INL/CON-18-51590-Revision-0

Real-time, In-line Assessment of Flow Performance for Compressible and Anisotropic Bulk Solids

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Idaho National Laboratory

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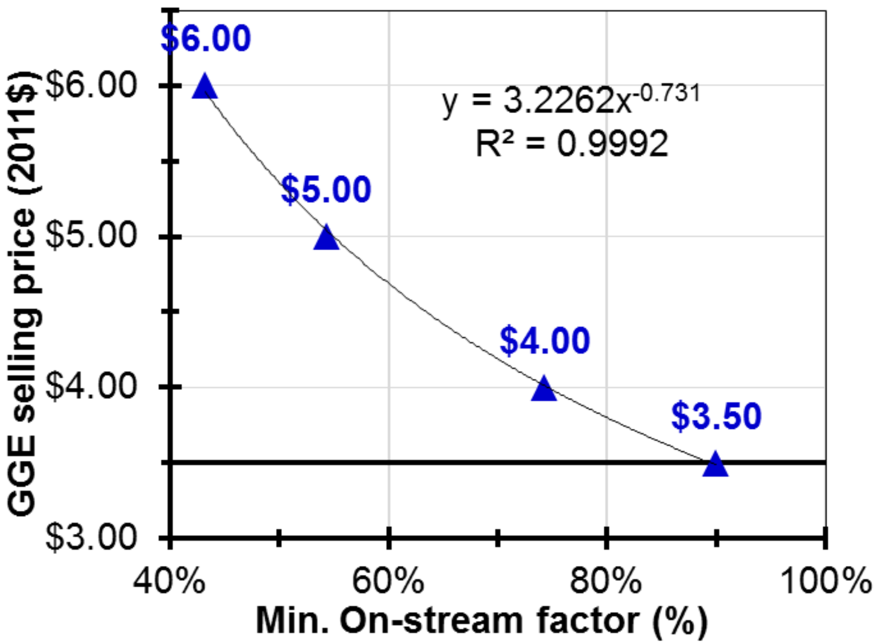
Motivation

- Enable biofuels by developing robust feeding and handling technologies
  - Directly supports DOE's Mission: "Develop and transform our renewable biomass resources into commercially viable, high performance biofuels"
  - F&H difficulties at pioneer biorefineries are leading to significant reduction in throughput versus design
  - Project metrics and targets driven by quantitative agreement between flow experiments and improved models. Enables:
    1. Improved design of equipment and processes
    2. In-situ, real-time QA/QC



Gallon of gasoline equivalent (GGE) selling price as a function of minimum on-stream factor. Source: values from recent NREL/PNNL analysis.

BFNUF

- Produces feedstocks for biofuels production processes
- Performs research to optimize and understand feedstock preprocessing operations.

Biofuels National User Facility (BFNUF) at INL

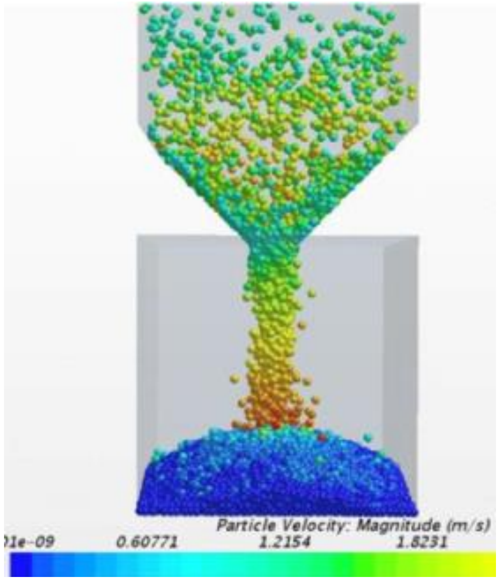
Project Approach

Goal

1. Understand and solve feeding and handling problems experienced by DOE's biofuels projects

Tasks

1. Determine scale-independent properties (characterization)
2. Develop computational models
   - Continuum and discrete element models
3. Validate models with physical tests
   - Physical tests focus on measuring the relationships between local compressive stress, shear stress and material strength for a variety of materials in multiple flow conditions.



Recent INL simulation of particles fed though hopper/silo

Lab-scale
- Physical tests
- Continuum & discrete element simulations

→

Pilot-scale
- Physical tests
- Continuum simulations

→

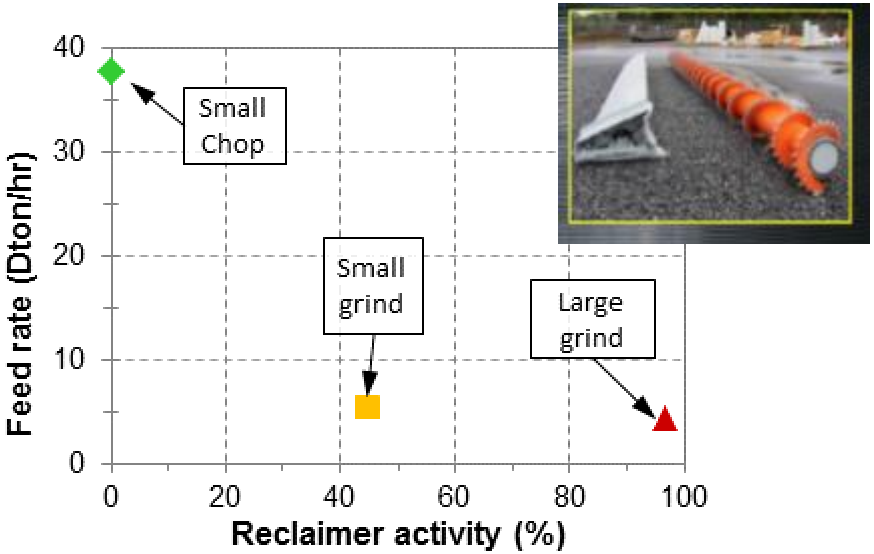
Industry-scale
- Continuum simulations

Project Approach

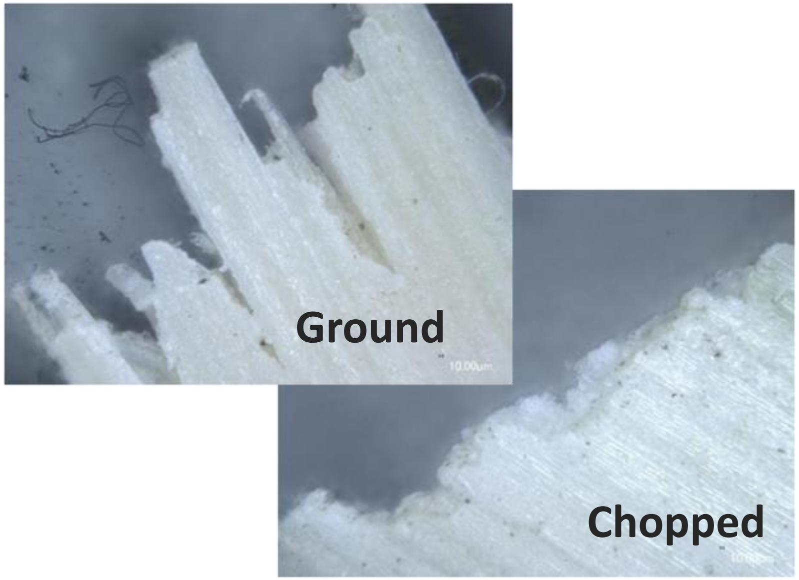
1. Determine scale-independent properties (characterization)
   - Individual particles
   - Bulk materials
2. Develop computational models
   - Discrete particle/element models (DEM)
   - Continuum approximation (finite element or FEM)
3. Validate models with physical tests, including
   - Failure mode (static tests)
   - Rate dependence (dynamic tests)
   - Stress history dependence (i.e. memory effect)
   - Anisotropy dependence (multi-dimensions)
   - Elastic vs. plastic behavior
   - Sensitivity to variation in key properties
   - Scale dependence (all of the above)
4. Develop rapid tests for QA/QC
   - Can be used in the near term by biorefineries
   - Will not require high level of expertise to employ

Example Application

Flow of chopped vs. ground switchgrass (SwGr) in a bin reclaimer (from BETO's High Tonnage Switchgrass Project)



(Womac, et al. Appl. Engin. Agric. 2015.)



- Chopped SwGr flowed freely with reclaimer off, while ground SwGr flowed at ≈20% of design capacity even at maximum motor speed (see figure)
  - Current designs for biofuels production employs grinders; however, flowability of ground material is problematic
- Across range of all measured properties, the only consistent difference was tip morphology (Westover, et al., Biofuels 2015)
- **Small change in preprocessing can have big impact on F&H performance**

Material Preparation

Corn stover (CS)

- Hammerground with 25 mm screen then ground further and dried

Pine forest residues (PFR)

- 2” chips hammerground with 25 mm screen then ground further and dried

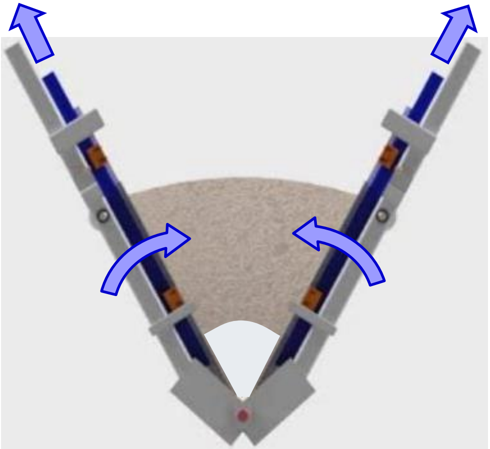
Material	Moisture contents (%)	
CS 25 mm grind	10	30
CS 13 mm grind	10	30
CS 3 mm grind	10	30
CS pellets	10	30
CS meal	10	30
PFR 25 mm gr, < 6mm	10	-
” “ sieved >1 mm	10	-
PFR 3 mm grind	10	25
PFR 0.5 mm grind	10	-

Pine particles ground with 25 mm screen.

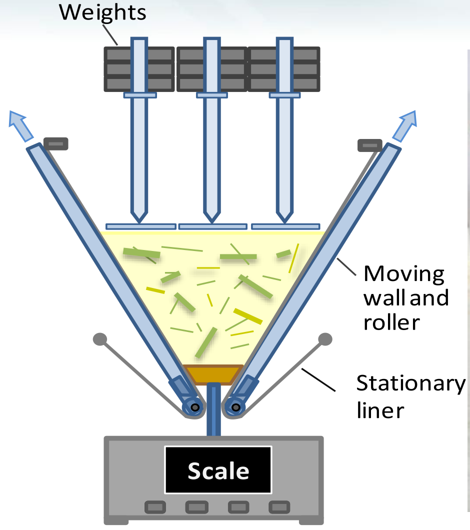
Corn stover

Characterization & Test Methods

- Characterization
  - Particle size: Ro-tap and digital imaging
  - Bulk density/compressiblity: axial load applied to material in cylindrical vessel
  - Shear properties: Schulze ring shear tester
- Semi-static hopper tests (arching)
  - Pilot-scale with 0.9 mm hopper
  - “ “ rotating walls to apply radial stress field
  - Lab-scale with 0.35 mm polycarbonate hopper (equipped with x-ray flow visualization)
- Dynamic hopper tests (stresses & flow)
  - Pilot-scale ‘steady’ flow using 1 ton/hr conveyor
  - Pilot-scale hopper with bin filled to ~ 1m meter depth above hopper
- Auger feeding tests (not discussed today)

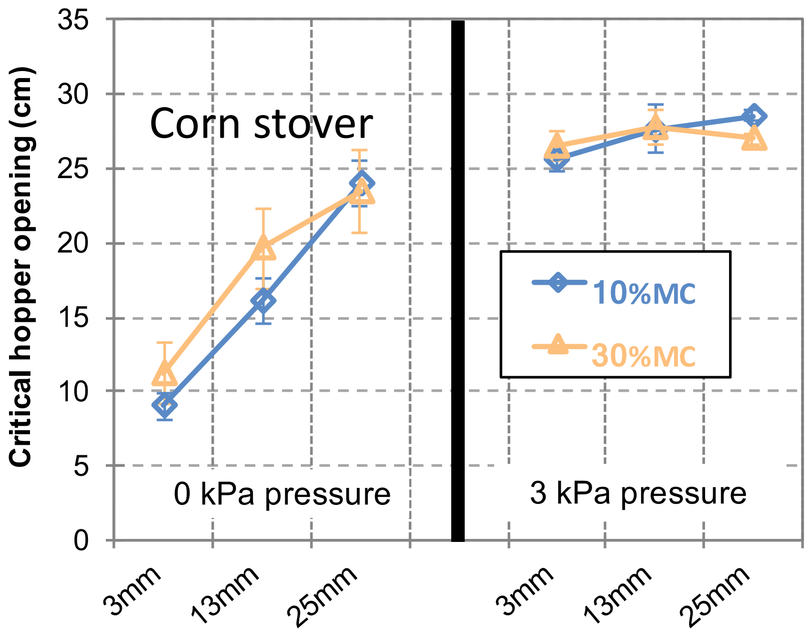


Pilot Scale Semi-static Tests



V-shaped hopper with moving walls

- As walls raise above critical arching width, material arch breaks and material falls
- Stationary liner insulates material from motion of walls
- Vertical applied pressure attempts to simulate or bound industry conditions
- Tests indicate strong flow dependence on particle size but not on moisture



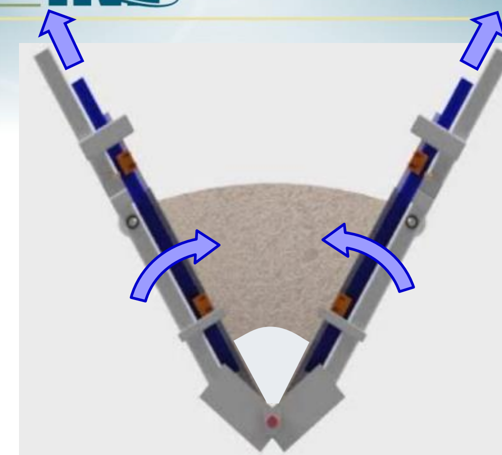
Issues

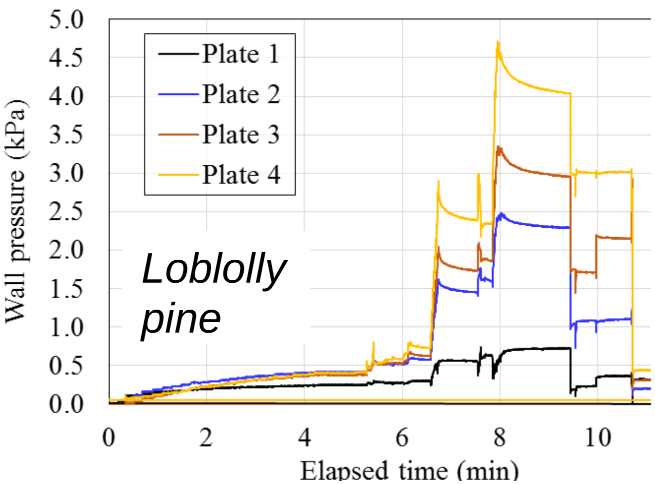
- Other pilot-scale operations show strong dependence of flow behavior on moisture content – the industrial relevance of these tests is not clear

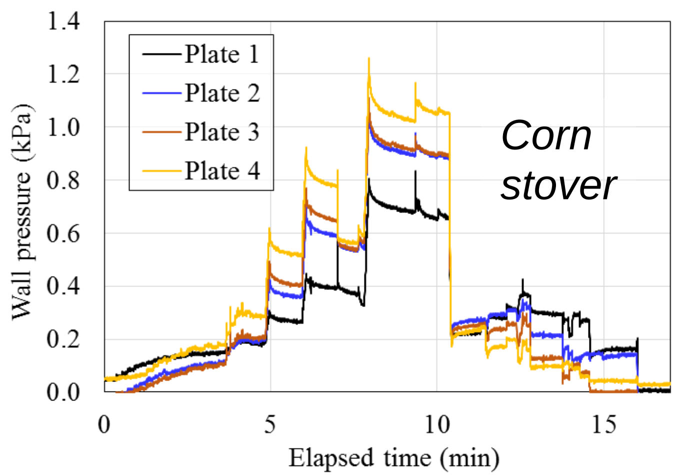
Hopper with Rotating Walls

Goal: establish a radial stress field

- Can achieve ~20 kPa radial stress for alternate method simulate or bound industrial conditions
    1. Walls rotate inward to create desired radial stress field
    2. Motorized walls raise to allow flow and measure critical hopper opening







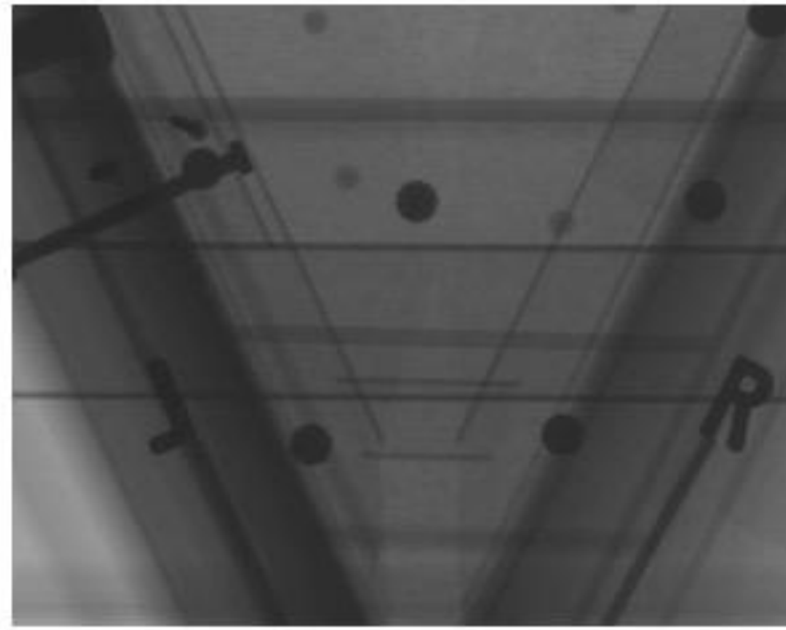
Wall pressure measurements for semi-static hopper tests. Things to note: (1) Pressure decreases with depth because the walls support the weight, and (2) Mechanical creep results in transient wall force loading.

Test method and understanding still in development so not discussed in detail today

Lab Scale Hopper
X-ray imaging





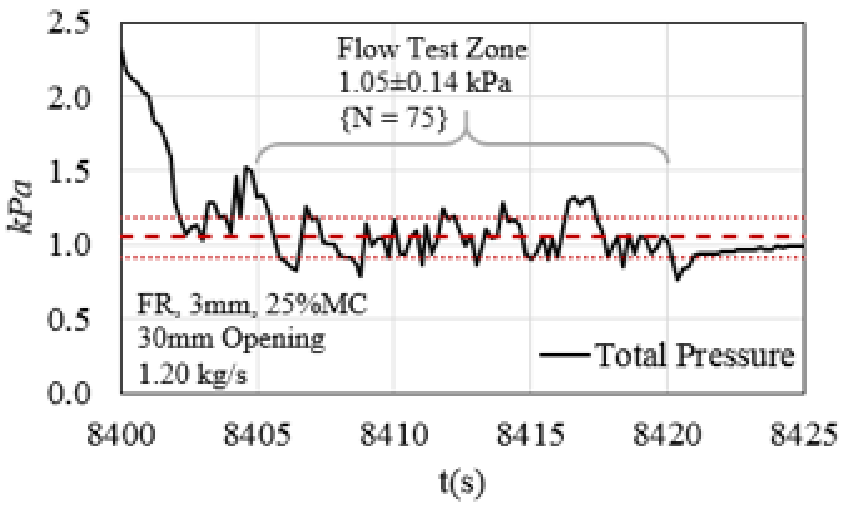


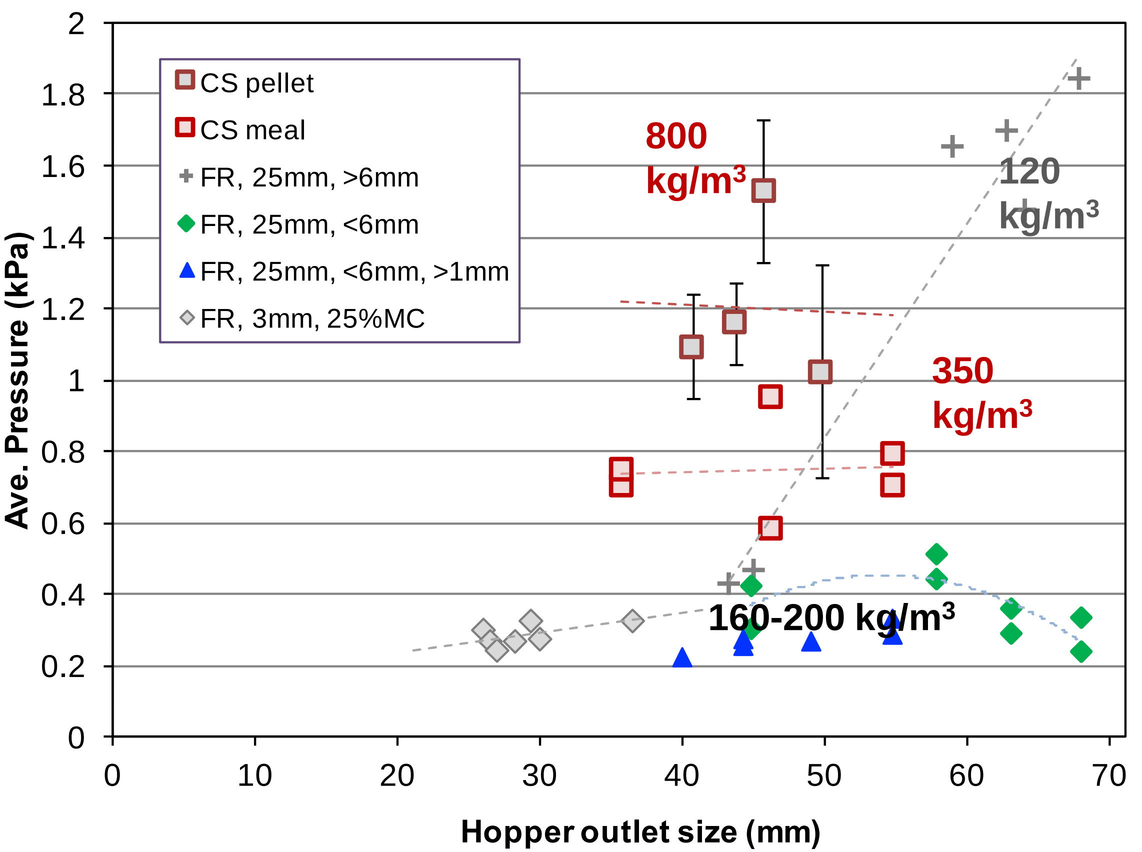
Large spheres are 9 mm diameter stainless balls. Small spheres are 6 mm silicon nitride balls approximately 50 mm behind the steel balls.

- *Silicon nitride balls are easily visualized using x-rays in 0.35 m long hopper*
- *Forces and size of polycarbonate hopper limited due to strength and x-ray imaging*
- *X-rays do not readily show biomass material boundaries*

Pilot Scale Hopper Tests
Wall Pressure Measurements

- Four pressure plates (2" tall x 4" long) embedded side-by-side in sliding wall starting 2" from bottom
- Average pressure increases with bulk density and particle size
- Materials with small particle sizes all exhibited pressures 0.2-0.4 kPa independent of hopper outlet size



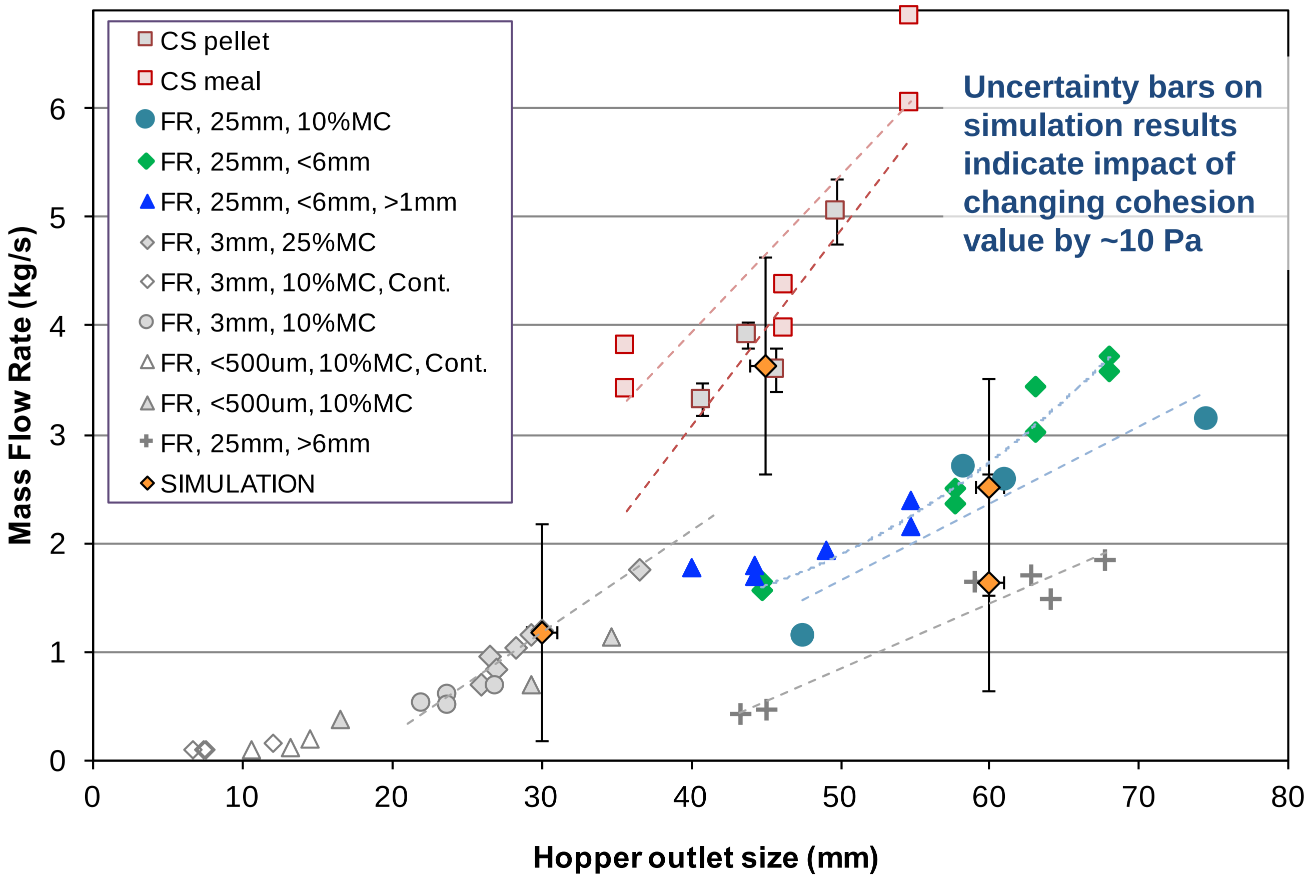


Pilot Scale Hopper Tests
Photographs

Pilot Scale Hopper Tests

Flow rate measurements compared to simulations

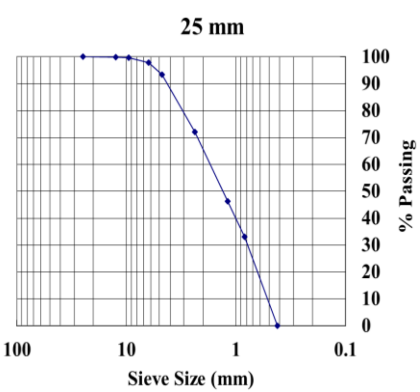
- Agreement between simulation and measurements within characterization accuracy
- Simulation uses simple Mohr-Coulomb model (discussed in separate presentation tomorrow)
- Flow is very sensitive to material cohesion
- Successfully controlled the flow rate in real-time by adjusting the hopper opening
- Results indicate that cohesion and angle of internal friction can be determined if approximate particle size distribution and bulk density are known.

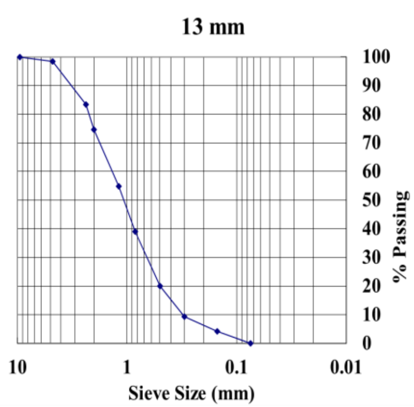


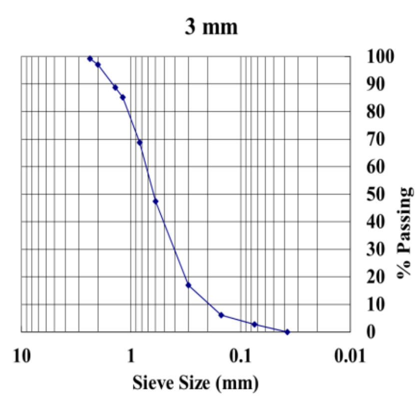
Additional Slides

Rotap Screening

Corn stover







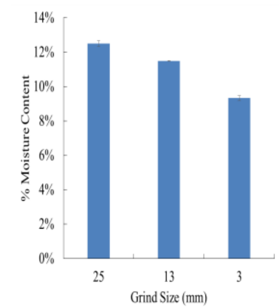


Figure 5: Percent moisture content of the three grind sizes