Evaluation of compaction equations applied to four biomass species

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Mani, S., Tabil, L.G. and Sokhansanj, S. 2004. **Evaluation of compaction equations applied to four biomass species.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **46**: 3.55-3.61. The compression behavior and compaction mechanism of wheat and barley straws, corn stover, and switchgrass grinds were investigated using three compaction equations viz. Heckel, Cooper-Eaton, and Kawakita-Lüdde models. Compression tests of biomass samples were conducted at different applied forces, moisture contents, and particle sizes using the single pelleter-Instron tester. For each test, the pressure-density data were collected to characterize the compression behavior of biomass grinds. Among the four biomass grinds studied, corn stover grind reached its maximum density at low pressure, whereas the other biomass grinds required high pressure to reach maximum density. The compression data were fitted to three compaction models for explaining the compaction mechanisms. Among the three models, the Kawakita-Lüdde and Cooper-Eaton models fitted well with the pressure-density data for all biomass grind samples. The Cooper-Eaton model parameters showed that the dominant compaction mechanisms for biomass grinds were rearrangement of particles followed by elastic and plastic deformation and that mechanical interlocking was negligible. From the Kawakita-Lüdde model, it was found that compacts prepared from switchgrass grind had higher yield strength than compacts made from other biomass grinds. Lower yield strength was predicted by the Kawakita-Lüdde model for compacts from corn stover grind. **Keywords:** agricultural crop residues, energy crops, compression test, compaction mechanism, compaction models.

Les propriétés caractéristiques de compression ainsi que les mécanismes de densification pour la paille de blé et d'orge, les tiges de maïs et les résidus de panic raide ont été étudiés en utilisant trois équations de densification, les modèles de Heckel, de Cooper-Eaton et de Kawakita-Lüdde. Des tests de densification de la biomasse ont été réalisés pour différentes forces de compression, teneurs en eau et grosseurs de particules en utilisant un appareil d'essais de compression Instron. Pour chacun des essais, les données de pression appliquée et de masse volumique résultante ont été utilisées pour caractériser les caractéristiques de densification des différents types de résidus analysés. Les résidus de tiges de maïs ont pu être compactés à leur masse volumique maximale sous l'action d'une faible force de compression, tandis que les autres résidus de biomasse ont nécessité l'application de pressions plus élevées pour atteindre un niveau de densification maximal. Les données expérimentales ont également été analysées avec les trois modèles de densification. Les valeurs prédites par les modèles de Kawakita-Lüdde et de Cooper-Eaton étaient en accord avec les données expérimentales de pression appliquée et de masse volumique résultante pour tous les échantillons de résidus de biomasse. Les paramètres du modèle Cooper-Eaton ont montré que les mécanismes dominants lors de la densification de résidus de biomasse sont la réorganisation des particules suivie par une déformation élastique et plastique et que la cohésion mécanique était négligeable. En utilisant le modèle de Kawakita-Lüdde, il a été démontré que les agglomérats préparés avec les résidus de panic raide avaient une résistance plus élevée que les agglomérats construits à partir des autres résidus de biomasse. Une résistance moins élevée a été prédite par le modèle de Kawakita-Lüdde pour des agglomérats de résidus de tiges de maïs. **Mots clés**: résidus agricoles; cultures énergétiques; mécanismes, modèles, essais de densification.

INTRODUCTION

The compaction behavior of bulk biomass depends upon the mechanical properties of solid particles. The compaction mechanism of different powder materials is different from each other. It is also important to understand the fundamental mechanism of the biomass compaction process, which is required in the design energy efficient compaction equipment to mitigate the cost of production and to study the effect of various process variables on compact density to enhance the quality of the product. In general, during the first stage of compression, particles rearrange themselves to form a closely packed mass. The particles retain most of their original properties, although energy is dissipated due to interparticle and particle-to-wall friction. As the compaction pressures increase, particles are forced against each other while undergoing elastic and plastic deformations. This increases interparticle contact area and as a result, bonding forces like van der Waal's forces become effective (Rumpf 1962; Sastry and Fuerstenau 1973; Pietsch 1997). Brittle particles may fracture under stress, leading to mechanical interlocking (Gray 1968). At higher pressures, internal pores within particles rupture until the density of the compacted bulk approaches the true or solid densities of the component ingredients. If the melting point of the ingredients in the mix that form a eutectic mixture is favorable, the heat generated at the point of contact can lead to a local melting of materials. Once cooled, the molten material forms very strong solid bridges (Ghebre-Sellassie 1989). Biomass contains components such as cellulose, hemicellulose, protein, lignin, crude fiber, and ash. Among these chemical components, lignin has a low melting point of about 140°C. When biomass is heated, lignin becomes soft and sometimes melts and exhibits thermosetting properties (van Dam et al. 2004). A similar compaction mechanism was identified in the alfalfa pelleting process (Tabil and Sokhansanj 1996). When alfalfa is compacted in a circular die pellet mill, the temperature of the compacted material reaches more than 90°C due to preconditioning of the material and the heat generated due to friction between the die and the material (Tabil 1996). During compression of pharmaceutical powders, a series of compression mechanisms has been suggested to be involved in the compression process, i.e. particle rearrangement, deformation, densification, fragmentation, and attrition (Alderborn and Wikberg 1996). In two studies (Johansson et al. 1995; Johansson and Alderborn 1996) in pharmaceutical tablet production, the compression behavior of pelletized microcrystalline cellulose has been investigated. The relevant compression mechanism was permanent deformation (change in the shape of the individual particles) and densification (contraction or porosity reduction of the individual compacts) and that fragmentation of the compacts was minute.

To further understand the compaction mechanism of powder materials, a number of models has been proposed (Walker 1923; Heckel 1961; Cooper and Eaton 1962; Kawakita and Lüdde 1971). Many of the compaction models applied to pharmaceutical and biomass materials have been discussed and reviewed in detail by Denny (2002) and Mani et al. (2003). Among the different compaction models, the Heckel and Cooper-Eaton models are still in use to study the compaction mechanism of pharmaceutical and cellulosic materials. The Kawakita-Lüdde model was proposed for soft and fluffy materials (Kawakita and Lüdde 1971). Tabil and Sokhansanj (1996) studied the applicability of such models for alfalfa pellets. They concluded that the Heckel and Cooper-Eaton models fitted well with the alfalfa compression data.

The objectives of the study were: 1) to understand the compaction mechanism of biomass grinds under different applied pressures, particle size, and moisture content during pelleting or cubing processes; and 2) to investigate the applicability of some of the existing compaction models to biomass grinds.

COMPACTION MODELS INVESTIGATED

Heckel (1961) proposed a model to express the compaction behavior of compressed powder. The equation expresses the density of powdered materials in terms of packing fractions as a function of applied pressure.

$$\ln \frac{1}{1-\rho_f} = mP + n \tag{1}$$

$$\rho_f = \frac{\rho}{\rho_1 X_1 + \rho_2 X_2} \tag{2}$$

where:

- ρ_f = packing fraction or relative density of the material after particle rearrangement,
- P = applied pressure (MPa),
- m, n = Heckel model constants,
- ρ = bulk density of compacted powder mixture (kg/m^3),
- ρ_1, ρ_2 = particle density of components of the mixture (kg/m^3), and
- X_1, X_2 = mass fraction of components of the mixture.

Shivanand and Sprockel (1992) showed that constant n is related to relative density at particle rearrangement.

$$n = \ln \frac{1}{1-\rho_f} \tag{3}$$

A high ρ_f value indicates that there will be a high 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 plastic deformation. A larger value for m (low yield pressure) indicates the onset of plastic deformation at relatively low pressure, a sign that the material is more compressible.

Cooper and Eaton (1962) classified two broad processes that are involved in compaction, based on the assumption that compaction proceeds through particle rearrangement and deformation. The first process is the filling of voids of the same order as the size of the original particles, which may require elastic deformation or even slight fracturing or plastic flow of particles. The second process involves the filling of voids that are substantially smaller than the original particles. The process can be accomplished by plastic flow or fragmentation, in which the former is more efficient because the material is always forced into the voids. Cooper and Eaton (1962) proposed Eq. 4 to describe the compaction behavior of ceramic powders.

$$\frac{V_0 - V}{V_0 - V_S} = a_1 \exp\left(\frac{-k_1}{P}\right) + a_2 \exp\left(\frac{-k_2}{P}\right) \tag{4}$$

where:

- V = volume of compact at pressure P (m^3),
- V_0 = volume of compact at zero pressure (m^3),
- V_S = void-free solid material volume (m^3), and
- a_1, a_2, k_1, k_2 = Cooper-Eaton model constants.

Kawakita and Lüdde (1971) published piston compression equations, Eqs. 5 and 6, from the observed relationship between pressure and volume:

$$\frac{P}{C} = \frac{1}{ab} + \frac{P}{a} \tag{5}$$

$$C = \frac{V_0 - V}{V_0} \tag{6}$$

where:

- C = degree of volume reduction or engineering strain and
- a, b = Kawakita-Lüdde 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 for soft and fluffy powders (Kawakita and Ludde 1971; Denny 2002), 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.

$$C_\infty = \frac{V_0 - V_\infty}{V_0} \tag{7}$$

where: V_∞ = net volume of the powder (m^3).

Hence, it is clear that constant a is equal to the initial porosity of the sample. Constant 1/b is related to the failure stress in the case of piston compression.

Table 1. Average composition (%DM) of selected biomass.

Component	Wheat straw	Barley straw	Corn stover	Switchgrass
Protein	5.70	6.60	8.70	1.59
Crude fat	1.61	1.33	1.33	1.87
Lignin	7.61	6.81	3.12	7.43
Cellulose	42.51	42.42	31.32	44.34
Hemicellulose	22.96	27.81	21.80	30.00

MATERIALS and METHODS

Crop samples

Wheat and barley straws, corn stover, and switchgrass were the biomass types tested in this work. Wheat and barley straws in square bales were obtained from an experimental farm near Saskatoon, Saskatchewan, Canada. The bales were of dimension 0.45 x 0.35 x 1.00 m. The moisture content measured was 8.3% (wb) for wheat and 6.9% for barley (Moisture content in this paper is expressed as wet basis, wb). Corn stover was collected in the form of whole plant after the ears had been removed from a sweet corn variety grown in Saskatoon. The moisture content of a composite sample of the stover was 6.2%. Switchgrass variety 'Pathfinder' was received from Montreal, Quebec, Canada. The moisture content was 5.2%. To adjust the moisture content, samples were removed from each of the biomass lots and wetted by spraying water on the sample. The average composition of each biomass sample is given in Table 1.

Physical and chemical properties

Biomass samples were ground using a small commercial hammer mill (Glen Mills Inc., Clifton, NJ) using three different screen sizes. The hammer mill screen sizes used in this study were 3.2, 1.6, and 0.8 mm.

Moisture content of the grinds was determined following the procedure given in ASTM Standard D 3173-87 for coal and coke (ASTM 1998). One gram of pulverized sample passing through sieve number 60 was taken and oven dried for one hour at 130°C. Mean particle size and standard deviation were determined according to ANSI/ASAE standard S319.3 JUL 97 (ASAE 2001). Bulk density of ground samples was measured using the Canadian Grain Commission official grain bulk density apparatus, which consisted of a funnel and a 0.5-L steel container. The container was filled through the funnel. The heaped grind was leveled gently by a rubber coated steel rod. The ratio of mass of grinds in the container over container volume yielded the bulk density. Particle density of grinds was measured using a modified pyc-nometry method developed by Mani et al. (2002).

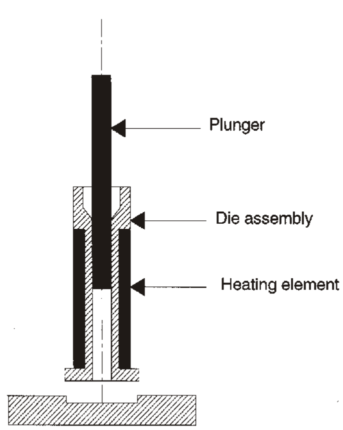

Fig. 1. Single pelleter unit.

Single pelleter unit

Figure 1 shows a schematic diagram of the single pelleter used to study the compression behavior of biomass. The pelleter was a plunger and cylinder assembly attached to the Instron Model 1011 testing machine (Instron Corp., Canton, MA). The cylinder had an internal diameter of 6.4 mm and a length of 135.5 mm. The cylinder was wrapped with a heating element covered by insulation material. Two type-T thermocouples were placed close to the inside of the cylinder wall at each of the cylinder ends. The thermocouple close to the base was connected to a temperature controller. The cylinder was installed on a stainless steel base.

Compression test

The experiments consisted of a complete block design consisting of four biomass grinds (wheat straw, barley straw, corn stover, and switchgrass), three levels of hammer mill screen sizes (3.2, 1.6, and 0.8 mm), and two moisture levels (12 and 15%). A known mass of grind samples (0.2-0.4 g) was compacted in the pelleter. Prior to each test, the cylinder was heated to 100°C to have a thermal environment similar to that in commercial pelleting of alfalfa. The crosshead of the Instron was fitted with a load cell (maximum capacity 5000 ± 6 N). The preset loads were 1000, 2000, 3000, 4000, and 4400 N. The crosshead speed was 50 mm/min. A preset load of 500 N was also used for corn stover grind, as it forms into single pellet even at low present load. Other biomass grinds did not produce single pellets at a preset load of 500 N.

To conduct a force deformation test, the pre-heated cylinder was filled manually with the grind sample. The material was compressed up to the specified preset load and held for 60 s before the plunger was withdrawn. The force-deformation data during compression and the force-time data during relaxation (60 s under a constant deformation) were logged by the computer. The compacted biomass was removed from the cylinder by gentle tapping and by using the plunger. The mass, length, and diameter of the compacted biomass were measured. Pressure-density data from the compression test for each biomass grind were fitted with different compaction models described by Eqs. 1-7. The model parameters were estimated using MS Excel software and SAS software packages. Model parameters for Cooper-Eaton model were determined using PROC NLIN program in the SAS software package (SAS 1999).

RESULTS and DISCUSSION

Physical properties of biomass grinds

Physical properties of biomass grinds from different hammer mill screen sizes are given in Table 2. Grinds from corn stover

Table 2. Physical properties of biomass grinds.

Biomass grinds	Moisture content (% wb)	Hammer mill screen size (mm)	Geometric mean particle diameter (mm)	Bulk density (kg/m^3)	Particle density (kg/m^3)
Wheat straw	8.30	3.2	0.64	98 (1)*	1027 (6)*
		1.6	0.34	107 (1)	1258 (8)
		0.8	0.28	121 (1)	1344 (2)
Barley straw	6.98	3.2	0.69	81 (1)	887 (7)
		1.6	0.38	101 (1)	1178 (7)
		0.8	0.32	112 (1)	1245 (8)
Corn stsover	6.22	3.2	0.41	132 (2)	1170 (5)
		1.6	0.26	156 (2)	1331 (4)
		0.8	0.19	158 (2)	1399 (4)
Switchgrass	8.00	3.2	0.46	115 (1)	946 (5)
		1.6	0.28	156 (2)	1142 (5)
		0.8	0.25	182 (1)	1173 (3)

* Numbers enclosed in parentheses are standard deviations for n=5.

Table 3. Particle rearrangement time for four biomass species.

Screen sizes (mm)	Time required for particle rearrangement (s)			
	Wheat	Barley	Corn stover	Switchgrass
3.2	99±2*	31±1	66±7	73±2
1.6	50±6	61±5	58±9	34±2
0.8	39±5	56±1	22±3	27±3

* Standard deviation for n=5.

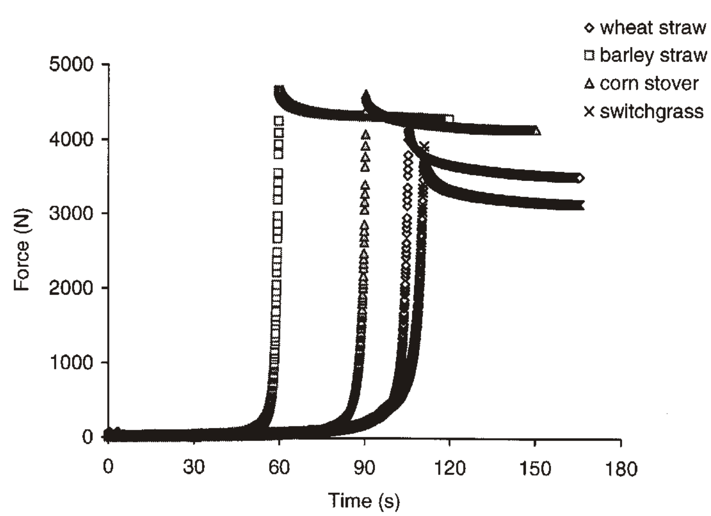

Fig 2. Typical compression curve of biomass grinds.

were the finest among the four biomass grinds. It can be observed that the larger the screen openings, the lower were the bulk and particle densities. Bulk and particle densities of wheat straw grind were slightly higher than that of barley straw grind. Switchgrass grind produced the highest bulk density of 182 kg/m^3 when passed through the hammer mill with a screen size of 0.8 mm. Among all four biomass grinds, corn stover grinds had the highest bulk and particle densities due to the smallest geometric mean particle diameter of the grind for the hammer mill screen sizes of 3.2 and 1.6 mm.

Compression test

Figure 2 shows a typical force-time diagram of compression and relaxation of biomass grinds at 12% moisture content when the load was set at 4400 N. The actual load achieved during compression at 4400 N was slightly higher than the preset load. This was due to the rapid movement of the crosshead of the Instron testing machine. As a result, the plunger which compresses the sample could not be stopped instantaneously and the maximum load exerted on the plunger exceeded the preset load. From Fig. 2, it can be seen that the compression curve was slowly increased during the initial stages of loading. It appears that during this period, particles moved and rearranged resulting from compression and the pore spaces were eliminated. This mechanism is called particle rearrangement, which occurs at low pressures. This initial stage was short for barley straw grinds but was long for corn stover, switchgrass, and wheat straw grinds. During particle rearrangement, the slope of the compression curve was constant and as the compressive force progressed, the slope increased indicating densification by elastic, plastic deformation, and perhaps interlocking of particles. The time at which the transition of slope occurred was taken as particle rearrangement time. Table 3 shows the rearrangement time for various biomass species and particle sizes. It can be seen from Table 3 that particle rearrangement occurred quickly when the particle sizes of the grinds were small and vice versa. However, this trend was not applicable to barley straw grind.

Table 4 shows a typical pressure and final pellet density relationship for each biomass at different screen sizes. Within the selected pressure range, corn stover grinds reached a maximum density. Any significant increase in pressure had no effect on pellet density. Therefore, it can be said that corn stover required less pressure to densify than other biomass grinds. Due to the limitation of the load cell mounted in the Instron testing machine, the maximum pressure was limited to 137 MPa. For other biomass grinds, a significant increase in applied pressure increased the pellet density.

Fit of compression data to the models

The Heckel model postulated that compression of powder is analogous to a first order chemical reaction. The Heckel model has been used to explain the compression behavior of many pharmaceuticals (Garekani et al. 2000), food powders (Ollet et al. 1993) and alfalfa grind (Tabil and Sokhansanj 1996).

Table 4. Typical pellet density and pressure relationships for four biomass grinds at moisture content of 12% (wb).

Applied pressure (MPa)	Screen size (mm)	Compact density of biomass pellets (kg/m^3)			
		Wheat	Barley	Corn stover	Switchgrass
31.08	3.2	748±25*	733±13	950±12	618±13
62.17		884±13	814±11	1090±15	805±18
93.25		956±18	873±16	1108±20	887±25
124.34		991±14	862±28	1126±14	945±40
136.77		1025±20	868±15	1140±32	1006±20
31.08	1.6	778±20	759±26	1095±16	754±17
62.17		889±23	849±17	1167±13	882±13
93.25		937±14	967±9	1163±13	936±16
124.34		980±9	988±31	1174±10	948±11
136.77		1030±28	1008±9	1171±8	949±7
31.08	0.8	822±8	681±19	1067±31	727±20
62.17		925±4	796±22	1147±13	870±34
93.25		962±8	943±29	1172±24	976±9
124.34		966±17	981±13	1177±14	993±10
136.77		1017±14	1017±10	1179±14	1016±17

* Standard deviations for n=5.

However, it did not fit well with the compression data of biomass grinds. The model also failed to explain the pressure-volume relationship of many powders and agglomerates (Adams and McKeown 1996). The Cooper-Eaton model fitted fairly well for all four biomass grinds at 12% (wb) moisture content. The Cooper-Eaton model parameters explain the prominent mechanism of biomass compaction and the corresponding pressure requirement. Biomass particles are generally fluffy, have porous structure, and are very brittle. The Kawakita-Lüdde model fitted very well with the compression data of biomass grinds. The Kawakita-Lüdde equation provides the relationship on the mechanical strength of the compact formed at different applied pressures. The model parameters a and 1/b were related to initial porosity of the particle bed and yield strength of compact formed, respectively. Adams and McKeown found a relationship between the parameter 1/b and the strength of the individual compact.

Physical significance of parameters

The parameters of the Kawakita-Lüdde and Cooper-Eaton models are presented in Table 5. Figure 3 shows the typical Cooper-

Table 5. Model parameters for Cooper-Eaton and Kawakita-Lüdde models of all biomass grinds.

Model parameters	Hammer mill screen size (mm)	Moisture content (% wb)							
		Wheat straw		Barley straw		Corn stover		Switchgrass	
		12	15	12	15	12	15	12	15
P_r (MPa)	3.2	2.0	1.7	0.8	1.0	1.2	0.7	3.3	4.8
	1.6	0.8	1.7	1.3	0.6	0.8	0.5	2.3	4.8
	0.8	0.4	0.6	3.1	1.9	0.9	0.6	5.5	5.1
P_d (MPa)	3.2	1.1	1.0	0.8	1.0	1.2	0.7	3.3	2.0
	1.6	2.0	1.7	1.8	2.0	0.8	0.5	2.0	2.0
	0.8	2.0	0.6	2.0	1.9	0.9	0.6	2.0	2.0
$a_1 + a_2$	3.2	1.01	1.00	1.00	0.99	1.01	0.99	1.03	1.03
	1.6	0.99	0.98	0.99	0.97	0.99	0.98	0.99	0.98
	0.8	0.97	0.95	0.99	0.98	0.98	0.97	1.00	0.97
a	3.2	0.91	0.91	0.91	0.90	0.89	0.88	0.91	0.91
	1.6	0.91	0.89	0.91	0.89	0.87	0.86	0.85	0.85
	0.8	0.89	0.86	0.91	0.89	0.87	0.86	0.85	0.82
a*	3.2	0.91	-	0.91	-	0.89	-	0.88	-
	1.6	0.92	-	0.91	-	0.88	-	0.86	-
	0.8	0.91	-	0.91	-	0.89	-	0.85	-
1/b (MPa)	3.2	1.64	1.60	0.71	1.07	1.09	0.63	3.65	3.92
	1.6	1.71	1.15	1.78	1.68	0.59	0.44	2.04	4.03
	0.8	1.29	1.32	3.05	1.70	0.75	0.60	3.97	4.03

a* indicates theoretical initial porosity of biomass grinds.

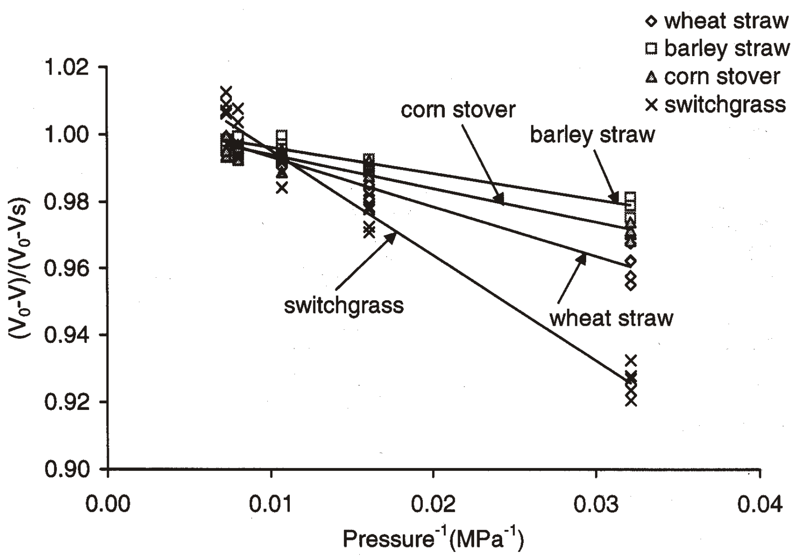

Fig. 3. Typical Cooper-Eaton plot for all biomass grinds with 3.2 mm screen size at a moisture content of 12% (wb).

Eaton plot for all biomass grinds with 3.2 mm screen size at moisture content of 12% (wb). The intercept a_1 of the Cooper-Eaton model yielded the relative density after particle rearrangement. The second intercept a_2 yielded the relative density after deformation. In general, all biomass grinds exhibit slightly lower a_1 values than a_2 values indicating that these particles densified more by elastic and plastic deformation than by particle rearrangement. Thus, compaction of biomass grinds occurs partly by particle rearrangement and partly by particle deformation. The sum of the first and second intercept ($a_1 + a_2$) yielded the theoretical density at infinite pressure, which ideally should be unity. The theoretical density was more than one for all biomass grinds from 3.2 mm screen size at 12% moisture content, which was similarly observed by Shivanand and Sprockel (1992) in cellulose acetate and cellulose acetate propionate and by Tabil and Sokhansanj (1996) in alfalfa grind. For all other biomass grinds, the theoretical density was less than one. The same a_1 and a_2 values indicated that a portion of the particles (50%) underwent particle rearrangement and the other particles (50%) underwent particle deformation.

According to Shivanand and Sprockel (1992), k_1 in the Cooper-Eaton model represents the pressure required to induce densification by particle rearrangement (P_r), whereas k_2 represents the pressure required to induce densification through deformation (P_d). For both wheat and barley straw grinds, the P_r values were slightly lower than the P_d values indicating that straw grinds required slightly less pressure for particle rearrangement than particle deformation. Overall, both wheat and barley straw had similar densification characteristics. Observations from the parameters, P_r and P_d, for corn stover grind indicated that all particles required equal amount of pressure for both particle rearrangement and particle deformation. Basically, the total applied pressure was distributed partly for particle rearrangement and partly for particle deformation. In the case of switchgrass grind densification, the high P_r value and low P_d value indicated that higher pressure was required for particle rearrangement than particle deformation. Therefore, it can be concluded that switchgrass grind was more difficult to densify by particle rearrangement than by particle deformation. This may be due to the more fibrous nature of switchgrass than other biomass grinds. When comparing values of P_r and P_d for the biomass grinds, higher values were observed for switchgrass grind and low values were observed for corn stover grind. Therefore, switchgrass grind was more difficult to densify among the biomass grinds tested; whereas, corn stover was the easiest to densify among the four biomass grinds studied.

The Kawakita-Lüdde parameter, a can be related to initial porosity (a^*) of biomass grinds. When comparing initial porosity with parameter a, both values were almost similar for all biomass grinds. The parameter 1/b indicates the yield strength or failure stress of the compact. A higher 1/b value indicates that a compact has high yield strength. It can be observed from Table 5 that compacts from switchgrass grind had higher yield strength than other biomass grinds. Low 1/b values were observed for compacts from corn stover grinds. Almost the same 1/b value was observed for compacts of both wheat and barley straw grinds. Therefore, it can be concluded that the compact from corn stover grind may have less failure stress, whereas the compacts made from switchgrass will be harder to break than other compacts made from grinds of cereal straws and corn stover.

CONCLUSIONS

The following conclusion can be drawn from this study:

1. Among three compaction models, the Kawakita-Lüdde and Cooper-Eaton models fitted well with the compression data of all biomass grinds.
2. The Cooper-Eaton model parameters for biomass grinds showed that the prominent compaction mechanisms for biomass grinds are by particle rearrangement and elastic and plastic deformation. However, the mechanism of mechanical interlocking and the ingredient melting phenomenon during compression of biomass must be studied for a comprehensive understanding of the compaction mechanism.
3. The Kawakita-Lüdde parameter a, was related to the initial porosity of biomass grinds studied. From the parameter 1/b, the yield strength of compacts made from switchgrass was predicted higher than compacts from straw and corn stover. The compacts from corn stover grind had low yield strength value (1/b).

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NOMENCLATURE

ρ	bulk density of compacted powder mixture (kg/m^3)
ρ_1, ρ_2	particle density of components of the mixture (kg/m^3)
ρ_f	packing fraction or relative density of the material after particle rearrangement
a, b	Kawakita-Lüdde model constants related to characteristic of the powder
a_1, a_2, k_1, k_2	Cooper-Eaton model constants
C	degree of volume reduction or engineering strain
m, n	Heckel model constants
P	applied pressure (MPa)
P_r	pressure required to induce densification by particle rearrangement (MPa)
P_d	pressure required to induce densification through deformation (MPa)
V	volume of compact at pressure P (m^3)
V_∞	net volume of the powder (m^3)
V_o	volume of compact at zero pressure (m^3)
V_S	void-free solid material volume (m^3)
X_1, X_2	mass fraction of components of the mixture