Compression Characteristics of Selected Ground Agricultural Biomass

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ABSTRACT

Agricultural biomass such as barley, canola, oat and wheat straw has the potential to be used as feedstock for bioenergy. However, the low bulk density straw must be processed and densified in order to facilitate handling, storage and transportation. It is important to understand the fundamental mechanism of the biomass compression process, which is required in the design of energy efficient compaction equipment to mitigate the cost of pre-processing and transportation of the product. Therefore, a comprehensive review of various compression models was performed and the compression behavior of selected ground agricultural biomass was studied. Five compression models were considered to determine the pressure-volume and pressure-density relationship to analyze the compression characteristics of biomass samples, namely: Jones (1960), Heckle (1961), Cooper-Eaton (1962), Kawakita-Ludde (1971) and Panelli-Filho (2001) models. Densification studies were conducted on four selected biomass samples at 10 % moisture content (w.b.) and 1.98 mm grind size using four pressure levels of 31.6, 63.2, 94.7 and 138.9 MPa. The mean densities of barley, canola, oat and wheat straw increased from 907 to 977 kg/m^3, 823 to 1003 kg/m^3, 849 to 1011 kg/m^3 and 813 to 924 kg/m^3, respectively. The Kawakita-Ludde model provided an excellent fit having R^2 values of 0.99 for selected agricultural straw samples. It was also concluded that the ground oat and canola straw had the highest level of porosity and failure stress, respectively. The parameters of Cooper-Eaton model indicated that the ground straw samples were densified easily by the particles rearrangement method and Jones model indicated that canola and oat straw were more compressible as compared to barley and wheat straw.

Keywords: Compression characteristics, densification, barley straw, canola straw, oat straw, wheat straw, compression models, biofuel, pelleting

1. INTRODUCTION

Agricultural biomass such as barley, canola, oat and wheat straw has the potential to be used as feedstock for biofuel industry (Campbell *et al.,* 2002; Sokhansanj *et al.,* 2006). However, due to low bulk density of straw, agricultural biomass has to be ground and compacted into dense and durable pellets in order to facilitate handling, storage and transportation (Adapa *et al.,* 2007; Mani *et al.,* 2003). In addition, because of uniform shape and size, densified products can be easily adopted in direct-combustion or co-firing with coal, gasification, pyrolysis, and in other biomass-based conversions (Kaliyan and Morey, 2006a).

The compression characteristics of ground agricultural biomass vary under various applied pressures. It is important to understand the fundamental mechanism of the biomass compression process, which is required in the design of energy efficient compaction equipment to mitigate the cost of production and enhance the quality of the product (Mani *et al.,* 2004). To a great extent, the strength of manufactured pellets depends on the physical forces that bond the particles together (Tabil and Sokhansanj, 1996). These physical forces come in three different forms during pellet production: a) thermal; b) mechanical; and c) atomic forces (Adapa *et al.,* 2002).
Pellets are formed by subjecting the biomass grinds to high pressures, wherein the particles are forced to agglomerate. It is generally accepted that the compression process is categorized in several distinct stages and difficult to let one simple monovariate equation cover the entire densification region (Sonnergaard, 2001). Compression of grinds is usually achieved in three stages (Holman, 1991). In the first stage, particles rearrange themselves under low pressure to form close packing. The particles retain most of their original properties, although energy is dissipated due to inter-particle and particle-to-wall friction. During the second stage, elastic and plastic deformation of particles occurs, allowing them to flow into smaller void spaces, thus increasing inter-particle surface contact area and as a result, bonding forces like van der Waal forces become effective (Rumpf, 1962; Sastry and Fuerstenau, 1973; Pietsch, 1997). Brittle particles may fracture under stress, leading to mechanical interlocking (Gray 1968). Finally, under high pressure the second stage of compression continues until the particle density of grinds has been reached. During this phase, the particles may reach their melting point and form very strong solid bridges upon cooling (Ghebre-Sellassie, 1989). Figure 1 shows the deformation mechanisms of powder particles under compression (Comoglu, 2007; Denny, 2002).

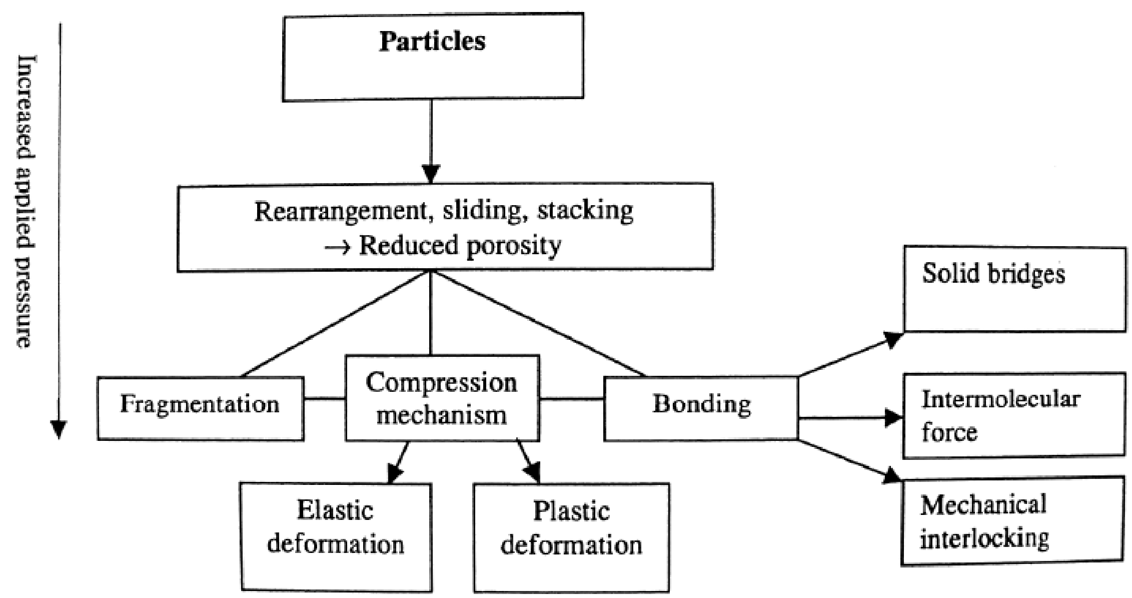

Figure 1. The defromation mechanisms of powder particles under compression (Comoglu, 2007; Denny, 2002)

Johansson *et al.* (1995) and Johansson and Alderborn (1996) studied the compression behavior of pelletized microcrystalline cellulose and described the compression mechanism as primarily composed of permanent deformation (change in the shape of the individual particles) and densification (contraction of porosity reduction of the individual compacts), followed by minute fragmentation of the compacts (Alderborn and Wikberg, 1996).

Biomass contains chemical compounds such as cellulose, hemicelluloses, protein, starch, lignin, crude fibre, fat, and ash. Protein plasticizes under heat and acts as a binder, which assists in increasing the strength of pelletized product (Winowiski, 1988; Briggs *et al.,* 1999). In the presence of heat and moisture, gelatinization of starch occurs, which results in binding of ground biomass (Wood, 1987; Thomas *et al.,* 1998). In addition, mechanical shearing during the densification process also improves starch gelatinization (Kaliyan and Morey, 2006a). At high temperature and pressure, lignin softens and helps the binding process. Lignin has thermosetting properties and a low melting point of about 140 °C (van Dam *et al.,* 2004). A similar compression mechanism involving chemical compounds was identified in the alfalfa pelleting process by Tabil and Sokhansanj (1996), for wheat straw, barley straw, corn stover and switch grass pelleting by Mani *et al.* (2004), and for fractionated alfalfa grinds by Adapa *et al.* (2002). Bilanski and Graham (1984) and O'Dogherty and Wheeler (1984) reported that at high compression pressures, biomass particles would be flattened/crushed damaging the cell structure and consequently releasing protein and pectin. These compounds would act as natural binders and aid the adhesion of biomass particles. Presence of natural binding compounds in the biomass particles is a major difference between biomass particles and ceramic or metallic or pharmaceutical powders (Kaliyan and Morey, 2006a).

Other differences of biomass particles include porosity, presence of multi-components (e.g. stem and leaf) with complex mechanical properties, and compressibility. Mohsenin (1986) reported that the major part of the residual deformation in biomass is due to the presence of pores or air spaces, weak ruptured cells on the surface, microscopic cracks, and other discontinuities which may exist in the structure of the material. This can be viewed as an analogy to the phenomenon of slip and dislocation in metals due to imperfections in their crystal structures. These defects in crystal structures are believed to be responsible for plastic or permanent deformation which results from slip, or glide, of part of the body over the other (Kaliyan and Morey, 2006a).
Therefore, the objectives of the current study were to: 1) review various compression models; and 2) study compression behavior of ground agricultural biomass (barley, canola, oat and wheat straw) subjected to various pressures.

2. REVIEW OF COMPRESSION MODELS

Densification or compaction of various powders or grinds is an essential process to manufacture products including ceramics, metallic parts, fertilizers, pharmaceuticals and agricultural biomass (Comoglu, 2007; Mani *et al.,* 2004; Panelli and Filho, 2001; Tabil, 1996). Ground particles (metallic or non-metallic) behave in different manner under different pressures. Therefore, it is important to study the change in compact density and volume under different pressures. One of the main purposes of fitting experimental data to an equation is usually to linearize the plots in order to make comparisons easier between different sets of data (Comoglu, 2007).

2.1 Walker Model

Walker (1923) reported a series of experiments on the compressibility of powders. He expressed the volume ratio, V_R, as a function of applied pressure, P, as shown below in equation 1.

$$\boldsymbol{V_R} = \boldsymbol{m} \ln \boldsymbol{P} + \boldsymbol{b} \tag{1}$$

where,

$$V_R = \frac{V}{V_S}$$

P = applied pressure, MPa; V_R = volume ratio; V = volume of compact at pressure P, m^3; V_S = void free solid material volume, m^3

Later, Stewart (1938) verified Walker's model and characterized the compression of non-metallic powders, and particles of sulphur, ammonium and sodium chloride and trinitrotoluene (TNT). Bal'shin in 1938 (Denny, 2002) applied the concept of fluid mechanics and provided theoretical justification to the Walker's model. The Walker model has not been in significant use since its inception (Comoglu, 2007). Though, Adapa *et al.* (2002) attempted to use Walker model to study the compression behavior of fractionated alfalfa; however, good fit compared to other models was not obtained.

2.2 Jones Model

Similarly, Jones (1960) expressed the density-pressure data of compacted metal powder in the form of equation 2.

$$\ln \rho = \boldsymbol{m} \ln \boldsymbol{P} + \boldsymbol{b} \tag{2}$$

where, ρ is bulk density of compact powder mixture, kg/m^3; m and b are constants.

2.3 Heckel Model

Heckel (1961) considered the compaction of powders to be analogous to a first-order chemical reaction. The pores are the reactant for the densification of the bulk product. The "kinetics" of the process may be described as proportionality between the relative densities of a metal powder compact, ρ_f, and the applied pressure, P (Eq. 3).

$$\ln \frac{1}{1-\rho_f} = \boldsymbol{mP} + \boldsymbol{b} \tag{3}$$

where,

$$b = \ln\left(\frac{1}{1-\rho_0}\right) \text{ and } \rho_f = \frac{\rho}{\rho_1 x_1 + \rho_2 x_2}$$

ρ_f = packing fraction or relative density of the material after particle rearrangement; ρ_0 = relative density of powder mixture, kg/m^3, ρ_1 and ρ_2 = particle density of components of the mixture, kg/m^3; x_1 and x_2 = mass fraction of components of the mixture.

The constants *b* and *m* are determined from the intercept and slope, respectively, of the extrapolated linear region of the plot of $ln(1/(1-\rho_f))$ vs *P*. A higher ρ_f value indicates that there is a higher volume reduction of the sample due to particle rearrangement. The constant *m* has been shown to be equal to the reciprocal of the mean yield pressure required to induce elastic deformation (York and Pilpel, 1973). A large *m* value (low yield pressure) indicates the onset of plastic deformation at relatively low pressure, thus, the material is more compressible. Depending on the property of material, some densify mostly by plastic deformation (e.g. fatty acids) while others densify by both particle rearrangement and plastic deformation (e.g. lactose powder). The Heckel model was also used to determine the compressibility of cellulose polymers by Shivanand and Sprockel (1992) and food material by Ollet *et al.* (1993).

2.4 Cooper-Eaton Model

Cooper-Eaton (1962) studied the compaction behavior of four ceramic powders. In each case, they assumed that compression is attained by two nearly independent probabilistic processes, namely, the filling of voids having equal size as particles and filling of voids smaller than particles. Based on these assumptions, the following equation was given:

$$\frac{V_o - V}{V_o - V_S} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_2}{P}} \quad (4)$$

where, V_0 = volume of compact at zero pressure, m^3; a_1, a_2, k_1, and k_2 = Cooper-Eaton model constants.

The difficulty in practical use of the equation is the assignment of some physical significance to the constant parameters of this equation. In addition, another drawback of this model is its applicability to only one-component system (Comoglu, 2007)

2.5 Kawakita and Ludde Model

Kawakita and Ludde (1971) performed compression experiments and proposed an equation for compaction of powders based on observed relationship between pressure and volume (Eq. 5).

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \quad (5)$$

where,

$$C = \frac{V_0 - V}{V_0}$$

C = degree of volume reduction or engineering strain; a and b = Kawakita-Ludde model constants related to characteristic of the powder.

The linear relationship between *P/C* and *P* allows the constants to be evaluated graphically. This compression equation holds true for soft and fluffy powders (Denny, 2002; Kawakita and Ludde, 1971), but particular attention must be paid on the measurement of the initial volume of the powder. Any deviations from this expression are sometimes due to fluctuations in the measured value of V_0. The constant a is equal to the values of $C = C_\infty$ at infinitely large pressure P.

$$C_\infty = \frac{V_0 - V_\infty}{V_0}$$

Where, V_∞ = net volume of the powder, m^3.

It has been reported that the constant a is equal to the initial porosity of the sample, while constant $1/b$ is related to the failure stress in the case of piston compression (Mani *et al.,* 2004).

Comoglu (2007) reported that the two most commonly used compression equations; Heckel (1961) and Kawakita and Ludde (1971), have not been proven to be successful in relating the densification behavior with the physical and mechanical properties of the materials. The Kawakita and Ludde (1971) equation works best for only limited range of materials, where the Heckel (1961) equation produces curved plots (instead of linear plots). Even though these two equations appear very different, it has been shown mathematically that for pressure that are relatively low compared to the yield strength, the Kawakita and Ludde, and Heckel equations are identical in form.

2.6 Shapiro Model

Shapiro's model is only valid over the first two stages of compression process (Shapiro, 1993). Therefore, it will not be suitable to study compression behavior of agricultural biomass grinds at high pressures; hence, it was not considered for further analysis. The Shapiro equation is as given below (Eq. 6):

$$\ln E = \ln E_0 - kP - bP^{0.5} \quad (6)$$

where, E_0 = initial porosity; k and b are Shapiro constants.

2.7 Soonergaard Model (log-exp-equation)

Sonnergaard (2001) proposed a log-exp-equation that simultaneously considered two processes: a logarithmic decrease in volume reduction by fragmentation and an exponential decay representing plastic deformation of powders (Eq. 7).

$$V = V_1 - w \log P + V_0 \exp(-P/P_m) \quad (7)$$

where, V_1 = volume at pressure 1 MPa; P_m = mean pressure, MPa; w is a constant.

Sonnergaard (2001) has suggested that his model provides better regression values compared to Cooper-Eaton model and Kawakita and Ludde model. However, the model is only suitable to describe compression of materials, when the investigation is performed at medium pressure range only (~50 MPa). Therefore, Sonnergaard model will not be suitable to study compression behavior of agricultural biomass grinds at high pressures and hence, will not be considered for further analysis in the current study.

2.8 Panelli-Filho Model

A new compression equation (8) was proposed by Panelli-Filho (2001), given as:

$$\ln\frac{1}{1-\rho_r} = \boldsymbol{A}\sqrt{\boldsymbol{P}} + \boldsymbol{B} \tag{8}$$

where, ρ_r is the relative density of the compact; A is a parameter related to densification of the compact by particle deformation and B is a parameter related to powder density at the start of compression.

A majority of compression models applied to pharmaceutical and biomass materials have been discussed and reviewed in detail by Adapa *et al.* (2002), Denny (2002) and Mani *et al.* (2003). Mani *et al.* (2004) reported that among the different compression models, the Heckel and Cooper-Eaton models are still in use to study the compression mechanism of pharmaceutical and cellulosic materials. The Kawakita-Ludde model was proposed for soft and fluffy materials (Kawakita and Ludde, 1971). Adapa *et al.* (2002) and Tabil and Sokhansanj (1996) studied the applicability of these models for alfalfa pellets. They have concluded that the Cooper-Eaton, Heckel and Panelli-Filho models provided better fit to the compression data. In the present study, five compression models were considered to determine the pressure-volume and pressure-density relationship to analyze the compression characteristics of barley, canola, oat and wheat straw namely: Jones (1960), Heckle (1961), Cooper-Eaton (1962), Kawakita-Ludde (1971) and Panelli-Filho (2001) models.

3. MATERIALS AND METHODS

3.1 Agricultural Biomass

Four types of agricultural biomass (barley, canola, oat and wheat straw) were used for the experiments. The straw samples were acquired in small square bale form (typically having dimensions of 0.45×0.35×1.00 m) during the summer of 2008 from the Central Butte area of Saskatchewan, Canada.

All of the straw samples were manually chopped using a pair of scissors and subsequently ground using a forage grinder (Model No. 70965, Retsch GmbH, Haan, Germany) with a screen opening size of 1.98 mm. The authors decided to use only one screen size of 1.98 mm based on the studies conducted by Adapa *et al.* (2004), which indicated that at this screen size, high quality fractionated alfalfa pellets were produced. In addition, literature review on the effect of grind size on compact density indicated the production of high density and quality pellets/briquettes at finer grind sizes (Kaliyan and Morey, 2006a and 2006b; Mani *et al.,* 2002 and 2004).

The initial moisture contents of ground barley, canola, oat and wheat straw were 6.7, 6.7, 5.3 and 4.0 % (w.b.), respectively. The moisture content of ground straw samples were raised to 10 % (w.b.) by adding/sprinkling calculated amount of water and subsequently stored the samples in plastic bags in a cold room kept at 4 °C for a minimum of 72 h. The moisture content was determined using ASAE Standard S358.2 (ASAE, 2006a), where oven drying of the samples was carried out at 103 °C for 24 h. Only one moisture level of 10 % (w.b.) was used and this was based upon literature review that at this moisture level high density and quality pellets/briquettes were produced from various straw and biomass (Hill and Pulkinen, 1988; Kaliyan and Morey, 2006b and 2007; Li and Liu, 2000; Mani *et al.,* 2006a; Obernberger and Thek, 2004; Shaw and Tabil, 2007; Stevens, 1987).

3.2 Particle Size Analysis

Prior to pelleting experiments, the geometric mean particle size of ground agricultural straw samples at 10 % moisture content (w.b.) was determined using ASAE Standard S319 (ASAE, 2006b). For each test, a 100 g sample was placed on a stack of sieves arranged from the largest to the smallest opening. A Ro-Tap sieve shaker (W. S. Tyler Inc., Mentor, OH) was used to determine the geometric mean particle size using U.S. sieve numbers 16, 20, 30, 50, 70 and 100 (sieve opening sizes: 1.190, 0.841, 0.595, 0.297, 0.210 and 0.149 mm, respectively). A 10 min sieve shaking time was considered to be appropriate due to the fluffy nature of the grinds. The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated in three replicates for each straw samples.

3.3 Bulk and Particle Density

Bulk density of ground agricultural straw was determined by carefully filling a standard 500 cm^3 cylindrical container (SWA951, Superior Scale Co. Ltd., Winnipeg, MB) with sample. After filling every third portion of the container with ground straw sample, it was tapped on a wooden table for approximately 10 times to allow the material to settle down. After completely filling the container, excess material at the top was removed by moving a steel roller in a zig-zag pattern. The mass per unit volume gave the bulk density of the biomass in kg/m^3. A gas multi-pycnometer (QuantaChrome, Boynton Beach, FL) was used to determine the particle density of the ground straw by calculating the displaced volume of nitrogen gas by a known mass of material, following the method reported by Adapa *et al.* (2005). Three replicates for each sample were performed for both bulk and particle density measurements.

3.4 Experimental Set-up

A single pelleting unit (Adapa *et al.,* 2006) having a close fit plunger die assembly was used to study the compression characteristics of fractionated alfalfa grinds (Adapa *et al.,* 2002). The cylindrical die was 135.3 mm long and 6.35 mm in diameter. Thermal compound (Wakefield Engineering Inc., Wakefield, MA) was coated on the outer surface of the die prior to wrapping the outer surface with copper shim stock. A dual element heating tape (Cole-Parmer Instrument Company, Vernon Hills, IL) was then wound evenly around the shim stock to provide the necessary heat. One T-type thermocouple, connected to the outer surface of the cylinder, was linked to a temperature controller to regulate the power input to the heater, thus allowing temperature control of the cylinder. Another T-type thermocouple was also connected to the outer cylinder wall, allowed verification of the cylinder temperature via a digital thermocouple reader (Shaw, 2008). The pellet die was fitted on a stainless steel base having a hole matching its outer diameter. This gave stability and allowed the plunger to move straight down with no lateral movement. The plunger was attached to the upper moving crosshead of the Instron Model 1011 testing machine (Instron Corp., Canton, MA).

3.5 Compression Test

The pelleting unit was used to make a single pellet in one stroke of the plunger from ground straw samples. The pellet die was maintained at a temperature of 95±1 °C in order to simulate frictional heating during commercial pelleting operation (Adapa *et al.,* 2006 and Mani *et al.,* 2006b). The mass of samples used for making pellets varied between 0.5 and 0.7 g. Compressive force was applied using the Instron Model 1011 testing machine fitted with a 5000 N load cell and a 6.3 mm diameter plunger. Four preset loads of 1000, 2000, 3000 and 4400 N corresponding to pressures of 31.6, 63.2, 94.7 and 138.9 MPa, were used to compress samples in the die. The crosshead speed of the Instron testing machine was set to 50 mm/min. After compression, the plunger was retained in place for 30 s once the preset load was attained in order to avoid spring-back effect of biomass grinds (Adapa *et al.,* 2006 and Mani *et al.,* 2006b). Later, the base plate was removed and the pellet was ejected (extruded) from the single pelleter by using the plunger.

3.6 Statistical Analysis

The experiments were set up as completely random experimental design with 10 replications and two variables (straw and pressure) factorial design. The volume and density were the dependent variables, while pressure was the independent variable. The mass, length and diameter of pellets were measured to determine the pellet volume (m^3) and density (kg/m^3). Ten replicates (pellets) were made using each ground straw samples. The model parameters were estimated using Excel (Microsoft Corp., 2003) software and SAS 8.2 software (SAS Institute, 1999). Model parameters for Cooper-Eaton model were determined using PROC NLIN program in the SAS software package. In order to further understand and explain the experimental variables and their interactions, the SAS general linear model (GLM) for completely randomized design (CRD) procedure was used and the Student-Neuman-Keuls test (SNK) was performed. The SNK method determines the difference between two groups at 5 % level of significance (SAS Manual, SAS Institute, 1999).

4. RESULTS AND DISCUSSION

4.1 Physical Properties

The geometric mean particle size, bulk and particle densities of ground barley, canola, oat and wheat straw at 10 % moisture content (w.b.) are listed in table 1. The SNK test indicated that the geometric mean particle size of oat straw (0.347 mm) was significantly smaller ($P<0.05$) than the other straw samples. The mean bulk density of ground canola straw was highest (273 kg/m^3); however, the bulk densities for all the straw samples were not statistically different ($P>0.05$). It was observed that ground wheat and barley straw had the highest (1585 kg/m^3) and lowest (1484 kg/m^3) mean particle densities, respectively. The mean particle density of barley, canola and oat straw were statistically similar, while the mean particle densities of canola, oat and wheat straw were not significantly different.

Table 1. Geometric mean particle size, bulk and particles densities for four ground agricultural straw samples at 10 % moisture content (w.b.)

Biomass	Geometric mean particle size (mm)	Bulk density (kg/m^3)	Particle density (kg/m^3)
Barley Straw	0.384 ± 0.003 a $^{\gamma\dagger\ddagger}$	261 ± 02 a	1484 ± 03 a
Canola Straw	0.391 ± 0.017 a	273 ± 11 a	1551 ± 47 ab
Oat Straw	0.347 ± 0.003 b	268 ± 04 a	1523 ± 15 ab
Wheat Straw	0.398 ± 0.006 a	269 ± 09 a	1585 ± 46 b

γ3 replicates; †95% confidence interval; ‡ Student-Neuman-Keuls test at 5% level of significance

4.2 Compression Test

Table 2 shows the effect of applied pressure on pellet density and volume for four ground agricultural straws. The actual compressive force recorded by the Instron machine was slightly higher than the preset values (applied load). The recorded compressive forces had higher variability at higher preset loads due to the inertia of crosshead and limitations in testing machine control. Two SNK analyses were performed on the collected data. In the first SNK analysis, treatment means for the same straw sample at different pressures were compared and the differences were shown by designations of the lower case letters a, b and c. The second SNK analysis was performed to determine the difference in treatment means for the four straw samples at the same pressure with the upper case letters D and E used to show the difference. Figure 2 shows that the pellet density for all four agricultural straw samples increased with an increase in pressure. The mean densities of barley, canola, oat and wheat straw pellets increased from 907 to 977 kg/m^3, 823 to 1003 kg/m^3, 849 to 1011 kg/m^3 and 813 to 924 kg/m^3, respectively. For barley and wheat straw pellets, the increase in density was significant ($P<0.05$) for an increase of pressure from 31.6 to 63.2 MPa (table 2). Table 2 also indicates that for canola and oat straw pellets, the increase in density was significant ($P<0.05$) for an increase in applied pressure from 31.6 to 94.7 MPa. Application of higher pressure (>94.7 MPa) did not affect the compact density as the pellets approached their respective particle densities. The wheat straw pellet has been an exception as although it had larger geometric mean particle size and particle densities (table 1), its density reached a maximum value at a pressure of 63.2 MPa. This could possibly be attributed to the lower total protein and lignin contents as compared to other straw material, which resulted in a better pellet. At pressures of 31.6 and 63.2 MPa, the density of pellet from barley straw was significantly higher than the densities of other agricultural straw pellets (table 2), which could be attributed to a combination of lowest particle density (1484 kg/m^3) and geometric mean particle size. However, at pressures of 94.7 and 138.9 MPa, the density of pellets from wheat straw was significantly lower than the densities of other agricultural straw pellets. This could be due to the fact that wheat straw had both highest particles density (1585 kg/m^3) and geometric mean particle size.

Generally, at any particular pressure, the density of pellets was highest for oat straw followed by barley, canola and wheat straw in decreasing order (table 2). This could be attributed to the geometric mean particle size for oat straw (0.347 mm), which was followed by barley (0.384 mm), canola (0.391 mm) and wheat (0.398 mm) straw in increasing order. The finer grind size has been reported to produce denser pellets (Kaliyan and Morey, 2006a and 2006b; Mani *et al.,* 2002 and 2004).

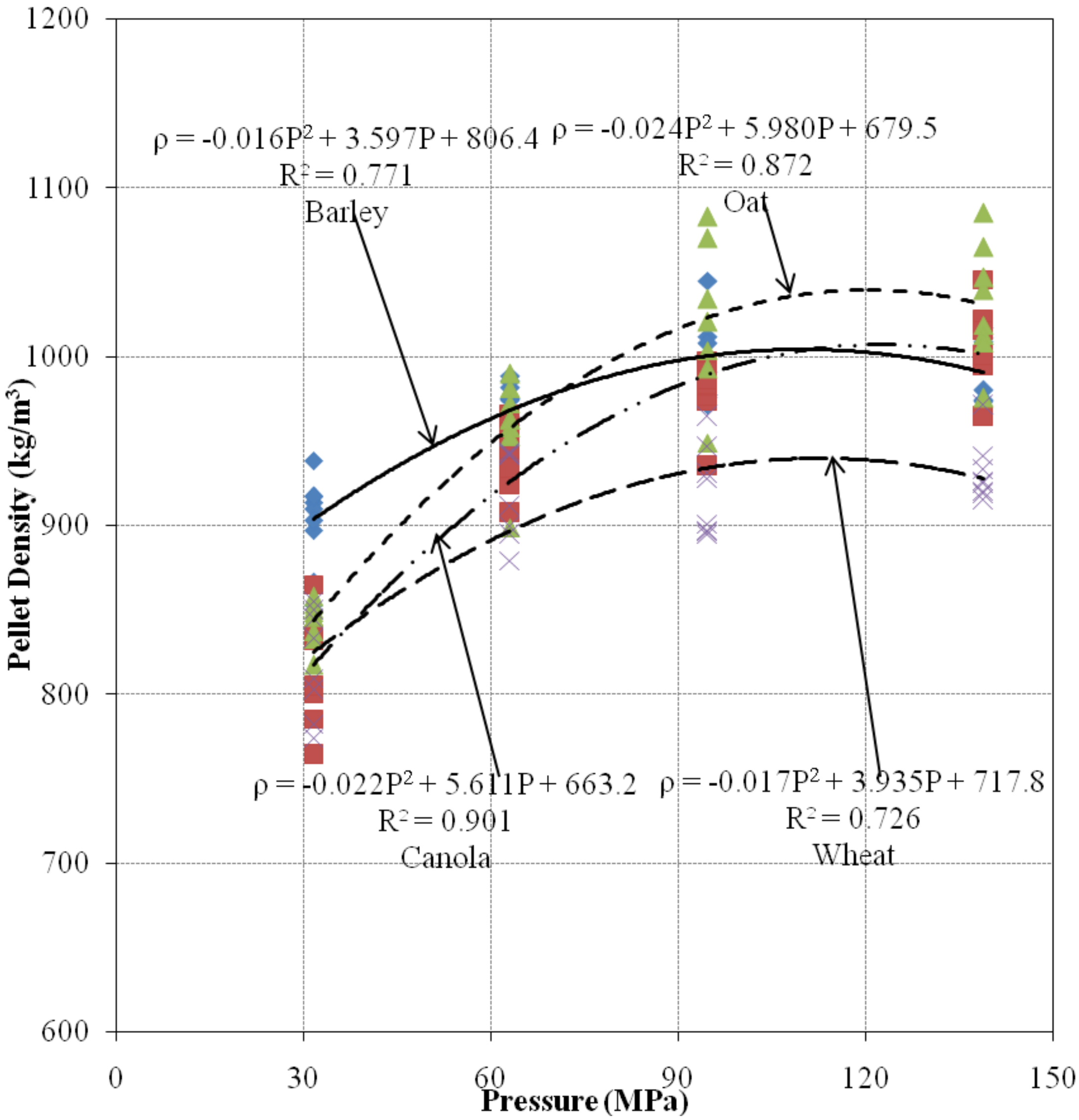

Figure 2. Density of pellets and their empirical equations for four agricultural straw samples at four pressure levels

Table 2. Observed compressive forces; measured pellet mass, diameter and length; and calculated volume and density data for selected agricultural biomass.

Biomass	Applied Load$^{\Psi}$ (N)	Compressive Force$^{\Psi\Psi}$ (N)	Pellet Mass (g)	Pellet Diameter (mm)	Pellet Length (mm)	Pressure (MPa)	ρ_p* (kg/m^3)	ρ_t** (kg/m^3)	ρ_b*** (kg/m^3)	Volume (mm^3)	
										V^{+}	Vs^{++}
Barley Straw	1000	1224 ± 42*†	0.58 ± 0.04	6.46 ± 0.02	19.55 ± 1.37	30.5 ± 0.2	907 ± 31 aD‡	1484 ± 03	261 ± 02	642 ± 46	392 ± 24
	2000	2339 ± 53	0.62 ± 0.03	6.48 ± 0.01	19.15 ± 1.15	60.6 ± 0.3	978 ± 14 bD			632 ± 38	416 ± 22
	3000	3395 ± 50	0.59 ± 0.05	6.47 ± 0.01	18.24 ± 1.38	91.2 ± 0.3	988 ± 26 bD			600 ± 45	399 ± 34
	4400	4725 ± 63	0.58 ± 0.05	6.47 ± 0.01	18.17 ± 1.32	133.8 ± 0.6	977 ± 38 bD			597 ± 45	394 ± 35
Canola Straw	1000	1214 ± 41	0.65 ± 0.06	6.49 ± 0.03	24.04 ± 2.24	30.2 ± 0.3	823 ± 73 aE	1551 ± 47	273 ± 11	796 ± 74	421 ± 36
	2000	2324 ± 36	0.68 ± 0.04	6.47 ± 0.02	22.15 ± 1.49	60.9 ± 0.3	934 ± 21 bE			728 ± 49	438 ± 25
	3000	3381 ± 42	0.68 ± 0.02	6.49 ± 0.01	21.06 ± 0.82	90.9 ± 0.4	980 ± 17 cD			695 ± 27	439 ± 14
	4400	4569 ± 31	0.70 ± 0.04	6.47 ± 0.01	21.19 ± 0.98	133.7 ± 0.4	1003 ± 21 cD			698 ± 32	452 ± 26
Oat Straw	1000	1211 ± 57	0.57 ± 0.03	6.49 ± 0.02	20.25 ± 1.09	30.2 ± 0.2	849 ± 22 aE	1523 ± 15	268 ± 04	669 ± 37	373 ± 20
	2000	2364 ± 33	0.58 ± 0.04	6.49 ± 0.01	18.55 ± 0.75	60.5 ± 0.3	937 ± 56 bE			614 ± 24	378 ± 26
	3000	3438 ± 51	0.60 ± 0.05	6.47 ± 0.01	18.43 ± 0.72	91.4 ± 0.3	991 ± 63 cD			605 ± 23	394 ± 34
	4400	4625 ± 21	0.61 ± 0.04	6.47 ± 0.01	18.48 ± 0.93	133.7 ± 0.6	1011 ± 54 cD			608 ± 31	403 ± 29
Wheat Straw	1000	1210 ± 49	0.52 ± 0.03	6.49 ± 0.04	19.37 ± 1.79	30.3 ± 0.4	813 ± 55 aE	1585 ± 46	269 ± 09	640 ± 63	327 ± 20
	2000	2383 ± 50	0.56 ± 0.06	6.48 ± 0.02	18.30 ± 1.75	60.7 ± 0.4	929 ± 30 bE			603 ± 57	353 ± 35
	3000	3333 ± 90	0.54 ± 0.05	6.48 ± 0.01	17.45 ± 1.56	91.1 ± 0.4	931 ± 34 bE			575 ± 52	338 ± 33
	4400	4687 ± 41	0.62 ± 0.03	6.48 ± 0.01	20.51 ± 0.99	133.4 ± 0.4	924 ± 23 bE			676 ± 32	394 ± 20

$^{\Psi}$ Preset compressive load on the Instron for forming pellets
$^{\Psi\Psi}$ Actual force registered by the Instron due to inertia
$^{*}\rho_p$ Pellet density
$^{**}\rho_t$ Particle density of the ground alfalfa leaf and stem mixture, n = 3
$^{***}\rho_b$ Bulk density of the ground alfalfa leaf and stem mixture, n = 3
$^{+}$V Volume of the compact at pressure P
$^{++}$Vs Void-free solid material volume
†95% confidence interval
‡ Student-Neuman-Keuls test at 5% level of significance
Number of replicates for each run of compaction, n = 10

4.3 Fitting Compression Models to Pressure, Density and Volume Data

Five compression models were fitted to the pressure-volume and pressure-density data to analyze the compression characteristics of barley, canola, oat and wheat straw. Tables 3 to 7 present the parameters obtained after curve fitting of Jones (1960), Heckle (1961), Cooper-Eaton (1962), Kawakita-Ludde (1971) and Panelli-Filho (2001) models, respectively. Jones (1960) derived a linear equation, which expressed the logarithmic value of density as a function of the logarithmic pressure. Low R^2 values were obtained when the Jones model was fitted to the pressure-density data (table 3). The R^2 values for barley, canola, oat and wheat straw were 0.42, 0.68, 0.63 and 0.46, respectively. Similar to Jones model (1960), the Heckel model (1961) was unable to explain the trend in variation of pressure and density data (table 4). However, the value of constant m provided valuable information about the onset of plastic deformation of the ground straw at relatively low pressure, thus, indicating that the material is more compressible. Higher m values for canola and oat straw (0.002) were observed as compared to barley and wheat straw (0.001) indicating they are more compressible. The R^2 values obtained for barley, canola, oat and wheat straw were 0.42, 0.71, 0.62 and 0.47, respectively.

Table 5 represents the parameters obtained when the Cooper-Eaton model (1962) was fitted to the experimental data. The dimensionless coefficients a_1 and a_2 represent the densification of powdered material by particle rearrangement and deformation, respectively. If the sum of coefficients (a_1 + a_2) is less than unity, it is an indication that other process must become operative before complete compaction is achieved. The a_1 values for four selected agricultural biomass were higher than a_2 values, which indicates that material densified easily by particle rearrangement. The sum of coefficients (a_1 + a_2) for barley and oat straw were near and below unity, which indicates that the samples almost reached their theoretical density. While the sum of coefficients for canola and wheat straw were observed to be above unity. The phenomenon of having sum of coefficient more than unity was also observed by Adapa *et al.* (2002), and Shivanand and Sprockel (1992), which implies that the densification could not be fully attributed to the two mechanisms of compression assumed by Cooper-Eaton (1962). The R^2 values obtained for barley, canola, oat and wheat straw were 0.52, 0.72, 0.64 and 0.64, respectively.

It has been observed that the Kawakita-Ludde model (table 6) provided the best fit scenario having R^2 values of 0.99 for all biomass samples (fig. 3). All other models were unable to sufficiently describe the compression behavior of selected agricultural biomass. In Kawakita-Ludde model, the constant a represents the initial porosity of the sample. Table 6 shows that the oat straw had the highest initial porosity value (0.751) followed by the canola (0.749), barley (0.738) and wheat (0.720) straw. The porosity value for oat straw can be related to its lowest geometric mean particle size (0.347 mm) while having similar bulk densities (268 kg/m^3) as the other samples (table 1). The parameter $1/b$ indicates the yield strength or failure stress of the compact. The highest value of failure stress (3.801) was observed for ground canola straw sample followed by oat (3.149), wheat (1.727) and barley (0.776) straw.

The Panelli-Filho model (2001) was unable to provide better fit to the pressure-density data. The R^2 values obtained for barley, canola, oat and wheat straw were 0.36, 0.74, 0.57 and 0.40, respectively (table 7).

Table 3. Jones Model $\ln \rho = \boldsymbol{m} \ln \boldsymbol{P} + \boldsymbol{b}$

Biomass	Constants		R^2 Values	SSE
	m	b		
Barley Straw	0.052	6.643	0.42	0.046
Canola Straw	0.138	6.243	0.71	0.094
Oat Straw	0.120	6.333	0.62	0.108
Wheat Straw	0.089	6.418	0.47	0.109

Table 4. Heckel Model $\ln \frac{1}{1-\rho_f} = \boldsymbol{mP} + \boldsymbol{b}$

Biomass	Constants		R^2 Values	SSE
	m	b		
Barley Straw	0.001	0.959	0.31	6.696
Canola Straw	0.002	0.724	0.70	5.102
Oat Straw	0.002	0.771	0.55	6.197
Wheat Straw	0.001	0.740	0.34	3.393

Table 5. Cooper – Eaton Model $\frac{V_0 - V}{V_0 - Vs} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_2}{P}}$

Biomass	Constants				R^2 Values	SSE
	a_1	a_2	k_1	k_2		
Barley Straw	0.7025	0.2000	1.3025	1.3024	0.52	0.004
Canola Straw	1.8141	-0.9117	-1.6542	-6.0377	0.72	0.014
Oat Straw	0.8958	0.0202	4.5734	-31.7373	0.64	0.012
Wheat Straw	1.4503	-0.6091	-11.3827	-23.3329	0.64	0.011

Table 6. Kawakita-Ludde Model $\frac{\boldsymbol{P}}{\boldsymbol{C}} = \frac{1}{\boldsymbol{ab}} + \frac{\boldsymbol{P}}{\boldsymbol{a}}$

Biomass	Constants		R^2 Values	SSE
	a	1/b		
Barley Straw	0.738	0.776	0.99	100.33
Canola Straw	0.749	3.801	0.99	81.58
Oat Straw	0.751	3.149	0.99	272.37
Wheat Straw	0.720	1.727	0.99	144.13

Table 7. Panelli – Filho Model $\ln \frac{1}{1-\rho_r} = \boldsymbol{A}\sqrt{\boldsymbol{P}} + \boldsymbol{B}$

Biomass	Constants		R^2 Values	SSE
	A	B		
Barley Straw	0.020	0.866	0.36	0.162
Canola Straw	0.045	0.530	0.74	0.153
Oat Straw	0.046	0.576	0.57	0.332
Wheat Straw	0.023	0.634	0.40	0.175

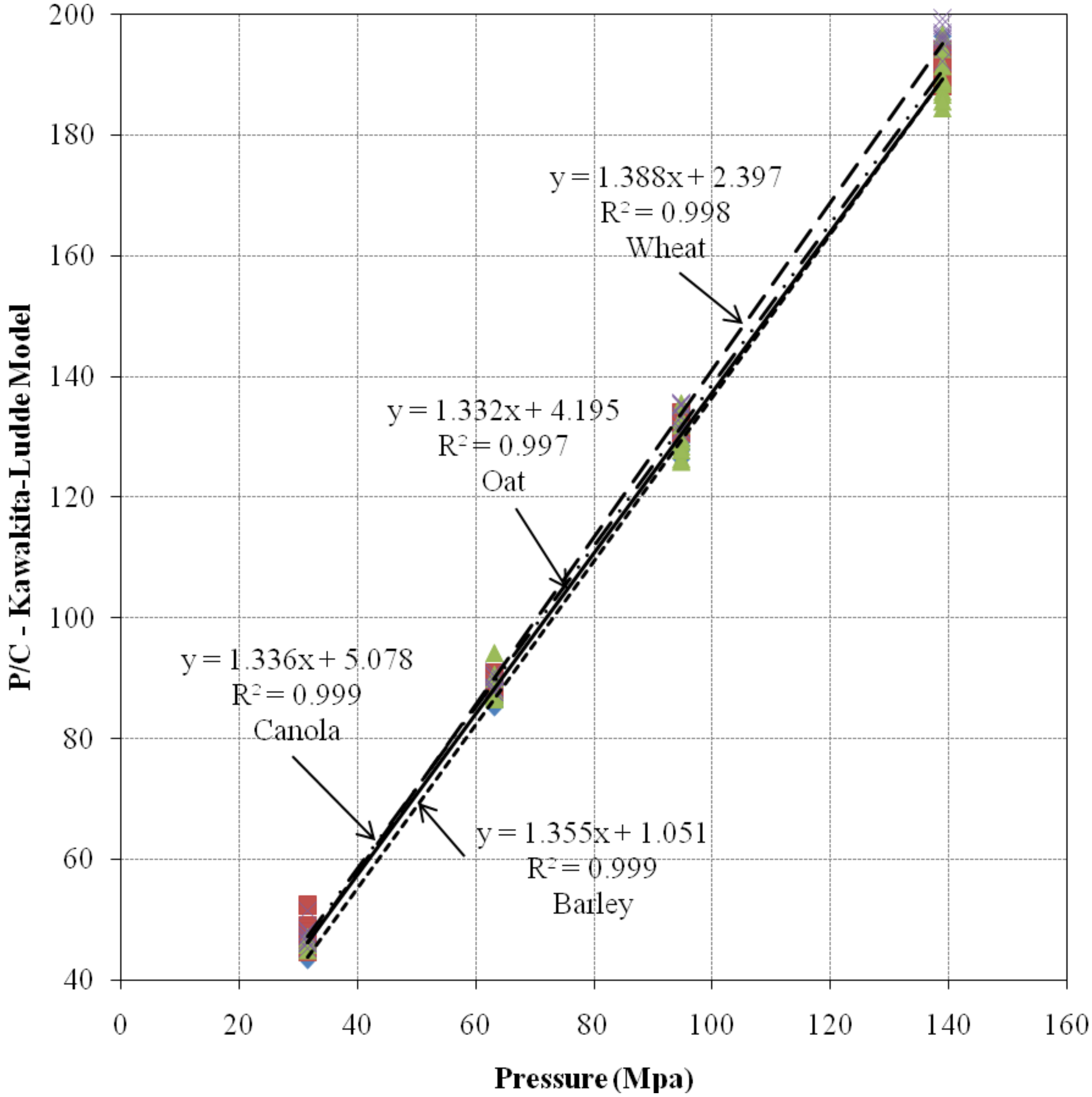

Figure 3. Kawakita-Ludde model fitted to the experimental data obtained from densification of selected agricultural biomass

5. CONCLUSIONS

A review of various existing compression models was successfully performed. In addition, the compaction characteristics of ground barley, canola, oat and wheat straw samples at 10 % moisture content (w.b.) and grind size of 1.98 mm was studied by subjecting the samples to four pressure levels of 31.6, 63.2, 94.7 and 138.9 MPa. Five models, namely: Jones (1960), Heckle (1961), Cooper-Eaton (1962), Kawakita-Ludde (1971) and Panelli-Filho (2001) models were fitted to the pressure-density-volume data. The Kawakita-Ludde model provided an excellent fit having R^2 values of 0.99 for four selected agricultural straw samples. It was also concluded that the ground oat and canola straw had the highest level of porosity and failure stress, respectively. The parameters of Cooper-Eaton model indicated that the ground straw samples were densified easily by the particles rearrangement method and Jones model indicated that canola and oat straw were more compressible as compared to barley and wheat straw.

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