Powder Technology 193 (2009) 79–86

Contents lists available at ScienceDirect

Powder Technology

journal homepage: www.elsevier.com/locate/powtec

Flowability parameters for chopped switchgrass, wheat straw and corn stover

Nehru Chevanan [a], Alvin R. Womac [a,*], Venkata S.P. Bitra [a], Daniel C. Yoder [a], Shahab Sokhansanj [b]

[a] Biosystems Engineering and Soil Science, University of Tennessee, Knoxville, 2506 E.J. Chapman drive, Tennessee, 37996-4531, United States
[b] Oak Ridge National Laboratory, Environmental Sciences Division, Oak Ridge, Tennessee, United States

ARTICLE INFO

Article history:
Received 29 July 2008
Received in revised form 13 November 2008
Accepted 10 February 2009
Available online 21 February 2009

Keywords:
Chopped biomass
Direct shear
Angle of internal friction
Cohesion
Flowability

ABSTRACT

A direct shear cell to measure the shear strength and flow properties of chopped switchgrass, wheat straw, and corn stover was designed, fabricated, and tested. Yield loci ($r^2=0.99$) determined at preconsolidation pressures of 3.80 kPa and 5.02 kPa indicated that chopped biomass followed Mohr–Coulomb failure. Normal stress significantly affected the displacement required for shear failure, as well as the friction coefficient values for all three chopped biomass types. Displacement at shear failure ranged from 30 to 80 mm, and depended on preconsolidation pressure, normal stress, and particle size. Friction coefficient was inversely related to normal stress, and was highest for chopped corn stover. Also, chopped corn stover exhibited the highest angle of internal friction, unconfined yield strength, major consolidation strength, and cohesive strength, all of which indicated increased challenges in handling chopped corn stover. The measured angle of internal friction and cohesive strength indicated that chopped biomass cannot be handled by gravity alone. The measured angle of internal friction and cohesive strength were 43° and 0.75 kPa for chopped switchgrass; 44° and 0.49 kPa for chopped wheat straw; and 48° and 0.82 kPa for chopped corn stover. Unconfined yield strength and major consolidation strength used for characterization of bulk flow materials and design of hopper dimensions were 3.4 and 10.4 kPa for chopped switchgrass; 2.3 and 9.6 kPa for chopped wheat straw and 4.2 and 11.8 kPa for chopped corn stover. These results are useful for the development of efficient handling, storage, and transportation systems for biomass in biorefineries.

1. Introduction

Biomass is potentially a renewable and sustainable source of energy in which lignocellulosic materials are converted to useful energy forms either by thermochemical or biochemical methods [1,2]. Engineering challenges foreseen in supplying biomass for these conversions in a biorefinery include harvesting, handling, storage, transportation, and processing [3–6]. At present, few biomass physical properties data are available for designing efficient handling, storage, transportation, and processing systems. Especially, there is a dearth of information on the flow properties of biomass, which is critical.

Direct shear testing is extensively used by soil engineers and food engineers for characterizing the shear strength of bulk flow materials [7], which is a measure of flowability. Direct shear testing involves preconsolidating the samples to a predetermined normal stress and subsequent shearing of the samples [8]. This results in understanding the effect of sample conditions on its shear strength properties.

Angle of internal friction measured by direct shear technique is an important factor in bulk storage structure design [9], since it affects the lateral pressure acting on storage bin walls. The lateral pressure in the shallow bins is determined using Rankine's equation (Eq. (1)) and in the deep bins determined using Jansen's equation (Eq. (2)) [10].

$$P = \frac{1}{2} w h^2 \left[\frac{\cos\phi}{\left(1 + \sqrt{2}\sin\phi\right)^2} \right] \tag{1}$$

$$P = wh \left[\frac{1 - \sin\phi}{1 + \sin\phi} \right] \tag{2}$$

where

P	lateral pressure (kPa)
w	bulk density of the material (kg/m^3)
h	height of fill (m)
ϕ	angle of internal friction.

Jenike developed a numerical methodology to determine minimum hopper angle, opening size, and characterize the bulk flow of particulate materials using direct shear techniques [11]. Jenike used the modified Mohr–Coulomb theory to determine the flow properties of bulk flow materials [12]. According to this theory, bulk solids exhibit a limiting function known as the yield locus, and stress conditions below this yield locus will not result in failure or plastic flow. In

* Corresponding author. Tel.: +1 865 974 7104; fax: +1 865 974 4514.
E-mail address: awomac@utk.edu (A.R. Womac).

0032-5910/$ – see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.powtec.2009.02.009

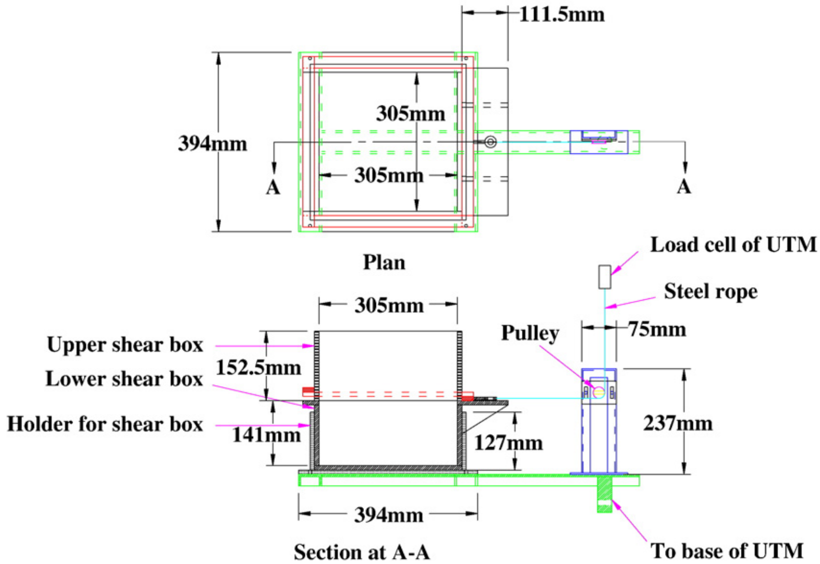

Fig. 1. Direct shear cell with attachment to connect to Universal Testing Machine (UTM).

Jenike's method, a direct shear cell is used to determine the maximum shear stress required to shear the samples at different normal stresses below a particular preconsolidation pressure [7]. Based on the normal and shear stress data, the yield locus at that particular preconsolidation pressure is determined. Consolidation stress causing zero shear strength, and consolidation stress causing maximum shear strength below the yield locus are measured as unconfined yield strength (σ_c) and major consolidation strength (σ_1), respectively, using Mohr's circles. Preconsolidation at different pressures results in different yield loci to determine different unconfined yield strengths and major consolidation strengths which may be used to characterize flow properties and design of bulk handling hoppers [13]. Slope of the linear relationship between unconfined yield strength and major consolidating strength is defined as flow function. Flow index is the inverse of the flow function, and it is used to characterize the bulk flow material as hardened, very cohesive, cohesive, easy to flow, or free-flowing [14].

Jenike's shear cell is extensively used to determine shear strength of bulk flow materials like food powders. Flow properties of milk powders with different fat content [15], confectionary sugar and detergent [16], fine lactose powder [17], wheat flour and sugar [18], and distillers dried grains with solubles [19] were studied by direct shear technique using commercially available Jenike's shear cells. Commercially-available Jenike's shear cells have an internal diameter of only 95.25 mm [15–20]. Chopped biomass contains particles as long as 250 mm, so Jenike's shear cell should not be used for measuring the shear strength of such materials. Molenda and Horabik [21] used a direct shear cell having an internal diameter of 210 mm and bedding height of 80 mm for determination of shear strength of cereal grains. However, little published works has been carried out on shear strength determination of chopped biomass with the direct shear technique.

The objectives of this research were as follows: 1. develop a shear cell for chopped biomass per guidelines of ASTM standards for shear testing for bulk solids and soils, and 2. examine the effect of particle size on friction and flow properties of chopped switchgrass, wheat straw, and corn stover.

2. Experimental

2.1. Fabrication of shear cell

A direct shear cell was fabricated per guidelines in the ASTM D3080-98 [20] (Fig. 1). The shear cell was fabricated from 9 mm acrylic sheet. The direct shear cell consisted of an upper shear box, lower shear box, and a shear box holder. The lower shear box had internal dimensions of 305 × 305 × 150 mm high. The upper shear box

Fig. 2. Direct shear cell filled with chopped biomass with preconsolidation load. Experiments were conducted by applying uniformly distributed load on the biomass using a 9 mm thick acrylic sheet over the biomass.

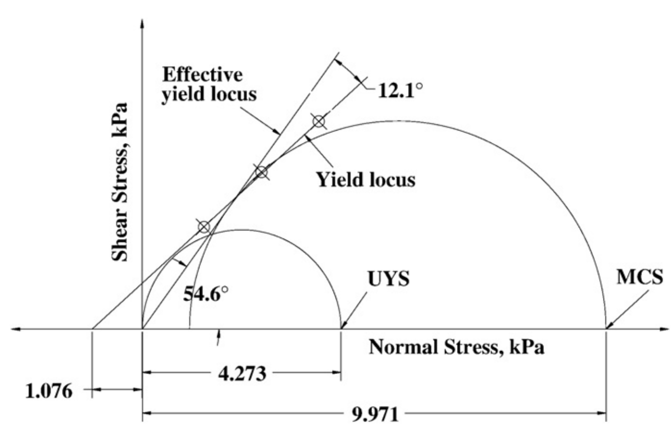

Fig. 3. Yield locus and Mohr's circles for zero shear stress and maximum shear stress at a preconsolidation pressure of 3.82 kPa for switchgrass samples having a geometric particle length of 7.80 mm.

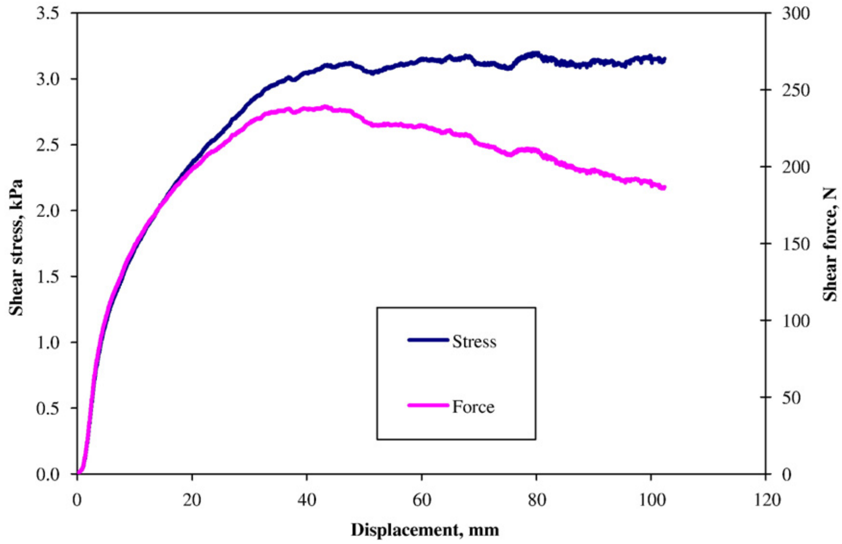

Fig. 4. Typical force–displacement curve for chopped biomass in direct shear testing.

was hollow and had internal dimensions of 305 × 305 × 150 mm high. The shear box holder had two sides parallel to the direction of shear and acted as guide for the upper shear box to move in line with the direction of shearing. A stand with necessary fixtures to connect the shear cell to a Universal Testing Machine (UTM) was fabricated using mild steel. The upper shear box was connected to the load cell of the UTM using a pulley and cable arrangement.

2.2. Tested material

Switchgrass, wheat straw, and corn stover were chopped in a knife mill (H.C. Davis Sons Mfg. Co., Inc., Bonner Springs, KS) using two different classifying screens. Particle size of the chopped biomass was determined using ASAE S424.1 [22]. The mass fractions retained on the screens having diagonal opening dimensions of 1.65, 5.61, 8.98, 18.0, 26.9 mm, and pan were used to determine the geometric mean length. Moisture content of the chopped materials was determined by ASAE S358.2 [23] that used a gravimetric method and drying the chopped biomass at 103 °C for 24 h.

2.3. Testing procedure

The upper and lower shear boxes were placed in position, and filled with chopped biomass to the top of the upper shear box. An acrylic plate of 302 × 302 × 9 mm thick was placed on the biomass. Different preconsolidation conditions were created in the chopped biomass to simulate the consolidation conditions occurring in the storage structures due to differences in the volume of biomass while handling. This was achieved by applying preconsolidation loads varying from 111 to 444 N on the acrylic sheet (Fig. 2).The normal load conditions were selected to simulate various load conditions occurring in chopped biomass at the bottom of storage structures of approximately 30 m high. Biomass was allowed to consolidate for 10 min. The preconsolidation load was then removed, and the box was filled again with biomass up to the top edge. The preconsolidation load was reloaded, and the biomass was allowed to consolidate for another 10 min. This procedure was repeated a third time, and shearing tests were conducted with the prepared sample.

The preconsolidation load was removed and a normal load less than the preconsolidation load was applied on the biomass. Direct shear tests were carried out using the UTM fitted with a load cell of 1000 N capacity (Alliance RT/30, MTS System Corporation, Eden Prairie, MN, USA). Testing software "Testworks 4.05" of MTS System Corporation operated the UTM and data acquisition. Sample shear rate was 9 mm/min. Data were collected at 10 Hz frequency over a shear distance of 100 mm. Force displacement data downloaded from the computer was used to determine various parameters. Maximum shear force was directly recorded from the universal testing machine. Shear stress was measured as a ratio of maximum shear force to the contact area between the biomass in the lower and upper shear box. The

Table 1
Displacement of upper shear box at maximum shear force and shear stress.

Biomass	Geometric mean length (mm)	Consolidation pressure (kPa)	Displacement at maximum shear force at different normal stresses (mm)				Displacement at maximum shear stress at different normal stresses (mm)			
			1.33 kPa	2.57 kPa	3.80 kPa	5.02 kPa	1.33 kPa	2.57 kPa	3.80 kPa	5.02 kPa
Switchgrass	7.81	3.80	49.7^{a} (4.8)	48.1^{a} (2.9)	45.0^{a} (5.5)	–	63.2$^{a–d}$ (11.9)	61.3$^{b–d}$ (7.8)	67.6$^{a–d}$ (13.8)	–
		5.02	44.2^{a} (8.4)	42.0^{a} (4.8)	48.1^{a} (0.1)	50.6^{a} (4.3)	64.9$^{a–d}$ (8.0)	60.6$^{b–d}$ (11.5)	72.9$^{a–c}$ (13.0)	74.4^{ab} (3.7)
	13.50	3.80	35.9^{a} (7.7)	44.0^{a} (7.6)	48.7^{a} (6.2)	–	54.3^{d} (8.8)	67.7$^{a–d}$ (7.2)	76.4^{ab} (5.7)	–
		5.02	45.6^{a} (10.7)	48.1^{a} (11.6)	43.7^{a} (4.4)	50.6^{a} (8.8)	56.5^{cd} (11.1)	67.0$^{a–d}$ (4.3)	78.4^{a} (11.7)	76.6^{ab} (13.4)
Wheat straw	7.09	3.80	36.2^{de} (6.8)	45.1$^{b–d}$ (6.0)	52.7^{ab} (0.7)	–	56.7$^{b–d}$ (2.2)	62.7$^{a–d}$ (8.4)	73.4^{a} (6.7)	–
		5.02	30.5^{e} (4.6)	39.3$^{c–e}$ (8.3)	44.2$^{b–d}$ (1.9)	50.0^{ab} (4.1)	48.1^{d} (14.1)	53.4^{cd} (4.1)	68.8^{ab} (10.5)	61.3$^{a–d}$ (4.3)
	10.39	3.80	38.7$^{c–e}$ (4.9)	49.2$^{a–c}$ (8.3)	48.5$^{a–c}$ (2.6)	–	51.9^{cd} (4.9)	68.7^{ab} (8.8)	71.0^{ab} (12.6)	–
		5.02	35.7^{de} (6.5)	43.7$^{b–d}$ (12.3)	47.9$^{a–c}$ (8.3)	56.6^{a} (4.0)	52.2^{cd} (3.5)	66.3$^{a–c}$ (13.0)	74.0^{a} (11.2)	70.3^{ab} (7.5)
Corn stover	7.80	3.80	36.6^{e} (4.7)	42.1^{de} (0.6)	45.1^{cd} (1.6)	–	49.2^{c} (7.2)	58.2^{bc} (6.5)	63.8$^{a–c}$ (3.2)	–
		5.02	37.3^{e} (10.3)	43.7^{de} (3.1)	53.9^{a} (8.4)	53.5^{a} (0.8)	41.6^{d} (13.1)	55.8^{bc} (1.7)	67.8^{ab} (9.2)	67.5^{ab} (10.4)
	14.89	3.80	42.1^{de} (1.5)	43.2$^{a–c}$ (2.2)	51.4$^{a–c}$ (0.8)	–	65.3^{ab} (9.4)	61.4$^{a–c}$ (10.7)	62.9$^{a–c}$ (1.6)	–
		5.02	41.4^{de} (4.6)	45.9$^{b–d}$ (3.2)	53.1^{ab} (5.8)	58.1^{a} (2.6)	65.7^{ab} (11.4)	56.9^{bc} (1.9)	65.6^{ab} (5.8)	75.4^{a} (7.4)

Mean values of three replications suffixed with different letters for a particular chopped biomass were significantly different at $p<0.05$. The values within the parenthesis are standard deviation.

Table 2
Treatment and interaction effects (p values) of the levels of particle size, preconsolidaton pressure, and normal stress on friction coefficient and displacement at maximum shear for chopped switchgrass.

	Displacement		Friction coefficient	
	Maximum force (N)	Maximum shear stress (kPa)	Force ratio (–)	Stress ratio (–)
Preconsolidation pressure (PP)	0.53	0.23	<0.01	<0.01
Normal stress (NN)	0.35	<0.01	<0.01	<0.01
Particle size (PS)	0.46	0.59	0.01	0.13
PP*NN	0.82	0.87	0.22	0.43
PP*PS	0.21	0.92	0.34	0.28
NN*PS	0.60	0.22	0.40	0.70
PP*NN*PS	0.11	0.97	0.20	0.36

contact area was calculated based on the displacement recorded at the location of maximum shear force.

The friction coefficient at different normal stresses was calculated two ways. Actual contact area decreased as the test progressed due to the movement of upper shear box over the lower box. Friction coefficient μ_f (N/N) was determined as a ratio of maximum shear force recorded to the normal force applied on the biomass. Friction coefficient μ_s (N mm^{-2}/N mm^{-2}) was measured as a ratio of maximum shear stress recorded to normal stress applied on the biomass.

Cohesive intercept stress and angle of internal friction were calculated using the Mohr–Coulomb Eq. (3), by linear regression

$$\tau = c + \sigma \tan(\phi) \tag{3}$$

Where

τ	shear stress (kPa)
c	Cohesion (kPa),
σ	Normal stress (kPa)
ϕ	Angle of internal friction (°)

The unconfined yield strength (σ_c), major consolidation strength (σ_1), effective angle of internal friction, and tensile strength were determined graphically using AutoCAD as explained by Jenike and Carson [24]. A typical graph for determination of these parameters is shown in Fig. 3.

2.4. Experimental design and statistical analysis

Experiments were conducted with two particle sizes and two levels of preconsolidation pressure for three different types of chopped biomass. Two chopped switchgrass samples had geometric mean length of 7.81 and 13.50 mm; two chopped wheat straw samples had geometric mean length of 7.09 and 10.39 mm; and two chopped corn stover samples had geometric mean length of 7.80 and 14.89 mm. Experiments were conducted at normal stresses of 1.33 kPa, 2.57 kPa, 3.80 kPa and 5.02 kPa when the sample was subjected to preconsolidation pressure of 5.02 kPa and normal stresses of 1.33 kPa, 2.57 kPa, and 3.80 kPa when the sample was subjected to preconsolidation pressure of 3.80 kPa. Three replicated measurements were made for each loading condition. The chopped biomasses used in our experiments were very dry, and the moisture contents of chopped switchgrass, wheat straw, and corn stover were 6.7 ± 0.6, 7.1 ± 1.0, and 7.7 ± 0.8% (wet basis), respectively.

Statistical analysis was carried out using SAS 9.1. [25]. Treatment and interaction effects of particle size, preconsolidation pressure, and normal stress on friction coefficients and displacement distances were carried out using three-factor ANOVA [26]. Statistical analysis was carried out for the three chopped biomasses separately. PROC GLM procedure was used for determining the statistical significance of the three factors at a 5% significance level. Means were estimated for the 3-way interaction and compared using LSD.

3. Results and discussion

In preliminary investigations, trials were conducted to obtain a uniformly consolidated sample in the shear cell. In direct shear testing, the method of filling the sample in the shear box introduces anisotrophy (non-isotropic stress) in the material and that affects yield locus. Anisotrophy introduced in the filled sample needed to be minimized for reliable data [21]. In our experiments, biomass was introduced in layers of approximately 10 mm thickness, and the preconsolidation load was applied on the biomass after filling the biomass to the top of the shear box. On application of preconsolidation load, the volume of chopped biomass was reduced by approximately 40 to 90% in the entire assembled upper and lower shear boxes. In order to maintain a sufficient height of the sample above the failure plane, a number of refillings were required. The visible reduction of volume in the shear cell for some time prevented the instantaneous shearing of the samples after filling. In the preliminary experiments, tests were conducted with varied preconsolidation times from 0 to 10 min. It was observed that a waiting time of 10 min between refillings has resulted in minimum variability in the measured shear strength between replications. This might be due to the reduction in the anisotrophy of the material during consolidation. It was very difficult to maintain a particular height of material above the shear plane due to the differences in compressibility of the chopped biomass. Hence, the procedure of the three refillings at 10-minute intervals was followed for all the samples for comparison purpose.

A typical stress–displacement curve from shear testing is shown in Fig. 4. Force required to shear the samples increased continuously, reached a peak value, and then decreased. Peak shear force was reached at a displacement of 30 to 60 mm for all chopped biomass tested in our experiments (Table 1). Shear stress was calculated based on the actual biomass contact area, which decreased as the test progressed. This calculated shear stress increased continuously, reached a maximum

Table 3
Treatment and interaction effects (p values) of the levels of particle size, preconsolidaton pressure, and normal stress on friction coefficient and displacement at maximum shear for chopped wheat straw.

	Displacement		Friction coefficient	
	Maximum force (N)	Maximum shear stress (kPa)	Force ratio (–)	Stress ratio (–)
Preconsolidation pressure (PP)	0.44	0.41	<0.01	<0.01
Normal stress (NN)	<0.01	<0.01	<0.01	<0.01
Particle size (PS)	0.12	0.13	0.05	0.08
PP*NN	0.97	0.77	0.38	0.30
PP*PS	0.30	0.14	0.01	0.18
NN*PS	0.78	0.55	0.55	0.46
PP*NN*PS	0.76	0.99	0.02	0.18

Table 4
Treatment and interaction effects (p values) of the levels of particle size, preconsolidaton pressure, and normal stress on friction coefficient and displacement at maximum shear for chopped corn stover.

	Displacement		Friction coefficient	
	Maximum force (N)	Maximum shear stress (kPa)	Force ratio (–)	Stress ratio (–)
Preconsolidation pressure (PP)	0.02	0.83	0.19	<0.01
Normal stress (NN)	<0.01	<0.01	<0.01	<0.01
Particle size (PS)	<0.01	0.01	0.94	0.34
PP*NN	0.15	0.31	0.93	0.09
PP*PS	0.12	0.49	0.02	0.02
NN*PS	0.78	0.01	0.81	0.75
PP*NN*PS	0.68	0.35	0.21	0.27

Table 5
Friction coefficients of chopped switchgrass, wheat straw and corn stover.

Biomass	Geometric mean length (mm)	Consolidation pressure (kPa)	Coefficient of friction as a ratio of normal and shear forces (μ_f) at different normal stresses				Coefficient of friction as a ratio of normal and shear stresses (μ_s) at different normal stresses			
			1.33 kPa	2.57 kPa	3.80 kPa	5.02 kPa	1.33 kPa	2.57 kPa	3.80 kPa	5.02 kPa
Switchgrass	7.81	3.80	1.35^{a} (0.09)	1.08^{bc} (0.11)	0.95^{de} (0.07)	–	1.65^{a} (0.09)	1.32^{bc} (0.13)	$1.18^{c–e}$ (0.07)	–
		5.02	1.15^{a} (0.12)	0.98^{cd} (0.02)	0.89^{de} (0.02)	0.86^{ef} (0.01)	1.45^{b} (0.19)	1.20^{cd} (0.04)	$1.11^{d–f}$ (0.04)	$1.11^{d–f}$ (0.02)
	13.50	3.80	1.33^{a} (0.07)	$0.97^{c–e}$ (0.04)	0.98^{cd} (0.06)	–	1.63^{a} (0.08)	1.22^{cd} (0.04)	1.26^{cd} (0.07)	–
		5.02	1.16^{b} (0.15)	0.90^{de} (0.09)	0.77^{f} (0.12)	0.75^{f} (0.14)	1.43^{b} (0.13)	$1.14^{e–f}$ (0.14)	1.01^{ef} (0.12)	0.99^{f} (0.13)
Wheat straw	7.09	3.80	1.006^{b} (0.18)	0.94^{bc} (0.04)	$0.92^{b–d}$ (0.06)	–	1.29^{b} (0.02)	$1.19^{b–d}$ (0.02)	$1.14^{c–e}$ (0.06)	–
		5.02	1.18^{a} (0.12)	$0.92^{b–d}$ (0.03)	$0.84^{c–e}$ (0.03)	0.80^{de} (0.05)	1.43^{a} (0.14)	$1.13^{c–e}$ (0.02)	1.09^{de} (0.02)	1.02^{e} (0.03)
	10.39	3.80	1.13^{a} (0.12)	0.95^{bc} (0.07)	$0.84^{c–e}$ (0.03)	–	1.32^{ab} (0.13)	$1.19^{b–d}$ (0.11)	1.09^{de} (0.07)	–
		5.02	0.95^{b} (0.09)	$0.87^{c–e}$ (0.13)	0.76^{e} (0.07)	0.76^{e} (0.04)	1.23^{bc} (0.09)	$1.12^{c–e}$ (0.12)	1.01^{e} (0.06)	1.01^{e} (0.04)
Corn stover	7.80	3.80	1.47^{b} (0.04)	$1.15^{c–e}$ (0.04)	$1.07^{e–g}$ (0.02)	–	1.72^{b} (0.05)	$1.38^{c–e}$ (0.04)	1.33^{ef} (0.03)	–
		5.02	1.59^{a} (0.10)	1.23^{c} (0.05)	$1.13^{d–f}$ (0.02)	1.06^{fg} (0.08)	1.73^{b} (0.07)	1.43^{cd} (0.05)	$1.36^{c–f}$ (0.02)	1.32^{ef} (0.08)
	14.89	3.80	1.54^{ab} (0.08)	1.20^{cd} (0.06)	$1.09^{e–g}$ (0.03)	–	1.86^{a} (0.06)	1.46^{c} (0.08)	$1.34^{d–f}$ (0.05)	–
		5.02	1.489^{b} (0.03)	1.231^{c} (0.13)	$1.120^{d–f}$ (0.05)	1.03^{g} (0.08)	1.69^{b} (0.03)	1.44^{cd} (0.12)	$1.35^{d–f}$ (0.05)	1.27^{f} (0.07)

Mean values of three replications suffixed with different letters for a particular chopped biomass were significantly different at $p<0.05$. Values inside the parenthesis are standard deviation.

value, and remained constant afterwards. According to ASTM standard D3080, to get best results the prepared specimen dimension should be at least 10 times the maximum particle dimension of the sample. For chopped biomass having very low aspect ratio, it is very difficult to arrive at the shear box dimensions. In reported cases of shear tests containing significant amounts of interlocking components, the shear stress increased to a peak value and reduced to a value equivalent to interlocking component and remained constant [8]. The recorded force and stress values with respect to displacement indicated that a shear box having a side dimension of 305 mm may be sufficient to obtain reliable data in direct shear testing of chopped biomass.

3.1. Displacement at failure

The Mohr–Coulomb critical state of friction theory is applicable for plastic materials such as soil and food powders where shearing occurs immediately after application of shear force without much compression [10]. The peak shear stress is reached within 6 mm displacement of the upper shear box in standard shear testing of particulate solids like food powders using Jenike's shear cell [27]. However, chopped biomass is highly compressible. On application of shearing force, the chopped biomass particles compressed initially, and later started to shear. The displacement recorded for reaching maximum shear force and maximum shear stress is given in Table 1. The maximum shear force was recorded at displacement of 46 ± 4 mm for chopped switchgrass, 44 ± 7 mm for chopped wheat straw, and 46 ± 7 mm for chopped corn stover. The maximum shear stress was observed at a displacement of 67 ± 8 mm for chopped switchgrass, 63 ± 9 mm for chopped wheat straw, and 61 ± 9 mm for chopped corn stover (Table 1). Higher displacement for shear failure indicated that biomass will pose more difficulties in development of efficient bulk handling mechanisms and structures in biorefineries.

Analysis of variance indicated that the particle size and preconsolidation pressure had no significant effect on the displacement at shear failure for chopped wheat straw and switchgrass. However, changing the normal stress did have a significant effect on the minimum displacement required for shear failure of chopped switchgrass and chopped wheat straw (Tables 2 and 3). In the case of chopped corn stover, both changing the normal stress as well as the particle size had significant effect on the displacement at shear failure (Table 4). None of

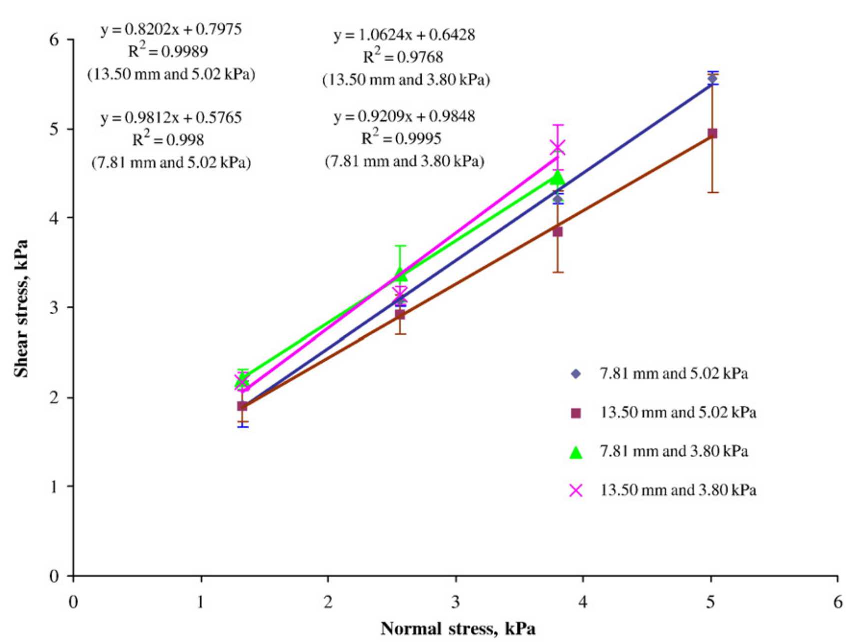

Fig. 5. Yield loci for chopped switchgrass with two geometric mean lengths and two preconsolidation pressures. Error bars represents ±1 SD.

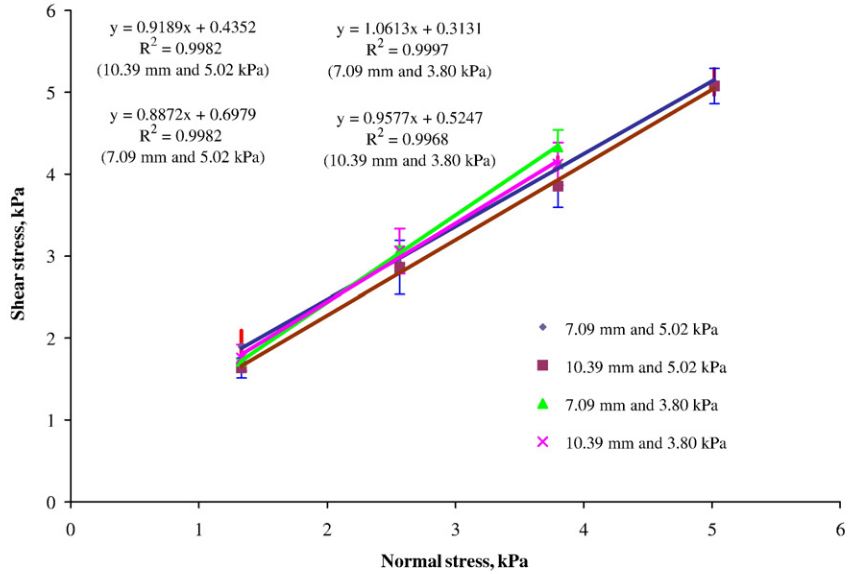

Fig. 6. Yield loci for chopped wheat straw with two geometric mean lengths and two preconsolidation pressures. Error bars represents ±1 SD.

the interaction effects were significant except for interaction effect of particle size and normal stress for chopped corn stover.

3.2. Friction coefficient

The friction coefficient was highest for chopped corn stover, followed by chopped switchgrass and chopped wheat straw. The friction coefficient measured as a ratio of stresses was always higher than the friction coefficient measured as a ratio of forces. This was expected, because, the contact area between the upper and lower shear boxes was continuously reducing and resulting in higher shear stress. Friction coefficient measured as a ratio of maximum shear force to the normal force was 1.0 ± 0.19 for chopped switchgrass, 0.92 ± 0.12 for chopped wheat straw, and 1.24 ± 0.19 for chopped corn stover. Friction coefficient measured as a ratio of maximum shear stress to normal stress was 1.26 ± 0.21 for chopped switchgrass, 1.16 ± 0.12 for chopped wheat straw and 1.48 ± 0.19 for chopped corn stover (Table 5). The high friction coefficient observed in chopped corn stover might be due to the presence of both fibrous particles from the rind and other irregular shaped particles from the pith. The friction coefficient increased for reduced normal stress for all three chopped biomass types. The same trend was observed by Richter [28] for chopped grass and corn silage.

Changing the normal stress had a significant effect on the friction coefficient measured as a ratio of shear and normal forces as well as a ratio of shear and normal stresses for all three chopped biomass (Tables 2–4). Friction coefficients measured at different preconsolidation pressures were significantly different for chopped switchgrass and wheat straw. However, the friction coefficient measured as a ratio of shear and normal forces was not significantly different for chopped corn stover at different preconsolidation pressures (Table 4). Particle size had no significant effect on the friction coefficient of chopped

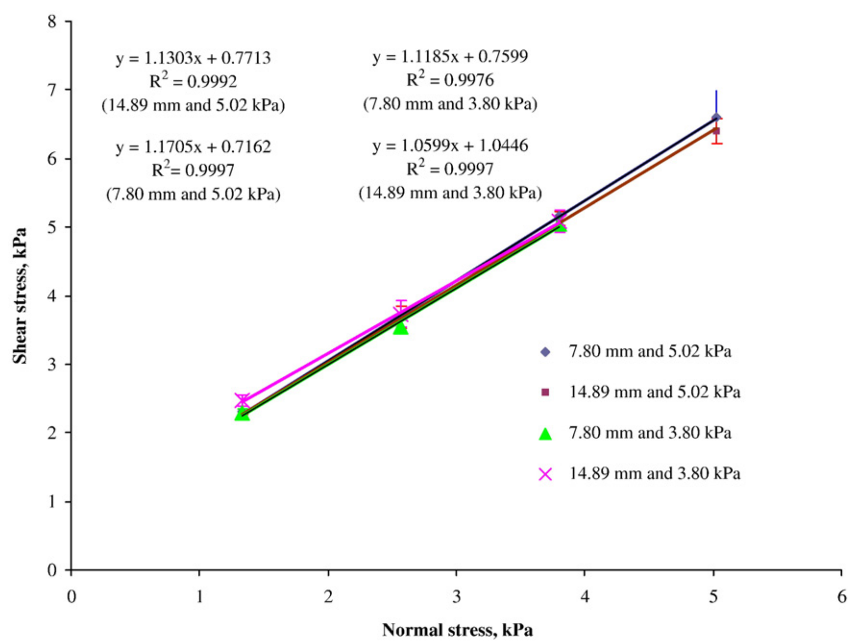

Fig. 7. Yield loci for chopped corn stover with two geometric mean lengths and two preconsolidation pressures. Error bars represents ±1 SD.

Table 6
Flow properties of chopped switchgrass, wheat straw and corn stover.

Biomass	Preconsolidation pressure (kPa)	Geometric mean length (mm)	Flow properties of biomass					
			Angle of internal friction (°)	Effective angle of internal friction (°)	Cohesion (kPa)	Unconfined yield strength (kPa)	Major consolidation strength (kPa)	Tensile strength (kPa)
Switchgrass	3.80	7.81	42.6	54.6	0.985	4.273	9.971	1.076
		13.50	46.7	54.6	0.643	3.336	9.332	0.621
	5.02	7.81	44.5	49.3	0.577	2.662	11.442	0.588
		13.50	39.4	47.2	0.798	3.251	10.923	0.941
Wheat straw	3.80	7.09	46.7	50.7	0.313	1.640	8.307	0.296
		10.39	43.8	49.9	0.525	2.380	8.595	0.563
	5.02	7.09	41.6	48.1	0.698	3.114	10.776	0.792
		10.39	42.6	46.6	0.435	1.877	10.647	0.467
Corn stover	3.80	7.80	48.2	56.7	0.760	3.812	10.875	0.679
		14.89	46.7	59.3	1.045	5.199	11.247	0.976
	5.02	7.80	49.5	55.8	0.716	3.734	12.625	0.566
		14.89	48.5	55.3	0.771	4.222	12.616	0.686

corn stover, whereas, the particle size had significant effect on the measured friction coefficient of chopped wheat straw and corn stover. Most of the interaction effects of the three factors on friction coefficients were not significantly different.

3.3. Experimental yield loci

The experimental yield loci obtained for chopped switchgrass, wheat straw, and corn stover are shown in the Figs. 5–7 respectively. The r^2 value of the yield loci (straight line relationship between normal and shear stresses) was found to be more than 0.99 for all three chopped biomass particles. The high r^2 value of the yield loci indicated that all three chopped materials closely followed the Mohr–Coulomb critical state of friction theory within the tested range. Generally as the preconsolidation pressure increased, the yield loci became a little flatter for chopped switchgrass and wheat straw, but in the case of corn stover, there was no noticeable change in the yield loci. The experiments were conducted with preconsolidation pressures of 3.80 and 5.02 kPa. The small difference in the yield loci was perhaps due to the small differences in the preconsolidation pressures tested in our experiments. Further experiments at different levels of preconsolidation pressures within the higher and lower limits of possible consolidation pressures in the storage and handling units for chopped biomass in biorefineries will lead to a better understanding of the yielding limits of chopped biomass. The slope and intercept value of the yield loci were found to be different for various particle sizes of the chopped switchgrass and wheat straw (Figs. 5 and 6). Changing the particle size of the chopped corn stover had no effect on either the intercept or slope value of the yield loci. These results indicated that the effect of varying the particle size had the least effect on the yield limits of chopped corn stover.

3.4. Flow properties

The resulting flow properties for chopped switchgrass, wheat straw, and corn stover are given in the Table 6. The cohesive strength of corn stover was found to be the highest, followed by switchgrass, and wheat straw. The measured cohesive strength was 0.75 ± 0.18, 0.49 ± 0.16, and 0.82 ± 0.15 kPa for chopped switchgrass, wheat straw, and corn stover respectively. The measured angle of internal friction was 43.3 ± 3.1°, 43.7 ± 2.2°, and 48.2 ± 1.2° for chopped switchgrass, wheat straw and corn stover respectively (Table 6). Highest angle of internal friction for chopped corn stover indicated that chopped corn stover will cause maximum resistance to flow and pose more problems in handling and storage related issues. The unconfined yield strength, major consolidation strength and tensile strength were found to be minimum for chopped wheat straw followed by chopped switchgrass and corn stover. Unconfined yield strength and major consolidation strength are the two most important factors affecting the arching of bulk materials in hoppers. The unconfined yield strength, major consolidation strength and tensile strength were, 3.38 ± 0.67, 10.42 ± 0.95, and 0.81 ± 0.24 kPa; 2.25 ± 0.65, 9.58 ± 1.31, and 0.50 ± 0.21 kPa; 4.22 ± 0.67, 11.84 ± 0.93 and 0.73 ± 0.18 kPa for chopped switchgrass, wheat straw, and corn stover respectively. The unconfined yield strength and major consolidation strength were observed to be highest for chopped corn stover which indicated that arches will be formed in the hopper more easily while handling chopped corn stover compared to chopped switchgrass and wheat straw. Fasina [29] used a rotational split type shear cell to determine the flow properties of switchgrass having a mean particle diameter less than 3 mm ground in a hammer mill. The measured angle of internal friction was 41.76 ± 0.92° and the measured unconfined yield strength was approximately 2.0 kPa at a major consolidation stress of 5.0 kPa. As per literature, bulk flow materials with cohesion less than 2 kPa and angle of internal friction less than 30° are amenable for handling with gravity alone [30]. The cohesive strength of all chopped biomass was found to be less than 1 kPa. However, a very high angle of internal friction makes the chopped biomass very difficult to handle with gravity alone.

4. Conclusions

A direct shear cell to measure the shear strength and flowability of chopped biomass was designed, developed and tested with three different types of chopped materials: switchgrass, wheat straw, and corn stover. Following conclusions were made based on the experiments:

1. Yield strength and other flow property results for the chopped biomass obtained from the direct shear cell were reliable and repeatable.
2. Shear failure of the prepared samples for different chopped materials occurred at a displacement raged from 30 mm to 80 mm in the direct shear cell.
3. Changing the normal stress had significant effect on friction coefficient of all three chopped biomass types. However, changing the particle size had significant effect on the friction coefficient of chopped switchgrass and wheat straw only.
4. Chopped corn stover exhibited the highest angle of internal friction, unconfined yield strength, major consolidation strength, and cohesive strength compared to chopped switchgrass and wheat straw indicating chopped corn stover will cause more challenges in handling and storage in biorefineries.
5. The angle of internal friction measured at different consolidating pressures were more than 30° for all three chopped materials tested in our experiments indicating chopped biomass cannot be handled by gravity alone in biorefineries.

Acknowledgement

We thankfully acknowledge the funding support provided through the USDA-NRCS Grant Agreement 68-3A75-4-136 and USDA-DOE Biomass Research and Development Initiative DE-PA36-04GO94002 for carrying out this project work.

References

[1] K. Ibsen, A. McAloon, E. Taylor, R. Wooley, W. Yee, Determining the cost of producing ethanol from corn starch and lignocellulosic feedstocks, NREL/TP-580-28893, US Department of energy, National Renewable Energy Laboratory, Golden, CO, 2000.
[2] A. Demirbas, Biomass resource facilities and biomass conversion processing for fuels and chemicals, Energy Conversion and Management 42 (2001) 1357–1378.
[3] T. Christopher, P.A. Pryfogle, N.A. Stevens, J.R. Hess, C.W. Radke, Value of distributed preprocessing of biomass feedstocks to a biorefinery industry, Paper No. 066151, American Society of Agricultural Engineers, St. Joseph, MI, 2006.
[4] S. Sokhansanj, J. Cushman, L. Wright, Collection and delivery of biomass for fuel and power production, The CIGR Journal of Scientific Research and Development V (2003) 1–22.
[5] M. Knauf, M. Moniruzzaman, Lignicellulosic biomass processing: a perspective, International Sugar Journal 106 (2004) 147–150.
[6] C.T. Wright, P.A. Pryfogle, N.A. Stevens, J.R. Hess, C.W. Radtke, Value of distributed preprocessing of biomass feedstocks to a biorefinery industry, Paper No.066151, American Society of Agricultural Engineers, St. Joseph, MI, 2006.
[7] M. Peleg, E.B. Bagley, Physical Properties of Foods, AVI Publishing Company Inc, Connecticut, CT, 1983.
[8] P. Juliano, B. Muhunthan, G.V. Barbosa Canovas, Flow and shear descriptors of preconsolidated food powders, Journal of Food Engineering 72 (2006) 157–166.
[9] R.H. Rong, S.C. Negi, J.C. Jofreit, Simulation of flow behavior of bulk solids in bins. Par 2: shear bands, flow corrective inserts and velocity profiles, Journal of Agricultural Engineering Research 62 (1995) 257–269.
[10] N.N. Mohsenin, Physical Properties of Plant and Animal Materials, Gordon and Breach Science Publishers, New York, NY, 1970.
[11] G.V. Barbosa-Canovas, E. Ortega-Rivas, P. Juliano, H. Yan, Food Powders: Physical Properties, Processing, and Functionality, Kluwer Academic Plenum Publishers, New York, NY, 2005.
[12] A.W. Jenike, Storage and flow of solids, Bulletin No. 123 of Utah Engineering Experiment Station, University of Utah, UT, 1964.
[13] J. Schwedes, Shearing behavior of slightly compressed cohesive granular materials, Powder Technology 11 (1975) 59–67.
[14] J.J. Fitzpatrick, S.A. Barringer, T. Iqbal, Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values, Journal of Food Engineering 61 (2004) 399–405.
[15] J.J. Fitzpatrick, T. Iqbal, C. Delaney, T. Twomey, M.K. Keogh, Effect of powder properties and storage conditions on the flowability of milk powders with different fat contents, Journal of Food Engineering 64 (2004) 435–444.
[16] S.P. Duffy, V.M. Puri, Effect of moisture content on flow properties of powders, ASAE Paper No. 944033, 1994, St. Joseph, MI.
[17] P. York, The use of glidants to improve the flowability of fine lactose powder, Powder Technology 11 (1975) 197–198.
[18] S. Kamath, V.M. Puri, H.B. Manbeck, R. Hogg, Flow properties of powders using four testers — measurement, comparison and assessment, Powder Technology 76 (1993) 277–289.
[19] V. Ganesan, K. Muthukumarappan, K.A. Rosentrater, Flow properties of DDGS with varying soluble and moisture contents using Jenike shear testing, Powder Technology 187 (2008) 130–137.
[20] ASTM, ASTM: D 3080-04, Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions, ASTM International, West Conshohocken, PA, 2007.
[21] M. Molenda, J. Horabik, On applicability of a direct shear test for strength estimation of cereal grain, Particle & Particle System Characterization 21 (2004) 310–315.
[22] ASAE, ASAE S424.1: Method of Determining and Expressing Particle Size of Chopped Forage Materials by Screening, ASAE Standards 2004, 48th EditionASAE, St. Joseph, MI, 2004.
[23] ASBE, ASAE S358.2: Moisture Measurement—Forages, ASAE Standards 2004, 48th EditionASAE, St. Joseph, MI, 2004.
[24] A.W. Jenike, J.W. Carson, Measurement principles of the flowability of powders, Advances in Ceramics 21 (1987) 759–766.
[25] SAS, SAS/STAT User's Guide, Ver. 9.1. SAS Institute Inc, Cary, NC, 2004.
[26] M.A. Rao, Statistical Research Methods in the Life Sciences, Duxbury Press, Pacific grove, CA, 1988.
[27] The Institution of Chemical Engineers, Standard Shear Testing Technique for Particulate Solids Using Jenike Shear Cell, The Institution of Chemical Engineers, Warwickshire, England, 1989.
[28] D.W. Richter, Friction coefficients of some agricultural materials, Agricultural Engineering 35 (1954) 411–413.
[29] O.O. Fasina, Flow and physical properties of switchgrass, peanut hull, and poultry litter, Transactions of the ASABE 49 (2006) 721–728.
[30] V.M. Puri, Characterizing powder flowability, Chemical Processing 65 (2002) 39–42.