluminum container used for determination of bulk density. Reduction in volume was recorded for every five taps. In the preliminary experiments we did not observe reduction in volume after 60 taps for chopped biomass. Hence the reported tapped-density was measured after 60 taps. Measurements were made in triplicate for all the samples.

The value of constants a_3 and b_3 were determined as explained by Peleg and Bagley (1983). Briefly, the slope and intercept values of linear relationship between n/γ_n versus n were used to determine the value of constants a_3 and b_3 by linear regression, per Eq. (4).

4. Results and discussion

4.1. Bulk density

Loose-filled bulk density of chopped switchgrass was the highest followed by chopped corn stover and wheat straw in a knife mill. Loose-filled bulk density of chopped switchgrass and corn stover having X_{gm} of 3.2 ± 0.2 mm was 108.4% and 31.9% higher than that of chopped wheat straw. Similarly, loose-filled bulk density of chopped switchgrass and corn stover having X_{gm} of 12.3 ± 0.5 mm was 80.6% and 37.4% higher than that of loose-filled bulk density of chopped wheat straw (Table 1). As particle size increased, loose-filled bulk density decreased. Mani et al. (2004b) observed a similar trend for wheat straw, switchgrass and barley straw ground in a hammer mill. This might be due to the fact that, as particle size increases, pore spaces between particles increase leading to decrease in bulk density.

Tapped bulk density measured after 60 tappings was highest for chopped switchgrass followed by chopped corn stover and wheat straw. The particle size had an inverse relationship with the increase in bulk density by tapping. The increase in bulk density by tapping of the samples with small X_{gm} was higher than the increase in bulk density by tapping of the samples with large $X_{gm.}$ These variations might be due to variation observed in the infinite compressibility achieved during tapping, and reduced effect of particle rearrangement due to particle size. The relationships between geometric mean length and densities were expressed using third order models (Table 2). Coefficient of determination (R^2) values were higher and more than 0.9 for chopped switchgrass and wheat straw. But for chopped corn stover, the R^2 value was less than 0.79. Chopped switchgrass and wheat straw contained particles of fairly uniform physical characteristics. Chopped corn stover contained both fibrous particles from the rind and other irregular shaped particles from the pith and affected the particle arrangement and packing during filling (Chevanan et al., in press). This may have led to very low R^2 value between the geometric mean length and bulk densities for chopped corn stover.

4.2. Compaction characteristics with normal pressure

A typical force–time curve obtained for three chopped biomass particles during compression is shown in Fig. 2. During initial

Table 1
Loose-filled and tapped bulk densities of selected particle size distributions of chopped biomass.

Chopped biomass	X_{gm} [A] (mm)	S_{gm} [B] (mm)	Loose-filled bulk[C] density (kg/m^3)	Tapped bulk[C] density (kg/m^3)
Switchgrass	3.30	2.52	105.18[a]	135.68[a]
	12.32	2.54	45.26[d]	51.63[d]
Wheat straw	3.35	2.12	50.46[c]	62.75[c]
	12.27	2.52	25.06[f]	27.68[f]
Corn stover	3.26	2.37	66.56[b]	80.24[b]
	12.79	2.09	34.44[e]	38.35[e]

[A] X_{gm} – geometric mean length.
[B] S_{gm} – standard deviation.
[C] Mean values of loose-filled bulk density and tapped bulk density measured after 60 taps suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$.

Table 2
Relationship between geometric mean length and densities of chopped biomass.

Chopped biomass	Model	Particle range (mm)	R^2
Switchgrass	$\rho_L = 161.152–26.135\ X_{gm} + 2.189\ (X_{gm})^2 – 0.065\ (X_{gm})^3$	2.65–14.69	0.93
	$\rho_T = 221.697–40.015\ X_{gm} + 3.454\ (X_{gm})^2 – 0.105\ (X_{gm})^3$	2.65–14.69	0.93
Wheat straw	$\rho_L = 89.030–14.078\ X_{gm} + 1.493\ (X_{gm})^2 – 0.061\ (X_{gm})^3$	3.17–12.27	0.90
	$\rho_T = 108.150–20.469\ X_{gm} + 2.116\ (X_{gm})^2 – 0.083\ (X_{gm})^3$	3.17–12.27	0.91
Corn stover	$\rho_L = 83.097–6.142\ X_{gm} + 0.411\ (X_{gm})^2 – 0.015\ (X_{gm})^3$	3.22–14.89	0.75
	$\rho_T = 117.545–14.256\ X_{gm} + 1.132\ (X_{gm})^2 – 0.035\ (X_{gm})^3$	3.22–14.89	0.79

ρ_L = Loose-filled bulk density (kg/m^3).
ρ_T = Tapped bulk density (kg/m^3).
X_{gm} = Geometric mean length (mm).

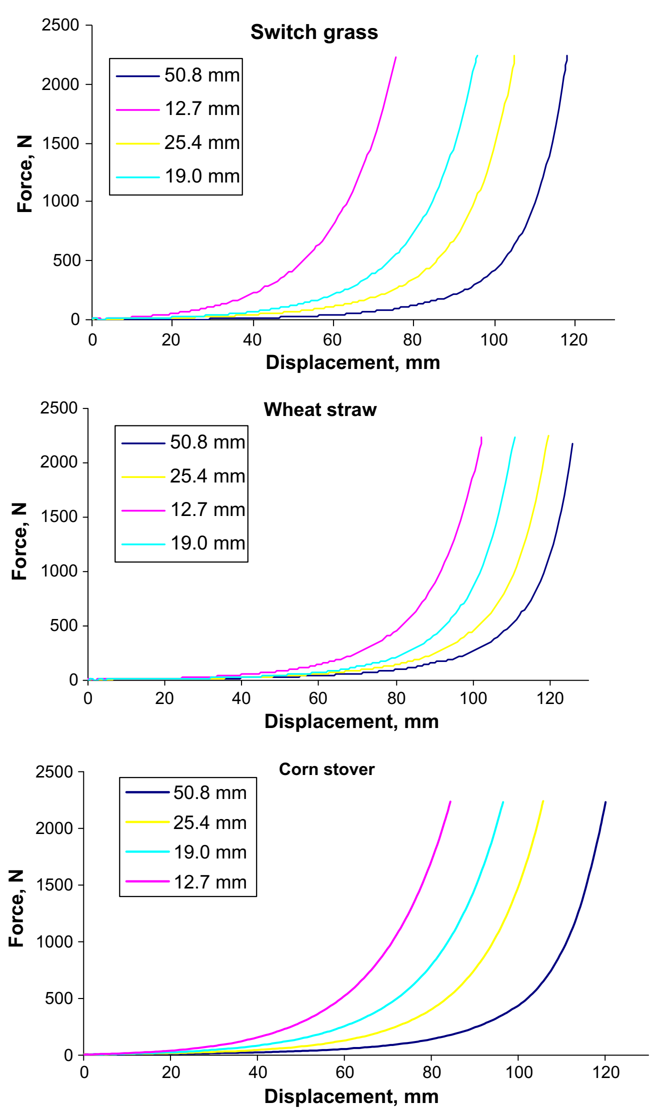

Fig. 2. Typical force – time curve obtained for chopped switchgrass, wheat straw and corn stover obtained with 12.7, 19.0, 25.4, and 50.8 mm classifying screens in the knife mill during compression.

stages of compression, only rearrangement of particles takes place and the particles retained their original properties. This is indicated by slow and constant increase in the force during compression. The change in slope after the initial constant period indicated that elastic and plastic deformation has started (Mani et al., 2004c). The initial region of rearrangement of particles was much longer for chopped wheat straw followed by chopped corn stover and switchgrass (Fig. 2). As expected, chopped biomass obtained with 50.8 mm classifying screen in the knife mill needed more displacement for rearrangement of particles during compression followed by chopped biomass obtained with 25.4, 19.0, and 12.7 mm classifying screens in the knife mill and in that order.

Wheat straw exhibited the greatest compressibility followed by switchgrass and corn stover had the lowest compressibility. Maxi-

Table 3
Effect of particle size on compressibility of chopped switchgrass.

Run no.	Knife mill screen size (mm)	X_{gm} (mm)[A]	S_{gm}[B] (mm)	Compressibility (%)[C] 5 kPa	20 kPa	60 kPa	120 kPa
S1	12.7	2.65	2.51	18.4^{za}	31.8^{tu}	43.2^{vw}	50.2^{vw}
S2	12.7	2.77	2.37	$20.8^{y–a}$	34.3^{s}	45.2^{u}	51.8^{uv}
S3	12.7	2.99	2.47	16.3^{za}	29.2^{vw}	40.5^{xy}	47.5^{xy}
S4	12.7	3.00	2.40	19.0^{yz}	$32.5^{s–u}$	43.7^{uv}	50.5^{v}
S5	12.7	3.17	2.65	15.9^{za}	28.3^{w}	39.2^{y}	46.2^{y}
S6	12.7	3.30	2.52	17.5^{za}	30.5^{uv}	41.7^{wx}	48.7^{wx}
S7	12.7	3.49	2.69	19.6^{yz}	33.8^{st}	45.3^{u}	52.3^{u}
S8	19.0	4.20	2.78	24.5^{wx}	39.9^{r}	51.5^{t}	50.1^{t}
S9	19.0	4.21	2.77	26.4^{vw}	41.8^{qr}	53.1^{st}	$59.4^{r–t}$
S10	19.0	4.45	2.50	$28.1^{s–v}$	$43.5^{o–q}$	$54.6^{p–s}$	$60.7^{o–r}$
S11	19.0	4.45	2.58	$30.3^{o–s}$	$45.8^{n–q}$	56.7^{o}	62.6^{n}
S12	19.0	4.70	2.54	$28.2^{s–v}$	$43.8^{n–q}$	$55.0^{o–s}$	$61.2^{n–q}$
S13	19.0	4.70	2.45	26.7^{vw}	42.6^{pq}	53.8^{rs}	$60.1^{q–s}$
S14	19.0	4.77	2.76	$29.9^{p–t}$	45.9^{mn}	56.4^{op}	62.9^{n}
S15	19.0	5.04	2.70	$30.5^{o–s}$	$44.7^{n–p}$	$55.8^{o–r}$	$61.9^{n–p}$
S16	19.0	5.21	2.57	$27.5^{t–v}$	$43.0^{o–q}$	$54.3^{q–s}$	$60.7^{o–r}$
S17	19.0	5.33	2.69	$28.5^{r–v}$	$44.2^{n–p}$	$55.5^{o–r}$	$61.7^{n–q}$
S18	19.0	5.34	2.63	$29.5^{q–u}$	45.1^{no}	$56.2^{o–q}$	62.3^{no}
S19	19.0	5.41	2.66	$28.7^{r–v}$	45.9^{mn}	56.4^{op}	62.9^{n}
S20	19.0	5.55	2.66	$27.0^{v–w}$	42.6^{pq}	53.9^{rs}	$60.3^{p–s}$
S21	19.0	5.77	2.65	23.7^{x}	39.9^{r}	51.9^{st}	58.9^{st}
S22	19.0	6.24	2.72	$31.5^{m–p}$	48.0^{lm}	58.9^{n}	64.7^{m}
S23	19.0	6.29	2.78	$27.0^{v–w}$	$43.2^{o–q}$	$54.8^{o–s}$	$61.2^{n–q}$
S24	25.4	6.46	2.81	$32.3^{j–p}$	$49.4^{j–l}$	$60.4^{k–n}$	$66.2^{k–n}$
S25	25.4	7.55	2.80	$32.1^{l–p}$	48.6^{l}	59.4^{mn}	65.3^{ml}
S26	25.4	7.63	2.68	$34.9^{g–i}$	$51.7^{g–i}$	$62.5^{g–j}$	66.0^{ml}
S27	25.4	7.81	2.77	$30.0^{o–t}$	48.2^{l}	59.8^{mn}	$68.8^{f–h}$
S28	25.4	8.32	2.52	$35.6^{f–h}$	$52.6^{f–h}$	$63.3^{f–h}$	$68.9^{f–h}$
S29	25.4	8.39	2.84	35.4^{gh}	$53.4^{e–g}$	$64.2^{e–g}$	$69.7^{e–g}$
S30	25.4	8.50	2.92	$32.4^{i–p}$	$49.3^{j–l}$	$60.2^{l–n}$	66.1^{ml}
S31	25.4	8.77	2.63	$34.1^{g–l}$	$51.6^{g–i}$	$62.7^{f–i}$	$68.5^{f–i}$
S32	25.4	8.85	2.57	$34.7^{g–k}$	$51.7^{g–i}$	$62.4^{g–j}$	$68.0^{g–j}$
S33	25.4	8.97	2.65	$32.5^{i–o}$	$49.7^{i–l}$	$60.9^{i–m}$	$66.8^{i–l}$
S34	25.4	9.20	2.65	38.3^{de}	55.2^{de}	65.7^{de}	71.2^{de}
S35	25.4	9.35	2.58	$32.1^{k–p}$	48.9^{kl}	59.9^{mn}	66.8^{ml}
S36	25.4	9.43	2.64	$34.8^{g–j}$	52.0^{gh}	$63.0^{f–h}$	$68.7^{f–h}$
S37	25.4	9.43	2.71	$36.4^{e–g}$	$53.4^{e–g}$	$63.9^{e–h}$	$69.4^{f–h}$
S38	25.4	9.70	2.76	$34.4^{g–l}$	$51.2^{g–j}$	$62.3^{g–k}$	$67.9^{h–k}$
S39	25.4	9.83	2.78	$31.03^{d–f}$	49.0^{kl}	$60.6^{j–n}$	$66.6^{j–l}$
S40	25.4	11.40	2.91	$38.1^{d–f}$	54.4^{ef}	64.6^{ef}	69.9^{ef}
S41	25.4	11.69	2.62	$33.3^{h–n}$	$50.9^{h–k}$	$62.1^{h–l}$	$67.9^{h–k}$
S42	25.4	11.86	2.62	$33.5^{h–m}$	$51.6^{g–i}$	$63.1^{f–h}$	$68.9^{f–h}$
S43	50.8	12.12	2.49	39.6^{cd}	57.0^{cd}	67.3^{cd}	72.5^{cd}
S44	50.8	12.32	2.54	40.0^{cd}	58.2^{bc}	68.4^{bc}	73.5^{bc}
S45	50.8	12.38	2.50	39.9^{cd}	57.3^{cd}	67.7^{c}	72.9^{cd}
S46	50.8	12.79	2.55	44.63^{a}	61.4^{bc}	71.2^{bc}	75.9^{a}
S47	50.8	13.18	2.79	41.9^{bc}	58.9^{bc}	68.9^{bc}	73.9^{bc}
S48	50.8	13.44	2.73	44.5^{a}	61.6^{a}	71.1^{a}	75.9^{a}
S49	50.8	12.74	2.70	42.8^{ab}	60.0^{ab}	70.2^{ab}	75.1^{ab}
S50	50.8	14.06	2.64	43.3^{ab}	60.0^{bc}	68.4^{bc}	73.2^{c}

[A] X_{gm} – Geometric mean length.
[B] S_{gm} – Standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$.

mum compressibility achieved at a consolidating pressure of 120 kPa, for chopped wheat straw, switchgrass, and corn stover particles were 81.0%, 75.9%, and 70.4%, respectively (Tables 3–5). As the geometric mean particle length increased, compressibility increased for all three chopped biomass particles. Increase in particle size resulted in increased pore space formed inside the bulk of biomass resulting in increased compressibility. Geometric mean length affected compressibility with increased effect at reduced consolidation pressure. The percent increase in compressibility due to increase in mean geometric particle length from 2.65 to 14.06 mm were 173.6%, 116.6%, 81.6%, and 64.3% at consolidating pressures of 5, 20, 60, and 120 kPa, respectively, for switchgrass (Table 3). In the same way, the percent increase in compressibility due to increase in geometric mean particle length from 3.31 to 12.27 mm were 51.5%, 35.9%, 26.3%, and 22.2% at a consolidating pressures of 5, 20, 60, and 120 kPa, respectively, for wheat straw (Table 4). In the case of corn stover, the percent increase in compressibility due to increase in geometric mean particle length from 3.22 to 14.89 mm was 117.7%, 79.3%, 55.1%, and 42.1% at consolidating pressures of 5, 20, 60, and 120 kPa, respectively (Table 5).

The pressure and volume data of chopped switchgrass, wheat straw, and corn stover collected during compressibility studies with different particle size distributions fitted well for Walker's model with R^2 values of more than 0.97 (Table 6–8). Values of parameter K_1 had similar trends as compressibility measured using Eq. (1). Pearson correlation coefficient observed between parameter K_1 and compressibility measured at different pressures was more than 0.9 for all three chopped biomass particles. Good correlation between parameter K_1 of the Walker model and compressibility of chopped alfalfa cubes was observed by Tabil and Sokhansanj (1997) also. As geometric mean particle length increased, the value of parameter K_1 increased for chopped switchgrass and wheat straw particle size distributions. Same trend was not observed for chopped corn stover particles.

The Kawakita and Ludde model fitted well for chopped switchgrass, wheat straw, and corn stover with coefficient of determinations greater than 0.99 for all three selected chopped biomass particles (Table 6–8). In the Kawakita and Ludde model, the parameter a_2 is a measure of initial porosity of the material and the parameter $1/b_2$ is a measure of yield strength of the compacted material (Denny, 2002; Kawakita and Ludde, 1971). As geometric mean particle length increased, values of the parameter a_2 increased for all three chopped biomass particles. This was expected, because as the geometric mean length increased, porosity increased resulting in increased value of parameter a_2 in the model. As the geometric mean length increased, yield strength (value of $1/b_2$) decreased for chopped switchgrass and wheat straw particles. But the same trend was not observed for chopped corn stover particles. Mani et al. (2004c) also observed that Kawakita and Ludde model fitted well for ground biomass in a hammer mill.

Table 4
Effect of particle size on compressibility of chopped wheat straw.

Run no.	Knife mill screen size (mm)	X_{gm}[A] (mm)	S_{gm}[B] (mm)	Compressibility (%)[C]			
				5 kPa	20 kPa	60 kPa	120 kPa
W1	12.7	3.17	2.06	33.4^{p}	49.6^{p}	60.4^{q}	66.3^{p}
W2	12.7	3.35	2.12	39.1^{j-o}	55.3^{m-o}	65.3^{n-p}	70.6^{no}
W3	12.7	3.38	2.07	34.5^{p}	50.6^{o}	61.4^{q}	67.2^{p}
W4	12.7	3.50	2.08	37.1^{o}	54.2^{o}	64.4^{p}	69.8^{o}
W5	12.7	3.67	2.18	33.6^{p}	50.3^{p}	61.4^{q}	67.4^{p}
W6	12.7	3.69	2.05	39.1^{j-o}	55.4^{l-o}	65.6^{m-p}	71.0^{m-o}
W7	19.0	4.21	2.15	38.0^{no}	54.7^{no}	65.2^{op}	70.7^{no}
W8	19.0	4.33	2.16	40.4^{h-m}	56.9^{i-m}	66.8^{i-n}	72.0^{i-n}
W9	19.0	4.36	2.19	47.1^{c-e}	62.9^{d}	72.0^{d}	76.5^{ef}
W10	19.0	4.37	2.13	40.7^{g-m}	57.2^{h-k}	67.0^{i-m}	72.0^{i-n}
W11	19.0	4.40	2.09	37.9^{no}	55.0^{no}	65.7^{m-p}	71.1^{m-o}
W12	19.0	4.47	2.18	41.2^{f-j}	58.1^{f-i}	68.1^{f-h}	73.1^{h-j}
W13	19.0	4.52	2.11	39.7^{j-n}	56.4^{j-m}	66.5^{i-o}	71.8^{j-n}
W14	19.0	4.61	2.19	39.9^{i-n}	56.2^{j-n}	66.1^{l-o}	76.5^{ef}
W15	19.0	5.19	2.23	47.6^{c-e}	63.2^{cd}	72.1^{d}	71.2^{l-o}
W16	19.0	5.33	2.23	39.8^{j-n}	56.2^{j-n}	66.2^{j-o}	71.5^{k-n}
W17	25.4	5.42	2.27	42.8^{f}	60.1^{e}	70.3^{e}	75.4^{fg}
W18	25.4	6.30	2.41	38.6^{m-o}	55.8^{k-o}	66.2^{j-o}	72.0^{i-n}
W19	25.4	6.53	2.29	40.8^{f-k}	58.3^{f-i}	68.8^{e-h}	74.1^{g-i}
W20	25.4	6.67	2.44	39.0^{k-o}	55.8^{k-o}	66.2^{j-o}	71.6^{k-n}
W21	25.4	6.76	2.25	41.9^{f-i}	58.8^{e-h}	69.0^{e-g}	74.1^{g-i}
W22	25.4	6.86	2.40	40.3^{h-m}	57.0^{i-l}	67.3^{h-l}	72.7^{i-l}
W23	25.4	7.06	2.15	40.9^{f-j}	57.7^{g-j}	67.7^{g-k}	72.7^{i-l}
W24	25.4	7.09	2.30	39.1^{j-o}	55.4^{l-o}	65.8^{m-p}	71.1^{m-o}
W25	25.4	7.09	2.37	38.8^{l-o}	55.7^{k-o}	66.1^{k-o}	71.6^{k-n}
W26	25.4	7.48	2.49	42.3^{f-h}	59.2^{e-g}	69.3^{ef}	74.4^{gh}
W27	25.4	7.77	2.50	42.7^{fg}	59.4^{e-g}	69.5^{ef}	74.5^{gh}
W28	25.4	7.91	2.39	38.7^{l-o}	56.2^{j-n}	67.0^{i-m}	72.4^{j-m}
W29	50.8	9.25	2.70	39.6^{j-n}	57.0^{i-m}	67.7^{g-f}	73.2^{h-j}
W30	50.8	10.10	2.50	47.6^{c-e}	64.8^{bc}	74.2^{bc}	78.7^{cd}
W31	50.8	10.25	2.63	50.9^{a}	67.5^{a}	76.3^{a}	80.4^{ab}
W32	50.8	10.39	2.38	49.2^{a-c}	66.4^{ab}	75.6^{ab}	80.0^{a-c}
W33	50.8	10.65	2.57	48.3^{b-d}	65.7^{b}	75.3^{ab}	79.9^{a-c}
W34	50.8	10.68	2.48	48.0^{c-e}	65.6^{b}	75.2^{ab}	79.9^{a-c}
W35	50.8	10.78	2.72	42.0^{f-h}	59.6^{ef}	70.2^{e}	75.5^{fg}
W36	50.8	11.57	2.42	50.1^{ab}	67.4^{a}	76.7^{a}	81.0^{a}
W37	50.8	10.82	2.49	47.1^{c-e}	64.8^{bc}	74.4^{bc}	79.0^{b-d}
W38	50.8	11.82	2.55	46.0^{e}	63.2^{cd}	73.0^{cd}	77.8^{de}
W39	50.8	12.27	2.52	47.0^{de}	65.0^{b}	74.7^{b}	79.3^{bc}

[A] X_{gm} – Geometric mean length.
[B] S_{gm} – Standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$.

Table 5
Effect of particle size on compressibility of chopped corn stover.

Run no.	Knife mill screen size (mm)	X_{gm}[A] (mm)	S_{gm}[B] (mm)	Compressibility (%)[C]			
				5 kPa	20 kPa	60 kPa	120 kPa
C1	12.7	3.22	2.42	20.0^{ij}	34.3^{j-l}	46.5^{jk}	54.1^{kl}
C2	12.7	3.26	2.37	24.1^{e-h}	38.7^{f-h}	50.8^{f-h}	58.2^{f-i}
C3	12.7	3.56	2.27	17.5^{j}	30.4^{m}	42.3^{l}	50.1^{m}
C4	19.0	5.49	2.50	21.9^{hi}	36.4^{h-k}	48.6^{h-j}	56.1^{i-k}
C5	19.0	6.40	2.49	25.2^{d-g}	41.1^{d-f}	53.3^{d-f}	60.5^{c-g}
C6	25.4	6.42	2.59	22.1^{hi}	37.3^{g-j}	50.0^{gh}	57.8^{g-i}
C7	25.4	6.85	2.50	29.4^{c}	45.9^{c}	57.9^{c}	64.9^{b}
C8	25.4	7.40	2.46	25.0^{d-g}	40.9^{d-f}	53.3^{d-f}	60.8^{c-f}
C9	25.4	7.52	2.31	22.4^{g-i}	37.5^{g-i}	49.8^{g-i}	57.4^{h-j}
C10	25.4	7.65	2.31	25.1^{d-g}	40.3^{d-g}	52.4^{e-g}	59.7^{d-h}
C11	25.4	7.73	2.22	26.9^{c-e}	42.4^{de}	54.3^{de}	61.4^{c-e}
C12	25.4	7.80	2.27	34.6^{b}	51.0^{b}	62.3^{b}	68.7^{a}
C13	25.4	7.80	2.33	19.8^{ij}	34.0^{kl}	46.3^{jk}	54.2^{kl}
C14	25.4	8.02	2.10	17.8^{j}	31.7^{lm}	44.2^{kl}	52.4^{lm}
C15	25.4	8.55	2.20	20.1^{ij}	34.5^{j-l}	46.8^{ij}	54.8^{j-l}
C16	25.4	8.56	2.41	24.0^{e-h}	39.1^{f-h}	52.4^{e-g}	60.0^{e-h}
C17	25.4	8.62	2.39	27.3^{cd}	43.5^{cd}	55.8^{cd}	63.0^{bc}
C18	50.8	12.79	2.09	38.1^{a}	54.5^{a}	65.3^{a}	71.2^{a}
C19	50.8	13.86	2.27	25.9^{d-f}	41.9^{d-f}	54.5^{de}	61.1^{c-e}
C20	50.8	14.03	2.28	23.6^{f-h}	39.2^{e-h}	52.1^{e-g}	59.9^{d-h}
C21	50.8	14.48	2.18	25.6^{d-f}	41.9^{d-f}	54.6^{de}	62.1^{b-d}
C22	50.8	14.89	2.22	36.0^{ab}	52.6^{ab}	63.9^{ab}	70.4^{a}

[A] X_{gm} – Geometric mean length.
[B] S_{gm} – Standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$.

4.3. Compaction characteristics with tapping

The relationship between volume reduction ratio and the number of taps is shown in Fig. 3. All three biomass materials reached the maximum volume reduction ratio by 50 taps. The highest vol-

Table 6
Effect of particle size of chopped switchgrass on parameters of Kawakita & Ludde model and Walker model.

Run no.	Knife mill screen size (mm)	X_{gm} [A] (mm)	S_{gm} [B] (mm)	Parameters of Walker model[C]		Parameters of Kawakita & Ludde model[C]	
				a_1 (–)	K_1 (–)	a_2 (–)	$1/b_2$ (kPa)
S1	12.7	2.65	2.51	1.952[st]	0.198[t–v]	0.538[wx]	11.8[bc]
S2	12.7	2.77	2.37	1.966[r–t]	0.202[tu]	0.549[vw]	10.2[d]
S3	12.7	2.99	2.47	1.887[tu]	0.184[uv]	0.514[yz]	13.1[a]
S4	12.7	3.00	2.40	1.949[st]	0.198[v]	0.540[wx]	11.3[c]
S5	12.7	3.17	2.65	1.837[tu]	0.173[v]	0.498[z]	13.0[a]
S6	12.7	3.30	2.52	1.907[t]	0.188[t–v]	0.523[xy]	12.2[b]
S7	12.7	3.49	2.69	1.604[u]	0.213[t]	0.559[v]	11.2[c]
S8	19.0	4.20	2.78	2.022[q–t]	0.254[s]	0.613[u]	9.2[e]
S9	19.0	4.21	2.77	2.203[p–s]	0.259[rs]	0.624[s–u]	8.4[fg]
S10	19.0	4.45	2.50	2.234[o–s]	0.265[q–s]	0.635[p–t]	7.8[f–j]
S11	19.0	4.45	2.58	2.249[n–r]	0.279[p–s]	0.653[op]	7.2[j–m]
S12	19.0	4.70	2.54	2.310[l–q]	0.273[p–s]	0.641[o–r]	7.9[f–i]
S13	19.0	4.70	2.45	2.288[m–q]	0.268[p–s]	0.631[r–t]	8.3[fg]
S14	19.0	4.77	2.76	2.261[n–q]	0.287[n–q]	0.656[o]	7.4[i–m]
S15	19.0	5.04	2.70	2.349[j–p]	0.269[p–s]	0.646[o–r]	7.4[i–m]
S16	19.0	5.21	2.57	2.276[m–q]	0.270[p–s]	0.637[p–t]	8.2[f–h]
S17	19.0	5.33	2.69	2.311[l–q]	0.288[p–s]	0.646[o–r]	7.8[f–j]
S18	19.0	5.34	2.63	2.314[l–q]	0.279[p–s]	0.650[o–q]	7.5[i–l]
S19	19.0	5.41	2.66	2.375[i–p]	0.268[p–s]	0.658[no]	7.6[h–k]
S20	19.0	5.55	2.66	2.263[n–q]	0.293[n–p]	0.633[q–t]	8.3[f–h]
S21	19.0	5.77	2.65	2.260[n–q]	0.266[q–s]	0.621[tu]	9.7[de]
S22	19.0	6.24	2.72	2.434[j–p]	0.306[m–o]	0.675[mn]	7.0[k–n]
S23	19.0	6.29	2.78	2.327[k–p]	0.281[o–r]	0.644[o–r]	8.4[f]
S24	25.4	6.46	2.81	2.522[e–m]	0.327[j–m]	0.690[i–m]	6.9[l–o]
S25	25.4	7.55	2.80	2.454[g–o]	0.311[l–n]	0.681[lm]	6.8[l–o]
S26	25.4	7.63	2.68	2.642[d–i]	0.349[g–j]	0.711[f–h]	6.5[n–p]
S27	25.4	7.81	2.77	2.596[d–l]	0.342[i–k]	0.692[i–m]	7.7[g–j]
S28	25.4	8.32	2.52	2.641[d–j]	0.353[f–i]	0.716[fg]	6.0[p–r]
S29	25.4	8.39	2.84	2.730[a–g]	0.374[e–g]	0.725[ef]	6.3[o–q]
S30	25.4	8.50	2.92	2.511[f–m]	0.324[j–m]	0.689[k–m]	6.9[l–o]
S31	25.4	8.77	2.63	2.651[c–i]	0.355[f–i]	0.721[e–g]	6.8[l–o]
S32	25.4	8.85	2.57	2.620[d–h]	0.343[i–k]	0.707[g–i]	6.3[o–q]
S33	25.4	8.97	2.65	2.564[e–l]	0.335[i–l]	0.696[h–l]	6.9[l–o]
S34	25.4	9.20	2.65	2.754[a–f]	0.378[d–f]	0.737[de]	5.7[qr]
S35	25.4	9.35	2.58	2.492[f–n]	0.320[k–m]	0.685[lm]	6.9[l–o]
S36	25.4	9.43	2.64	2.643[d–i]	0.353[f–i]	0.714[f–h]	6.4[n–p]
S37	25.4	9.43	2.71	2.654[c–i]	0.356[f–i]	0.719[e–g]	6.0[p–r]
S38	25.4	9.70	2.76	2.598[d–l]	0.343[i–k]	0.706[g–j]	6.4[n–p]
S39	25.4	9.83	2.78	2.617[d–k]	0.347[h–j]	0.698[g–k]	7.5[i–m]
S40	25.4	11.40	2.91	2.617[d–k]	0.348[g–j]	0.722[e–g]	5.6[rs]
S41	25.4	11.69	2.62	2.655[c–i]	0.354[f–i]	0.708[f–i]	6.8[m–o]
S42	25.4	11.86	2.62	2.727[a–h]	0.371[e–h]	0.719[fg]	6.9[l–o]
S43	50.8	12.12	2.49	2.832[a–e]	0.397[c–e]	0.749[cd]	5.4[rs]
S44	50.8	12.32	2.54	2.941[a–c]	0.421[a–c]	0.761[bc]	5.5[rs]
‘S45	50.8	12.38	2.50	2.857[a–o]	0.402[cd]	0.754[cd]	5.4[rs]
S46	50.8	12.79	2.55	2.660[c–i]	0.433[ab]	0.780[a]	4.6[t]
S47	50.8	13.18	2.79	2.880[a–d]	0.408[bc]	0.761[bc]	5.0[st]
S48	50.8	13.44	2.73	2.997[ab]	0.434[a]	0.780[a]	4.6[t]
S49	50.8	12.74	2.70	3.006[a]	0.445[a]	0.774[ab]	5.0[st]
S50	50.8	14.06	2.64	2.712[b–h]	0.427[a–c]	0.751[cd]	4.6[t]

[A] X_{gm} – geometric mean length.
[B] S_{gm} – standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$; a_1 and k_1 – parameters of walker model a_2 and b_2 – parameters of Kawakita and Ludde model.

Table 7
Effect of particle size of chopped wheat straw on parameters of Kawakita & Ludde model and Walker model.

Run no.	Knife mill screen size (mm)	X_{gm} [A] (mm)	S_{gm} [B] (mm)	Parameters of Walker model[C]		Parameters of Kawakita and Ludde model[C]	
				a_1 (–)	K_1 (–)	a_2 (–)	$1/b_2$ (kPa)
W1	12.7	3.17	2.06	2.481[p]	0.317[q]	0.688[n]	6.6[ab]
W2	12.7	3.35	2.12	2.635[l–p]	0.352[n–q]	0.728[j–m]	5.4[h–m]
W3	12.7	3.38	2.07	2.516[op]	0.324[pq]	0.697[mn]	6.4[a–c]
W4	12.7	3.5	2.08	2.638[l–p]	0.353[n–q]	0.722[k–m]	5.7[d–j]
W5	12.7	3.67	2.18	2.569[n–p]	0.336[o–q]	0.700[l–m]	6.7[a]
W6	12.7	3.69	2.05	2.680[j–p]	0.362[m–o]	0.733[i–m]	5.4[g–m]
W7	19	4.21	2.15	2.711[h–p]	0.368[l–o]	0.731[i–m]	5.7[d–h]
W8	19	4.33	2.16	2.730[h–p]	0.374[l–n]	0.742[h–k]	5.2[j–m]
W9	19	4.36	2.19	2.938[e–i]	0.422[f–i]	0.784[b–f]	4.1[o–q]
W10	19	4.37	2.13	2.728[h–p]	0.374[l–n]	0.743[h–k]	5.1[k–m]
W11	19	4.4	2.09	2.755[h–o]	0.379[j–n]	0.736[i–l]	5.8[d–g]
W12	19	4.47	2.18	2.839[g–n]	0.396[h–m]	0.754[f–k]	5.1[k–m]
W13	19	4.52	2.11	2.743[h–p]	0.376[k–n]	0.741[h–k]	5.4[g–m]
W14	19	4.61	2.19	2.669[k–p]	0.360[m–p]	0.734[i–l]	5.2[i–m]
W15	19	5.19	2.23	2.902[f–l]	0.413[g–k]	0.783[c–f]	4.0[o–q]
W16	19	5.33	2.23	2.708[h–p]	0.369[l–o]	0.737[i–k]	5.3[g–m]
W17	25.4	5.42	2.27	3.035[d–q]	0.441[fg]	0.776[d–h]	5.0[i–n]
W18	25.4	6.3	2.41	2.816[g–n]	0.391[h–m]	0.744[g–k]	5.7[d–i]
W19	25.4	6.53	2.29	2.974[e–h]	0.428[f–h]	0.767[e–i]	5.4[g–m]
W20	25.4	6.67	2.44	2.759[h–o]	0.380[j–n]	0.740[i–k]	5.5[e–k]
W21	25.4	6.76	2.25	2.914[f–k]	0.414[g–j]	0.763[e–j]	5.1[k–m]
W22	25.4	6.86	2.4	2.820[g–n]	0.393[h–m]	0.750[f–k]	5.4[h–m]
W23	25.4	7.06	2.15	2.793[g–n]	0.388[i–n]	0.750[f–k]	5.1[k–m]
W24	25.4	7.09	2.3	2.707[i–p]	0.367[l–o]	0.735[i–l]	5.5[e–k]
W25	25.4	7.09	2.37	2.767[h–o]	0.379[j–n]	0.741[h–k]	5.8[d–f]
W26	25.4	7.48	2.49	2.930[f–k]	0.418[g–i]	0.766[e–i]	5.0[l–n]
W27	25.4	7.77	2.5	2.918[f–k]	0.416[g–j]	0.767[e–i]	4.9[mn]
W28	25.4	7.91	2.39	2.863[f–l]	0.423[f–i]	0.815[a–c]	6.1[b–d]
W29	50.8	9.25	2.7	2.962[f–i]	0.402[h–l]	0.759[f–j]	6.0[c–e]
W30	50.8	10.1	2.5	2.935[f–i]	0.496[cd]	0.807[a–d]	4.3[o–q]
W31	50.8	10.25	2.63	2.347[a–c]	0.514[b–d]	0.823[a]	3.8[q]
W32	50.8	10.39	2.38	3.412[ab]	0.529[a–c]	0.819[ab]	4.1[o–q]
W33	50.8	10.65	2.57	2.454[ab]	0.536[ab]	0.821[a]	4.3[op]
W34	50.8	10.68	2.48	3.137[c–e]	0.540[ab]	0.820[a]	4.3[op]
W35	50.8	10.78	2.72	3.120[c–f]	0.458[ef]	0.779[c–g]	5.3[h–m]
W36	50.8	11.57	2.42	3.533[a]	0.555[a]	0.830[a]	4.0[pq]
W37	50.8	10.82	2.49	3.347[a–c]	0.513[b–d]	0.811[a–d]	4.4[o–p]
W38	50.8	11.82	2.55	3.215[b–d]	0.483[de]	0.799[a–e]	4.5[no]
W39	50.8	12.27	2.52	3.414[ab]	0.529[a–c]	0.815[a–c]	4.4[op]

[A] X_{gm} – geometric mean length.
[B] S_{gm} – standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$; a_1 and k_1 – parameters of walker model a_2 and b_2 – parameters of Kawakita and Ludde model.

ume reduction ratio was observed for chopped wheat straw followed by chopped switchgrass and corn stover. Maximum volume reduction ratios observed for finely chopped switchgrass, wheat straw, and corn stover were 0.159, 0.165, and 0.154, respectively. Maximum volume reduction ratios observed for coarsely chopped switchgrass, wheat straw, and corn stover were 0.107, 0.117, and 0.098, respectively. Difference in volume reduction ratio between coarse and finely chopped biomass particles may be due to difference in physical characteristics such as particle size, shape, particle density, and surface roughness properties.

Linear relationship between n and n/γ_n for chopped switchgrass, wheat straw and corn stover is shown in Fig. 4. Very high R^2 value indicated that the chopped biomass followed Sone's model for describing the compaction characteristics due to tapping. In Sone's model, a_3 value represents infinite compressibility by tapping, and b_3 value represents the degree of difficulty of tapping (Sone, 1969). In our experiments, a_3 values of the fine chopped particles were significantly higher than that of the coarse chopped biomass particles, indicating that the infinite compressibility increased for fine chopped biomass particles. Infinite compressibility was highest for chopped switchgrass indicated by the a_3 values followed by wheat straw and corn stover (Table 9). Values of b_3 of all the fine chopped biomass were less than the coarse chopped biomass indicating that as the particle size decreased, the samples compacted easily leading to rapid increase in bulk density by tapping. In the same way, the difficulty in packing/compaction by tapping of corn stover was the highest followed by switchgrass and wheat straw indicated by the b_3 values (Table 9).

Table 8
Effect of particle size of chopped corn stover on parameters of Kawakita and Ludde model and Walker model.

Run no.	Knife mill screen size (mm)	X_{gm} [A] (mm)	S_{gm} [B] (mm)	Parameters of Walker model[C]		Parameters of Kawakita and Ludde model[C]	
				a_1 (−)	K_1 (−)	a_2 (−)	$1/b_2$ (kPa)
C1	12.7	3.22	2.42	2.107^{hi}	0.230^{ij}	0.579$^{k–l}$	11.7$^{b–d}$
C2	12.7	3.26	2.37	2.223$^{e–h}$	0.255$^{f–i}$	0.615$^{g–i}$	9.8$^{f–h}$
C3	12.7	3.56	2.27	1.972^{j}	0.200^{k}	0.539^{m}	12.9^{ab}
C4	19	5.49	2.5	2.171$^{f–i}$	0.244$^{g–j}$	0.597$^{i–k}$	10.9$^{c–f}$
C5	19	6.4	2.49	2.344$^{c–e}$	0.282$^{d–f}$	0.640$^{d–h}$	9.5^{gh}
C6	25.4	6.42	2.59	2.270$^{d–g}$	0.265$^{e–g}$	0.617$^{f–i}$	11.1$^{c–e}$
C7	25.4	6.85	2.5	2.508^{b}	0.322^{c}	0.680^{bc}	8.2^{i}
C8	25.4	7.4	2.46	2.371^{cd}	0.287^{de}	0.643$^{d–g}$	9.8$^{f–h}$
C9	25.4	7.52	2.31	2.233$^{e–h}$	0.258$^{f–h}$	0.611$^{h–j}$	10.8$^{c–f}$
C10	25.4	7.65	2.31	2.288$^{d–f}$	0.268$^{e–g}$	0.627$^{e–h}$	9.5^{gh}
C11	25.4	7.73	2.22	2.342$^{c–e}$	0.282$^{d–f}$	0.645$^{d–f}$	8.8^{ih}
C12	25.4	7.8	2.27	2.653^{a}	0.352^{b}	0.713^{ab}	6.7^{j}
C13	25.4	7.8	2.33	2.118^{hi}	0.231$^{h–j}$	0.580$^{k–l}$	12.0^{bc}
C14	25.4	8.02	2.1	2.085^{ij}	0.224^{jk}	0.567^{lm}	13.5^{a}
C15	25.4	8.55	2.2	2.143$^{g–i}$	0.236$^{h–j}$	0.585$^{j–h}$	11.9^{bc}
C16	25.4	8.56	2.41	2.278$^{d–f}$	0.268$^{e–g}$	0.625$^{e–i}$	10.0$^{e–h}$
C17	25.4	8.62	2.39	2.453^{bc}	0.306^{cd}	0.663^{cd}	8.9^{hi}
C18	50.8	12.79	2.09	2.761^{a}	0.377^{ab}	0.755^{a}	6.3^{j}
C19	50.8	13.86	2.27	2.376^{cd}	0.292^{de}	0.648^{de}	10.2$^{e–g}$
C20	50.8	14.03	2.28	2.354$^{c–e}$	0.282$^{d–f}$	0.636$^{d–h}$	10.5$^{d–g}$
C21	50.8	14.48	2.18	2.450^{bc}	0.305^{cd}	0.657^{cd}	9.8$^{f–h}$
C22	50.8	14.89	2.22	2.781^{a}	0.380^{a}	0.730^{ab}	6.6^{j}

[A] X_{gm} – geometric mean length.
[B] S_{gm} – standard deviation.
[C] Mean values suffixed with different letters in a column are significantly different (LSD) at $p < 0.05$; a_1 and k_1 – parameters of walker model a_2 and b_2 – parameters of Kawakita and Ludde model.

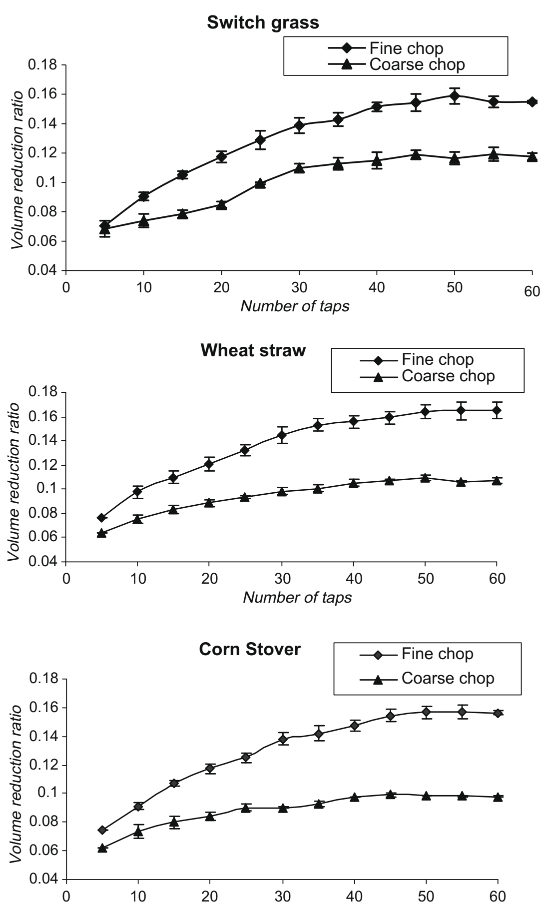

Fig. 3. Effect of number of taps on volume reduction ratio of biomass.

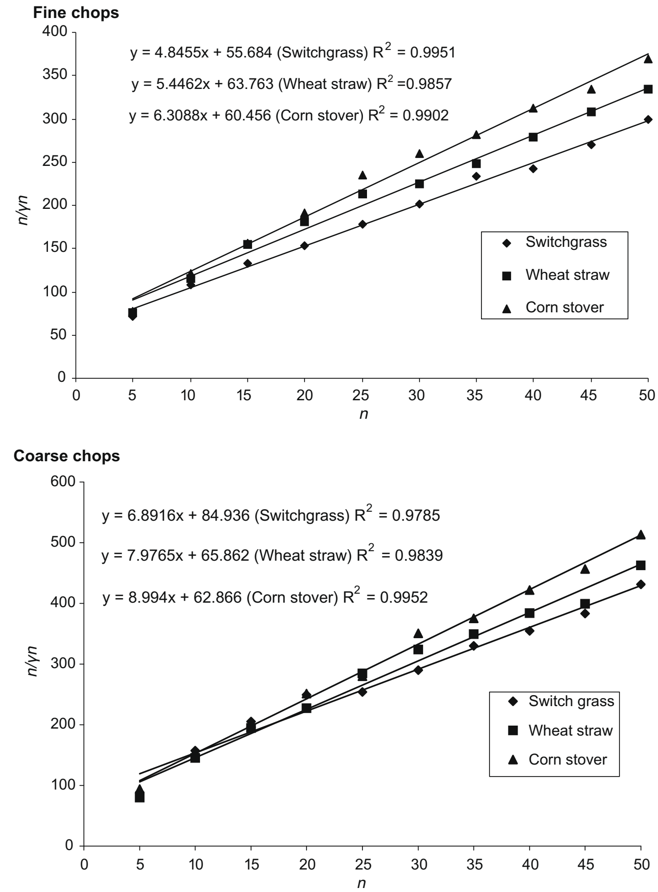

Fig. 4. Linear relationship between number of taps (n) and ratio of n/volume ratio (n/γ_n).

Table 9
Coefficients of Sone's model for switchgrass, wheat straw and corn stover.[A].

Sample	A_3	B_3
Wheat straw (fine)	0.191^{b}	0.090^{f}
Wheat straw (coarse)	0.121^{e}	0.128^{c}
Switchgrass (fine)	0.195^{a}	0.097^{e}
Switchgrass (coarse)	0.140^{d}	0.161^{b}
Corn stover (fine)	0.186^{c}	0.100^{d}
Corn stover (coarse)	0.108^{f}	0.173^{a}

A_3 and B_3 – parameters of Sone's model.
[A] Values suffixed with different letters in a column were significantly different.

5. Conclusions

Experiments were conducted to study the compaction characteristics by tapping and by application of normal pressure affecting the bulk density of switchgrass, wheat straw, and corn stover chopped in a knife mill. Based on the experiments, the following conclusions are made: Chopped switchgrass had maximum loose-filled and tapped bulk density followed by chopped corn stover and wheat straw. Significant differences in compressibility were observed for the chopped biomass with different particle size distributions obtained by different classifying screens in a knife mill. Pressure–volume relationships of chopped biomass fitted well for Walker model and Kawakita and Ludde model indicated by very high coefficient of determination values. Parameter of Walker model correlated well with the compressibility data with Pearson correlation coefficient of greater than 0.9 for chopped switchgrass, wheat straw, and corn stover. Compressibility achieved by tapping was highest for chopped switchgrass followed by chopped wheat straw and corn stover. However, chopped wheat straw particles settled rapidly by tapping compared to chopped switchgrass and corn stover.

Acknowledgement

We thankfully acknowledge the funding support provided through the USDA-NRCS Grant Agreement 68-3A75-4-136 and USDA-DOE Biomass Research and Development Initiative DE-PA36-04GO94002 for carrying out this project work.

References

Adapa, P., Schoenau, G., Tabil, L., Sokhansanj, S., Singh, A., 2005. Compression of fractionated sun-cured and dehydrated alfalfa chops into cubes: pressure and density models. Canadian Biosystems Engineering 47 (3), 33–39.

ASABE Standards, 2006. S424.1: Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening. ASABE, St. Joseph, Michigan.

Bouton, J., 2007. Energy crops and their implications for forages. In: Proceedings of Western Alfalfa and Forage Conference.

Chevanan, N., Womac, A.R., Bitra, V.S., Yoder, D.C., Sokhansanj, S., in press. Flowability parameters for chopped switchgrass, wheat straw and corn stover. Powder Technology.

Chevanan, N., Womac, A.R., Bitra, V.S., 2008. Loose-filled and Tapped Densities of Chopped Switchgrass, Corn Stover and Wheat Straw. Paper No. 084085. ASABE, St. Joseph, MI.

Chevanan, N., Rosentrater, K.A., Muthukumarappan, K., 2007. Twin screw extrusion processing of feed blends containing distillers dried grains with solubles (DDGS). Cereal Chemistry 84 (5), 428–436.

Cooper, A.R., Eaton, L.E., 1962. Compaction behavior of several ceramic powders. Journal of American Ceramic Society 45 (3), 97–101.

Denny, P.J., 2002. Compaction equations: a comparison of the Heckel and Kawakita equations. Powder Technology 127, 162–172.

Emami, S., Tabil, L.G., 2008. Friction and compression characteristics of chickpea flour and components. Powder Technology 182, 119–126.

Fasina, O.O., 2006. Flow and physical properties of switchgrass, peanut hull, and poultry litter. Transactions of ASABE 49 (3), 721–728.

Fayed, M.E., Skocir, T.S., 1997. Mechanical Conveyors: Selection and Operation. Technomic Publishing, Lancaster, Pennsylvania.

Gray, W.A., 1968. Compaction after deposition. In: The Packing of Solid Particles. Barnes and Noble, New York, pp. 89–107.

Heckel, R.W., 1961. An analysis of powder compaction phenomena. Transactions of the Mettalurgical Society of AIME 221, 1001–1008.

Ibsen, K., McAloon, A., Taylor, F., Wooley, R., Yee, W., 2000. Determining the Cost of Producing Ethanol from Corn Starch and Lignocellulosic Feedstocks, NREL/TP-580-28893. US Department of Energy, National Renewable Energy Laboratory, Golden, Colorado.

Kawakita, K., Ludde, K.H., 1971. Some considerations on powder compression equations. Powder Technology 4, 61–68.

Knauf, M., Moniruzzaman, M., 2004. Lignocellulosic biomass processing: a perspective. International Sugar Journal 106 (1263), 147–150.

Lam, P.S., Sokhansanj, S., Bi, X., Mani, S., Womac, A.R., Hoque, M., Peng, J., JayaShankar, T., Naimi, L.J., Narayan, S., 2007. Physical Characterization of Wet and Dry Wheat Straw and Switchgrass – Bulk and Specific Density, Paper No. 076058. ASABE, St. Joseph, Michigan.

Mani, S., Tabil, L.G., Sokhansanj, S., 2004a. Mechanical properties of corn stover grind. Transactions of ASABE 47 (6), 1983–1990.

Mani, S., Tabil, L.G., Sokhansanj, S., 2004b. Grinding performance and physical properties of wheat and barley straws, corn stover and switchgrass. Biomass and Bioenergy 27, 339–352.

Mani, S., Tabil, L.G., Sokhansanj, S., 2004c. Evaluation of compaction equations applied to four biomass species. Canadian Biosystems Engineering 46 (3), 55–61.

Perlack, R.D., Wright, L.L., Turhollow, A.F., Graham, R.L., Stokes, B.J., Erbach, D.C., 2005. Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of A Billion Ton Annual Supply. Report Prepared for DOE under contract DE-AC05-000R22725, Department of Energy, Washington DC.

Peleg, M., Bagley, E.B., 1983. Physical Properties of Foods. AVI Publishing Company Inc., Connecticut.

Sanderson, M.A., Read, J.C., Reed, R.R., 1999. Harvest management of switchgrass for biomass feedstock and forage production. Agronomy Journal 91, 5–10.

Sokhansanj, S., Kumar, A., Turhollow, F.A., 2006. Development and implementation of integrated biomass supply analysis and logistics model (IBSAL). Biomass and Bioenergy 30, 838–847.

Sone, T., 1969. Consistency of Foodstuffs. Reidell Publishing Company, Dordecht, Holland.

Tabil, L.G., Sokhansanj, S., 1997. Bulk properties of alfalfa grind in relation to its compaction characteristics. Applied Engineering in Agriculture 13 (4), 499–505.

Walker, E.E., 1923. The properties of powders – part VI: the compressibility of powders. Transactions of the Faraday Society 19 (1), 73–82.

Wright, C.T., Pryfogle, P.A., Stevens, N.A., Hess, J.R., Radke, C.W., 2006. Value of Distributed Preprocessing of Biomass Feedstocks to A Biorefinery Industry. Paper No. 066151. ASABE, St. Joseph, Michigan.