Compression, Relaxation, and Adhesion Properties of Selected Biomass Grinds

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ABSTRACT

The compression, relaxation, and frictional (adhesion) properties of peat moss, wheat straw, oat hull, and flax shive grinds were evaluated. Grinds of 9 to 10% moisture (w.b.) were compressed in a heated (95°C) cylindrical plunger-die apparatus at loads of 500, 1000, 2000, 3000, 4000, and 4400 N (15.8, 31.6, 63.2, 94.7, 126.3, 138.9 MPa, respectively). Peat moss was the only feedstock that was able to produce cohesive pellets at the 500 N load. The Jones (1960) and Walker (1923) compression models showed that flax shives had the highest compressibility among the four grinds. Compressive loads greater than 1000 N produced a significant reduction in diametral expansion of the pellets, while loads exceeding 2000 N significantly reduced the longitudinal pellet expansion; following a 14 day assessment period. The least amount of dimensional expansion was observed for the peat moss pellets. Relaxation testing of the four grinds indicated that there was no significant difference between asymptotic modulus (E_A) values at 1000 and 2000 N. Peat moss had the highest E_A value at 3000 N, while both peat moss and oat hulls had significantly higher E_A values than the other two feedstocks at 4000 and 4400 N. External friction (adhesion) analysis on mild steel indicated that peat moss had the highest coefficient of external friction, while flax shives had the highest value of adhesion coefficient.

Keywords. Peat moss, wheat straw, oat hulls, flax shives, compressibility, asymptotic modulus, adhesion

1. INTRODUCTION

Increased interest in biomass for the production of chemicals and energy is prevalent due to a variety of social, political, economic, and environmental factors. Disadvantages associated with the utilization of biomass as an energy source include inefficient transportation and large volume requirements for storage (Van Pelt, 2005). Densification of biomass, both for bioenergy and animal feed utilization, has been employed to mitigate the cost associated with transportation, handling, and storage. Also, densified biomass improves fuel feeding in co-firing operations, as well as provides increased regulation of combustion, thus reducing particulate emissions (Li and Liu, 2000; Sokhansanj et al., 2005). In terms of animal feed, the increased bulk density improves handling and animal performance while decreasing spillage and wind loss (Briggs et al., 1999).

A wealth of information with respect to compression and densification of biomass grinds has been generated from studies on alfalfa (Adapa et al., 2002; Adapa et al., 2004; Adapa et al., 2005; Tabil and Sokhansanj, 1996; Tabil and Sokhansanj, 1997). Investigations into the densification (specifically pelleting) of wood residues (Li and Liu, 2000) continue to emerge due to the fact that consumers are seeking alternate methods of heating homes and businesses. Following a similar trend of value-addition and sustainable development, literature is emerging which investigates the compression and densification of other forms of processing residues (Chin and Siddiqui, 2000; Demirbaş, 1999; Demirbaş et al., 2004; Husain et al., 2002; Mani et al., 2004a; Mani et al., 2006; Yaman et al., 2000).

Sokhansanj et al. (2003) identified that one of the main objectives of densification research is to quantify material characteristics for their effect on the quality of compacted material. Design of densification equipment and the selection of operating parameters are highly dependent on the input feedstock. Therefore, knowledge of material properties is imperative to ensure minimal energy consumption during the densification process, which in turn will improve the economic feasibility of the process. The objective of the study was to generate information on the mechanical properties of four biomass feedstock grinds; namely, peat moss, wheat straw, oat hulls, and flax shives. Specific properties evaluated in this study included: compressibility, asymptotic modulus, coefficient of external friction, and adhesion coefficient.

2. MATERIALS AND METHODS

2.1 Biomass Feedstock Procurement

Peat moss was acquired from a landscaping retailer in Saskatoon, SK, and was used without any particle size reduction. Wheat straw was obtained from a farm near Saskatoon, SK. It was ground in a hammer mill (Model Y60, Buhler Industries Inc., Winnipeg-Morden, MB) fitted with a 3.2 mm screen. Oat hulls were procured from an oat processing operation in Martensville, SK, and were used as is. A flax fiber decortication operation in Winkler, MB, was used to source the flax shives, which were ground through a hammer mill with a 6.4 mm screen.

2.2 Chemical Composition

A chemical analysis of the four biomass samples was conducted by Enviro-Test Laboratories (Saskatoon, SK). The analysis included the determination of protein, ash, fat, crude fiber, neutral detergent fiber (NDF), acid detergent fiber (ADF), lignin, and starch. AOAC method 984.13 (AOAC International, 1995) was used to determine protein content, while AOAC method 942.05 (AOAC International, 1990a) was followed to evaluate ash content. Fat (ether extract) content was found using AOAC method 920.39 (AOAC International, 1990b), and the crude fiber was determined by AOAC method 962.09 (AOAC International, 1990c). The National Forage Testing Association's NDF – amylase procedure (NFTA, 1993) was used to determine NDF content. Lignin and ADF content were found via AOAC method 973.18 (AOAC International, 1990d). Starch content was enumerated using the method of Holm et al. (1986).

2.3 Particle Size

Particle size analysis was performed on the four biomass grinds following ASAE Standard S319.3 (ASAE Standards, 2005). U.S. sieve numbers 4, 6, 8, 12, 16, 20, 40, 50, 70, 100, 140, and 200 (sieve opening sizes: 4.76, 3.36, 2.28, 1.68, 1.19, 0.841, 0.420, 0.297, 0.210, 0.149, 0.105, and 0.074 mm, respectively) were used and the shaking was accomplished using a Ro-Tap sieve shaker (W. S. Tyler Inc., Mentor, OH). The geometric mean diameter (d_{gw}) of the sample and geometric standard deviation of particle diameter (S_{gw}) were calculated according to the aforementioned standard using three replicates for each feedstock.

2.4 Moisture Conditioning

Moisture content of the four biomass grinds was determined following ASAE Standard S358.2 (ASAE Standards, 2005). Wheat straw was found to have a moisture content below the desired range, and was therefore conditioned to 9 to 10% wet basis (w.b.) by adding a pre-calculated mass of water using mass balance. Peat moss and flax shives had moisture contents higher than the desired range of 9 to 10 % w.b., and were subsequently dried to 9 to 10% w.b. in a conditioning chamber at a temperature of 80°C. The moisture level of the oat hulls was within the desired range (9 to 10% w.b.).

2.5 Density

The bulk density of each biomass grind was determined by passing the grind through a funnel which sat above a standard 0.5 L steel cup (SWA951, Superior Scale Co. Ltd., Winnipeg, MB). Blockages in the funnel were avoided by using a thin steel wire during biomass flow. Once the cup had filled, the excess was removed by moving a steel roller in a zig-zag pattern across the top of the cup. The mass within the cup was then determined, and the bulk density was calculated as the mass of the grind in the cup divided by the volume of the cup. Three replicates were performed for each feedstock.

A gas multi-pycnometer (QuantaChrome, Boynton Beach, FL) was used to determine the particle density of the biomass grinds by calculating the displaced volume of nitrogen gas by a known mass of material, following the method reported by Mani et al. (2004b). Three replicate tests were performed on each sample.

2.6 Compressibility

Biomass grinds were compressed in the cylindrical single pelleter (plunger-die) assembly used by Adapa et al. (2002), Mani et al. (2004a), Tabil and Sokhansanj (1996), and Tabil and Sokhansanj (1997). An Instron model 1011 (Instron Corp., Canton, MA) was equipped with a 6.35 mm diameter flat faced plunger which was used to compress the grinds in the die at pre-set loads of 500, 1000, 2000, 3000, 4000, and 4400 N, corresponding to pressures of 15.8, 31.6, 63.2, 94.7, 126.3, 138.9 MPa, respectively. The die assembly was heated by an externally wound nichrome wire heater to 95^{o}C (±2^{o}C) in order to simulate thermal conditions during commercial pelleting. Approximately 0.5 g of sample was placed in the single pelleter die chamber prior to loading. No preheating of the material was carried out. The plunger compressed the sample using a crosshead speed of 50 mm/min. The die was fitted with a steel base upon which the samples were compressed. Force-displacement data was logged on a computer until the pre-set load was reached (completion of compression), at which point the plunger remained in a stationary position (constant strain) for 60 s and the force-time data was logged to study the in-die relaxation behavior of the pellets. Upon completion of the compression-relaxation test, the single pellets were removed by removing the stainless steel base and applying a gentle force with the plunger. Pellet diameter and length were recorded using digital calipers and the mass was determined using a digital scale. The diameter and length of the pellets were recorded again after 14 days of storage in sealed plastic bags held at ambient conditions in order to obtain the diametral and longitudinal expansions, respectively. For each sample, the compression test at each load was repeated 10 times. The four biomass varieties and five highest pre-set loads were evaluated for their effect on the diametral and longitudinal expansions. PROC MIXED of SAS 9.1 (Statistical Analysis System, Cary, NC) was used to analyze the factorial treatment design ($P = 0.05$).

The pressure-density data obtained during compression testing were fitted to the model proposed by Jones (1960) for metal powder compression (Equation 1). Variable definitions are shown in Section 7.

$$\ln \rho = m \cdot \ln P + b \qquad (1)$$

The pressure-volume data were fitted to the model (Equation 2) proposed by Walker (1923) which was used to described the compression of powders such as metallic lead, ammonium nitrate, potassium chloride, sodium chloride, potassium nitrate, ammonium chloride, calcium carbonate, and barium nitrate.

$$V_R = m' \cdot \ln P + c \qquad (2)$$

Heckel (1961) defined compressibility as an indicator of the extent to which the density of a powder is increased by a given pressure. The linear regression function in Microsoft Excel (Microsoft Corporation, Redmond, WA) was used to fit experimental data to the aforementioned compression models.

2.7 Asymptotic Modulus

Since stress relaxation is a reflection of physical changes that occur under constant strain, the phenomenon may be interpreted as due to internal flow and rearrangement of liquid bridges or plasticizing of the particle's texture itself (Peleg and Moreyra, 1979). Peleg (1979) presented a method for normalizing relaxation data from solid foods, which was applied to powder compaction by Peleg and Moreyra (1979). Moreyra and Peleg (1980) provided further explanation of the normalization equation proposed by Peleg (1979) (Equation 3); to which the force-time relaxation data were fitted.

$$\frac{F_0 \cdot t}{F_0 - F(t)} = k_1 + k_2 \cdot t \qquad (3)$$

Moreyra and Peleg (1980) explained that the slope of Equation 3 (k_2) can be considered an index of how "solid" the compacted specimen is on a short time scale. Liquids would have a slope of unity ($k_2 = 1$) indicating that the stresses will eventually relax to zero. Therefore, the value of k_2 for any solid must be greater than 1. It was further noted that any larger value of the slope indicates that there are stresses that will eventually remain un-relaxed (a solid state property). The constant k_2 was used to calculate an asymptotic modulus (E_A) in Equation 4, proposed by Scoville and Peleg (1981) and used by Moreyra and Peleg (1981) on food powders.

$$E_A = \frac{F_0}{A\varepsilon}\left(1 - \frac{1}{k_2}\right) \qquad (4)$$

The asymptotic modulus is representative of the ability of a compressed powder to sustain un-relaxed stresses (Scoville and Peleg, 1981). It is also a relatively clear indication of compact solidity since it reflects the stresses that the compact can support without dissipation through plastic flow of the solid matrix or flow and reorientation of the interparticle bridges (Moreyra and Peleg, 1981). The four biomass varieties and five initial loads were evaluated for their effect on the asymptotic modulus. PROC MIXED of SAS 9.1 was used to analyze the factorial treatment design (P = 0.05).

While the aforementioned models for compressibility and asymptotic modulus determination have been utilized to model the compression of powders commonly used in the metallurgical and pharmaceutical industries, they have been proven to accurately predict the compression behavior of many biomass materials (Adapa et al., 2005; Mani et al., 2004a; Tabil and Sokhansanj, 1996; Tabil and Sokhansanj, 1997).

2.8 Adhesion

The coefficient of external friction of the four biomass grinds on mild steel was evaluated using the Wykeham Farrance shear box apparatus (Wykeham Farrance International, Ltd., Slough, U.K.). The methodology and calculation of the coefficient of external friction were identical to those used by Mani et al. (2004c). The sample of interest was placed in the 100 mm square shear box. The sample filled the top half of the shear box, and rested upon a mild steel plate placed in the bottom half of the shear box. Normal loads of 100, 400, 2000, and 4000 N were applied to the material via a load hanger, and the bottom half of the shear box was pulled horizontally at a rate of 0.4 mm/min. The resulting shear force and horizontal displacement were recorded by a load cell and a linear variable differential transformer (LVDT), respectively. A total of three replicates were performed for each combination of feedstock and normal load. All the adhesion tests were carried out at ambient conditions. Equation 5, proposed by Chancellor (1994) and Puchalski and Brusewitz (1996), allows the determination of the coefficient of external friction (slope) and the adhesion coefficient (intercept) through the use of linear regression. Chancellor (1994) further defined the coefficient of adhesion as the shear resistance per unit area with no normal force.

$$\tau = \mu\sigma + C_a \qquad (5)$$

3. RESULTS AND DISCUSSION

3.1 Physical Properties and Chemical Composition

Results for feedstock particle size, bulk and particle densities, along with chemical composition are reported in table 1. The oat hulls sample had the lowest geometric mean diameter, and thus was the finest of the four samples followed by flax shives, wheat straw, and peat moss. Oat hulls also had the highest bulk and particle densities, while peat moss had the lowest bulk density, and wheat straw had the lowest particle density. Peat moss had the highest lignin content, followed by flax shives. Flax shives had the highest fiber content among the biomass grinds. Both wheat straw and oat hulls had low lignin content but were high in starch content relative to the other two feedstocks. Starch, protein, and lignin have been shown to contribute to the natural binding of densified biomass (Thomas et al., 1998; Granada et al., 2002). Starch gelatinization appears to be the key to elucidating the natural binding capabilities of this chemical constituent, while protein denaturation and plasticization allows these molecules to interact with other molecules. When thermally softened or plasticized, lignin exhibits adhesive properties (van Dam et al., 2004).

Table 1. Physical properties and chemical composition of peat moss, wheat straw, oat hull, and flax shive grinds.

Physical properties	Peat moss	Wheat straw	Oat hulls	Flax shives
Geometric mean diameter (mm)*	0.74	0.65	0.47	0.64
Geometric standard deviation (mm)*	0.96	0.59	0.43	0.37
Bulk density (kg/m^3)*	88.3 (0.3)	112.6 (4.1)	234.5 (2.4)	108.0 (22.0)
Particle density (kg/m^3)*	1308.3 (6.4)	1286.1 (10.1)	1407.2 (6.3)	1346.1 (7.9)
Chemical composition (% dry matter)				
Protein	5.8	4.8	4.5	3.1
Ash	5.0	7.6	5.2	2.7
Fat (Ether Extract)	2.5	1.4	1.6	1.0
Crude fiber	33.7	37.0	30.5	56.9
Neutral detergent fiber (NDF)	83.1	64.4	77.6	82.3
Acid detergent fiber (ADF)	87.3	50.2	41.6	67.6
Lignin	28.6	6.6	5.0	17.0
Starch	1.7	6.3	7.2	2.7

* Values in parentheses are standard deviations (n = 3)

3.2 Compressibility

Typical force-time plots for compression/relaxation testing of the five highest pre-set forces are depicted in figure 1. The compression force increases gradually and spikes just prior to achieving the pre-set maximum load for each test. The maximum load achieved was always slightly higher than the pre-set value due to momentum effects of the Instron crosshead. Following the peak compressive load, the force relaxes (constant strain test) to an asymptotic value. Typical force-time plots for the four biomass grinds compressed to 4400 N are shown in figure 2. Peat moss required more time to reach the pre-set load than the other three grinds. This could potentially be a result of its lower bulk density and higher geometric standard deviation of particle diameter, allowing increased particle rearrangement during the initial stages of compression, prior to elastic and plastic deformation.

Peat moss was the only feedstock that would produce cohesive pellets at the 500 N pre-set load; and was subsequently the only material for which this load was used in compression modeling. For all other biomass grinds, only the five highest (1000, 2000, 3000, 4000, and 4400 N) loads were considered. The compressibility of each grind, determined by the Jones and Walker models (m and m’, respectively), is listed in table 2. Both models fitted well to the experimental data, as indicated by the R^2 values; however, the Jones model had a slightly better fit. The compressibilities are consistent between the two models, with flax shives having the highest, followed by peat moss, wheat straw, and oat hulls.

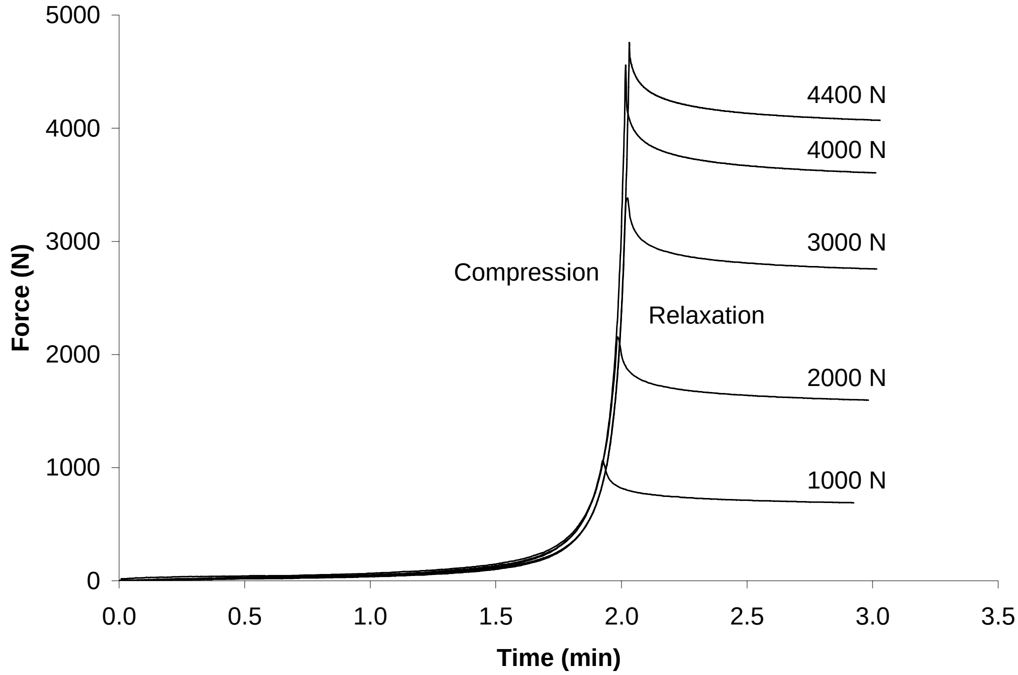

Figure 1. Typical force-time curves during peat moss compression/relaxation.

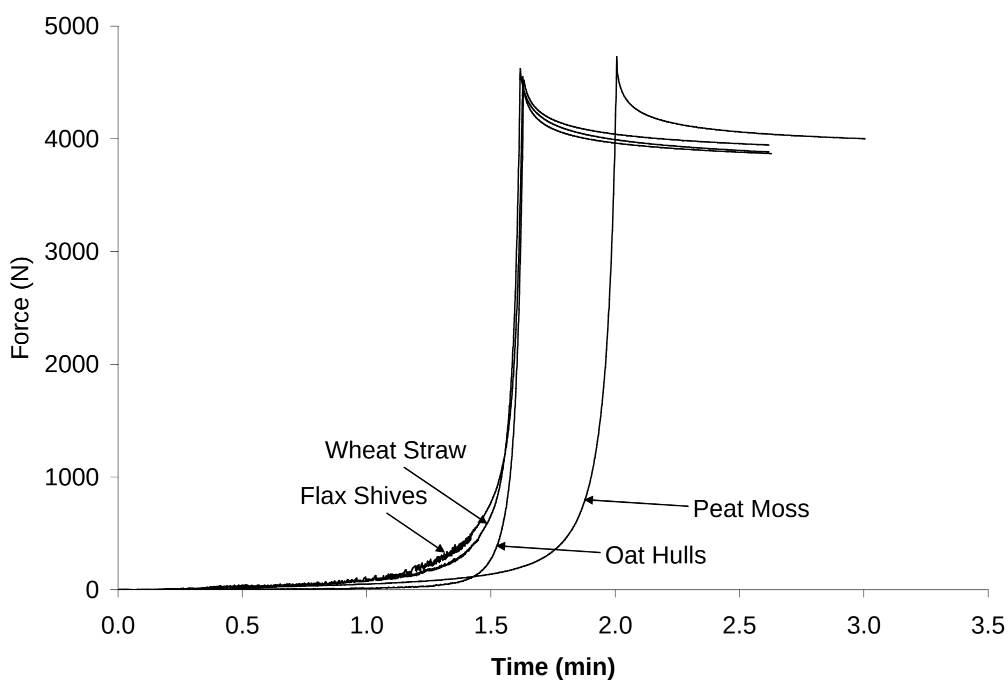

Figure 2. Typical force-time curves of peat moss, wheat straw, oat hull, and flax shive grinds at the 4400 N pre-set compression load.

Table 2. Empirically established constant values for compression models.

Biomass grind	Compressibility (Slope m or m')	Intercept (b or c)	R^2	Standard error
Jones: $\ln \rho = m \cdot \ln P + b$				
Peat Moss	0.30	5.91	0.97	0.007
Wheat Straw	0.28	6.02	0.96	0.008
Oat Hulls	0.23	6.24	0.98	0.005
Flax Shives	0.35	5.62	0.93	0.013
Walker: $V_R = m' \cdot \ln P + c$				
Peat Moss	-0.34	2.48	0.93	0.012
Wheat Straw	-0.27	2.15	0.94	0.010
Oat Hulls	-0.24	2.06	0.97	0.006
Flax Shives	-0.41	2.86	0.89	0.021

3.3 Dimensional Expansion

Diametral measurement of the pellets (immediately after removal from the die) showed that all the samples expanded slightly immediately following compression (i.e. pellet diameters exceeded 6.35 mm). The length of the pellets depended upon the applied load and the mass of material being compressed; therefore, the dimensional expansion values were reported on a percentage basis.

For both diametral and longitudinal expansions, the interaction between biomass feedstock and pre-set load was not significant. Table 3 presents the effect of pre-set load on the diametral and longitudinal expansions of the single pellets. The standard deviations are high because the data were averaged across different biomass types for the initial loads and across different pre-set loads for the feedstock portion of the table. As a general trend, pellet expansion was reduced in both dimensions by increasing the load. However, the mean diametral expansion at the 4400 N load was higher than that at 4000 and 3000 N, but not significantly higher ($P>0.05$). For diametral expansion, loads greater than 1000 N were able to provide a significant reduction in expansion, while loads higher than 2000 N were able to provide a significant reduction in longitudinal expansion.

Table 3 also highlights the effect of biomass feedstock on diametral and longitudinal expansion of the single pellets produced in compression testing. Wheat straw had the highest values ($P<0.05$) for both diametral and longitudinal expansion. Peat moss expanded the least, producing the lowest values for diametral and longitudinal expansion. The higher performance of peat moss, and flax shives to some extent, in the dimensional expansion tests may be due to their chemical composition. Table 1 shows that peat moss and flax shives had a higher lignin content as compared to the other two feedstocks. Lignin is the component that permits adhesion in the wood structure, and is a rigidifying and bulking agent (Anglès et al., 2001). The adhesive properties of thermally softened lignin are thought to contribute considerably to the strength characteristics of briquettes made of lignocellulosic materials (Granada et al., 2002). Also, peat moss had a higher protein content than the other three feedstocks. Tabil (1996) explained that if sufficient natural protein is available, it will plasticize under heat, improving the quality of the pellets.

Table 3. Effect of pre-set compression load and biomass feedstock on the diametral and longitudinal expansions (after 14 days) of single pellets produced by compression.

Pre-set load (N)	Diametral expansion (%)	Longitudinal expansion (%)
1000	0.66 (0.73)^{B}	3.67 (2.83)^{B}
2000	0.39 (0.35)^{A}	3.10 (2.67)^{B}
3000	0.34 (0.34)^{A}	1.38 (1.87)^{A}
4000	0.32 (0.36)^{A}	1.55 (1.40)^{A}
4400	0.37 (0.41)^{A}	1.34 (1.93)^{A}
Feedstock	Diametral expansion (%)	Longitudinal expansion (%)
Peat moss	0.25 (0.26)^{B}	0.95 (0.99)^{C}
Wheat straw	0.73 (0.33)^{A}	4.27 (2.64)^{A}
Oat hulls	0.27 (0.43)^{B}	1.99 (2.56)^{B}
Flax shives	0.42 (0.64)^{B}	1.63 (1.56)^{BC}

Means (n = 10) with the same superscript letter are not significantly different (P>0.05).
Multi-treatment comparisons using Tukey's method.
Values in parentheses are standard deviations.

3.4 Asymptotic Modulus

The asymptotic modulus values resulting from the application of Equations 3 and 4 to the relaxation data are shown in table 4. As reported by Scoville and Peleg (1981), the asymptotic modulus is indicative of compact solidity as well as the ability of the compacts to sustain the un-relaxed stresses. Peat moss and oat hulls had significantly higher E_A values than the other two feedstocks at pre-set loads of 4000 and 4400 N. Peat moss alone had the highest E_A value at 3000 N, and there was no significant difference in asymptotic modulus values at the lower two loads (1000 and 2000 N). It also can be seen that higher asymptotic modulus values correlate to lower dimensional expansions. Chemical composition did not appear to have any bearing on the relaxation characteristics of the four biomass grinds.

Relaxation data for the pre-set compression test peak loads were fitted to a power-law model (Equation 6) to show the effect of initial stress (i.e. pre-set compressive load) on E_A; as demonstrated by Tabil and Sokhansanj (1997).

$$E_A = a\sigma_0^d \qquad (6)$$

The asymptotic modulus values increased with increasing initial stress, and the power-law model provided an excellent fit for the experimental data ($R^2 = 0.99$).

Table 4. Mean asymptotic modulus values for peat moss, wheat straw, oat hulls, and flax shives.

Pre-set load (N)	Asymptotic modulus, E_A (MPa)			
	Peat moss	Wheat straw	Oat hulls	Flax shives
1000	24.7 (0.7)^H	25.48 (1.2)^H	24.0 (0.7)^H	26.2 (1.0)^H
2000	54.9 (2.5)^G	53.52 (0.8)^G	53.4 (0.7)^G	54.7 (0.9)^G
3000	93.9 (6.3)^E	84.86 (1.4)^F	86.2 (1.1)^F	86.1 (1.0)^F
4000	125.1 (5.3)^C	117.06 (1.3)^D	122.6 (2.5)^C	118.2 (1.5)^D
4400	139.1 (1.6)^A	129.83 (1.9)^B	138.0 (2.1)^A	132.1 (1.5)^B
Power-law model				
a	0.4732	0.5709	0.4121	0.6340
d	1.1304	1.0904	1.1656	1.0728
R^2	0.99	0.99	0.99	0.99

Means (n = 10) with the same superscript letter are not significantly different (P>0.05).
Multi-treatment comparisons using Tukey's method.
Values in parentheses are standard deviations.

3.5 Adhesion

Oscillations were experienced in the force-displacement curves (fig. 3), which Peleg (1977) describes as the "slip-stick" effect. It was explained that the pertinent force-displacement curve should be the one connecting the oscillation peaks. The force-displacement curves for all four grinds showed the same trend.

Figure 4 demonstrates the relationship between the normal and shear stresses, and shows the values of coefficient of external friction as well as adhesion coefficient for the biomass grinds. For comparison purposes, literature examining the frictional properties of biomass grinds is limited. Mani et al. (2004c) reported that there were significant increases in coefficient of friction of corn stover with particle size and moisture (P<0.05). Their values for coefficient of wall friction on galvanized steel were slightly lower than those obtained in this study. The adhesion coefficient values are difficult to compare due to the fact that the materials are different. However, the values of adhesion coefficient for wheat straw and flax shives are higher than those found for corn stover by Mani et al. (2004c). Usrey et al. (1992) found that the friction coefficient of rice straw was 0.489 on polished steel.

Additional testing may be required to improve the confidence of the frictional characteristics of peat moss, wheat straw, oat hulls, and flax shives. More detailed studies incorporating the effect of moisture content, particle size, and possibly even temperature are also required.

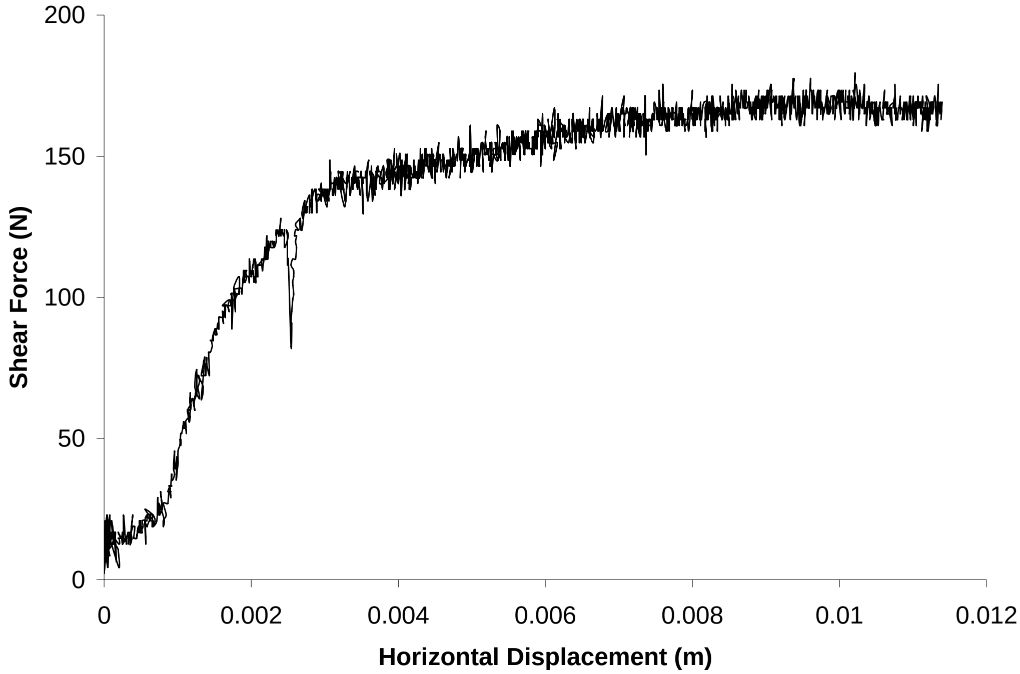

Figure 3. Plot of shear force vs. horizontal displacement from frictional analysis of peat moss.

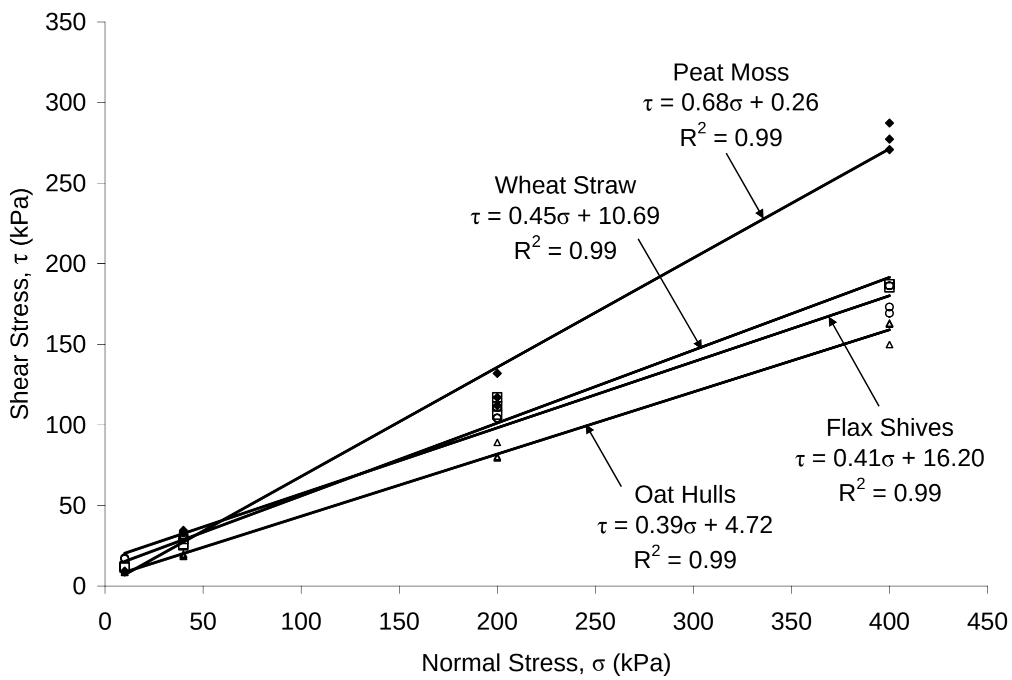

Figure 4. Shear stress resulting from applied normal stress for frictional analysis (slope represents coefficient of external friction and intercept represents coefficient of adhesion in kPa).

4. CONCLUSIONS AND RECOMMENDATIONS

Following evaluation of the results from this study, the following conclusions were drawn:

- Flax shives produced the highest compressibility value of the four feedstocks.
- Loads greater than 1000 N were able to provide a significant reduction in diametral expansion of single pellets produced via compression, while loads higher than 2000 N were able to provide a significant reduction in longitudinal expansion.
- Peat moss pellets expanded the least (diametrally and longitudinally) following a 14 day dimensional expansion test. This is potentially due to the relatively higher levels of lignin and protein in the peat moss feedstock as compared with the other three feedstocks.
- Peat moss and oat hulls had significantly higher E_A values than the other two feedstocks at initial loads of 4000 and 4400 N. Peat moss alone had the highest E_A value at 3000 N, and there was no significant difference in asymptotic modulus values at the lower two loads (1000 and 2000 N). Therefore, peat moss (and oat hulls at the highest two loads) was the most rigid feedstock, indicating its increased ability to sustain un-relaxed stresses.
- The asymptotic modulus (E_A) values of the biomass grinds increased with increasing compression load. The effect of compression stress on asymptotic modulus of the four biomass grinds was accurately predicted by a power-law model (R^2=0.99).
- Flax shives produced the highest adhesion coefficient, while peat moss produced the highest coefficient of external friction. More studies investigating the effect of particle size and moisture content are recommended to generate more robust frictional data.

5. ACKNOWLEDGEMENTS

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7. NOMENCLATURE

a = constant of power-law model
A = cross-sectional area of pellet die (m^2)
b = model constant (Jones model)
c = model constant (Walker model)
C_a = adhesion coefficient (kPa)
d = constant of power-law model
E_A = asymptotic modulus (MPa)
F_0 = initial force for relaxation test (pre-set compressive load) (N)
F(t) = force at time t during relaxation test (N)
k_1, k_2 = relaxation model constants
m = Jones model constant; compressibility
m' = Walker model constant; compressibility
P = compressive pressure (MPa) = compressive load (N)/cross-sectional area of pellet die (m^2)
t = time (s)
V = observed volume of powder within the pellet die (m^3)
V_R = volume ratio = V/V_s
V_s = theoretical volume of solid particles (m^3)

ε = strain (calculated using plunger displacement)
ρ = density of compact (kg/m^3)
σ = normal stress during adhesion test (kPa)
σ_0 = initial stress for relaxation test (MPa)
τ = shear stress during adhesion test (kPa)
μ = coefficient of external friction