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Analysis of Corn Stover Structural Properties for Mechanical Processing Applications

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ABSTRACT

The research objective of this study is to examine the behavior of chopped corn stover biomass as it undergoes a variety of mechanical loading conditions. Biomass materials, including corn stover, have unique properties that make it challenging to effectively and efficiently feed into thermochemical conversion systems that produce biofuels and bioproducts. These properties include large particle size, fibrous structure, and low density, to name a few. The most common difficulty in creating a system like this for corn stover is plugging within mechanical and pneumatic feeding systems. It is hypothesized that the material properties of fibrous corn stover contribute to its flowability characteristics. By placing different corn stover samples under varying loading conditions, the spectrum of physical properties of this fibrous agricultural residue can be better understood to analyze these previous issues. First, several corn stalk samples were placed in a three-point bending apparatus in order to analyze the energy requirements to chop a stalk, as well as to obtain a quantitative value for the fiber strength and resistance. This is important to make chopping operations more efficient. Then, a bulk solid shearing test was performed in order to determine some of the fluid-like properties associated with chopped biomass, such as internal friction. This is one of the properties that lead to consistent plugging in a piping system. By combining these two tests with future studies, a material database can be created for fibrous corn stover in order to better understand their flow and feeding characteristics.

Keywords: biomass, corn stover, processing, conveyance, fiber strength, bulk solid, material properties.

INTRODUCTION

In the United States, approximately 10% of the transportation fuels currently in use are from renewable sources. However, most of these renewable sources come from food-based products, including corn and soybeans. Public demand for renewable energy from non-food sources, including agricultural residues and dedicated energy crops, has increased drastically. These sources are potentially valuable because of their relatively high energy content, as well as minimal effect on food production worldwide. The recent "Billion Ton Study" (1; 2), developed by the United States Department of Energy and United States Department of Agriculture, has been performed to estimate the United States' biomass potential based on future assumptions and advances in technology. The study set a goal of producing 16 billion gallons of cellulosic biofuels and 4 billion gallons of advanced biofuels every year. This amount would take the place of about 30% of the U.S. consumption of petroleum by 2030. With the rising cost and sustainability issues of petroleum, biofuels are a viable solution to these problems.

Agricultural residues, including corn stover, are the feedstocks of choice for biofuel production. Corn stover is an agricultural residue that consists of the leaves and stem of *zea mays*, and it is a prime source of cellulose, hemicellulose, and lignin (3). This chemical composition has resulted in this residue being viewed as a possible renewable resource to increase production of biofuels, biochemicals, and other bioproducts (4). With the rising cost of corn (up more than 7% since October 2011), the most corn was planted in 2012 than had been in the past 75 years (5). With this increasing supply of corn, this post-harvest residue has become a valuable supply of biomass, making corn stover an even more viable solution for the creation of biofuels and bioproducts.

Over the last century, agricultural equipment has been designed specifically for handling, transporting, and processing corn stover and other agricultural materials. However, systems that convert biomass feedstocks to biofuels at a large scale pose unique challenges. Research activities pertaining to biomass-to-biofuel conversion systems have focused on the logistics, economics, and viability of these processes at pilot and commercial scales (6;

7; 8; 9). Additionally, there have been studies that have focused on integrating logistics and process models for conducting economic analysis of these materials (10; 11). However, the research into understanding the effects of the structure of corn stover during chopping, shredding, and conveying operations has only yielded the difficulties and obstacles faced in creating efficient biomass feeding systems.

Biofuels have the potential to be an environmentally friendly option for energy, but feeding and handling systems have not yet been designed to make biomass processing efficient enough to be economically feasible. One of the main roadblocks in creating an effective and efficient continuous feeding system deals with plugging in pipes during biomass flows. This is especially prevalent in the use of thermochemical processes. In a thermochemical process, chopped biomass is fed into a reactor, which operates in an absence of oxygen at either high temperatures (200-400°C), or at high pressures if this temperature is not easily achieved (12; 13). In this reactor, the biomass decomposes to a point in which it loses its firm, fibrous structure. This allows it to be more efficient in combustion or gasification to produce byproducts, such as bio-oil, bio-char, and "syngas" (12; 14; 15; 16).

There have been many past problems with feeding the chopped biomass into these types of reactors continuously, and thus a constant-feeding apparatus has not yet been created (17; 18; 19; 20). High flow rates of biomass in a bulk solid form in rigorous operating conditions often causes conveyors or augers to become plugged. Additionally, some biomass processors have cited that the high temperatures emitted by the thermochemical processes will cause some of the biomass sample to react and combust outside of the reaction chamber, thus creating a safety issue around the reactor, as well as reducing the biofuel yield. These problems are due to the unique material properties of biomass in chopped, bulk form. Thus, there is a need for understanding flow characteristics of fibrous biomass materials for effective and efficient feeding into a high pressure or high temperature system so that a continuous feeding system can be designed and implemented.

Several material properties of biomass materials make it relatively difficult to feed into agricultural systems, especially those of the biochemical and thermochemical nature. Most notably, biomass materials such as corn stover are fibrous materials. Because of this, biomass is anistropic, which means that its strength depends on the orientation of the applied load relative to the fibers (21). The strength of the sample needs to be analyzed in all directions, as the material will be stronger in the direction parallel to the fibers and much weaker in the direction perpendicular to the fibers. Additionally, biomass materials are relatively soft compared to other common materials that are sent through a reactor. These particles have a high internal friction during movement, which causes them to tend to plug piping and conveyance systems. Several other factors have been listed that are the main contributors influencing the flowability of bulk solids and granular powders, including: moisture content, humidity, temperature, pressure, particle size, angle of repose, bulk density, and compressibility (22).

Corn stover is a composite material, thus meaning that it does not have a consistent material structure. Visual examples of this unique structure can be seen in Figure 14. It has an outer wall, called the sclerenchyma, which is the epidermal “skin” of the material, and an inner portion called the parenchyma, which is a complex matrix of “fibrils” (9). Fibrils are networks of interwoven cellulose fibers enclosed in a polymer liquid crystal made up of polysaccharides, lignin, and structural proteins (23). Thus, the inner fibrous matrix is what gives the corn stover sample the majority of its strength. Based on the variables of the overall structure of the composite corn stover, it has often been deemed too difficult to find their mechanical properties.

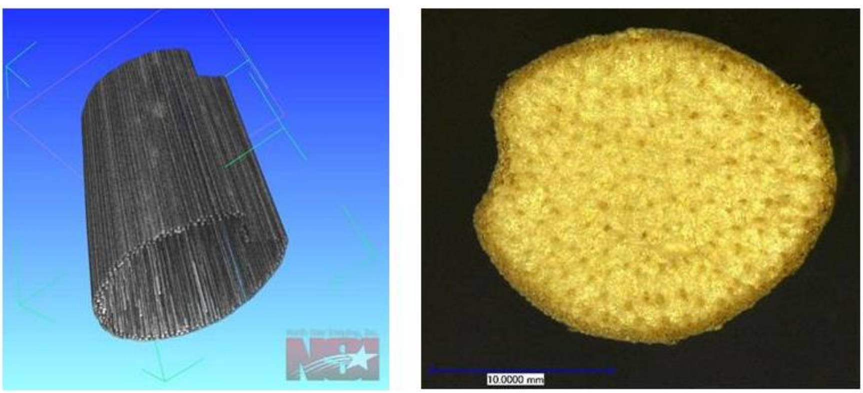

Figure 14. CT Reconstruction (left) and microscopic analysis (right) of corn stalk samples

This study is going to address two different parts of the corn stover processing system. First, this study investigates the loading and stresses incurred to chop corn stover. Three-point bending tests are a significant study of the bending resistance of a material when placed under a load. Thus, three-point loading could be placed on a corn stalk in order to find the maximum fiber bending resistance of the entire sample. Figure 15 shows a basic schematic of a three-point bending setup. Although corn stover is relatively soft, as noted before, it is also stronger than many of the species of woody biomass. Bending resistance would be able to quantify that strength and note the energy requirements to chop the material.

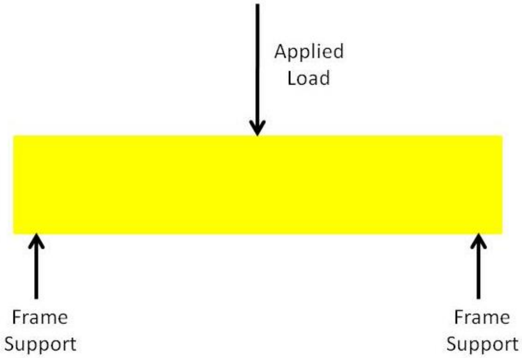

Figure 15. Force diagram schematic of a three-point bending test

The second part of this study investigates the flowability of chopped corn stover biomass in a post-processed function. Analyzing chopped biomass as a bulk solid has the capability to establish flow characteristics and fluid-like properties for a two-phase solid-gaseous flow. Thus, shearing a compressed bulk solid sample of particles would provide insight into the internal friction and viscosity of corn stover biomass as a packed bed. Some related tests have been performed on corn stover, switchgrass, wheat straw, and other types of biomass (24). However, these experiments have yet to be verified as an accurate, repeatable testing setup, so this research would aid in that aspect. Also, extended studies would attempt to quantify some of the most important properties of biomass flow and incorporate them into flow models in the future.

BACKGROUND

This project's main focus is on analyzing different stresses and strains placed on the sample being tested under a loading condition. The two main stresses used in loading situations are normal stress and shear stress. The two formulas are very similar, as can be seen in Equations 1 and 2.

$$\sigma = \frac{F_n}{A} \quad \text{(Eq. 1)}$$

Where: σ = normal stress

F_n = normal force

A = cross-sectional area perpendicular to applied normal force

$$\tau = \frac{F_s}{A} \quad \text{(Eq. 2)}$$

Where: τ = shear stress

F_s = shearing load

A = cross-sectional area perpendicular to shear force

Due to the fibrous composition of corn stover, the bending strength of the stalk in general is difficult to quantify. Some fibers will be placed under much more stress than others when placed in a three-point bending loading situation. However, the maximum bending resistance of the fibers can be analyzed for an individual stalk. The maximum fiber bending resistance is defined by the following:

$$\sigma_{max,bending} = \frac{F_{max} * \frac{L}{2} * c}{I} \quad \text{(Eq. 3)}$$

Where: $\sigma_{max,bending}$ = maximum fiber bending resistance

F_{max} = applied force at failure

L = length of sample

c = distance from central axis to application of maximum stress

I = second moment of inertia

Since corn stover has a non-standard shape with an outer layer of stalk (Figure 14), the second moment of inertia is calculated from the following equation.

$$I = \frac{\pi}{4}(b_{out} * a_{out}^3 - b_{in} * a_{in}^3) \quad \text{(Eq. 4)}$$

Where: I = second moment of inertia

b and a = respective distances

out = to the outer edge of the stalk

in = to the inside edge of the outer stalk layer

One important characteristic when it comes to classifying solids in a multi-phase flow is the internal friction. This is a mechanical property that can help to establish how particles interact with each other and analyze the forces needed to overcome plugging within a conveyance or piping system. The equation to calculate the internal friction coefficient in a bulk solid shearing situation can be found in Eq. 5:

$$\mu = \frac{F_s}{F_n} \quad \text{(Eq. 5)}$$

Where: μ = internal friction coefficient

F_s = shearing force at failure

F_n = normal force applied to specimen

Two of the important material characteristics that were used based upon prior research (24) in testing of bulk solid biomass include the angle of internal friction and cohesion. These characteristics can be established using the Mohr-Coulomb failure criterion, which uses normal and shear stress on a load cell to find these values:

$$\tau = \sigma \tan(\theta) + c \quad \text{(Eq. 6)}$$

Where: τ = shear stress

σ = normal stress

θ = angle of internal friction

c = cohesion

These values will not necessarily be applied to biomass flow, but will be used as a self-check of the data obtained in this experiment compared to that of prior similar experiments.

EXPERIMENTAL STUDIES

Three-Point Bending

Three-point bending tests were performed on corn stalks in order to see the physical properties of biomass on a macroscopic scale. The test applied a load at a constant linear velocity on the center of a corn stalk and noted the point in which the specimen failed. The loading rates selected were anywhere between 4 mm/min to 8 mm/min. The apparatus used for these tests can be seen in Figure 16.

Figure 16. Three-point loading apparatus

Tests were run using various diameters of specimen in order to analyze what kind of an effect that would play on the strength of the stalk. When running these tests, the maximum bending fiber resistance was measured, which is a physical property that can describe the strength of the material. Bending fiber resistance is a significant piece of the corn stover material property spectrum that needs to be understood in order to design more efficient biomass processing and chopping systems.

Bulk Solid Shearing

Another device was designed for shear strength and stress testing, following the ASTM standard testing procedure for soil (D3080/D3080M-11). This test was adapted in order to test many of the same bulk fluid properties of chopped corn stover, such as shear stress and viscosity, showing a link between how granular materials can have fluid-like properties. In this device, the chopped corn stover sample was placed in a container with a sliding top.

The container's top was pulled at various speeds in order to separate the sample, simulating the particles flowing and encountering an obstacle. The design of this model can be seen in Figure 17.

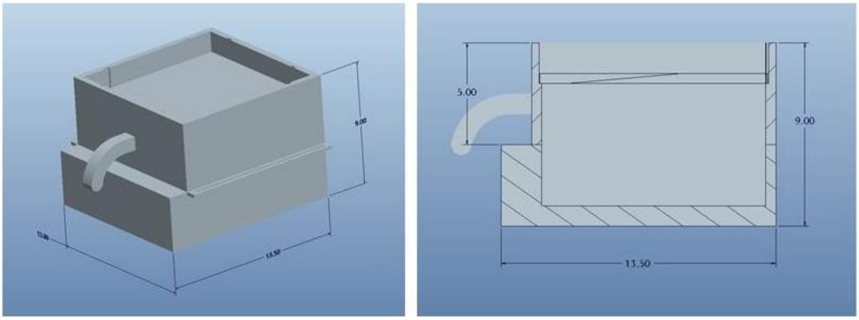

Figure 17. Pro-Engineer model of the shear stress testing device, the models shown are an isometric view (left) and a cross-sectional view (right)

All of these tests were done using the Material Testing System (MTS®) machine in the Material Evaluation and Testing Laboratory (METLAB). The experimental setup of one of the tests can be seen in Figure 18. After the shear box was filled with chopped corn stover, different normal stress loads were placed on the top of the box in order to compress the sample. Two different preconsolidation pressures were used in order that the sample could be considered a bulk solid. These pressures were selected to be either 4.06 kPa or 5.41 kPa. Ten tests were then run for each preconsolidation pressure, using various reduced normal pressures during the testing. These testing pressures varied from 1.35 kPa to 5.41 kPa.

Then, the MTS machine was used to apply a constant rate of pulling to the system to slide the top portion of the shear cell. The rate selected for all of the tests was 9 mm/min. The selection of weight, pulling rate, and other initial settings were established based on a similar test performed by Chevanan *et al* (24).

As this machine applied a load to the system, it registered the shear load based on the box displacement computationally. These were then analyzed and interpreted in order to obtain the desired data from the experiments. The most important parameters that this test analyzed included internal friction, angle of internal friction, and cohesion.

Figure 18. Experimental setup of bulk shearing test

RESULTS AND DISCUSSION

Three-Point Bending

Thirty samples were put through flexure testing using the three-point bending apparatus. Figure 19 shows a subset of the tested samples.

Figure 19. Selected specimens after three-point bending tests

Previously, the cross-sectional area for each specimen was found using an extracted area from microscopic analysis. The microscope used had the capabilities of performing a JMP regression in order to calculate an accurate cross-sectional area, which is difficult to physically measure due to the oval shape of basic corn stover.

Using these cross-sectional area values, the maximum fiber bending resistance was calculated for each sample using the stress calculations noted in Equation 3. The samples were separated into “large” diameter samples and “small” diameter samples. The “small” diameter samples had cross-sectional areas ranging from 10.21 mm^2 to 29.16 mm^2. The “large” diameter samples were deemed to be any specimen with a cross-sectional area larger than 30 mm^2, with the largest sample tested measuring at 115.4 mm^2. This separation was made after the data was initially analyzed and a large difference between the stresses was found at this point. It was theorized that this occurred because of the way that larger samples failed compared to smaller samples. Larger samples compressed much more before failure, whereas the smaller samples compressed relatively little before fiber fracture. Figure 20 shows the data for each test performed.

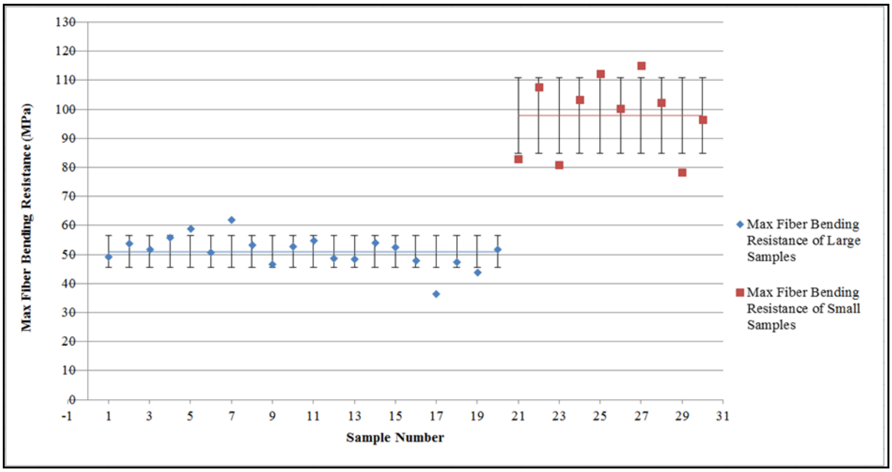

Figure 20. Maximum fiber bending resistance results for three-point bending tests

Based on these results, averages were taken for each type of sample. The "large" diameter samples had an average maximum fiber bending resistance of 50.98 MPa, and the "small" diameter samples had an average maximum fiber bending resistance of 97.83 MPa. This is a notable difference that must be taken into account when further analyzing the material properties of corn stover.

Bulk Solid Shearing

The most basic data taken from this experiment was the output of the MTS machine monitoring shear load and shear stress against the shear box displacement. A sample of these graphs using the normal stress of 4.05kPa can be seen in Figure 21. Also, a graph of the shear stress against the applied normal stress for every test was created. The data points from this experiment were compared to data obtained in a previous similar experiment (24) for validation. Figure 9 shows this comparison. The linear trends were relatively similar, but this experiment output shear stress values consistently lower than the prior experiment. This could be attributed a systematic error in the slight differences between the testing procedures and setups.

Using the values of the normal load and the shear load at failure, an internal friction coefficient was determined using the calculations in Equation 5. A graph of all of the data points for these tests can be seen in Figure 23. The average internal friction of all of these tests was 1.07 N/N. The graph of all of the data shows a relatively close correlation between each different test, thus this average can be assumed to be a relatively accurate value for other similar chopped corn stover samples.

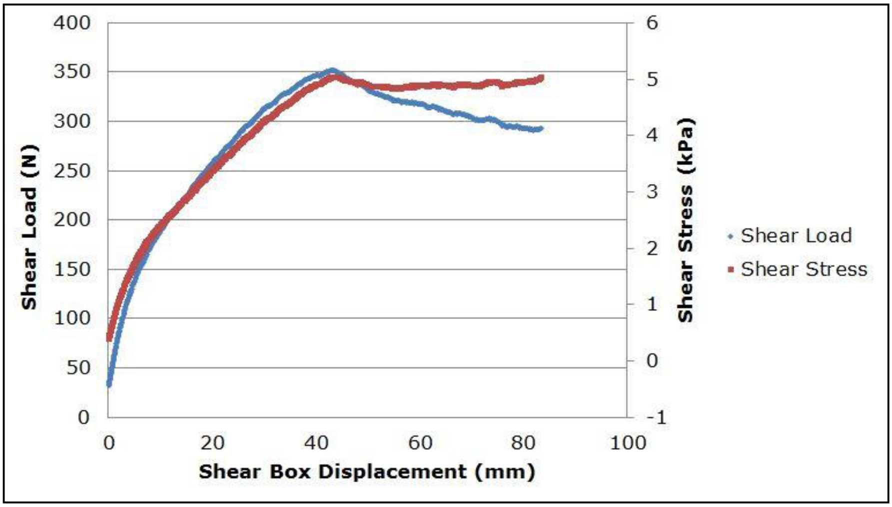

Figure 21. Shear load and stress versus shear box displacement

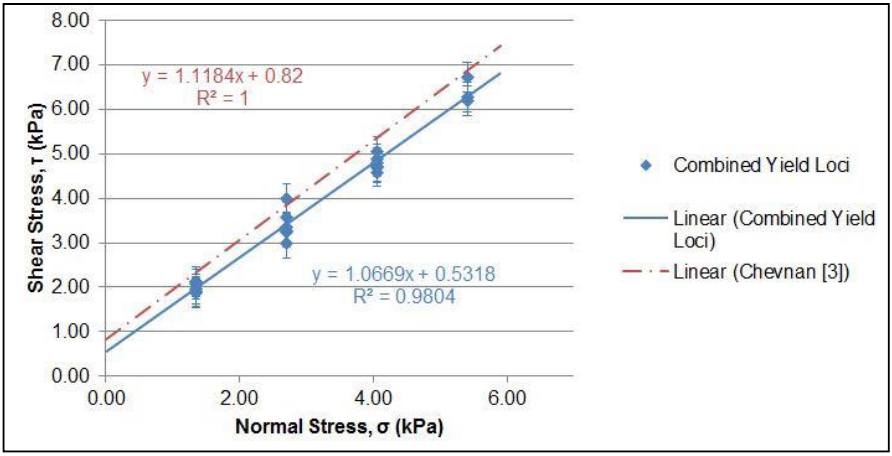

Figure 22. Shear stress versus normal stress comparison between similar experiments

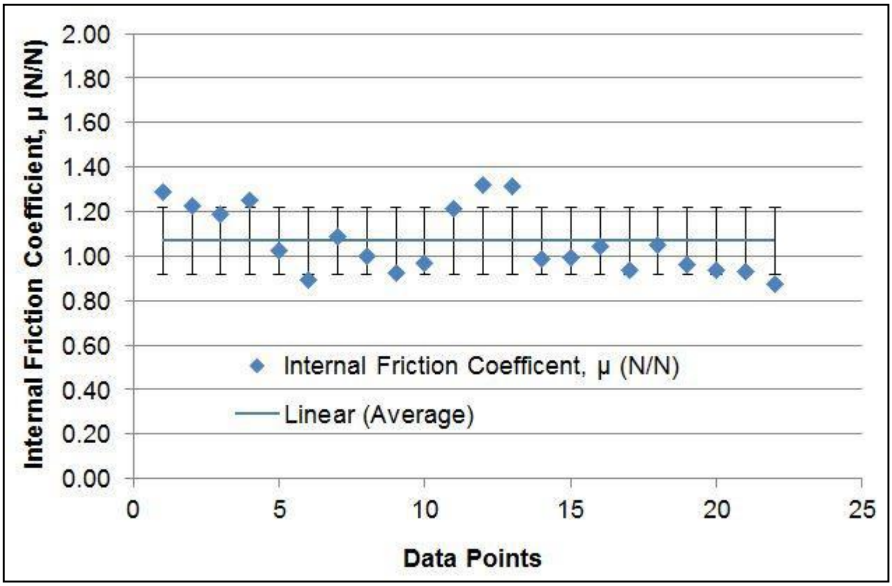

Figure 23. Internal friction coefficient for each test

As another check to see the validity of the testing procedure between this experiment and Chevanan et al. (24), the angle of internal friction and cohesion were found and compared to that prior test. These were all done using the calculations in Equation 6. A culmination of all of the data for each preconsolidation pressure and comparison to the prior experiments can be found in **Error! Reference source not found.**.

Situation	Linear Regression Slope, tan(ϕ) (kPa/kPa)	Angle of Internal Friction, ϕ (°)	Cohesion (kPa)
Preconsolidation Pressure, 4.05 kPa	1.08	47.12	0.52
Preconsolidation Pressure, 5.40 kPa	1.02	45.52	0.62
Combined Data	1.07	46.85	0.53
Data from Chevanan *et al*. (24)	1.12	48.20	0.82

Table 4. Shear stress effect tests

Based on these values, there are again minor deviations between this test and prior tests completed, but this appears to be a similar systematic error similar to the internal friction analysis. Thus, it was deemed that this kind of test is a repeatable test that could be performed for many different types of biomass materials.

CONCLUSIONS

For the three-point bending testing, the smaller diameter samples were noted to have much more resistance to bending, resulting in an average value of 97.83 MPa. This was compared to the average value of 50.98 MPa for the maximum fiber bending resistance of the larger samples. This data could provide to be valuable in further investigation of chopping operations of corn stover to make the process quicker and more efficient.

In the bulk solid shearing experiment, numerous data points found within the testing were compared to Chevanan *et al* (24). This was done in order to determine whether the testing method proposed was valid. The data found in this experiment was considered repeatable and noted to be a validation of the similar tests. An average value of 1.07 N/N for the internal friction coefficient was found. The internal friction coefficient has been determined to be one of the most important material characteristics when it comes to chopped solids in a multiphase flow, so this data must be interpreted further to overcome any difficulties in conveyance of chopped corn stover. Angle of internal friction and cohesion were two other material properties also analyzed, and the results were similar to those in Chevanan *et al* (24). This further added to the validation of this testing procedure for other biomass materials.

FUTURE WORK

For the three-point bending test, future research will be done to analyze why there was such a large difference in the maximum fiber bending resistance when the sample cross-sectional area changed to just over 3.000E-5 m^2. Structural analysis could be conducted as to why larger samples compressed noticeably more before failure than the smaller samples. Also, further testing and validation of these results must be completed before the test can be considered repeatable.

An extension of the three-point bending tests in this experiment was in dealing with the application of computational analysis in comparison of an experimental three-point bending test using Finite Element Analysis (FEA) software. The program Pro-Engineer Mechanica can be used to mirror the experimental three-point bending test computationally. Some experimental tests were performed for validation of this as a possible extended study, using a combination of material property ranges established for other similar biomass materials. Prior research has found general characteristics and property ranges associated with similar biomass materials, such as sunflower stalk pith (25) and cotton stalk (26). Thus, these ranges were used as starting values.

The analysis for this experiment dealt with stalk displacement, maximum principal stress, and maximum principal strain. The results of a 4.5 kg_f load case can be seen in Figure 24. The next step in this research project is to take any experimental data for material properties of corn stover and put them into the Pro-Engineer Mechanica database in order to run a more accurate model and validate it against the experimental tests.

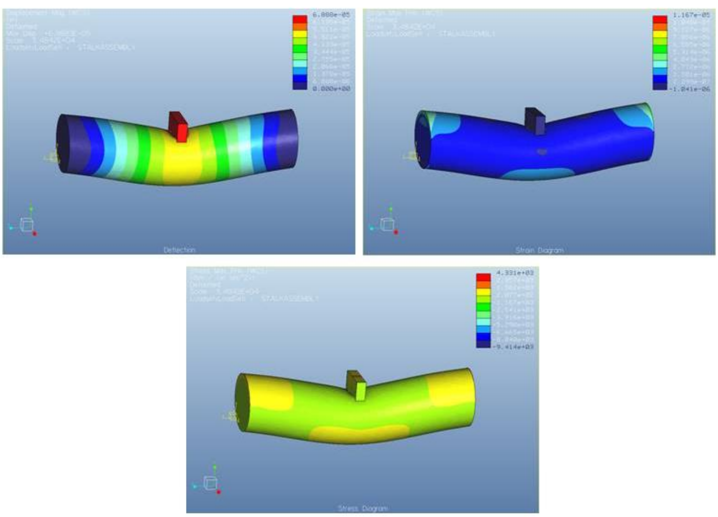

Figure 24. Three-point bending FEA results: displacement (top left), maximum principal strain (top right), and maximum principal stress (bottom)

Since the bulk solid shearing tests were done to mimic prior tests performed and validate their results, the further testing will deal with the results and calculating further fluid property values of the chopped solid, such as viscosity. Also, in order to more accurately simulate flow through a piping system, the pulling speed of the MTS machine will be increased far beyond the 9 mm/min rate used. Though this slow rate is beneficial for establishing certain material properties, it is unrealistic for properties simulated in pipe flow.

As an extension of this bulk shearing experimental test, certain computational modeling can be done to correspond to these tests. FEA and CFD models can be created to analyze these tests using CT scanning capabilities. The first step in performing any of these computational tests is to accurately import a CAD model for manipulation. These three-dimensional reconstructions (Figure 25) created by a CT scan machine in the METLAB showed that high fidelity models can be made using this equipment. With the use of further software packages, point cloud data could be generated and imported into a CAD interface to create a workable model. A CAD model could then be used in a multitude of other aspects, including CFD and FEA models in order to actually analyze a flow system with this material.

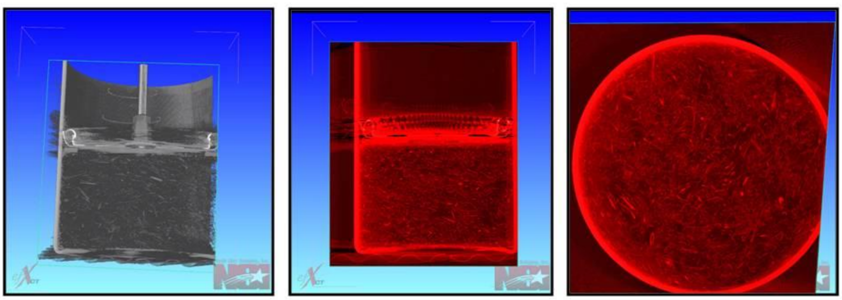

Figure 25. CT reconstructions of biomass undergoing compressive loading, two front views (left and center) are shown, as well as a top view (right)

It has been theorized that this overall project can extend beyond the scope of the industries of biofuels. Notable research has been performed dealing with similar tests on spherical substances that have small particle sizes and high bulk densities (27; 28; 29). However, relatively few materials fall under these characteristics. There is little research done on nonspherical materials with large particles and low bulk densities, as this project attempts to specifically investigate these materials. Not only do cotton stalk, corn stover, and other types of biomass relate to these sorts of testing, but other areas could be influenced as well. Just as the importance of this research relates to conveyance of biomass through a tube or pipe system, the data obtained could be extended to woody residues, municipal refuse, algae, paper, pharmaceuticals, and even blood flow. Numerous types of pressurized flows could be influenced by this project.

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REFERENCES

[1] Perlack, R., Wright, L., Turhollow, A., Graham, R., Stokes, B., and Erbach, D., 2005, “Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply,” U.S. Department of Energy, Oak Ridge, TN.

[2] Perlack, D., and Stokes, B., 2011, “U.S. Billion-Ton Update: Biomass Supply for a Bioenergy and Bioproducts Industry,” U.S. Department of Energy, Oak Ridge, TN.

[3] Rubin, E., 2008, "Genomics of Cellulosic Biofuels," Nature, **454**, pp. 841-845.

[4] Gao, J., Qian, L, Thelen, K., Hao, X., da Costa Sousa, L., Lau, M., Balan, V., and Dale, B., 2011, "Corn Harvest Strategies for Combined Starch and Cellulosic Bioprocessing to Ethanol," Agronomy Journal, **103**(3) pp. 844-850.

[5] Polansek, T., and Abbott, C., 2012, “U.S. Farmers Plan to Plant the Most Corn in 75 Years,” Reuters News, pp. 2-4.

[6] Abodeely, J., McCorkle, D., Bryden, K., Muth, D., Wendt, D., and Kenney, K., 2010, "Integration of Feedstock Assembly System and Cellulosic Ethanol Conversion Models to Analyze Bioenergy System Performance," Idaho National Laboratory, Idaho Falls, ID.

[7] Sokhansanj, S., Turhollow, A., Tagore, S., and Sudhagar, M., 2006, "Integrating Biomass Feedstock with an Existing Grain Handling System for Biofuels," *ASABE Annual International Meeting,* ASABE, Portland, OR.

[8] Tumuluru, J.S., Wright, C., Kenney, K., and Hess, J.R., 2010, "A Technical Review on Biomass Processing: Densification, Preprocessing, Modeling, and Optimization," *ASABE Annual International Meeting,* ASABE, Pittsburgh, PA.

[9] Wright, C., Pryfogle, P., Stevens, N., Hess, J.R., and Radtke, C., 2006, "Value of Distributed Preprocessing of Biomass Feedstocks to a Bioenergy Industry," *ASABE Annual International Meeting,* ASABE, Portland, OR.

[10] Searcy, E., Flynn, P., Ghafoori, E., and Kumar, A., 2007, "The Relative Cost of Biomass Energy Transport," Applied Biochemistry and Biotechnology, **136-140**, pp. 1-14.

[11] Thorsell, S., Eppelin, F., Huhnke, R., and Taliaferro, C., 2004, "Economics of a Coordinated Biorefinery Feedstock Harvest System: Lignocellulosic Biomass Harvest Cost," Biomass & Bioenergy, **27**, pp. 327-337.

[12] Bergman, P., and Kiel, J., 2005, "Torrefaction for Biomass Upgrading," Energy Research Centre of the Netherlands, Petten, Netherlands.

[13] Pimchuai, A., Dutta, A., and Basu, P., 2010, "Torrefaction of Agriculture Residue to Enhance Combustible Properties," Energy Fuels, **24**, pp. 4638-4645.

[14] Abdullah, H., and Wu, H., 2009, "Biochar as a Fuel: 1. Properties and Grindability of Biochars Produced from the Pyrolysis of Mallee Wood under Slow-Heating Conditions," Energy and Fuels, **23**, pp. 4174-4181.

[15] Mullen, C., 2010, "Bio-oil and Bio-char Production from Corn Cobs and Stover by Fast Pyrolysis," Biomass and Bioenergy, **34**, pp. 67-74.

[16] Roos, C., 2009, "Clean Heat and Power Using Biomass Gasification for Small- to Medium-Scale Industrial and Agricultural Projects," Northwest CHP Application Center, Olympia, WA.

[17] Boyd, T., 2011, "Mass and Energy Balance for Torrefied Pellet Production," NORAM, Vancouver, British Columbia.

[18] Ferrell, J., 2009, "2009 Biomass Program Peer Review Report: An Independent Evaluation of Program Activities for FY2008 and FY2009," U.S. Department of Energy, Washington, D.C.

[19] Madrali, S., 2011, "Overview of Torrefaction Activities in Canada." CanmetENERGY, Ottowa, Ontario.

[20] Wild, M., 2011, "The Ratio Behind Torrefaction," Wild and Partner KG, Appenzell, Switzerland.

[21] McEnteggart, I., 2010, "Composites: Physical Testing Solutions," Advanced Materials and Processes, pp. 26-27.

[22] Ganesan, V., Rosentrater, K.A., and Muthukumarappan, K., 2008, "Flowability and Handling Charactersitics of Bulk Solids and Powders- A Review with Implications for DDGS," Biosystems Engineering, **101**, pp. 425-435.

[23] Ding, S., and Himmel, M., 2006, "The Maize Primary Cell Wall Microfibril: A New Model Derived from Direct Visualization," Journal of Agricultural and Food Chemistry, **54**, pp. 597-606.

[24] Chevanan, N., Womac, A., Bitra, V., Yoder, D., Sokhansanj, S., 2009, "Flowability Parameters for Chopped Switchgrass, Wheat Straw, and Corn Stover," Powder Technology, **193**, pp. 79-86.

[25] Du, Z., and Sun, X., 2010, "The Preparation and Performance of Biomass Cushioning Packaging Material Prepared by Sunflower Stalk Pith," Advanced Materials Research, **113-114**, pp. 1468-1471.

[26] Nickerson, R.F., 1940, "Cotton Fibers: Constitution, Structure, and Mechanical Properties," Industrial and Engineering Chemistry, **32(**11), pp. 1454-1462.

[27] Abdullah, E.C., and Geldart, D., 1999, "The Use of Bulk Density Measurements as Flowability Indicators," Powder Technology, **102**(2), pp. 151-165.

[28] Fisher, R., 1971, "Features of Coarse-Grained, High-Concentration Fluids and Their Deposits," Journal of Sedimentary Research, **41**(4), pp. 916-927.

[29] Mattsson, J., and Kofman, P., 2002, "Method and Apparatus for Measuring the Tendency of Solid Biofuels to Bridge over Openings," Biomass and Bioenergy, **22(**3), pp. 179-185.