**Effect of Ammonia Fiber Expansion (AFEX™) Pretreatment on Compression Behavior of
Corn stover, Prairie cord grass and Switchgrass**

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22 **ABSTRACT**

23 Understanding the fundamental mechanisms involved in densification of bulky
24 lignocellulosic feedstocks is imperative. This study was carried out to understand the effect of
25 Ammonia Fiber Expansion (AFEX™) pretreatment on the compression behavior of corn stover,
26 prairie cord grass, and switchgrass. Samples were ground using three different hammer mill
27 screen sizes (2, 4, and 8 mm) and were subjected to AFEX™ pretreatment. Untreated and
28 AFEX™ pretreated samples were moisture adjusted to four levels (8, 12, 16, and 20% wb) and
29 were compressed using a single pelleting unit. Physical properties comprising bulk density,
30 particle density of the samples and unit density of pellets were determined for each combination.
31 AFEX™ pretreated corn stover with moisture content of 20% at screen size of 2 mm produced
32 pellets with 21% higher unit density compared to untreated corn stover pellets. AFEX™
33 pretreated prairie cord grass and switchgrass with 20% moisture content at a screen size of 2 mm
34 produced pellets having 25% and 21% higher unit density. The decrease in hammer mill screen
35 size and the increase in moisture content and applied pressure increased the pellet unit density.
36 Data obtained from the compression experiment were fitted with different compaction models
37 viz. Jones, Walker, and Kawakita and Ludde. The Kawakita and Ludde model exhibited high
38 degree of accuracy (R^2 - 0.99 and 1.00) in all the samples. The constant value '1/b' in Kawakita
39 and Ludde model represents the yield strength of the compacts, and the lower 1/b values were
40 obtained for AFEX™ pretreated samples compared to untreated samples. This implies the impact
41 of pretreatment, which in turn made the biomass easier to compress. Lower values of yield
42 strength were obtained at high moisture content (16 and 20% wb) signifying that AFEX™
43 pretreated biomass at high moisture content leads to onset of deformation at relatively low
44 pressure to produce highly compacted pellets.

1. Introduction

The supply of sustainable and economical energy is a primary concern for many nations. One alternative solution is to make use of abundantly available renewable lignocellulosic materials to produce biofuels. According to studies, there are approximately 1.3 billion tons of biomass available annually from both harvested agricultural lands and forests in the United States (U.S. Department of Energy, 2011). Furthermore, production of biofuels from lignocellulosic materials may lead to a reduced dependency on fossil fuels and lower greenhouse gas emissions (Degenstein, 2013; McKendry, 2002). Developing technologies to produce cost effective biofuels is a key challenge and biofuels production from lignocellulosic feedstocks poses several impediments.

One of the limitations of employing lignocellulosic feedstocks for biofuel production is its low bulk density. It leads to handling, storage, and transportation issues that can directly dictate the cost of the feedstock leading to high production cost (Hoover et al., 2014). To maintain an economic and sustainable feedstock supply to the biorefineries, the compaction of low bulk density biomass is crucial (Adapa et al., 2010). Besides, understanding the biomass compaction mechanisms will aid in the design of energy efficient compaction equipment, reducing the production cost, and increasing the quality of compacted products (Mani et al., 2004a). Theerarattananoon et al. (2011) stated that the densification of biomass feedstocks can assist in increasing the bulk density, reducing the transportation costs, improving the storability, and creating better environment to handle the feedstocks using existing grain handling equipment. The quality of the densified feedstocks depends on feedstock characteristics (moisture content, chemical composition, particle size, etc.) and process variables (temperature, pressure retention time, etc.).

The lignocellulosic biomass structure is composed of a highly complex matrix of cellulose, hemicellulose, and lignin. These components are interlinked by ether, ester, carbon-carbon, and hydrogen bonds (Faulon and Carlson, 1994). Among these components, lignin allows the particles to stick together during the densification process. Lignin softening will take place when the biomass is compacted under high temperature and pressure exhibiting thermosetting properties (van Sam et al., 2004). Kaliyan and Morey (2010) studied the significance of natural binders (lignin and protein) present in corn stover and switchgrass at a microscopic level. Solid bridges were formed when the natural binders were subjected to melting and cooling. The study concluded that the activation of natural binders by regulating moisture and temperature is vital to produce durable densified products.

The interlinkage between the components makes the feedstock recalcitrant and several physical, chemical, physicochemical, and biological pretreatment methods have been extensively studied to alter this complex structure (Brodeur et al., 2011). Sokhansanj et al. (2005) implied that the recalcitrant structure of lignocellulosic biomass should be altered to activate the natural binders to enhance the densification process, and this can be achieved by the application of pretreatment. Adapa et al. (2010) attributed the enhancement in the compact density of canola, oat, and wheat straw to the melting and depolymerization of lignin during steam explosion pretreatment.

Ammonia Fiber Expansion (AFEX™) is a promising technology for pretreating agricultural residues for bioenergy production (Bals et al., 2010a). The method encompasses treating biomass with anhydrous ammonia in a high pressure Parr reactor for a short residence time before explosively releasing the pressure (Dale, 1986). This instantaneous drop in pressure results in solubilization and redeposition of lignin components on the biomass surface after

ammonia is evaporated (Dale, 1986; Chundawat et al., 2011). AFEX™ pretreatment involves treating biomass with liquid ammonia at a moderate temperature (80-150 °C) and pressure (200-400 psi) in an enclosed stainless steel reactor for a short residence time (5-30 min) before releasing the pressure (Bals et al., 2010a). This rapid drop in pressure results in physical disruption of the biomass structure, thus exposing the cellulose and hemicellulose fibers (Dale, 1986; Balan et al., 2009; Chundawat et al., 2011; Kumar et al., 2009). The important impacts of this pretreatment include cellulose decrystallization, hemicellulose hydrolyzation, and lignin depolymerization (Bals et al., 2010b; Chundawat et al., 2011). Campbell et al. (2013) investigated the packed bed AFEX™ reactor for pretreatment of corn stover and wheat straw. Durable pellets were formed from AFEX™ pretreated corn stover and wheat straw without any external binding agents. The lignin in the biomass acts a natural binding agent in sticking the fibers together during the densification process. The results of the study showed that the pelleting operations can be made efficient after biomass is subjected to AFEX™ pretreatment. Hoover et al (2014) studied the impact of the AFEX™ pretreatment and pelleting variables on pellet quality and sugar yield of corn stover. The results of the study showed that the pelleting of AFEX™ pretreated biomass produced pellets with durability of more than 97.5%.

Mani et al. (2003) emphasized the requirement of research works on compression characteristics of different biomass to develop a cost effective compaction process. It is imperative to understand how the pretreated biomass behave during densification. The objective of our work is to study the impact of AFEX™ pretreatment and the effect of three variables, namely biomass moisture content, applied pressure, and hammer mill screen size on the responses namely bulk density, particle density, and pellet unit density. The feedstocks selected were corn stover, prairie cord grass, and switchgrass and a single pelleting unit was employed for

pelleting. In addition, the results obtained experimentally were rigorously tested using three different compaction models, namely Walker (1923), Jones (1960), and Kawakita and Ludde (1971) to examine the compression characteristics of the untreated and AFEX™ pretreated biomass feedstocks such as corn stover, prairie cord grass, and switchgrass.

2. Materials and Methods

2.1. Feedstock preparation

The feedstocks corn stover (2008), prairie cord grass, and switchgrass (2009) obtained from local farms in Brookings, South Dakota were ground with three different screen opening sizes *viz.* 2, 4 (Hammer Mill, Thomas Wiley laboratory mill, Swedesboro, NJ) and 8 mm (Speed King, Winona Attrition mill Co, Winona MN). The ground materials were sealed in plastic bags and sent to the Biomass Conversion Research Laboratory (BCRL, Michigan State University, MI) for AFEX™ pretreatment. The pretreatment conditions were optimized individually for each feedstock based on the recalcitrant nature of lignocellulosic biomass (Balan et al., 2009) by BCRL. The key variables employed during the AFEX™ process were pretreatment time, ammonia-to-biomass ratio, temperature, and feedstock moisture content. The AFEX™ pretreatment conditions used for different feedstocks are given in Table 1. The pretreated materials were sealed in plastic bags and stored in a refrigerator at 4°C until further use.

2.2. Moisture conditioning

The moisture content of the samples was determined using ASABE (2006) standard and was reported in percent wet basis. The initial moisture content of the stored untreated feedstocks varied from 4 to 8% and for the AFEX™ pretreated feedstocks the moisture content varied from

and 5 to 8% on a wet basis. Moisture content was varied at four different levels (8, 12, 16, and 20% on wet basis) and the selection of moisture content range was based on Kaliyan and Morey (2009) study. In their study, the authors optimized the conditions to produce durable briquettes from corn stover and switchgrass by varying the moisture content from 8 to 20%. To achieve the desired moisture levels, a calculated quantity of water was added to the samples in a plastic container, and the contents were tumbled manually. Moisture adjusted samples were stored in sealed plastic bags at 4°C overnight and the samples were brought to room temperature prior to the beginning of experiments.

2.3. Compression test using single pelleting unit

To study the compression performance of the AFEX™ pretreated and untreated biomass grinds, tests were carried out in a single pelleting unit (Mani et al., 2002; Tabil and Sokhansanj, 1996 and 1997). The unit consists of a piston and cylinder assembly with a base plate resting on the platform. The piston was connected to the crosshead of the texture analyzer (TA HD plus, Texture Technologies Corp, NY) as shown in Fig.1. Internal diameter and height of the cylinder were 6.35 and 76.2 mm respectively. The cylinder was wrapped with a heating element to heat the contents of the cylinder during the compression. Thermocouples were attached to the cylinder and the temperature was regulated by a temperature controller (SDC 120KC-A, Brisk heat corporation, OH). The cylinder section was rested on the base plate, which had an internal diameter matching the diameter of the cylinder. Feedstocks with different combinations of moisture contents (8,14, 16 and 20% w.b) and hammer mill sizes (2, 4, and 8 mm) were pelleted at different loading conditions (1000, 2000, 3000, 4000, and 5000 N) with corresponding pressure (31.6, 63.2, 94.8, 126.4 and 158.0 MPa) using the single pelleting unit. Samples of a quantity of 0.5 to 0.7 g were loaded into the cylinder and the piston was allowed to compress in a

single stroke. The temperature of the cylinder was maintained at $100\pm 2^{\circ}\text{C}$ to mimic the commercial pelleting process (Mani et al., 2004b). Experimental variables selected and the levels of each variable are given in Table 2. The crosshead speed of the texture analyzer was set at 50 mm min^{-1} . After reaching the preset load, the piston was allowed to detain at an indicated preset load for a period of 30 s to avoid the spring back effect. The piston was raised and bottom plate was attached to the cylinder to eject the pellet produced by lowering the piston. Five replications were produced for each combination.

2.4. Physical properties

The physical properties estimation of the untreated, AFEX™ pretreated, pelletized untreated and pelletized AFEX™ pretreated samples were carried out. Physical properties include bulk density, particle density, and pellet unit density were calculated and the values were fitted with different compaction models. The procedures adopted for determination of different physical properties are given below:

2.4.1. Bulk density of feedstocks

Bulk density is the important characteristic of the biomass as it directly influences the delivery cost of the feedstock to a biorefinery. Besides, it also impacts the storage and material handling system (Lam et al., 2008). Bulk density is the ratio of mass of biomass to the total volume they occupy. It is used as a measure to determine the material flow consistency. The bulk density of the samples was determined using a hopper and stand (Product code 151, Seedburo equipment Co, Des Plaines, IL) apparatus. A cylindrical metal container with a known volume of 0.5 L was placed below the hopper to collect the samples fed into the hopper. The mass of the

179 sample present in the container was measured for each feedstocks and the bulk density of
180 feedstocks was calculated by dividing the mass of the sample by the volume of the vessel.

181 **2.4.2. Particle density of feedstocks**

182 Gas pycnometer is widely used to determine and characterize solids in powder form. In
183 this study, Micrometritics multivolume gas pycnometer (1305, Norcross, GA) was used to
184 determine the particle density of the samples. The total pore volume was measured by passing
185 the medium gas to fill the void spaces in the cell containing the sample. Helium gas was used as
186 a medium gas and the volume of the sample was calculated from the drop in pressure when the
187 known amount of gas was allowed to expand into the cell containing the sample. Sample volume
188 was calculated using the formula specified in the instrument manual.

$$V_{\text{sample}} = V_{\text{cell}} - \frac{V_{\text{exp}}}{\left[\left(\frac{P_1}{P_2}\right) - 1\right]}$$

189 Where P_1 indicates the pressure in the sample cell ; P_2 indicates the pressure after
190 expansion of the gas in sample and reference cell; V_{cell} designates empty volume of the sample
191 cell (cm^3), and V_{exp} designates expansion volume added (cm^3). Particle density was calculated by
192 dividing the mass of sample by volume of sample calculated. Five replications were carried out
193 for each sample to determine bulk and particle densities.

194 **2.4.3. Pellet unit density**

195 The dimensions (height and diameter) of the pellets were measured using a digital vernier
196 caliper (Digimatic, Mitutoyo Corp. Japan) and the mass of pellets using a digital balance (Mettler

PM 2500, Delta range, Columbus, OH). The ratio of mass of a pellet to its volume provided the pellet unit density, and three replications were performed under each condition.

2.5. Analysis of variance (ANOVA)

Regulating the process and feedstock parameters supports the production of quality compacted products. Carone et al. (2011) represented a simplified model for an industrialization process and the study results showed the influence of temperature, moisture content and hammer mill screen size and their interactions on density and hardness of the pellets. The study concluded that, high temperature, low moisture content, and reduced biomass size, in the same order governed the model in determining the pellets quality. In this study, the effect of moisture content, screen size, and applied force on compression characteristics of corn stover, prairie cord grass, and switchgrass was carried out using the analysis of variance (ANOVA) method. Least significant difference (LSD) at 0.05 level of significance was also carried out using SAS software (SAS 9.3, Cary, NC). The data were analyzed with PROC GLM procedure to determine the main and interaction effects, and the level of significance was set at 5%. Model parameters of Walker, Jones, and Kawakita and Ludde model were estimated using Microsoft Excel 2010 (Microsoft Corp., Seattle, WA 2010).

2.6. Compaction equations

Data obtained from the compression experiments were fitted with different powder compaction models *viz.* Walker (1923), Jones (1960), and Kawakita and Ludde (1971) to understand the behavior of samples during compression under different conditions.

2.6.1 Walker model (1923)

Walker, based on a series of experiments on powder compressibility proposed the relationship of volume ratio (V_R) as function of applied pressure (P) as mentioned in Eq 1.

$$V_R = m_1 \cdot \ln P + z_1 \quad (1)$$

Where,

V_R : Volume ratio (V/V_s); m_1 & z_1 : model constants; P : Applied pressure (Pa); V : Volume of compact at pressure P (m^3); V_s : void free solid material volume (m^3).

2.6.2 Jones model (1960)

Jones studied the compression behavior of industrial metal powders and used the Eq 2 to express the relationship between density and pressure data obtained.

$$\ln \rho = m_2 \cdot \ln P + z_2 \quad (2)$$

Where,

ρ : Packing density (kg/m^3); m_2 : model constant (compressibility); z_2 : model constant;
 P : Applied pressure (Pa)

2.6.3 Kawakita and Ludde model (1971)

Kawakita and Ludde evaluated the relationship between pressure and volume change in compaction of powders to ascertain the behavior of materials during compaction. The model is given by Eq 3

$$\frac{P}{C} = \left(\frac{1}{ab} \right) + \left(\frac{P}{a} \right) \quad (3)$$

Where,

C: Degree of volume reduction $[(V_0 - V)/V_0]$; a & b: Model constants;

V_0 : Volume of compact at zero pressure (m^3); P: Applied pressure (MPa)

3. Results and Discussion

3.1. Bulk and particle density

Bulk and particle densities of the untreated and AFEXTM pretreated biomass samples are given in Table 3. Table 4 shows the ANOVA test results for factors affecting bulk and particle density of both untreated and AFEXTM pretreated samples. The outcomes of the analysis showed the significant effect ($p < 0.0001$) of moisture content, hammer mill screen size, feedstock type, and their interactions on bulk and particle density of the samples. Bulk density and particle density of untreated and AFEXTM pretreated biomass samples decreased with an increase in hammer mill screen size. Larger screen size particles tend to occupy more pore volume than the smaller particles (Mani et al., 2004a), leading to decrease in bulk and particle densities. AFEXTM pretreatment increased the bulk and particle density of all three biomass samples, and this can be attributed to the brittle and friable nature of biomass after AFEXTM pretreatment (Hoover et al., 2014). The highest bulk density was observed for prairie cord grass for both untreated (199.5 kg m^{-3}) and AFEXTM pretreated (232.0 kg m^{-3}) samples. The reason could be due to the grinds from prairie cord grass may have been finer than other biomasses (Mani et al., 2006). The bulk density of the biomass also increased with increase in moisture content as the addition of water increases the weight. Besides, moisture conditioned AFEXTM pretreated corn stover had shown significant increase in bulk density as compared to moisture conditioned untreated corn stover. Particle density of all three AFEXTM pretreated biomass increased significantly compared to the

untreated samples. Adapa et al. (2010) attributed the increase in particle density of canola, oat, and wheat straw after steam explosion pretreatment to the disintegration of long chain lignocellulosic structure into short chains during pretreatment. In the case of AFEXTM pretreatment, one of the important alterations occurring is the swelling and physical disruption of the lignocellulosic matrix structure (Dale, 1986; Balan et al., 2009). This effect could have made the feedstocks more fragile and crumble contributing to the increased particle density after AFEXTM pretreatment.

3.2. Pellet unit density

Table 5 shows the analysis of variance (ANOVA) results for pellet unit density of both untreated and AFEXTM pretreated feedstocks. The analysis showed that all the selected variables (applied pressure, moisture content, hammer mill screen size, and feedstock) and their interactions had significant contribution in determining the pellet unit density ($p < 0.0001$). The diameter of pellets ranged from 6.36 to 6.55 mm designating the expansion of pellets after extruding from the die. Table 6 shows the pellet unit density of all untreated and AFEXTM pretreated samples. Pellet unit density of untreated and AFEXTM pretreated corn stover increased gradually with an increase in applied pressure and moisture content for all screen size samples. No increase in pellet unit density was observed when the moisture content was raised above 12% for untreated corn stover. Mani et al. (2006) reported the significant role of moisture content in determining the bulk density of corn stover briquettes. Low moisture corn stover (5–10%) resulted in denser, more stable, and more durable briquettes than high moisture corn stover (15%). The study showed the occurrence of surface cracks when the moisture content of the feed was increased above 10 %. In this study, untreated corn stover produced maximum pellet unit densities of 1169.3 kg m⁻³ (2 mm hammer mill screen size) and 1153.6 kg m⁻³ (4 mm

hammer mill screen size), when the moisture content was maintained at 12 %. AFEX™ pretreated corn stover (2 mm hammer mill screen size) produced pellets with unit density of 1419.4 kg m⁻³. As the screen size was increased to 4 mm, pellets with unit density similar to the ones observed for 2 mm were produced at high loading and moisture content. A significant reduction in unit density of the pellets was observed at all moisture levels and loading conditions when the screen size was increased to 8 mm. The decrease in pellet unit density with increase in screen size can be attributed to smaller surface area available for binding. Increased surface area for smaller particle size aids in promoting better binding between the particles (Payne, 1978).

In the case of untreated prairie cord grass, a gradual increase in pellet unit density was observed as the moisture content was increased, and the maximum pellet unit density was obtained at the moisture content between 12 and 16 %. In all circumstances, AFEX™ pretreated prairie cord grass pellets unit density increased with increase in moisture content and applied pressure. At 20% moisture content, maximum pellet unit densities of 1430.7 kg m⁻³ and 1427.9 kg m⁻³ was produced at hammer mill screen size of 2 mm and 4 mm respectively. Untreated prairie cord grass produced relatively less unit density pellets in all the conditions. Pellets produced at 158.0 MPa applied pressure with 16% biomass moisture content (4 mm hammer mill screen size) had high unit density (1083.1 kg m⁻³). Pellets with low unit density were produced with a screen size of 8 mm under all conditions. Increase in moisture content increased the pellet unit density of untreated and AFEX™ pretreated prairie cord grass.

AFEX™ pretreated switchgrass samples produced pellets with low unit density compared to AFEX™ pretreated corn stover and prairie cord grass pellets. In all cases, AFEX™ pretreated samples produced high density pellets. This might be due to the increased availability of lignin in the pretreated feedstocks for binding. AFEX™ pretreatment causes the biomass to swell and

disrupt the lignocellulosic matrix structure, thus solubilizing and mobilizing the lignin to biomass surface (Dale, 1986; Chundawat et al., 2011). This availability of lignin on the surface could have increased the binding property resulting in high density pellets. Shaw (2008) studied the effect of steam explosion pretreatment on the compression characteristics of poplar and wheat straw and had observed similar results. This increased density of the pellets can have significant reduction in cost associated with biomass transportation. Hoover et al. (2014) stated the increase in bulk density of AFEX™ pellets in comparison with untreated corn stover pellets leads to benefits in transportation, as only fewer trips are necessary to transport the same quantity of material.

3.3. Compaction model results

Density data of the samples and the pressure applied to compress the biomass were fitted with Walker, Jones and Kawakitta Ludde models. Table 7 shows the model constants obtained after the pressure and density data were fitted to the Walker model (1). Constant ' m_1 ' in the equation represents the compressibility of the material. Compressibility is the change in density due to applied pressure (Peleg, 1973) and a higher extent indicates high compressibility of the material. Compressibility values of the samples ranged from 0.010 (AFEX™ pretreated corn stover, 4 mm, 20% wb) to 0.372 (untreated switchgrass, 4 mm, 8% wb). R^2 values for the fitting ranged from 0.64 (AFEX™ prairie cord grass, 8 mm, 20% wb) to 0.99 (corn stover 8 mm, 12% wb and prairie cord grass, 2 mm, 8% wb). It was found that an increase in moisture content decreased the compressibility values of all untreated and AFEX™ pretreated biomass samples. Minor increase in compressibility was noted for all three AFEX™ pretreated feedstocks when the hammer mill screen size was increased from 2 mm to 4 mm. The effect of hammer mill screen size for the untreated feedstocks was unclear. Untreated switchgrass was more

compressible than untreated corn stover and prairie cord grass. Among AFEXTM pretreated samples, corn stover had high compressible value than all three biomass. AFEXTM pretreated samples showed decreased compressibility values signifying the impact of pretreatment. Shaw (2008) showed reduction in the compressibility, when poplar and wheat straw were subjected to steam expansion pretreatment.

Constant values of the Jones model were obtained when the logarithm of pellet unit density and applied pressure were fitted into the equation (2). Table 8 shows the constant values obtained from the Jones model. Similar to Walker model, the term ' m_2 ' in the Jones model represents the compressibility. Decrease in compressibility value was observed after the biomass were subjected to AFEXTM pretreatment. Besides, increment in moisture content decreased the compressibility representing the increased packing density of the biomass with increase in moisture. R^2 values for this model ranged from 0.53 (AFEXTM corn stover, 2 mm, 20% wb) to 0.99 (untreated corn stover 8 mm, 12% wb and untreated prairie cord grass, 2 mm, 8% wb). Hammer mill screen size showed no considerable effect on compressibility of AFEXTM pretreated feedstocks, whereas the increase in compressibility values were observed for untreated feedstocks with increase in hammer mill screen size.

One of the ideal requirements of a compaction equation is to have a sufficient accuracy, which can be defined in terms of the goodness of fit (Sonnergard, 2001). A higher degree of accuracy was obtained (R^2 values - 0.99 & 1.00) when the data were fitted to Kawakita and Ludde model, representing the best fit conditions for all samples. Constant values obtained from the Kawakita and Ludde model are shown in Table 9. The term ' a ' in the model designates initial porosity of the sample and the value increased with an increase in hammer mill screen size. Among all untreated samples, corn stover (8 mm, 8% wb) had high initial porosity (0.938) and

prairie cord grass (2 mm, 20% wb) had low porosity (0.817). In the case of AFEXTM pretreated samples, high initial porosity (0.909) was observed for corn stover and low porosity (0.827) for prairie cord grass. In the case of AFEXTM pretreated samples 'a' values ranged from 0.827 to 0.909, whereas untreated biomass samples ranged from 0.817 to 0.938. Denny (2002) identified that the constant 'a' does not represent initial porosity in all cases due to the non-linearity of the plots. Decrease in the initial porosity of the all the samples after AFEXTM pretreatment can be witnessed from table 9 and Shaw (2008) observed similar decrease in initial porosity of poplar wood and wheat straw during steam explosion pretreatment. The author observed a weak relationship between the constant 'a' and the theoretical initial porosity. The other term '1/b' in the model designates the yield strength or failure stress of the compacts, which in other words indicate the compressibility of the material (Kawakita and Ludde, 1971). Higher 1/b value was witnessed for untreated samples and the value ranged from 1.075 to 7.209. Relatively lower 1/b value was observed for pretreated samples, which signifies the impact of AFEXTM pretreatment and the requirement of less pressure to produce compacted biomass products. Adapa et al. (2009) reported the impact of steam explosion pretreatment on barley, canola, oat and wheat straw grinds. AFEXTM pretreated corn stover (2 mm, 20% wb) produced low (0.033) and untreated prairie cord grass (4 mm, 8% wb) produced high yield strength value (7.209). Increase in the moisture content decreased the 1/b value implying the significance of moisture content in compacting. Mani et al. (2003) stated the significance of moisture content, which plays a vital role in determining the density and strength of the densified products. In this study, lower values of yield strength were observed at high moisture content (16 and 20% wb) representing AFEXTM pretreated biomass at high moisture content leads to an onset of deformation at relatively low

pressure. Moisture content had a mixed effect on the yield strength in the case of untreated biomass samples.

4. Conclusions

This study was intended to understand the compression mechanisms of untreated and AFEXTM pretreated corn stover, prairie cord grass and switchgrass. Single pelleting unit was employed for production of pellets and moisture content of the feedstocks, hammer mill screen size, and applied pressure were varied. The results of statistical analysis showed the moisture content, screen size, and applied pressure had significant effect on pellet unit density of both AFEXTM pretreated and untreated biomass samples ($p < 0.0001$). Pellets produced from 8 mm hammer mill screen size feedstocks exhibited lowest pellet unit density. Compression data obtained from different conditions were fitted with different compaction models. Kawakita and Ludde model provided the best fit for all biomass (R^2 - 0.99 & 1.00) among the three models selected. Constant value '1/b' represents the yield strength, and lower value for AFEXTM pretreated biomass signifies the impact of pretreatment making the biomass to compress with less pressure. Lower values of yield strength were observed at high moisture content (16 and 20% wb) indicating AFEXTM pretreated biomass at high moisture content leads to an onset of deformation at relatively low pressure. Moisture content plays a vital role in compacting AFEXTM pretreated biomass samples and also, increase in the moisture content reduced the application of load to obtain highly compacted pellets.

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502 **Fig.1 Single pelleting unit positioned in the texture analyzer**
503

- **Cross head containing load cell**
- **Piston**
- **Cylinder wrapped with heating element**
- **Bottom plate**

Fig. 1

517 **Table 1.** AFEX™ pretreatment conditions employed for different biomass*

Feedstock	NH ₃ loading	Moisture	Pretreatment soaking time (min)
	NH ₃ to dry biomass loading (w/w)	content (db %)	
Corn stover	1:1	60	15
Prairie cordgrass	1:2	40	30
Switchgrass	1:2	50	30

518 *Pretreatment was carried out at 100°C

519 **Table 2.** Experimental variables
520

Feedstock	Corn stover, Prairie cordgrass, Switchgrass, AFEX™ Corn stover, AFEX™ Prairie cordgrass, and AFEX™ Switchgrass
Moisture content (% wet basis)	8,12,16, and 20
Load (N)	1000, 2000, 3000, 4000, and 5000
Hammer mill screen size (mm)	2, 4, and 8

522
523 **Table 3.** Bulk and particle density of untreated and AFEX™ pretreated corn stover, prairie cord
524 grass, and switchgrass
525

Hammer mill Screen size (mm)	Moisture content (%) w.b	Bulk density (kg/m ³)		Particle density (kg/m ³)	
		Untreated Corn stover	AFEX™ Corn stover	Untreated Corn stover	AFEX™ Corn stover
2	8	111.33 ± 0.9 ³¹	199.41 ± 2.6 ⁸	970.94 ± 4.4 ²¹	1345.80 ± 9.2 ⁹⁻¹¹
	12	118.90 ± 1.3 ³⁰	202.00 ± 3.7 ^{7,8}	960.02 ± 8.2 ^{22,23}	1336.12 ± 9.6 ^{11,12}

4	16	124.79± 2.6 ²⁹	209.54 ± 2.8 ⁶	947.06 ± 7.3 ²⁴⁻²⁶	1325.56 ± 6.7 ¹²⁻¹⁴
	20	127.12 ± 0.6 ²⁹	216.06 ± 2.9 ⁵	941.26 ± 8.8 ^{26,27}	1321.36 ± 6.0 ^{13,14}
	8	97.30 ± 1.1 ³⁵⁻³⁷	179.77 ± 2.6 ^{10,11}	954.85 ± 8.2 ^{23,24}	1325.47 ± 10.5 ¹²⁻¹⁴
	12	100.04 ± 2.4 ^{33,34}	192.33 ± 3.7 ⁹	939.66 ± 9.1 ^{26,27}	1317.06 ± 10.0 ¹³⁻¹⁵
	16	104.42 ± 1.3 ³²	199.83 ± 2.8 ⁸	919.50 ± 8.0 ²⁸	1308.47 ± 9.0 ¹⁵⁻¹⁷
	20	108.82 ± 1.4 ³¹	206.01 ± 2.9 ⁶	895.06 ± 6.8 ^{29,30}	1302.10 ± 9.1 ¹⁷
	8	79.21 ± 5.9 ^{41,42}	134.12 ± 1.1 ²⁷	842.32 ± 9.0 ^{31,32}	1322.82 ± 9.2 ^{13,14}
	12	82.47 ± 2.4 ⁴⁰	138.08 ± 2.1 ^{25,26}	834.47 ± 7.7 ³²⁻³⁴	1320.76 ± 11.7 ^{13,14}
	16	88.47 ± 2.3 ³⁹	142.46 ± 2.0 ²³	830.90 ± 4.7 ^{33,34}	1305.39 ± 5.7 ^{16,17}
	20	91.35 ± 3.0 ³⁸	150.18 ± 1.9 ^{21,22}	824.37 ± 10.1 ³⁴	1301.38 ± 13.8 ¹⁷
		Untreated Prairie cord grass	AFEX™ Prairie cord grass	Untreated Prairie cord grass	AFEX™ Prairie cord grass
2	8	199.54 ± 1.0 ⁸	232.09 ± 2.3 ⁴	1069.38 ± 7.6 ¹⁸	1435.17 ± 8.1 ^{1,2}
	12	203.53 ± 2.3 ⁷	235.90 ± 1.3 ³	1062.68 ± 5.6 ¹⁸	1427.07 ± 3.9 ^{2,3}
	16	207.86 ± 2.8 ⁶	243.68 ± 2.2 ²	1051.11 ± 3.2 ¹⁹	1419.86 ± 3.9 ^{3,4}
	20	217.36 ± 1.7 ⁵	250.90 ± 1.7 ¹	1043.70 ± 7.8 ¹⁹	1408.68 ± 8.3 ^{5,6}
	8	155.98 ± 1.3 ¹⁹	163.33 ± 1.3 ^{16,17}	988.88 ± 8.0 ²⁰	1441.38 ± 9.5 ¹
4	12	159.92 ± 2.5 ¹⁸	169.16 ± 1.7 ^{13,14}	960.80 ± 5.8 ²¹⁻²³	1438.36 ± 9.4 ¹
	16	164.90 ± 2.4 ^{15,16}	172.27 ± 2.4 ¹²	942.12 ± 4.7 ²⁵⁻²⁷	1418.76 ± 5.8 ³⁻⁵
	20	167.53 ± 2.2 ^{14,15}	177.60 ± 2.2 ¹¹	935.05 ± 9.2 ²⁷	1415.63 ± 6.9 ^{4,5}
8	8	95.41 ± 3.9 ³⁷	134.42 ± 1.3 ²⁷	966.87 ± 9.9 ^{21,22}	1399.05 ± 8.6 ⁶

Table 4. ANOVA for factors affecting bulk density and particle density

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Bulk density					
FS	5	457285.73	91457.14	16341.9	<.0001
SS	2	75050.97	37525.48	6705.19	<.0001
FS*SS	10	157162.89	15716.28	2808.24	<.0001

Source	DF	Type I SS	Mean Square	F Value	Pr > F
Bulk density					
MC	3	5548.82	1849.60	330.49	<.0001
FS*MC	15	2002.91	133.52	23.86	<.0001
SS*MC	6	91140.40	15190.06	2714.22	<.0001
FS*SS*MC	30	125611.73	4187.05	748.16	<.0001
Particle density					
FS	5	18594599.42	3718919.88	53062.9	<.0001
SS	2	225245.03	112622.51	1606.94	<.0001
FS*SS	10	249540.68	24954.07	356.05	<.0001
MC	3	61448.57	20482.86	292.26	<.0001
FS*MC	15	12157.42	810.49	11.56	<.0001
SS*MC	6	6165.52	1027.59	14.66	<.0001
FS*SS*MC	30	13268.49	442.28	6.31	<.0001

*FS – Feedstock; SS – Screen size; MC – Moisture content;

Table 5. ANOVA for factors affecting pellet unit density of untreated and AFEX™ pretreated feedstocks

Source	DF	Type I SS	Mean Square	F Value	Pr > F
FS	5	45847370.64	9169474.13	169563	<.0001
SS	2	2428375.94	1214187.97	22452.9	<.0001
FS*SS	10	607678.30	60767.83	1123.72	<.0001
MC	3	853307.99	284436.00	5259.82	<.0001
FS*MC	15	499873.63	33324.91	616.25	<.0001
SS*MC	6	30198.51	5033.09	93.07	<.0001
FS*SS*MC	30	256999.91	8566.66	158.42	<.0001
PR	4	4954803.05	1238700.76	22906.2	<.0001
FS*PR	20	735717.04	36785.85	680.25	<.0001

Source	DF	Type I SS	Mean Square	F Value	Pr > F
SS*PR	8	41681.44	5210.18	96.35	<.0001
FS*SS*PR	40	340287.45	8507.19	157.32	<.0001
MC*PR	12	192285.39	16023.78	296.31	<.0001
FS*MC*PR	60	162720.21	2712.00	50.15	<.0001
SS*MC*PR	24	32408.32	1350.35	24.97	<.0001
FS*SS*MC*PR	120	164514.19	1370.95	25.35	<.0001

*FS – Feedstock; SS – Screen size; MC – Moisture content; PR – Applied pressure

Table 6. Pellet unit density of untreated and AFEX™ pretreated samples

Moisture (%) wb	Applied pressure (MPa)	Pellet unit density (kg/m ³)					
		Untreated C	Untreated P	Untreated	AFEX TM CS	AFEX TM PC	AFEX TM SG
		S	CG	SG		G	
2 mm hammer mill screen size							
8	31.6	1044.6 ±	770.9 ±	702.9 ±	1065.3 ±	1158.5 ±	1135.8 ±
		4.1 ¹⁰⁸⁻¹¹⁰	8.6 ^{155,156}	11.1 ¹⁶⁸	8.4 ^{103,104}	4.6 ⁸²⁻⁸⁶	9.7 ⁸⁹⁻⁹¹
	63.2	1108.4 ±	910.6 ±	737.8 ±	1216.5 ±	1191.3 ±	1216.3 ±
		6.7 ⁹⁵⁻⁹⁷	6.8 ^{132,133}	8.5 ¹⁵⁹⁻¹⁶¹	3.03 ⁷⁰⁻⁷³	4.0 ^{76,77}	3.7 ⁷⁰⁻⁷³
	94.8	1159.5 ±	983.2 ±	811.1 ±	1283.7 ±	1223.2 ±	1260.3 ±
		4.6 ⁸²⁻⁸⁶	2.5 ¹¹⁸⁻¹²¹	4.9 ¹⁴⁹⁻¹⁵¹	2.5 ⁵²⁻⁵⁹	4.9 ⁶⁹⁻⁷¹	3.3 ⁶²⁻⁶⁵
	126.4	1159.6 ±	1026.2 ±	951.3 ±	1313.1 ±	1266.0 ±	1274.6 ±
		7.4 ⁸²⁻⁸⁶	7.3 ¹¹³⁻¹¹⁵	5.6 ¹²⁵⁻¹²⁷	6.2 ³⁷⁻⁴²	8.8 ⁶⁰⁻⁶⁴	2.3 ⁵⁸⁻⁶⁰
	158.0	1153.1 ±	1064.5 ±	1039.1 ±	1358.5 ±	1294.8 ±	1318.7 ±
		3.8 ⁸⁴⁻⁸⁷	5.4 ¹⁰³⁻¹⁰⁵	7.9 ¹⁰⁹⁻¹¹¹	3.7 ²⁵⁻²⁹	7.6 ⁴⁷⁻⁵³	5.0 ³⁵⁻⁴⁰
12	31.6	1086.0 ±	876.6 ±	723.9 ±	1297.3 ±	1179.3 ±	1101.1 ±
		10.4 ^{100,101}	6.9 ^{136,137}	7.9 ¹⁶²⁻¹⁶⁵	5.2 ⁴⁶⁻⁴⁹	8.9 ⁷⁸⁻⁸⁰	10.1 ⁹⁷⁻⁹⁹
	63.2	1132.5 ±	929.0 ±	767.2 ±	1325.3 ±	1212.9 ±	1276.1 ±
		3.4 ⁹⁰⁻⁹²	9.1 ¹²⁸⁻¹³⁰	6.4 ^{156,157}	8.6 ³⁴⁻³⁶	12.3 ⁷¹⁻⁷³	6.5 ⁵⁵⁻⁶⁰
	94.8	1165.7 ±	1010.0 ±	835.9 ±	1392.4 ±	1254.6 ±	1322.3 ±
		1.9 ⁸¹⁻⁸³	8.0 ¹¹⁷	4.3 ¹⁴³⁻¹⁴⁵	11.1 ¹³⁻¹⁷	6.6 ^{64,65}	9.2 ³⁵⁻³⁹
	126.4	1148.9 ±	1026.6 ±	976.5 ±	1409.2 ±	1323.5 ±	1353.6 ±
		12.0 ⁸⁶⁻⁸⁸	5.8 ¹¹²⁻¹¹⁵	8.4 ¹¹⁹⁻¹²¹	0.5 ⁵⁻¹¹	6.4 ³⁵⁻³⁷	6.7 ²⁷⁻³⁰
	158.0	1169.3 ±	1062.5 ±	1058.2 ±	1410.8 ±	1345.0 ±	1363.3 ±
		9.2 ⁸⁰⁻⁸²	3.1 ¹⁰³⁻¹⁰⁵	7.6 ¹⁰⁴⁻¹⁰⁷	8.2 ⁵⁻⁹	9.6 ³⁰⁻³²	7.2 ²⁴⁻²⁷

16	31.6	1083.7 ±	833.4 ±	714.9 ±	1388.0 ±	1325.9 ±	1300.1 ±
		7.9 ^{100,101}	8.5 ¹⁴⁴⁻¹⁴⁶	8.1 ¹⁶⁵⁻¹⁶⁷	5.4 ¹⁵⁻¹⁹	5.1 ³⁴⁻³⁶	6.0 ⁴³⁻⁴⁷
	63.2	1113.1 ±	903.1 ±	739.8 ±	1397.6 ±	1393.8 ±	1345.3 ±
		8.6 ⁹⁴⁻⁹⁶	4.7 ^{133,134}	8.2 ^{159,160}	5.5 ¹¹⁻¹⁶	3.6 ¹²⁻¹⁷	6.6 ³⁰⁻³²
	94.8	1130.4 ±	957.6 ±	869.7 ±	1405.1 ±	1397.7 ±	1348.0 ±
		7.8 ⁹¹⁻⁹³	5.1 ¹²⁴⁻¹²⁶	6.6 ^{137,138}	3.3 ⁷⁻¹²	6.7 ¹²⁻¹⁶	2.2 ²⁹⁻³²
	126.4	1169.6 ±	1013.5 ±	990.5 ±	1417.7 ±	1400.8 ±	1369.1 ±
		5.6 ⁸⁰⁻⁸²	2.9 ^{116,117}	4.5 ¹¹⁸	4.3 ²⁻⁵	8.1 ⁹⁻¹³	4.2 ²¹⁻²⁵
	158.0	1155.5 ±	1054.3 ±	1083.1 ±	1419.4 ±	1402.2 ±	1372.4 ±
		7.7 ⁸³⁻⁸⁷	2.7 ¹⁰⁴⁻¹⁰⁸	5.4 ¹⁰⁰⁻¹⁰²	12.1 ¹⁻⁵	6.1 ⁷⁻¹³	7.1 ²⁰⁻²³
20	31.6	1053.7 ±	840.3 ±	712.8 ±	1400.5 ±	1371.1 ±	1302.9 ±
		10.9 ¹⁰⁵⁻¹⁰⁸	9.4 ¹⁴²⁻¹⁴⁵	5.6 ¹⁶⁵⁻¹⁶⁸	13.5 ⁹⁻¹³	9.8 ²⁰⁻²³	14.2 ⁴²⁻⁴⁷
	63.2	1113.6 ±	912.2 ±	742.6 ±	1415.2 ±	1415.7 ±	1376.4 ±
		7.5 ⁹⁴⁻⁹⁶	7.2 ¹³¹⁻¹³³	6.5 ¹⁵⁹	5.4 ⁴⁻⁶	7.5 ⁴⁻⁶	7.2 ¹⁹⁻²³
	94.8	1115.6 ±	967.9 ±	822.9 ±	1420.0 ±	1416.1 ±	1378.5 ±
		6.8 ^{94,95}	9.7 ¹²²⁻¹²⁴	7.4 ¹⁴⁶⁻¹⁴⁸	9.9 ¹⁻⁵	9.6 ³⁻⁶	4.5 ¹⁸⁻²²
	126.4	1172.5 ±	1033.7 ±	971.7 ±	1413.3 ±	1427.9 ±	1382.8 ±
		10.6 ⁷⁹⁻⁸¹	8.2 ¹¹⁰⁻¹¹³	8.8 ¹²¹⁻¹²³	5.0 ⁵⁻⁷	7.2 ^{1,2}	8.5 ¹⁷⁻²⁰
	158.0	1157.1 ±	1065.4 ±	1078.2 ±	1414.5 ±	1430.7 ±	1388.5 ±
		2.1 ⁸³⁻⁸⁶	5.9 ^{103,104}	2.8 ^{101,102}	8.0 ^{5,6}	7.6 ¹	10.4 ¹⁴⁻¹⁸
4 mm hammer mill screen size							
8	31.6	954.6 ±	671.4 ± 9.6 ¹⁷⁰	615.9 ±	1065.1 ±	1195.1 ±	1155.2 ±
		7.8 ^{125,126}		10.2 ¹⁷³	8.1 ^{103,104}	9.7 ^{75,76}	13.1 ⁸³⁻⁸⁷
	63.2	1061.8 ±		705.2 ±	1230.0 ±	1205.9 ±	1182.2 ±
		6.4 ¹⁰³⁻¹⁰⁵		6.0 ¹⁵⁹⁻¹⁶²	7.6 ^{167,168}	7.8 ^{68,69}	12.3 ⁷³⁻⁷⁵
	94.8	1102.1 ±		797.9 ±	1294.8 ±	1221.2 ±	1224.8 ±
		7.3 ⁹⁶⁻⁹⁸		5.4 ^{140,141}	7.6 ^{152,153}	7.6 ⁴⁷⁻⁵³	14.1 ⁶⁹⁻⁷²
	126.4	1135.0 ±		925.6 ±	1339.4 ±	1258.1 ±	1253.3 ±
		6.9 ⁸⁹⁻⁹¹		12.1 ¹¹¹⁻¹¹⁴	8.4 ^{129,130}	2.5 ³¹⁻³³	7.8 ⁶⁴⁻⁶⁶
	158.0	1142.5 ±		947.5 ±	1364.6 ±	1295.8 ±	1299.5 ±
		10.7 ⁸⁸⁻⁹⁰		5.7 ¹⁰⁴⁻¹⁰⁸	3.2 ^{126,127}	8.6 ²⁴⁻²⁷	12.3 ⁴⁷⁻⁵²
12	31.6	971.4 ±	720.3 ±	645.9 ±	1164.0 ±	1253.0 ±	1089.3 ±
		5.2 ¹²¹⁻¹²³	7.9 ¹⁶³⁻¹⁶⁵	7.7 ^{171,172}	6.3 ⁸¹⁻⁸⁴	7.5 ^{65,66}	10.5 ⁹⁹⁻¹⁰¹
	63.2	1083.5 ±	803.7 ±	727.0 ±	1253.8 ±	1361.5 ±	1242.2 ±
		4.8 ¹⁰⁰⁻¹⁰²	6.9 ¹⁴⁹⁻¹⁵²	8.6 ¹⁶¹⁻¹⁶⁴	1.3 ^{65,66}	9.4 ²⁴⁻²⁷	5.1 ^{66,67}
	94.8	1104.3 ±	892.2 ±	812.3 ±	1366.6 ±	1400.1 ±	1284.3 ±
		5.2 ⁹⁵⁻⁹⁸	4.3 ^{134,135}	9.1 ¹⁴⁷⁻¹⁵⁰	12.2 ²⁴⁻²⁶	3.3 ⁹⁻¹⁴	11.1 ⁵¹⁻⁵⁸

539
540
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	126.4	1123.2 ±	1030.2 ±	903.1 ±	1382.6 ±	1411.7 ±	1299.3 ±
		7.4 ⁹²⁻⁹⁴	3.1 ¹¹¹⁻¹¹⁴	1.4 ¹³⁴	4.4 ¹⁷⁻²⁰	8.7 ⁵⁻⁹	6.1 ⁴⁴⁻⁴⁸
	158.0	1153.6 ±	1079.0 ±	952.6 ±	1401.2 ±	1415.8 ±	1303.4 ±
		6.9 ⁸⁴⁻⁸⁷	8.8 ^{101,102}	7.1 ^{125,126}	8.8 ⁹⁻¹³	4.3 ⁴⁻⁶	9.1 ⁴²⁻⁴⁷
16	31.6	962.8 ±	801.8 ±	689.0 ±	1282.7 ±	1268.2 ±	1142.9 ±
		9.9 ¹²³⁻¹²⁵	0.5 ¹⁵⁰⁻¹⁵²	8.7 ¹⁶⁹	4.9 ⁵⁴⁻⁵⁹	10.9 ⁶⁰⁻⁶³	11.2 ⁸⁸⁻⁹⁰
	63.2	1032.5 ±	844.8 ±	729.2 ±	1391.8 ±	1362.0 ±	1262.8 ±
		6.1 ¹¹¹⁻¹¹³	3.9 ¹⁴¹⁻¹⁴³	4.4 ¹⁶⁰⁻¹⁶⁴	14.6 ¹³⁻¹⁷	9.5 ²⁴⁻²⁷	6.5 ⁶¹⁻⁶⁴

Table 7. Model values obtained from Walker model (1923)

Screen size (mm)	Moisture content (%)	m ₁	z ₁	R ²	SSE*	m ₁	z ₁	R ²	SSE*
Untreated Corn stover					AFEX™ Corn stover				
2	8	-0.237	5.522	0.91	0.053	-0.097	2.872	0.98	0.008
	12	-0.199	4.805	0.94	0.036	-0.144	3.686	0.91	0.032
	16	-0.192	4.696	0.89	0.049	-0.032	1.583	0.94	0.005
	20	-0.181	4.481	0.93	0.035	-0.037	1.655	0.80	0.013
4	8	-0.103	2.779	0.96	0.015	-0.169	4.156	0.96	0.024
	12	-0.090	2.510	0.93	0.017	-0.126	3.307	0.96	0.017
	16	-0.096	2.616	0.97	0.011	-0.049	1.862	0.74	0.021
	20	-0.105	2.765	0.95	0.017	-0.010	1.108	0.75	0.004
8	8	-0.271	5.864	0.97	0.033	-0.158	3.971	0.95	0.023
	12	-0.185	4.288	0.99	0.008	-0.113	3.138	0.91	0.025
	16	0.134	3.332	0.98	0.010	-0.062	2.179	0.97	0.007
	20	-0.136	3.341	0.97	0.016	-0.034	1.624	0.97	0.003
Untreated Prairie cord grass					AFEX™ Prairie cord grass				
2	8	-0.257	5.808	0.99	0.014	-0.080	2.640	0.94	0.013
	12	-0.233	5.360	0.96	0.034	-0.096	2.883	0.92	0.019
	16	-0.230	5.308	0.96	0.033	-0.034	1.660	0.79	0.012
	20	-0.173	4.241	0.93	0.033	-0.026	1.470	0.89	0.006
4	8	-0.359	7.725	0.94	0.065	-0.055	2.176	0.86	0.016
	12	-0.285	6.284	0.97	0.035	-0.083	2.568	0.91	0.018
	16	-0.191	4.501	0.89	0.047	-0.074	2.386	0.95	0.012
	20	-0.179	4.276	0.96	0.024	-0.037	1.695	0.94	0.006
8	8	-0.235	5.567	0.95	0.037	-0.129	3.511	0.95	0.020
	12	-0.183	4.521	0.93	0.035	-0.077	2.517	0.90	0.018
	16	-0.203	4.941	0.89	0.052	-0.041	1.817	0.92	0.008
	20	-0.216	5.140	0.93	0.041	-0.010	1.233	0.64	0.005
Untreated Switchgrass					AFEX™ Switchgrass				
2	8	-0.223	5.204	0.91	0.050	-0.099	2.907	0.98	0.008
	12	-0.188	4.549	0.92	0.038	-0.146	3.740	0.91	0.033
	16	-0.183	4.472	0.89	0.047	-0.044	1.809	0.78	0.033

	20	-0.171	4.244	0.93	0.033	-0.024	1.398	0.89	0.006
	8	-0.372	7.918	0.97	0.045	-0.078	2.530	0.93	0.015
4	12	-0.328	7.020	0.97	0.041	-0.125	3.373	0.88	0.033
	16	-0.284	6.175	0.94	0.052	-0.108	3.016	0.95	0.017
	20	-0.279	6.096	0.93	0.055	-0.042	1.764	0.91	0.009
	8	-0.248	5.633	0.98	0.018	-0.117	3.248	0.96	0.015
8	12	-0.191	4.523	0.97	0.020	-0.078	2.497	0.90	0.018
	16	-0.180	4.311	0.98	0.016	-0.068	2.285	0.90	0.016
	20	-0.184	4.371	0.98	0.016	-0.068	2.278	0.96	0.009

*SSE - Sum of squared errors

Table 8 Model values obtained from Jones model (1960)

Screen size (mm)	Moisture content (%)	m ₂	z ₂	R ²	SSE*	m ₂	z ₂	R ²	SSE*
Untreated Corn stover					AFEX™ Corn stover				
2	8	0.067	5.802	0.89	0.017	0.148	4.416	0.98	0.014
	12	0.044	6.234	0.87	0.012	0.058	0.928	0.92	0.011
	16	0.045	6.198	0.91	0.010	0.014	0.954	0.95	0.002
	20	0.062	5.891	0.89	0.015	0.005	7.144	0.53	0.004
4	8	0.133	4.911	0.96	0.015	0.154	4.322	0.97	0.018
	12	0.101	5.144	0.94	0.017	0.122	4.947	0.96	0.017
	16	0.109	4.973	0.96	0.014	0.050	6.295	0.74	0.021
	20	0.121	4.753	0.95	0.020	0.010	7.052	0.75	0.004
8	8	0.277	1.764	0.98	0.022	0.140	4.541	0.97	0.018
	12	0.196	3.238	0.99	0.007	0.102	5.249	0.92	0.021
	16	0.151	4.096	0.98	0.014	0.059	6.051	0.97	0.006
	20	0.154	4.055	0.97	0.019	0.033	6.552	0.97	0.003
Untreated Prairie cord grass					AFEX™ Prairie cord grass				
2	8	0.220	2.838	0.99	0.008	0.068	5.862	0.94	0.012
	12	0.200	3.213	0.97	0.024	0.084	5.599	0.92	0.018
	16	0.155	4.057	0.94	0.027	0.033	6.623	0.79	0.012
	20	0.198	3.232	0.97	0.022	0.025	6.782	0.89	0.006
4	8	0.302	1.236	0.92	0.064	0.047	6.251	0.85	0.014
	12	0.258	2.079	0.95	0.041	0.077	5.815	0.91	0.016
	16	0.185	3.444	0.87	0.051	0.070	5.945	0.95	0.010
	20	0.176	3.621	0.95	0.027	0.036	6.574	0.94	0.006
8	8	0.183	3.290	0.93	0.035	0.108	5.124	0.96	0.015
	12	0.155	3.880	0.92	0.032	0.068	5.888	0.91	0.015
	16	0.145	4.004	0.83	0.044	0.038	6.471	0.92	0.007
	20	0.174	3.500	0.89	0.035	0.010	6.992	0.64	0.005
Untreated Switchgrass					AFEX™ Switchgrass				
2	8	0.198	3.097	0.89	0.040	0.088	5.505	0.98	0.007
	12	0.171	3.603	0.92	0.035	0.132	4.732	0.92	0.020

	16	0.163	3.717	0.88	0.044	0.033	6.601	0.94	0.005
	20	0.153	3.894	0.92	0.032	0.038	6.520	0.80	0.013
	8	0.326	0.734	0.94	0.056	0.070	5.823	0.92	0.014
4	12	0.312	1.038	0.94	0.052	0.112	5.081	0.89	0.014
	16	0.287	1.516	0.92	0.061	0.101	5.305	0.96	0.014
	20	0.282	1.598	0.90	0.068	0.043	6.415	0.92	0.007
	8	0.219	2.573	0.98	0.021	0.103	5.207	0.97	0.012
8	12	0.182	3.309	0.96	0.024	0.072	5.806	0.91	0.016
	16	0.171	3.505	0.98	0.013	0.071	5.857	0.91	0.014
	20	0.176	3.416	0.98	0.018	0.065	5.958	0.96	0.008

*SSE - Sum of squared errors

Table 9 Kawakita and Ludde (1971) model constant values

Screen size (mm)	Moisture content (%)	1/b (1/MPa)	a	R ²	SSE	1/b (1/MPa)	a	R ²	SSE
Untreated Corn stover					AFEX TM Corn stover				
2	8	3.251	0.897	0.99	0.94	2.371	0.863	1.00	0.19
	12	3.089	0.887	0.99	0.94	0.887	0.861	1.00	0.20
	16	3.341	0.878	0.99	0.99	0.253	0.853	1.00	0.06
	20	2.996	0.871	0.99	0.79	0.032	0.847	1.00	0.05
4	8	0.825	0.919	1.00	0.04	1.407	0.873	1.00	0.03
	12	0.769	0.917	1.00	0.11	1.136	0.859	1.00	0.17
	16	1.075	0.914	1.00	0.26	0.312	0.851	1.00	0.11
	20	1.207	0.910	1.00	0.30	0.067	0.847	1.00	0.02
8	8	2.035	0.938	1.00	0.07	1.918	0.909	1.00	0.04
	12	1.614	0.929	1.00	0.18	1.377	0.907	1.00	0.11
	16	1.383	0.923	1.00	0.25	0.934	0.900	1.00	0.09
	20	1.388	0.921	1.00	0.23	0.541	0.894	1.00	0.07
Untreated Prairie cord grass					AFEX TM Prairie cord grass				
2	8	5.659	0.842	0.99	0.72	1.786	0.827	0.99	0.51
	12	4.904	0.832	0.99	0.58	2.161	0.833	0.99	0.63
	16	3.962	0.822	0.99	0.94	0.448	0.828	1.00	0.11
	20	5.370	0.817	1.00	0.19	0.398	0.826	1.00	0.04
4	8	7.209	0.885	0.99	1.28	0.841	0.877	1.00	0.32
	12	5.892	0.877	0.99	1.33	0.738	0.884	1.00	0.08
	16	4.268	0.862	0.99	1.39	0.760	0.882	1.00	0.06
	20	3.971	0.858	0.99	0.89	0.425	0.878	1.00	0.08
8	8	2.728	0.903	0.99	0.78	1.024	0.900	1.00	0.10
	12	2.115	0.902	0.99	0.60	0.584	0.896	1.00	0.05
	16	2.684	0.897	0.99	0.79	0.298	0.898	1.00	0.03
	20	2.587	0.896	0.99	0.58	0.238	0.894	1.00	0.08
Untreated Switchgrass					AFEX TM Switchgrass				
2	8	4.572	0.868	0.99	1.31	1.341	0.869	1.00	0.27
	12	4.199	0.859	0.99	1.27	1.589	0.875	1.00	0.13

	16	4.428	0.851	0.99	1.31	0.436	0.865	1.00	0.08
	20	3.962	0.844	0.99	1.04	0.384	0.865	1.00	0.09
4	8	4.399	0.927	0.99	1.04	1.144	0.880	1.00	0.37
	12	4.184	0.925	0.99	0.95	1.186	0.877	1.00	0.17
	16	4.092	0.921	0.99	1.03	1.227	0.878	1.00	0.09
	20	4.494	0.916	0.99	1.33	0.462	0.872	1.00	0.03
8	8	2.379	0.920	1.00	0.42	0.965	0.903	1.00	0.08
	12	1.957	0.919	0.99	0.51	0.602	0.898	1.00	0.04
	16	1.745	0.913	1.00	0.31	0.554	0.897	1.00	0.06
	20	1.901	0.913	1.00	0.43	0.743	0.893	1.00	0.19

550 *SSE - Sum of squared errors

551