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Research paper

The effects of physical and chemical preprocessing on the flowability of corn stover

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A R T I C L E I N F O

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A B S T R A C T

Continuous and reliable feeding of biomass is essential for successful biofuel production. However, the challenges associated with biomass solids handling are commonly overlooked. In this study, we examine the effects of preprocessing (particle size reduction, moisture content, chemical additives, etc.) on the flow properties of corn stover. Compressibility, flow properties (interparticle friction, cohesion, unconfined yield stress, etc.), and wall friction were examined for five corn stover samples: ground, milled (dry and wet), acid impregnated, and deacetylated. The ground corn stover was found to be the least compressible and most flowable material. The water and acid impregnated stovers had similar compressibilities. Yet, the wet corn stover was less flowable than the acid impregnated sample, which displayed a flow index equivalent to the dry, milled corn stover. The deacetylated stover, on the other hand, was the most compressible and least flowable examined material. However, all of the tested stover samples had internal friction angles >30°, which could present additional feeding and handling challenges. All of the "wetted" materials (water, acid, and deacetylated) displayed reduced flowabilities (excluding the acid impregnated sample), and enhanced compressibilities and wall friction angles, indicating the potential for added handling issues; which was corroborated via theoretical hopper design calculations. All of the "wetted" corn stovers require larger theoretical hopper outlet diameters and steeper hopper walls than the examined "dry" stovers.

1. Introduction

Continuous and stable biomass feeding is essential for successful operation of a biofuel production facility. Yet, solids feeding equipment commonly becomes jammed, bridged, or blocked with material, resulting in slowed reactor throughput and/or complete process interruption. Despite the significance of achieving uninterrupted feeding and the regularity of biomass feeding issues, more emphasis has been placed on the thermal, chemical, and biological deconstruction of biomass than on biomass handling problems. As a result, only a limited amount of information [1–3] has been published on the design and operation of biomass feeding systems.

Biomass feeding and handling is challenging for a variety of reasons. Biomass particles are inherently heterogeneous, varying greatly in size, shape, density, moisture content, and compressibility. Large particles, excessive moisture, and an insufficient (or too high) pressure differential between the feed hopper and reactor can all lead to feed system failure. In addition, feeders are commonly designed to handle a particular material under a specific set of preprocessing conditions (i.e., milling size, moisture content, chemical additive concentration, etc.). Minor alterations to the biomass, such as changes in moisture content or particle size, can significantly impact solids-handling systems. It is common for a feed system to work well for one material and completely fail for another with similar properties [4].

Further complicating this issue, biomass feedstocks are regularly preprocessed prior to entering reactor feed systems. Preprocessing can be fairly conventional, like milling to pass a certain screen size. However, preprocessing can also include chemical processing to enrich the biomass deconstruction process. Chemical additives not only increase the moisture content within the biomass, but they can potentially influence physical and chemical

Abbreviations: AICS, acid impregnated corn stover; DACS, deacetylated corn stover; GCS, ground corn stover; INL, Idaho National Laboratory; IR, infrared; MCS (dry), dry milled corn stover; MCS (wet), wet milled corn stover; NREL, National Renewable Energy Laboratory.

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Nomenclature

α	Maximum hopper half angle (°)
A_R	Particle aspect ratio (–)
B	Minimum hopper outlet diameter (m)
C	Compressibility (%)
CAS	Critical applied stress (kPa)
f_c	Unconfined yield stress (kPa)
FF	Flow function (–)
ff	Flow factor (–)
ff_c	Flowability (or flow) index = σ_1/f_c (–)
g	Gravitational constant (9.81 m s^{-2})
μ_w	Coefficient of wall friction (–)
l	Particle length (μm)
MC	Moisture content = Moisture mass fraction, w_{H2O} (%)
n	Number of sized particles (–)
N	Normal stress (kPa)
N_c	Pre-shear critically consolidated normal stress (kPa)
m_w	Mass of water contained in a wet sample (g)
m_t	Total mass of a wet sample (g)
ϕ	Angle of internal friction (°)
ϕ_e	Effective angle of internal friction (°)
ρ_b	Bulk density (kg m^{-3})
Ra	Surface roughness (μm)
σ_1	Major principal stress (kPa)
$m_t\tau$	Shear stress (kPa)
τ_0	Cohesion (kPa)
V	Sample volume at a given normal stress (cm^3)
V_0	Initial, conditioned sample volume (cm^3)
w	Particle width (μm)

properties, and as a result, affect flowability.

Analyzing the flowability and physical properties of biomass is key to the design of efficient and effective biomass feeders [3]. Measuring biomass bulk density, compressibility, cohesion, internal friction, yield stress, and wall friction help determine a material's flowability and inform proper hopper design. However, only a limited number of studies have been published on the flowability of biomass and its impact on feed system design. Fasina [5] evaluated the affect of mill screen size on the compressibility and flowability of peanut hull, switchgrass, and poultry litter; while Chevanan et al. [6] designed, fabricated, and tested a direct shear cell to measure the shear strength and flow properties of chopped switchgrass, wheat straw, and corn stover. Zhou et al. [7] studied the affects of particle size and moisture content on particle density, bulk density, compressibility index, and porosity of two hybrid corn stovers, while Ileleji and Zhou [8] examined the effects of particle size and moisture content on the angle of repose of bulk corn stover. Samaniuk et al. [9] investigated the use of water soluble polymers as rheological modifiers to reduce the yield stress of wetted corn stover samples using a unique torque rheometer. Gil et al. [10], on the other hand, analyzed the effects of moisture content, particle size, and particle shape on the handling behavior of poplar and corn stover. Miccio et al. [11] studied the flow properties and tendency for arch formation of sawdust and ground olive husk using a ring shear apparatus and an arching tester. A recent study by Crawford et al. [12] evaluated the flowability of pure and blended biomass feedstocks, and linked the flow properties of the biomass materials to their pelleting energy requirements.

Although previous studies have investigated the effects of milling screen size and moisture content on the flow properties of various feedstocks, no study has specifically examined how preprocessing conditions, including chemical additives, affect the flowability of a single biomass species. In this manuscript, our objectives were to: 1) measure the compressibility and flow properties of corn stover under various processing conditions, 2) evaluate how moisture content, particle size, and chemical additives influence corn stover flowability, and 3) use the compressibility, shear cell, and wall friction measurements for theoretical hopper design calculations (see Section Appendix A for details) as a relative method to compare handling strategies for the preprocessed corn stover feedstocks.

2. Materials and methods

2.1. Materials

Corn stover is a crop residue consisting of all portions of the plant left after corn grain harvest (the stock, stem, leafs, and cob). Corn stover is a desirable biofuel feedstock because it is not used as human or animal food, and large quantities are available as a byproduct of corn agriculture. The corn stover examined in this study was provided by Idaho National Laboratory (INL, Idaho Falls, ID, USA). All of the milling and/or grinding of the corn stover was performed by, or contracted out through, INL. The corn stover was single-pass harvested in Boone County, IA (USA) in the fall of 2011. However, detailed information on the chain of custody for this specific substrate was unavailable. Therefore, the cultivar cannot be specified and while the authors believe that this work illustrates the difference between preprocessing strategies, unknown substrate factors may have influenced the obtained results.

All chemical processing or wetting of the stover was performed at the National Renewable Energy Laboratory. The following subsections describe the preprocessing conditions for the five tested corn stover samples (see Fig. 1).

2.1.1. Ground

Bales of corn stover were fed through a two-stage, full-scale grinding process using the Feedstock Process Demonstration Unit (PDU) as part of DOE's Biomass Feedstock National User Facility (BFNUF) located at Idaho National Laboratory (Idaho Falls, ID, USA). First, material was processed through a Vermeer BG-480 (Pella, IA, USA), which has two horizontal grinding drums with swinging hammers powered by two, 149 kW motors [13], and passed through a 5 cm screen. Then, the 5 cm screened material was processed through a Bliss hammer mill (Ponca City, OK, USA) with a 6.35 mm screen. The ground corn stover (GCS) sample was prepared for a separate feedstock pelleting study.

2.1.2. Milled (dry)

Baled corn stover was milled in a single-stage milling process using a Bliss hammer mill equipped with a 6.35 mm screen. The dry milled corn stover (MCS (dry)) sample was used as the base feedstock for the remaining corn stover samples (wet milled, acid impregnated, and deacetylated).

2.1.3. Milled (wet)

DI water was added to a subsample of MCS (dry) material to a