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Compaction Behavior of Some Biomass Grinds

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Abstract

The compaction behavior of biomass grinds such as wheat straw, barley straw, corn stover and switch grass were investigated at different applied forces, moisture contents, and particle sizes using single pelleter-Instron tester setup. The single pelleter was heated to 100°C and the residence time of the compressed material in the single pelleter was 60 s. The physical properties such as moisture content, bulk density and true density of the biomass grinds were determined. The collected pressure-density data were fitted with four compaction models viz. Heckel, Walker, Jones and Cooper-Eaton model. Among all models, the Cooper-Eaton model fitted fairly well for all biomass grinds at 12% moisture content. At 15% moisture content, only barley straw and switchgrass grind data fitted well with the Cooper-Eaton model. Compression data for corn stover and wheat straw grinds at 15% (wb) moisture content should be established at lower preset load levels to explain the compression characteristics of the material.

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INTRODUCTION

Densification of biomass is one of the important processes for effective handling and storage of bulky biomass materials. Biomass such as straws, corn stover and switchgrass can be utilized for making pellets and for production of ethanol. Biomass residues have low bulk densities and thus, low volumetric heating values. Thus handling and storage are major obstacles in bio-based energy production. The bulk density of loose straw and bagasse is around 40 kg/m³; the highest bulk density of un-processed biomass is around 250 kg/m³ for some wood residues (Demirbas 2001; Tripathi et al. 1998). Conversion of low bulk density biomass into a densified form for energy conversion improves handling, transportation and storage. So, effective handling and transportation of bulky biomass can be possible by transforming them into denser and durable form. So, studying the compaction behavior of these materials becomes more important in achieving this goal. The quality and strength of the densified mass depends on the physical properties of the material, applied forces and other process variables etc.

No work was conducted on the compressive characteristics of biomass materials under pressure. So the present study was undertaken to determine the compression characteristics of biomass grinds by uniaxial compression test and fitting different compaction models to the test results.

REVIEW OF LITERATURE

Compaction mechanism of different powder materials will be different from each other. In general, during the first stage of compression, particles rearrange themselves to form a closely packed mass. During this phase, the original particles retain most of their properties, although energy is dissipated due to interparticle and particle-to-wall friction. At high pressures, the particles are forced against each other even more and undergo elastic and plastic deformation, thereby increasing interparticle contact. Because the particles approach each other closely enough, short range bonding forces like van der Waal's forces, electrostatic forces and sorption layers become effective. Brittle particles may fracture under stress leading to mechanical interlocking. Mechanical interlocking is the only bonding mechanism that does not involve atomic forces and is expressed to contribute very little to the overall strength of the pellet (Gray 1968). At still higher pressures, reduction in volume continues until the density of the pellet approaches the true densities of the component ingredients. If the melting points of the ingredients in a powder mix that form a eutectic mixture is favorable, the heat generated at a point of contact can lead to a local melting of materials. Once cooled, the molten material forms very strong solid bridges (Ghebre-Sellassie 1989).

In order to explain the compaction process, models have been developed by many researchers for both metallic and non-metallic powders to express the compaction behavior of powders. Some of them are presented below.

Spencer et al. (1950) and 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 function of applied pressure.

$$\ln \frac{1}{1-\rho_f} = mP + b \quad (1)$$

where:

ρ_f = packing fraction or relative density of the material after particle rearrangement

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

ρ = bulk density of compacted powder mixture

ρ_1 and ρ_2 = particle density of components of the mixture

X_1 and X_2 = weight fraction of components of the mixture

P = applied pressure

m and b = constants.

Shivanand and Sprockel (1992) showed that constant b is related to the relative density at particle rearrangement:

$$b = \ln \frac{1}{1-\rho_f} \quad (2)$$

A higher ρ_f value indicates that there will be a higher volume reduction of the sample due to particle rearrangement. Constant m has been shown to be equal to the reciprocal of the mean yield pressure required to induce elastic deformation. 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 compacted 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 used to determine the compressibility of cellulose polymers by Shivanand and Sprockel (1992), food materials by Ollet et al. (1993) and alfalfa grind by Tabil (1996).

The other equations used to represent the compression of powders relate the pressure P in making the compacts to the volume or density characteristics of the material. The equation of Walker (1923), verified by Stewart (1950) and Snow et al. (1984) was used to characterize the compaction of non-metallic powders and the particles of sulfur, ammonium and sodium chloride and trinitrotoluene (TNT).

$$V_R = m \ln P + b \quad (3)$$

where:

V_R = packed volume ratio

$$= V/V_S$$

V = volume of compact at pressure P

V_S = void-free solid material volume

m and b = constants

In analyzing the compaction behavior of ceramic powders, Cooper and Eaton (1962) classified two broad processes that are involved, 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. The following model is used to describe compaction behavior of ceramic powders.

$$\frac{V_0 - V}{V_0 - V_s} = a_1 e^{-\frac{k_1}{P}} + a_2 e^{-\frac{k_2}{P}} \quad (4)$$

where:

V_0 = volume of compact at zero pressure

a_1, a_2, k_1 & k_2 = constants

Jones (1960) used the following equation to represent the compression behavior of industrial metal powders:

$$\ln \rho = m \ln P + b \quad (5)$$

where:

ρ = packing density of compact.

MATERIALS AND METHODS

Material preparation

Wheat and barley straws in square bales were obtained from the University of Saskatchewan experimental farm. The bales were of standard dimensions of 1.00 x 0.45 x 0.35 m with moisture contents of 8.3% wet basis (wb) for wheat and 6.9% (wb) for barley. Corn stover was collected in the form of whole plant without cobs from a sweet corn variety grown in Saskatoon with moisture content of 6.2% (wb). Switchgrass var 'Pathfinder' was received at 5.2% (wb) moisture content from Resource Efficient Agricultural Production (REAP), Montreal, QC.

Biomass samples were ground using a hammer mill (Glen Mills Inc. NJ) with three different hammer mill screen sizes for the compression study. The hammer mill screen sizes used in this study were 3.175 (1/8 inch), 1.588 (1/16 inch) and 0.794 (1/32 inch) mm. Table 1 shows the chemical composition of biomass materials used in this study.

Single pelleter

Figure 1 shows a single pelleter unit, used to study the compression behavior of biomass grinds. The pelleter unit was basically a plunger and die assembly attached to the Instron Model 1011 testing machine (Instron Corp., Canton, MA) as shown in Figure 2. The pelleter die had a diameter of 6.35 mm and a length of 135.34 mm. It had a wooden handle and a heating element was wound up on its cylindrical portion and was insulated. There were two type T thermocouples

placed close to the die wall at the both ends. The thermocouple close to the base of the die was connected to a temperature controller. The die was fitted on a stainless steel base.

Compression test

Compression test was conducted using a single pelleter unit for four biomass grinds with three different particle sizes (3.175, 1.588 and 0.794 mm) at 12% (wb) and 15% (wb) moisture content. Initially the samples were conditioned to the required moisture content by adding a calculated amount of water and stored in an airtight bag for 48 hours at 5°C to attain equilibrium moisture content. A known amount of grind samples was pelleted in the single pelleter unit. The die was heated to 100°C in order to simulate the heating during commercial pelleting process for alfalfa grind. Compression of the grind was performed by the Instron testing machine fitted with a 5000 N load cell and a 6.3 mm plunger. The preset loads used for the test were 1000, 2000, 3000, 4000 and 4400N and at a crosshead speed of 50 mm/min. The sample was fed into the heated die and 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 stress relaxation were logged in the computer. The pellet formed was removed by gentle tapping using a plunger. The mass, length and diameter of the pellets were measured to establish a pressure-density relationship.

Physical properties

Particle size of biomass grinds from different hammer mill screen sizes was determined from sieve analysis. A sample of 100 g was placed in a stack of sieves arranged from the largest to the smallest opening. The sieve series selected were based on the range of particles in the sample. For the grinds from the 3.175 mm hammer mill screen opening, sieve numbers 10, 14, 16, 18, 20, 30, 40, 50, 70, 100, 140 and 200 were used. For grinds from 1.588 mm hammer mill screen opening, sieve numbers used for analysis were 20, 30, 40, 50, 70 and 100. For the fine grinds from 0.794 mm hammer mill screen opening, sieve numbers were 30, 40, 50, 70, 100, and 140. The set of sieves was placed on the Ro-Tap sieve shaker (Tyler Industrial Products, OH). The duration of sieving was 10 min, which was previously determined through several trials. This time duration would be sufficient for straw grinds, because of their fluffy and fibrous nature. After sieving, the mass retained on each sieve was weighed. Sieve analysis was repeated three times for each grind sample. The particle size was determined according to ANSI/ASAE standard S319.3 JUL97 (ASAE 2001). The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) by mass were calculated accordingly.

Moisture content of the biomass sample was determined based on the ASAE standard S358.2 DEC 99 (ASAE 2001). Moisture content of the biomass grinds was determined according to the ASTM standard D3173-87 (ASTM 1998).

Bulk density of ground samples was measured using the bulk density apparatus for grains. The grinds were placed on the funnel and dropped at the center of a 0.5 L steel cup continuously. Since the grind was fluffy and did not flow down through the funnel, it was stirred using a wire in order to maintain a continuous flow of the material. The cup was leveled gently by a rubber coated steel rod and weighed. Weight per volume ratio gave the bulk density of the grinds in kg/m^3 .

Particle density of grinds was measured using a gas multipycnometer (Quantachrome Corporation, FL) by measuring the true volume of the grind and the particle density in kg/m^3 was calculated.

RESULTS AND DISCUSSION

Physical properties

For the same hammer mill screen size, geometric mean particle diameter of wheat straw grind was slightly smaller than that of barley straw grind. This might be due to the variation in moisture content of straw materials as well as difference in mechanical properties of wheat and barley straws. Grinds from corn stover were the finest among the four biomass grinds. Bulk and particle densities of biomass grinds from different hammer mill screen sizes are given in Table 2. 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 181.56 kg/m^3 when passed through the hammer mill with a screen size of 0.794 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 3.175 and 1.588 mm.

Compression test

Figure 3 depicts the pellets formed from different biomass grinds during compression test. Based on the visual observation of all biomass pellets, pellets formed from corn stover grind were stronger than other biomass pellets. Variations observed in the compression data may be due to measurement errors of the pellet dimensions and mass and the inherent variability of the sample itself.

Figure 4 shows a typical force-time diagram during compression of biomass grinds at 12% (wb) moisture content. Initially the line was linear and its slope was small. At this stage, most of the air present in voids was expelled out and particle rearrangement occurred. As compressive force progressed, the slope increased indicating densification by elastic and plastic deformation of biomass grinds.

Tables 3, 4, 5 and 6 list the pressure-density data of individual pellets at each preset compressive load for wheat straw, barley straw, corn stover and switchgrass grinds, respectively. For all biomass grinds, as compressive load increased, the density of the pellet approached close to the particle density value of the grind. But in the case of corn stover grinds, the density of the pellet reached magnitudes close to the particle density value even at low pressures, which showed that corn stover grind could be compressed so easily at low pressures. High protein content in corn stover grinds could also lead to high compact density at low pressure as protein melts at high temperature and acts as a binder during compression. Compact density of the biomass grinds got slightly increased as the hammer mill screen size decreased except for wheat straw grinds. It was observed from the tables that at 15% (wb) moisture content, there was no improvement on pellet density due to the presence of more water in the system.

Fitting the pressure-density data to the compression models

The pressure-density data for all biomass grinds were fitted to the Heckel, Walker, Copper-Eaton and Jones models described in Equations 1, 3, 4 and 5 respectively. Tables 7, 8, 9, and 10 list the model parameters for all biomass grinds at two different moisture content. Figure 5 shows a typical Cooper-Eaton model plots for wheat straw grinds at 12% (wb) moisture content.

The Heckel model postulated that compression of powder is analogous to a first order chemical reaction. From Table 7, it is observed that the R^2 value of the fit for all biomass grinds was not high, ranging between 0.1 (for corn stover grind) to 0.95 (for barley straw grind). The sum of square of error (SSE) of the model ranged between 0.048 to 13.793.

The Walker model describes the relationship of the packed volume ratio (V_R is ratio of the volume of the compact at pressure P to the void-free solid material volume) or relative density of the pellet with the applied pressure. V_R is also termed as resistance of the powder or the grind. From Table 8, the R^2 value for the Walker model was in the range of 0.75 to 0.96 for all biomass grinds except for wheat straw grind at 15% (wb) moisture content and corn stover grind.

Cooper-Eaton model explains the relationship between the fractional volume compacted to the applied pressure. Figure 5 shows typical Cooper-Eaton plots of wheat straw grind at 12% (wb) moisture content. The parameters for the model was determined by PROC NLIN of the SAS (1999) and presented in Table 9. The R^2 value was above 0.9 for all the biomass grinds at 12% (wb) moisture content except for corn stover grinds. Higher R^2 value was also observed for barley straw grind and switchgrass grind at 15% (wb) moisture content. The SSE value was very low for all the biomass grinds with values between 0.0001 to 0.004.

Jones model gives the linear relationship between the logarithm of density and the logarithm of applied pressure. Table 10 shows the parameters of the model for all biomass grinds. This model gives the lower R^2 value of 0.11 for corn stover grind with 1/32 inch screen size at 15% (wb) moisture content and the highest of 0.97 for switchgrass grind with 1/8 inch screen size at 12% (wb) moisture content. The SSE value ranged from 3.9 to 0.013.

Among the four models, Cooper-Eaton model fitted fairly well for all four biomass grinds for all particle size range at 12% (wb) moisture content. This model assumed that the compaction of power was achieved by two stages during compression. In the first stage of compression, particle voids are filled with small particles by particle rearrangement and in the later stage, voids are filled with sizes smaller than the particles by particle deformation. Particle thermal deformation was not taken into account in this model. This model also assumed that the particle size and void size distributions are normally distributed. Compression data from corn stover grind was not fitted well with any of the models. The reason is that corn stover grind was approaching maximum pellet density even at lower pressures. The increase of compressive load did not affect its pellet density, indicating that the material reached its maximum possible pellet density. So compression data has to be collected at lower preset loads (less than 1000 N) in order to explain the compression characteristics of the material.

Physical significance of parameters

The parameters of the Cooper-Eaton model and their physical significance are presented in Table 9. The intercept a_1 yielded the relative density after particle rearrangement. Corn stover grind and barley straw grind showed high a_1 values, indicating that these materials densified easily by particle rearrangement. The lower values were observed for wheat straw and switchgrass grinds at 15% (wb) moisture content. 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 barley straw and switchgrass grinds, 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. Since Cooper-Eaton model fitted fairly well with the data, the densification of biomass grinds could not be explained with two mechanisms of compaction assumed by Cooper-Eaton (1962).

According to Shivanand and Sprockel (1992), k_1 in the Cooper-Eaton model represents the pressure required to induce densification by particle rearrangement, whereas k_2 represents the pressure required to induce densification through deformation. Observations from the parameters for switchgrass grind (1/8 inch screen size) at 12% (wb) moisture content indicated that more

particles underwent particle deformation and also it required less pressure. But the low a_1 value and the high k_1 value of switchgrass grind indicated that few particles underwent particle rearrangement, which required high pressure than that of particle deformation. In the case of wheat straw grinds at 15% (wb) moisture content, they require almost equal amount of pressure required for both particle rearrangement and particle deformation, although more particles underwent particle rearrangement. More switchgrass grind particles at 15% (wb) underwent particle deformation with less pressure requirement. Whereas very few barley straw grind particles at 12% (wb) underwent particle deformation, which also required high pressures.

CONCLUSION

The following conclusion can be drawn from the above study:

1. Among four compression models, the Cooper-Eaton model fitted fairly well with the compression data for all biomass grinds at 12% (wb) moisture content. At 15% (wb) moisture content, barley straw grind and switchgrass grind data fitted well with the compression model.
2. Among four biomass grinds, corn stover was the most compressible materials. Based on the observations from Cooper-Eaton model, compression behavior of biomass grinds varied very diversely. Other suitable compression models also should be tried for each biomass grinds to characterize the behavior of the materials under compression.

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Table 1: Chemical composition of biomass grinds

Components	Wheat straw grind	Barley straw grind	Corn stover grind	Switchgrass grind
Moisture, % (wb)	5.66	5.24	7.36	5.89
Protein, % DM*	5.70	6.60	8.70	1.59
Crude fat, % DM	1.61	1.33	1.33	1.87
Lignin, % DM	7.61	6.81	3.12	7.43
Neutral Detergent Fiber, % DM	73.08	77.04	56.24	81.77
Acid Detergent Fiber, % DM	50.12	49.23	34.44	51.77

* DM – dry matter

Table 2: Physical properties of selected biomass grinds

Material	Moisture content (% , wb)	Hammer mill screen size (mm)	Geometric mean particle diameter (mm)	Geometric standard deviation (mm)	Bulk density (kg/m ³)	Particle density (kg/m ³)
Wheat straw grind	8.30	3.175	0.639	0.306	97.37 (0.78)*	1026.57 (6.39)*
		1.588	0.342	0.196	106.73 (1.02)	1258.45 (7.91)
		0.794	0.281	0.201	121.29 (1.32)	1344.07 (1.92)
Barley straw grind	6.98	3.175	0.691	0.364	80.99 (0.71)	887.34 (6.57)
		1.588	0.383	0.222	101.44 (0.50)	1178.05 (6.69)
		0.794	0.315	0.217	112.13 (0.74)	1245.36 (7.51)
Corn Stover grind	6.22	3.175	0.412	0.261	131.37 (2.25)	1169.91 (4.54)
		1.588	0.262	0.447	155.64 (2.15)	1330.78 (4.24)
		0.794	0.193	0.308	157.73 (1.54)	1399.16 (3.89)
Switch grass grind	8.00	3.175	0.456	0.255	115.4 (1.31)	945.97 (4.60)
		1.588	0.283	0.391	156.20 (1.99)	1142.36 (4.79)
		0.794	0.253	0.438	181.56 (1.17)	1172.75 (2.71)

* Number enclosed in parenthesis are standard deviations for n = 5.

Table 3: Density change of wheat straw grinds during compression

Preset compressive load, N	Wheat straw grind (1/8 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.3±0.5	748±25	29.5±0.7	725±34
2000	60.2±0.6	884±13	57.2±1.2	826±37
3000	91.3±0.9	956±18	88.1±2.5	894±23
4000	120.9±2.3	994±17	114.2±3.1	863±54
4400	131.8±1.7	1009±35	127.8±1.1	937±29
Preset compressive load, N	Wheat straw grind (1/16 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.8±0.3	778±20	30.9±0.6	690±31
2000	61.6±0.3	889±23	60.4±1.4	833±40
3000	91.8±0.5	937±14	91.3±0.7	947±27
4000	122.7±0.6	993±37	121.3±3.1	853±53
4400	134.9±1.2	1019±38	133.6±1.7	872±36
Preset compressive load, N	Wheat straw grind (1/32 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.4±0.2	822±8	31.0±0.6	792±28
2000	61.0±0.3	925±4	61.4±0.2	847±10
3000	91.6±0.3	984±21	91.6±0.5	836±15
4000	122.2±0.2	966±17	122.2±0.9	833±16
4400	134.5±0.4	993±23	134.3±0.9	851±16

Table 4: Density change of barley straw grind during compression

Preset compressive load, N	Barley straw grind (1/8 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.7±0.2	733±13	30.5±0.3	638±20
2000	61.2±0.5	814±11	61.1±0.8	736±16
3000	91.8±0.7	873±16	91.8±1.3	738±19
4000	122.5±1.1	862±28	120.4±0.7	784±10
4400	133.8±1.0	868±15	133.9±1.8	778±12
Preset compressive load, N	Barley straw grind (1/16 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.5±0.1	759±26	30.5±0.4	662±19
2000	61.4±0.4	849±17	60.6±0.5	720±16
3000	92.1±0.7	964±12	91.1±0.9	776±14
4000	122.0±0.7	1007±60	121.2±0.8	786±30
4400	134.5±1.0	1009±9	134.4±0.9	823±13
Preset compressive load, N	Barley straw grind (1/32 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	28.6±0.3	681±19	31.2±0.5	683.1±16
2000	58.6±1.2	795±33	59.6±0.5	848±6
3000	89.4±1.6	917±37	89.4±1.4	872±15
4000	121.5±1.5	989±24	118.8±0.8	908±31
4400	133.8±0.8	1011±11	131.5±0.7	880±25

Table 5: Density change of corn stover grind during compression

Preset compressive load, N	Corn stover grind (1/8 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	29.8±0.4	943±11	29.9±0.1	958±13
2000	60.1±0.3	1090±15	60.3±0.3	1040±25
3000	90.2±0.5	1108±20	91.0±0.7	1048±28
4000	120.7±0.6	1126±14	122.0±1.6	1051±15
4400	133.3±0.6	1140±32	133.1±0.8	1052±16
Preset compressive load, N	Corn stover grind (1/16 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.8±0.2	1095±16	30.9±0.1	1070±24
2000	61.5±0.3	1185±35	61.6±0.3	1085±27
3000	92.3±0.9	1185±44	92.5±0.4	1095±25
4000	123.3±0.6	1170±15	124.0±0.4	1119±43
4400	135.9±0.3	1167±13	135.2±0.5	1094±6
Preset compressive load, N	Corn stover grind (1/32 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.0±0.3	1098±54	30.0±0.2	1063±14
2000	59.8±0.7	1162±27	59.7±0.7	1069±23
3000	90.0±1.1	1172±241	89.2±1.0	1083±17
4000	121.1±0.5	1177±14	119.9±0.5	1086±10
4400	133.2±0.9	1175±20	130.9±0.8	1070±23

Table 6: Density change of switchgrass grinds during compression

Preset compressive load, N	Switchgrass grind (1/8 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.1±0.3	618±13	30.0±0.3	604±33
2000	60.0±0.6	804±18	59.6±1.1	789±18
3000	88.7±0.7	887±25	88.0±2.0	843±10
4000	120.0±2.0	945±40	117.1±3.4	904±21
4400	131.2±1.9	1006±20	128.5±4.5	969±29
Preset compressive load, N	Switchgrass grind (1/16 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	29.8±1.4	745±47	31.1±0.2	661±21
2000	62.1±1.0	786±16	61.7±0.5	765±16
3000	92.3±0.7	908±44	90.7±2.1	844±22
4000	123.3±0.5	948±11	119.6±0.4	857±10
4400	134.8±0.8	948±8	130.7±1.4	920±15
Preset compressive load, N	Switchgrass grind (1/32 inch hammer mill screen size)			
	12% (wb) moisture content		15% (wb) moisture content	
	Pressure, MPa	Density, kg/m ³	Pressure, MPa	Density, kg/m ³
1000	30.0±0.3	727±20	30.0±0.6	679±17
2000	60.3±0.5	870±34	60.7±0.5	788±22
3000	91.9±0.3	976±9	91.2±1.0	848±5
4000	121.1±0.9	993±10	119.5±1.1	868±16
4400	132.9±1.3	1016±17	132.7±2.6	899±27

Table 7: Fit of Heckel model to the compression data

Wheat straw grind			
Screen size, mm	Model parameters	R ² value	SSE*
At 12% (wb) m. c			
3.175	m = 0.000 ; b = 0.419	0.82	8.246
1.588	m = 0.000 ; b = 0.788	0.86	0.298
0.794	m = 0.000 ; b = 0.914	0.75	0.183
At 15% (wb) m. c			
3.175	m = 0.000 ; b = 0.977	0.66	2.042
1.588	m = 0.000 ; b = 0.845	0.35	0.824
0.794	m = 0.000 ; b = 0.920	0.29	0.048
Barley straw grind			
At 12% (wb) m. c			
3.175	m = 0.000 ; b = 1.301	0.53	13.793
1.588	m = 0.000 ; b = 0.732	0.93	0.288
0.794	m = 0.000 ; b = 0.545	0.95	0.148
At 15% (wb) m. c			
3.175	m = 0.000 ; b = 1.116	0.81	0.463
1.588	m = 0.000 ; b = 0.754	0.88	0.109
0.794	m = 0.000 ; b = 0.794	0.70	0.302
Corn stover grind			
At 12% (wb) m. c			
3.175	m = 0.000 ; b = 1.149	0.60	13.705
1.588	m = 0.000 ; b = 1.937	0.11	2.175
0.794	m = 0.000 ; b = 1.590	0.39	0.425
At 15% (wb) m. c			
3.175	m = 0.000 ; b = 1.792	0.48	1.216
1.588	m = 0.000 ; b = 1.673	0.17	0.547
0.794	m = 0.000 ; b = 1.488	0.10	0.088
Switchgrass grind			
At 12% (wb) m. c			
3.175	--	--	--
1.588	m = 0.000 ; b = 0.900	0.84	1.005
0.794	m = 0.000 ; b = 0.900	0.93	3.906
At 15% (wb) m. c			
3.175	--	--	--
1.588	m = 0.000 ; b = 0.900	0.77	1.673
0.794	m = 0.000 ; b = 0.900	0.92	0.386

* SSE – Sum of Square of Errors, n = 5

Table 8: Fit of Walker model to the compression data

Wheat straw grind			
Screen size, mm	Model parameters	R ² value	SSE*
At 12% (wb) m. c			
3.175	m = -0.312 ; b = 7.125	0.94	8.246
1.588	m = -0.266 ; b = 6.285	0.94	0.298
0.794	m = -0.180 ; b = 4.692	0.87	0.183
At 15% (wb) m. c			
3.175	m = -0.256 ; b = 6.223	0.77	0.142
1.588	m = -0.274 ; b = 6.592	0.62	0.336
0.794	m = -0.063 ; b = 2.742	0.40	0.043
Barley straw grind			
At 12% (wb) m. c			
3.175	m = -0.130 ; b = 3.438	0.85	0.022
1.588	m = -0.275 ; b = 6.294	0.93	0.043
0.794	m = -0.411 ; b = 8.908	0.75	0.457
At 15% (wb) m. c			
3.175	m = -0.167 ; b = 4.246	0.86	0.034
1.588	m = -0.217 ; b = 5.527	0.90	0.045
0.794	m = -0.282 ; b = 6.620	0.82	0.124
Corn stover grind			
At 12% (wb) m. c			
3.175	m = -0.154 ; b = 4.041	0.85	0.030
1.588	m = -0.050 ; b = 2.117	0.40	0.029
0.794	m = -0.048 ; b = 1.882	0.46	0.020
At 15% (wb) m. c			
3.175	m = -0.070 ; b = 2.407	0.68	0.017
1.588	m = -0.028 ; b = 1.728	0.22	0.020
0.794	m = -0.014 ; b = 1.557	0.11	0.011
Switchgrass grind			
At 12% (wb) m. c			
3.175	m = -0.384 ; b = 8.107	0.96	0.045
1.588	m = -0.226 ; b = 5.399	0.86	0.065
0.794	m = -0.310 ; b = 6.931	0.96	0.042
At 15% (wb) m. c			
3.175	m = -0.384 ; b = 8.153	0.94	0.070
1.588	m = -0.321 ; b = 7.266	0.95	0.038
0.794	m = -0.277 ; b = 6.478	0.95	0.032

* SSE – Sum of Square of Errors, n = 5

Table 9: Fit of Cooper-Eaton model to the compression data

Wheat straw grind				
Screen size, mm	Model parameters		R ² value	SSE*
At 12% (wb) m. c				
3.175	a ₁ = 0.827; k ₁ = 5.7x10 ⁶	a ₂ = 0.154; k ₂ = -9.6x10 ⁶	0.96	0.0005
1.588	a ₁ = 0.056; k ₁ = 1.0 x10 ⁸	a ₂ = 0.941; k ₂ = 1.2 x10 ⁶	0.94	0.0006
0.794	a ₁ = 0.827; k ₁ = 1.5 x10 ⁶	a ₂ = 0.300; k ₂ = 1.5 x10 ⁶	0.93	0.0003
At 15% (wb) m. c				
3.175	a ₁ = 0.654; k ₁ = 2.1 x10 ⁶	a ₂ = 0.300; k ₂ = 2.1 x10 ⁶	0.79	0.002
1.588	a ₁ = 0.655; k ₁ = 2.5 x10 ⁶	a ₂ = 0.300; k ₂ = 2.5 x10 ⁶	0.72	0.004
0.794	a ₁ = 0.628; k ₁ = 5.8 x10 ⁶	a ₂ = 0.300; k ₂ = 5.8 x10 ⁶	0.49	0.0006
Barley straw grind				
At 12% (wb) m. c				
3.175	a ₁ = 1.160; k ₁ = 4.4 x10 ⁵	a ₂ = -0.157; k ₂ = -7.1x10 ⁶	0.90	0.0001
1.588	a ₁ = 1.001; k ₁ = 3.5 x10 ⁶	a ₂ = 0.005; k ₂ = -6.5x10 ⁷	0.95	0.0014
0.794	a ₁ = 0.937; k ₁ = 5.7 x10 ⁶	a ₂ = 0.066; k ₂ = 2.3 x10 ⁷	0.76	0.0043
At 15% (wb) m. c				
3.175	a ₁ = 0.995; k ₁ = 5.7 x10 ⁶	a ₂ = -0.004; k ₂ = -4.0 x10 ⁷	0.89	0.0003
1.588	a ₁ = 0.123; k ₁ = 3.6 x10 ⁷	a ₂ = 0.857; k ₂ = 1.1 x10 ⁶	0.90	0.0004
0.794	a ₁ = 1.399; k ₁ = -4.7 x10 ⁶	a ₂ = -0.437; k ₂ = -1.5 x10 ⁷	0.95	0.0004
Corn stover grind				
At 12% (wb) m. c				
3.175	a ₁ = 0.983; k ₁ = 2.5 x10 ⁶	a ₂ = -0.003; k ₂ = -7.1 x10 ⁷	0.96	0.0002
1.588	a ₁ = 1.108; k ₁ = -3.5 x10 ⁶	a ₂ = -0.139; k ₂ = -2.1 x10 ⁷	0.69	0.0002
0.794	a ₁ = 1.003; k ₁ = 6.4 x10 ⁴	a ₂ = -0.002; k ₂ = -5.6 x10 ⁷	0.54	0.0003
At 15% (wb) m. c				
3.175	a ₁ = 1.004; k ₁ = -7.5 x10 ⁵	a ₂ = -0.019; k ₂ = -3.4 x10 ⁷	0.82	0.0002
1.588	a ₁ = 0.966; k ₁ = 7.6 x10 ⁵	a ₂ = 0.010; k ₂ = -2.9 x10 ⁷	0.22	0.0004
0.794	a ₁ = 0.963; k ₁ = 1.1 x10 ⁵	a ₂ = 0.000; k ₂ = 0.000	0.12	0.0002
Switchgrass grind				
At 12% (wb) m. c				
3.175	a ₁ = 0.311; k ₁ = 1.3 x10 ⁷	a ₂ = 0.723; k ₂ = 2.4 x10 ⁴	0.98	0.0004
1.588	a ₁ = 0.977; k ₁ = 8.0 x10 ⁵	a ₂ = -0.002; k ₂ = -8.9 x10 ⁷	0.94	0.0006
0.794	a ₁ = 0.964; k ₁ = 5.4 x10 ⁶	a ₂ = 0.040; k ₂ = -2.2 x10 ⁷	0.97	0.0008
At 15% (wb) m. c				
3.175	a ₁ = 0.196; k ₁ = 1.2 x10 ⁷	a ₂ = 0.830; k ₂ = 1.5 x10 ⁶	0.96	0.0009
1.588	a ₁ = 0.201; k ₁ = 3.7 x10 ⁷	a ₂ = 0.801; k ₂ = -8.6 x10 ⁵	0.95	0.0009
0.794	a ₁ = 0.132; k ₁ = 3.2 x10 ⁷	a ₂ = 0.843; k ₂ = 7.9 x10 ⁵	0.96	0.0008

* SSE – Sum of Square of Errors, n = 5

Table 10: Fit of Jones model to the compression data

Wheat straw grind			
Screen size, mm	Model parameters	R ² value	SSE*
At 12% (wb) m. c			
3.175	m = 0.203 ; b = 3.132	0.95	0.015
1.588	m = 0.177 ; b = 3.606	0.93	0.018
0.794	m = 0.122 ; b = 4.626	0.87	0.016
At 15% (wb) m. c			
3.175	m = 0.157 ; b = 3.901	0.76	0.054
1.588	m = 0.161 ; b = 3.804	0.59	0.129
0.794	m = 0.038 ; b = 6.027	0.39	0.016
Barley straw grind			
At 12% (wb) m. c			
3.175	m = 0.117 ; b = 4.588	0.85	0.018
1.588	m = 0.204 ; b = 3.103	0.94	0.018
0.794	m = 0.265 ; b = 1.966	0.96	0.023
At 15% (wb) m. c			
3.175	m = 0.133 ; b = 0.-4.19	0.86	0.020
1.588	m = 0.135 ; b = 4.173	0.90	0.019
0.794	m = 0.177 ; b = 3.513	0.83	0.047
Corn stover grind			
At 12% (wb) m. c			
3.175	m = 0.120 ; b = 4.802	0.86	0.018
1.588	m = 0.040 ; b = 6.320	0.36	0.020
0.794	m = 0.046 ; b = 6.218	0.47	0.018
At 15% (wb) m. c			
3.175	m = 0.060 ; b = 5.846	0.68	0.013
1.588	m = 0.023 ; b = 6.578	0.22	0.014
0.794	m = 0.011 ; b = 6.784	0.11	0.007
Switchgrass grind			
At 12% (wb) m. c			
3.175	m = 0.315 ; b = 1.014	0.97	0.023
1.588	m = 0.165 ; b = 3.788	0.88	0.028
0.794	m = 0.226 ; b = 2.703	0.95	0.018
At 15% (wb) m. c			
3.175	m = 0.305 ; b = 1.174	0.95	0.031
1.588	m = 0.19 ; b = 3.219	0.88	3.906
0.794	m = 0.183 ; b = 3.372	0.95	0.013

* SSE – Sum of Square of Errors, n = 5

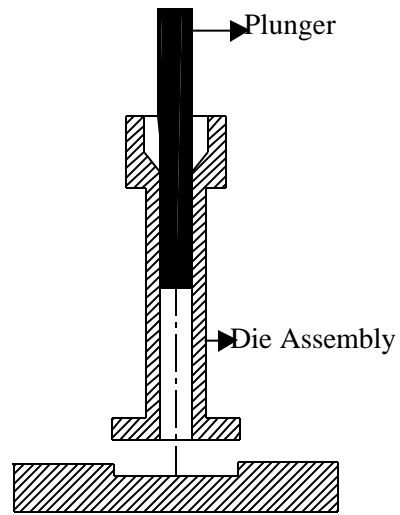


Figure1: Single pelleter unit.

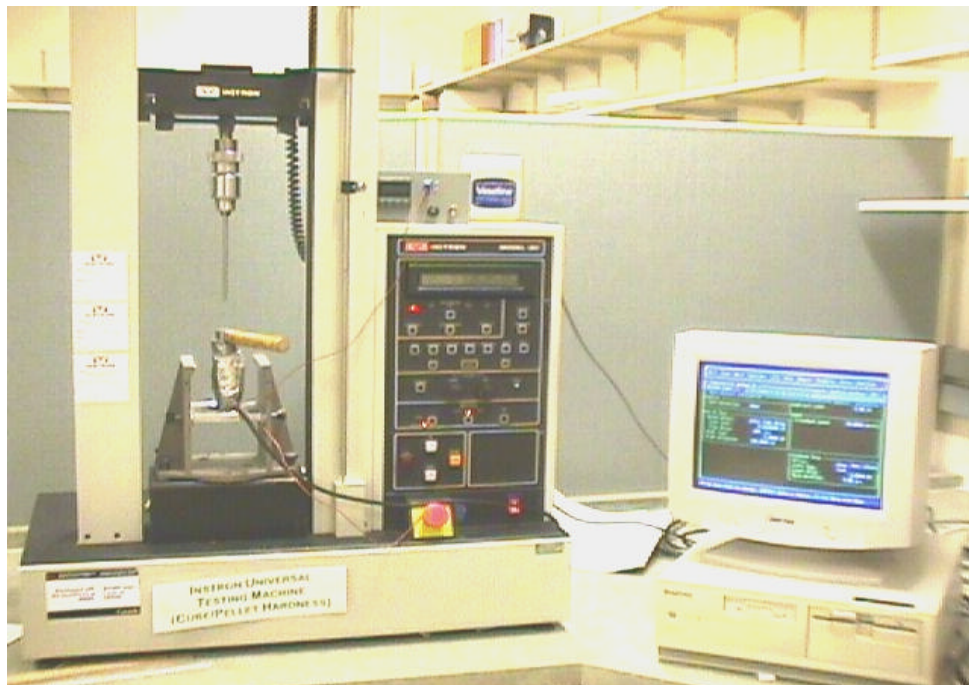


Figure 2: Compression test setup.



Figure 3: Biomass pellets produced from single pelleter unit.

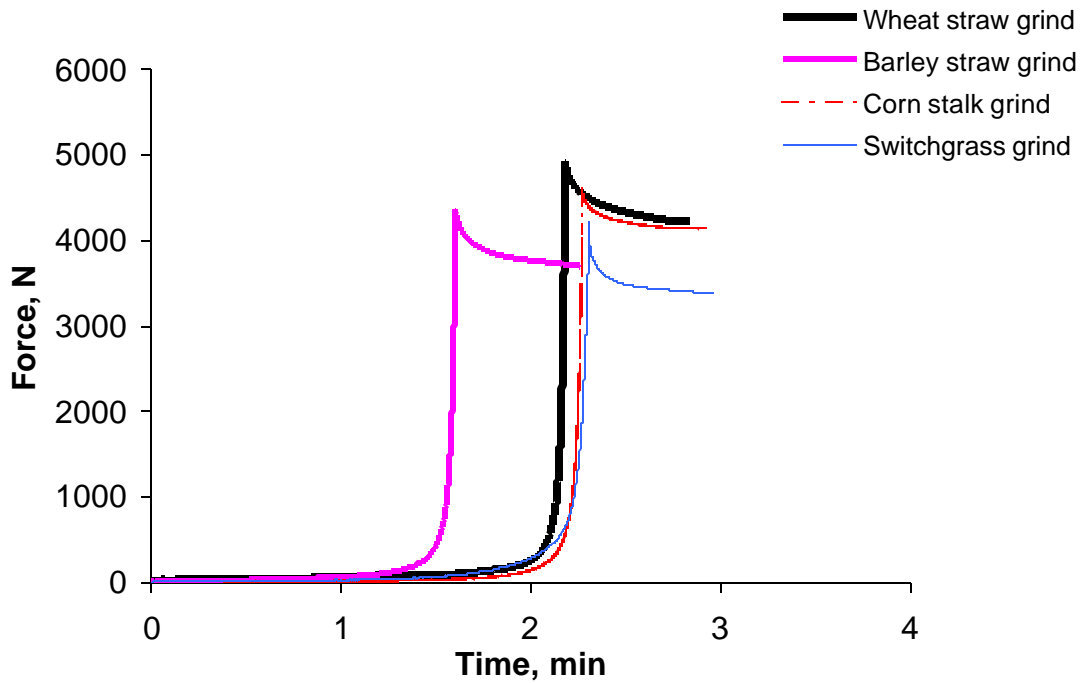


Figure 4: Typical compression curve of biomass grinds.

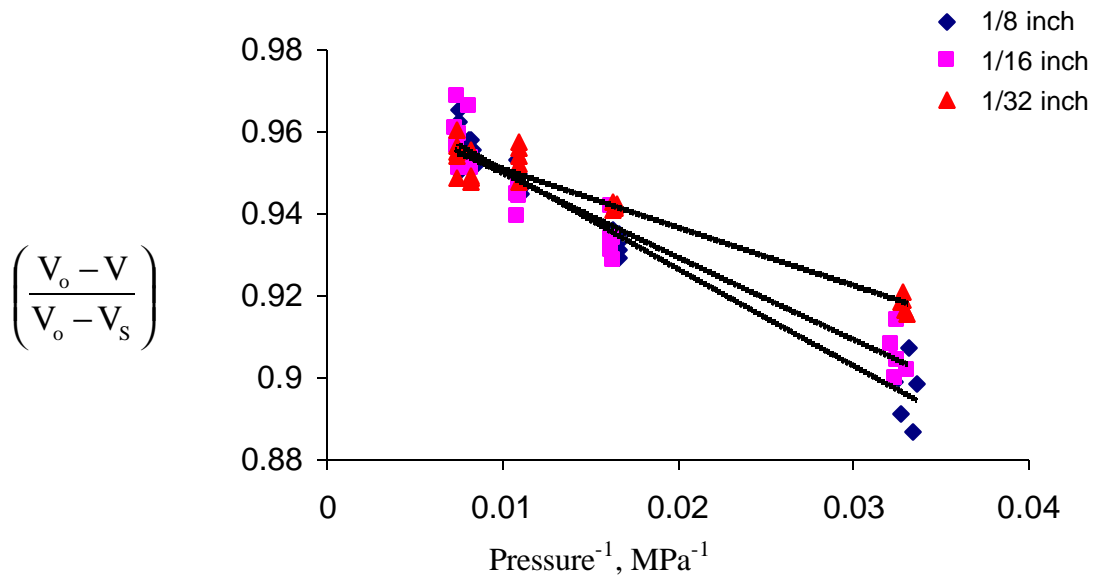


Figure 5: Typical Cooper-Eaton plots of wheat straw grind at 12% (wb) moisture content.