Biomass Flow Mechanical Properties Characterization

Hojae Yi [1], Virendra M. Puri[1], Christopher Lanning[2], and James H. Dooley[2]

[1]The Pennsylvania State University

[2]Forest Concepts, LLC.

ASABE 2020

Introduction

- Unreliable handling of biomass is widely observed in plants using milled biomass.
- Flow behavior of bulk solids is manifestation of mechanical interactions between the particulate material and a handling equipment (Prescott & Barnum, 2000).
- Overall, the current issue of unreliable biomass handling is contributed both by the limitation of characterization method and by the use of inappropriate analytical biomass flow models.
- This study aims to show the use of a true triaxial tester in characterizing bulk biomass flow behavior.

Materials

- Crop residue and woody biomass samples are studied.

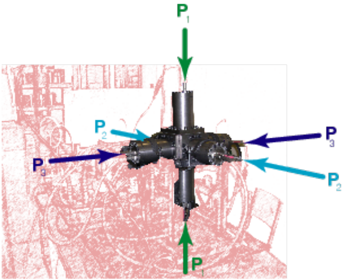
Corn stover is a crop residue that is estimated to be more than three-fourth of primary crop residues, which are profitable to collect (Perlack *et al.*, 2011; USDOE, 2011)

- Difficulties in handling is an obstacle in establishing corn stover as profitable and reliable biomass.
- Oven-dried corn stover are nominally sized 2 mm rotary-sheared and screened using Crumbler (Forest Concepts LLC.)

Douglas fir is a common softwood in Northwest US with better handling characteristics.

- Fuel-grade Douglas fir chips are nominally sized 1 mm rotary-sheared and screened using Crumbler (Forest Concepts LLC.)

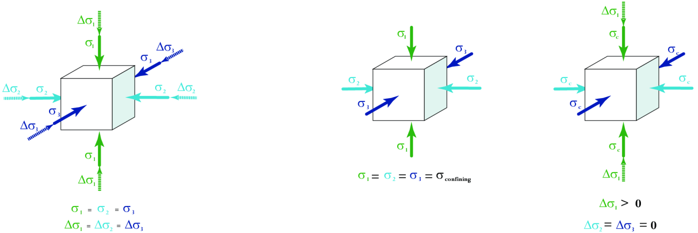
Cubical Triaxial Tester



- The Cubical Triaxial Tester (CTT) has a cubical cavity at the center to house a test specimen.
- The cubical test specimen is subjected to 3 orthogonal pressures simulating 3 principal stresses during the tests.
- Because the CTT uses flexible membranes for the sample holding and the application of the pressure, the die-wall friction effect on the sample is considered minimal.

Triaxial Tests

- The advantages and versatility of the CTT lies in its reproducibility and ability to perform any tests with proportional stress paths among principal stresses.
- Two types of triaxial tests are conducted to determine biomass flow model parameters, namely the hydrostatic trixial compression (HTC) test and the conventional triaxial compression (CTC) test.



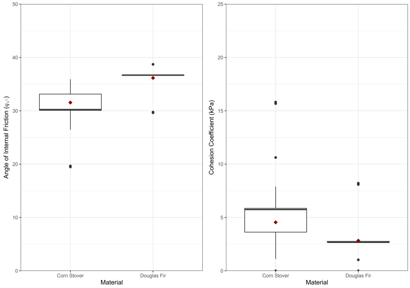
Determination of Biomass Flow Model Parameters

- The characterization protocol of shear-cell tests entails the misalignment between force-displacement measurement direction and theoretical framework of a constitutive model (Schwedes, 2003).
- This study uses the CTT in characterizing the flowability of milled biomass to establish the conformity of a measurement protocol with the first principle-based material model to calibrate.
- A set of HTC and CTC tests with the CTT are used in determining parameters of widely used elastoplasticity models including Mohr-Coulomb model, Drucker-Prager/Cap model, and modified Cam-clay Model.

Biomass Flow Models: Mohr-Coulomb Model

- Mohr-Coulomb model is a basis of widely used Jenike's approach in predicting a hopper flow (Jenike, 1961, 1964, 1967).
- A flow of bulk material is defined by a straight line in the normal stress (σ) and shear stress (τ) plane with a slope of ϕ, which is angle of internal friction, and the shear stress intercept (c), which is cohesion coefficient.

$$\tau = c + \sigma \tan \phi$$



- ϕ is larger for Douglas fir 2 mm than Corn stover 1 mm.
- c is higher for corn stover 2 mm than Douglas fir 1mm.

Biomass Flow Models: Drucker-Prager/Cap Model I

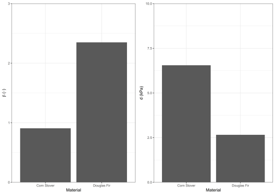
- Drucker-Prager model (Chen, 1994; Dimaggio & Sandler, 1971; Drucker & Prager, 1952) comprises a straight failure envelope defined on a plane with the hydrostatic stress axis and deviatoric stress axis.
- An advantage of the CTT over a shear-cell type tester is that the consolidation stress is maintained at the same level for all three principal axes.

$$F_1 = \sqrt{J_2} - \beta I_1 - d$$

, where J_2 is the second invariant of a deviatoric tensor and I_1 is the first invariant of a Cauchy stress tensor, and β and d are positive material parameters. β and d are analogous to ϕ and c in the Mohr-Coulomb envelope.

- From the results of CTT tests with different consolidation stresses, the I_1 and J_2 at failure can be directly estimated using principal stresses.

Biomass Flow Models: Drucker-Prager/Cap Model II



Drucker-Prager/Cap envelopes of air-dired Cornstover 2mm and Douglas Fir 1mm

- The slope (β) of the Drucker-Prager envelop is higher for Douglas fir 1 mm than Corn stover 1 mm.
- The intercept of Drucker-Prager envelope (d) is higher for corn stover 2 mm than Douglas fir 1mm.
- It is notable that the trend of coefficients of Drucker-Prager envelope is the same as Mohr-Coulomb model parameters.

Biomass Flow Models: modified Cam-Clay Model I

- Modified Cam-Clay model (Chen, 1994; Roscoe & Burland, 1968; Schofield & Wroth, 1968) is based on the critical state theory (Schofield & Wroth, 1968).

$$f = M^2 I_1^2 - M^2 I_1 I_{01} + 27 J_2^2$$

, where I_1 is hydrostatic stress (pressure) and I_{01} is an applied consolidation pressure.

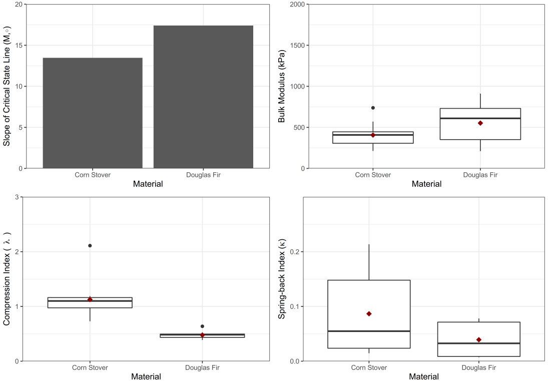
- The cap is defined with the compression index (λ) and spring-back index (κ), which are the slope of the hydrostatic consolidation line and the hydrostatic swelling line on the $e - \ln p$ plane, respectively.

$$d\varepsilon_v^p = \left(\frac{\lambda - \kappa}{1 + e_0} \right) \frac{dI_{01}}{I_{01}}$$

, where e_0 is the initial void ratio.

- λ and κ can be directly obtained from HTC test results representing the relationship between the void ratio and $\log I_1$.

Biomass Flow Models: modified Cam-Clay Model II



- The bulk modulus (K) indicating the stiffness of the bulk biomass is higher for Douglas fir 2 mm.
- The Compression index (λ) and Spring-back index (κ) are higher for the Corn stover 1 mm.

- Overall, Corn stover 1 mm is softer (smaller K) while it compresses more (larger λ) and expand more (larger κ) than Douglas Fir 2 mm.
- In summary, bulk Corn stover 1 mm will experience larger degree of volumetric changes than Douglas Fir 2 mm during handling under similar stress conditions.
- Therefore, it is intuitive to deduce that Corn stover 1 mm will be more difficult to handle.

Conclusion

- Penn State's Cubical Triaxial tester (CTT) is used in characterizing the mechanical responses of bulk Corn stover and Douglas Fir.
- Using the three-dimensional stress and strain in principal directions obtained from HTC and CTC tests, parameters of Mohr-Coulomb, Drucker-Prager/Cap, and modified Cam-Clay models are determined.
- Owing to the true three-dimensionality of the test results and coincidence with the theoretical framework of analytical models, the parameter determination procedure is unambiguous.
- Owing to the minimized die-wall effect in the test results, the obtained bulk biomass mechanical properties are believed to reflect truer biomass flow behavior.
- Utilizing CTT will overcome the existing gap in engineering practices of biomass handling and highlight shortcomings of theoretical limitations of biomass flow models.

Acknowledgment I

This work was supported by the Department of Energy under Grant DE-EE0008254 and partially supported by USDA NIFA Agricultural Experiment Station project PEN-4601.

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

USDA NIFA

United States Department of Agriculture
National Institute of Food and Agriculture

References I

Chen, W.-F. (1994). *Constitutive equations for engineering materials Volume 2: Plasticity and Modeling* (Rev. ed, Vol. 2). Elsevier.

Dimaggio, F. L., & Sandler, I. S. (1971). Material Model for Granular Soils. *Journal of Engineering Mechanics*.

Drucker, D. C., & Prager, W. (1952). Soil mechanics and plastic analysis or limit design. *Quarterly of Applied Mathematics*, *10*(2), 157–165.

Jenike, A. W. (1961). Gravity Flow of Bulk Solids, Bulletin No. 108. *Bulletin of the University of Utah*, *52*(29), 322.

Jenike, A. W. (1964). Storage and Flow of Solids, Bulletin No. 123. *Bulletin of the University of Utah*, *53*(26), 198.

Jenike, A. W. (1967). Quantitative design of mass-flow bins. *Powder Technology*, *1*(4), 237–244.

Perlack, R. D., Eaton, L. M., Turhollow Jr, A. F., Langholtz, M. H., Brandt, C. C., Downing, M. E., Graham, R. L., Wright, L. L., Kavkewitz, J. M., Shamey, A. M., et al. (2011). US billion-ton update: Biomass supply for a bioenergy and bioproducts industry.

Prescott, J. K., & Barnum, R. A. (2000). On powder flowability. *Pharmaceutical Technology; Cleveland*, *24*(10), 60–82.

Roscoe, K. H., & Burland, J. B. (1968). On the Generalized Stress-Strain Behavior of Wet Clay.

Schofield, A., & Wroth, P. (1968). *Critical state soil mechanics*. McGraw-Hill.

Schwedes, J. (2003). Review on testers for measuring flow properties of bulk solids. *Granular Matter*, *5*(1), 1–43.

References II

USDOE. (2011). *U.s. billion-ton update: Crop residues and agricultural wastes.*