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## Biomass Flow Mechanical Properties Characterization

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- 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.

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## 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.

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- 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.

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#### 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.

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



- $\phi$  is larger for Douglas fir 2 mm than Corn stover 1 mm.
- *c* is higher for corn stover 2 mm than Douglas fir 1mm.

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## 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  $\beta$  and d are positive material parameters.  $\beta$  and d are analogous to  $\phi$  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.

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## 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.

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## Biomass Flow Models: modified Cam-Clay Model I

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

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

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

• The cap is defined with the compression index  $(\lambda)$  and spring-back index  $(\kappa)$ , 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.

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•  $\lambda$  and  $\kappa$  can be directly obtained from HTC test results representing the relationship between the void ratio and  $\log I_1$ .

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## 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  $(\lambda)$  and Spring-back index  $(\kappa)$  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.

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## 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.

Yi et al. (Penn State)



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