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FLOWABILITY PARAMETERS FOR CHOPPED SWITCHGRASS, WHEAT STRAW AND CORN STOVER

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***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. The shear strength measured at various normal stresses was found to be significantly different. Shear strength for all three chopped biomass types measured at a particular normal stress was not significantly different. The R^2 value of the experimental yield loci was found to be more than 0.99 for all three chopped biomass, indicating that the chopped biomass followed the Mohr-Coulomb theory for critical state of friction. The experimental yield loci developed at a preconsolidation pressure of 4.92 kPa showed that the cohesive strength of chopped corn stover was the highest. The effect of changing the particle size had a profound effect on the angle of internal friction of chopped switchgrass compared to chopped wheat straw and chopped corn stover. The friction coefficients measured at different normal pressures were always more than 1 for chopped corn stover. But for chopped switchgrass and wheat straw, the friction coefficient was found to be less than 1 for a normal stress of above 2.55 kPa. These results indicate that changing the particle size of chopped biomass will have a profound effect on the flowability of chopped switchgrass compared to chopped wheat straw and corn stover. These results are useful for development of handling, storage and transportation equipments for biomass in biorefineries.

Keywords. *Switchgrass, wheat straw, corn stover, direct shear test, yield loci, unconfined yield strength.*

Introduction

Biomass is a renewable and sustainable source for energy production (Ibsen et al. 2000; Demirbas 2001), in which lignocellulosic materials are converted to energy either by thermochemical or biochemical methods. In biochemical methods, lignocellulosic materials are converted to ethanol, which can be conveniently used as a fuel. Many organizations are on the threshold of converting lignocellulosic material to ethanol at a commercial scale, but continuous research and development is necessary to produce ethanol from lignocellulosic materials at price competitive with that of fossil fuels. Some of the engineering challenges foreseen in this process include development of harvesting, handling, storage, transportation, and process equipments in a biorefinery (Christopher et al. 2006; Sokhansanj et al. 2003; Knauf and Moniruzzaman, 2004; Wright et al. 2004). At present few data are available for designing efficient handling, storage, transportation, and processing equipment. Hence, it is important to develop more information on the engineering properties of this biomass. Especially critical is more information on the flow properties of biomass, which are critical in the design of handling, storage and transportation equipment.

Direct shear testing is extensively used by soil engineers and food engineers for characterizing the shear strength of bulk flow materials (Peleg and Bagley, 1983). Direct shear testing involves preconsolidating the samples to a predetermined normal stress, and subsequent shearing of the samples (Juliano et al. 2006). This results in understanding the effect of sample conditions on its shear strength properties.

Jenike developed a mathematical methodology for determining the minimum hopper angle, opening size, and characterizing the bulk flow of biomaterials like food powders using direct shear techniques (Barbosa Canovas, 2005). Jenike used unconfined yield stress and major consolidating stress data to characterize flow properties and design of hopper dimensions (Schwedes, 1975). In this method, the testing material is preconsolidated to a predetermined normal pressure. A direct shear cell is then used to determine the maximum shear stress required to shear the samples at different normal stresses below the preconsolidation stress (Peleg and Bagley, 1983). Based on the normal and shear stress data, the angle of internal friction and the cohesion are determined using the Mohr-Coulomb equation. Based on the angle of internal friction and cohesion values, the unconfined yield stress (σ_c) and major consolidation stress (σ_1) at the given preconsolidation pressure are calculated. The experiment is repeated with different pre-consolidation pressures to obtain different unconfined yield stresses and major consolidation stresses. The slope of the linear relationship between unconfined yield stress and major consolidating stress is defined as the flow function. The flow index is the inverse of flow function, and is used to characterize the bulk flow material as hardened, very cohesive, cohesive, easy to flow, or free-flowing material (Fitzpatrick et al, 2004).

Angle of internal friction is also a very important factor in designing storage structures (Rong et al. 1995). The lateral pressure acting on storage bin walls is determined based on the angle of internal friction of the stored materials. Angle of internal friction is a factor in both Rankine's and Janssen's equations used for determining the lateral pressure in shallow and deep bins, respectively (Mohsenin, 1970). Even though much work has been done on determining the shear strength of biomaterials using the direct shear technique, no such work has been done on shear strength determination of chopped biomass.

The objectives of this research were to: 1. Develop a shear cell for chopped biomass as per ASTM standards, and 2. Study the effect of particle size on the flow properties of chopped biomass.

Methods and Materials

Chopped biomass

Switchgrass, wheat straw and corn stover were chopped in a knife mill at different rotational speeds, feed rates, and with different classifying screens. The chopped biomass obtained was found to have varying particle size distributions, and these were used as the raw material for our experiments.

Particle size

The particle size was studied using method no. ASAE S424.1 (ASAE, 2004). The mass fractions retained on the screens having diagonal opening dimensions of 1.65 mm, 5.61 mm, 8.98 mm, 18.0 mm, 26.9 mm, and pan were used to determine the geometric mean length (X_{gm}).

Fabrication of shear cell

A direct shear cell was fabricated as per the guidelines in the ASTM D3080-98 (ASTM, 2007) and shown in the figure 1. The shear cell was fabricated with acrylic sheet of 9 mm thickness. 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 X 305 X 150 mm high. The upper shear box was hollow and had internal dimensions of 305 X 305 X 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 the Universal testing machine was fabricated mild steel. The upper shear box was connected to the load cell of the universal testing machine using a pulley and cable arrangement.

Testing procedure

The upper and lower shear boxes were placed in position, and were filled to the top of the upper shear box with chopped biomass. An acrylic plate of 302 X 302 mm and 9 mm thick was placed on the biomass. A pre-consolidation load of 42.625 kg (4.92 kPa) was placed on the acrylic sheet, and the biomass allowed to consolidate for 10 minutes. Afterwards, the preconsolidation load was removed, and the box was filled again with biomass up to the top edge. The pre-consolidation load was replaced, and the biomass allowed to consolidate for another 10 minutes. This procedure was repeated a third time, so the biomass was allowed to pre-consolidate for a total of 30 minutes.

After preconsolidation, the consolidation load was removed and a normal load of 11.643 kg (25% of preconsolidation load) was applied on the biomass. The prepared sample was then sheared at a constant speed of 9 mm per minute by pulling the upper shear box with the universal testing machine. A computer connected to the universal testing machine recorded the force displacement curves. This experiment was repeated with normal loads of 50%, 75% and 100% of the preconsolidation load. All the experiments were conducted for a shearing distance of 100 mm. The force and displacement data were downloaded from the computer and were used to measure the maximum shear force, and maximum shear stress.

Friction coefficients at different normal forces were calculated as the ratio of maximum shear force recorded to the normal force applied on the biomass.

The cohesive strength and angle of internal friction were calculated using the Mohr-Coulomb equation (1), by linear regression

$$\tau = c + \tan(\phi)\sigma \qquad (1)$$

Where τ – shear stress (kPa)

c – Cohesion strength (kPa),

ϕ - Angle of internal friction (°)

σ – Normal stress (kPa)

The unconfined yield strength (σ_c) of the chopped biomass was determined using the following equation (Fasina, 2006)

$$\sigma_c = \frac{2c(1+\sin\phi)}{\cos\phi} \qquad (2)$$

Experimental design

Two chopped switchgrass samples having geometric mean length of 7.81 mm (KMSG29) and 13.50 mm (KMSG4), two chopped wheat straw samples having geometric mean length of 7.09 mm (KMWS20) and 10.39 mm (KMWS11), and two chopped corn stover samples having geometric mean length of 7.80 mm (KMCS17) and 14.89 mm (KMCS3) were used for testing. Experiments were conducted with one preconsolidation stress of 4.92 kPa and four normal stresses of 1.23 kPa, 2.46 kPa, 3.67 kPa and 4.92 kPa. All experiments were replicated three times.

Results and Discussion

A typical stress-displacement curve from shear testing is shown in Figure 2. The force required to shear the samples increased continuously, reached a peak value, and then decreased. The peak shear force was reached at a displacement of 35 to 60 mm for all the chopped biomass tested in our experiments. The shear stress was calculated based on the actual biomass contact area, which decreased as the test progressed, since the upper shear box was moving over the lower box. This calculated shear stress increased continuously, reached a maximum value, and remained constant afterwards. According to the literature, in direct shear testing the peak force required to shear the samples is contributed to by friction forces, cohesion forces, and forces caused by interlocking of the particles (Juliano et al. 2004). In reported cases of shear tests containing significant amounts of interlocking component, the shear stress increased to a peak value and reduced to a value equivalent to interlocking component and remains constant(Juliano et al. 2004). As per ASTM standard D3080 to get good results, the prepared specimen dimension should be at least 10 times the maximum particle dimension of the sample. For chopped biomass having very less aspect ratio, it is very difficult to arrive at the shear box dimensions. Our results indicated that the shear box having 305 mm side is sufficient to obtain reliable data in direct shear testing of chopped biomass.

Friction coefficient

The chopped biomass friction coefficient was in the range of 0.765 to 1.586 for the various normal pressures (Table 1). A friction coefficient greater than 1 means that the shear force required was greater than the applied normal force. The friction coefficient increased for reduced normal pressure for all three chopped biomass types. The same trend was observed by Richter (1954) for chopped grass and corn silage.

The friction coefficient was highest for chopped corn stover, followed by chopped switchgrass and chopped wheat straw. The friction coefficient was always more than 1 for chopped corn stover, indicating that the shear force required was always more than the normal force. This might be due to the chopped corn stover contained both fibrous particles from the rind and other irregular shaped particles from the pith. In wheat straw, the friction coefficient was more than 1 when the applied normal pressure was 1.23 kPa. In switchgrass, the friction coefficient was more than 1 when the applied normal pressure was less than 2.46 kPa.

For all three chopped biomass types, changing the particle size caused no statistically significant difference in the friction coefficient except at the lowest applied normal pressure of 1.23 kPa for chopped corn stover and chopped wheat straw (Table 1).

Experimental Yield Loci

The experimental yield loci obtained for chopped switchgrass, wheat straw, and corn stover are shown in the figures 3, 4, and 5 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 materials. The high R^2 value of the yield loci indicated that all three chopped materials followed the Mohr-Coulomb critical state of friction theory very well within the tested range.

The shear strength of the corn stover was found to be the highest, followed by switchgrass and wheat straw. The variability in the measured shear stress value increased with increased particle size for all three chopped biomass types (Figures 3, 4 and 5). However, the shear stress value measured at a particular normal stress value was found to be statistically similar. Shear stress statistically differed between normal stress levels.

The slope and intercept value of the yield loci were found to be different for various particle sizes of the chopped switchgrass (Figure 3). In the case of chopped wheat straw, varying the particle size resulted in significant differences in the intercept value of the yield loci only. 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 strength of chopped corn stover.

Flow properties

The resulting flow properties for chopped switchgrass, wheat straw, and corn stover are given in the Table 2. The cohesive strength of all chopped biomass was found to be less than 1 kPa. The cohesive strength of corn stover was found to be the highest, followed by switch grass, and wheat straw. The small and large particle sizes caused the maximum difference in cohesive strength for wheat straw, followed by switchgrass and corn stover.

The measured angle of internal friction for the chopped biomass ranged from 39.6 to 49.8°. The angle of internal friction was highest for corn stover, followed by switchgrass and wheat straw (Table 2). Changing the particle size resulted in larger differences in angle of internal friction in switchgrass, with only slight differences for corn stover and wheat straw.

Unconfined yield strength at a pre-consolidation pressure of 4.92 kPa was found to be maximum for chopped corn stover, followed by chopped switchgrass and chopped wheat straw. Changing the particle size resulted in a maximum change in the unconfined yield strength for wheat straw, followed by chopped switchgrass and chopped corn stover. Similar values of yield strength and other flow properties for switchgrass and wheat straw indicate that handling and storage equipment can be similar for these chopped biomass materials. However, the differences in the corn stover properties indicate that chopped corn stover may require different designs or modifications for handling large quantities of this biomass in biorefineries.

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. The 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 are reliable and repeatable.
2. The shear strength of chopped corn stover was the highest, followed by chopped switchgrass and corn stover.
3. Changing the particle size had a profound effect on the flowability of chopped switchgrass and wheat straw, but much less effect on the flowability of chopped corn stover.
4. The unconfined yield strength of corn stover measured at a pre-consolidation pressure of 4.92 kPa was found to be the highest for chopped corn stover, followed by chopped switchgrass and chopped wheat straw.

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Table 1. Friction coefficients of chopped switchgrass wheat straw and corn stover (Pre-consolidation pressure = 4.92 kPa)

Biomass	Geometric mean length (mm)	Coefficient of friction (μ) at different normal pressures			
		1.23 kPa	2.46 kPa	3.67 kPa	4.92 kPa
Switchgrass	7.81	1.246^{a}	1.021^{b}	$0.909^{b\text{-}d}$	$0.877^{c\text{-}e}$
	13.50	1.254^{a}	0.941^{bc}	0.790^{de}	0.765^{e}
Wheat straw	7.09	1.280^{a}	0.961^{bc}	$0.859^{c\text{-}e}$	0.816^{e}
	10.39	1.033^{b}	0.903^{cd}	$0.780^{d\text{-}e}$	0.779^{e}
Corn stover	7.80	1.586^{a}	1.227^{c}	1.128^{d}	1.058^{de}
	14.89	1.489^{b}	1.231^{c}	1.120^{de}	1.028^{e}

*Mean values suffixed with different letters for a particular biomass were significantly different (LSD) at $P<0.05$.

Table 2. Calculated flow properties of chopped switchgrass wheat straw and corn stover (pre-consolidating pressure = 4.92 kPa)

Biomass	Geometric mean length (mm)	Flow properties of biomass			
		Angle of internal friction (°)	Cohesion (kPa)	R^2	Unconfined yield strength (kPa)
Switchgrass	7.81	44.7	0.699	0.998	3.349
	13.50	39.6	0.911	0.999	3.869
Wheat straw	7.09	40.6	0.789	0.998	3.341
	10.39	41.6	0.530	0.998	2.358
Corn stover	7.80	49.8	0.836	0.999	4.563
	14.89	48.7	0.920	0.999	4.880

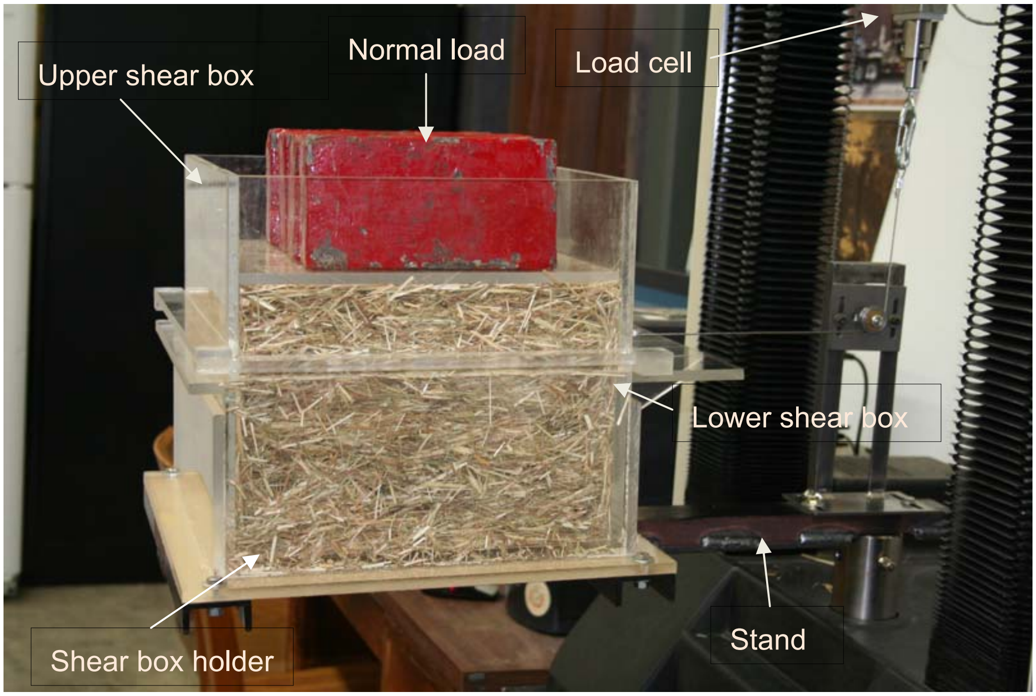

Figure 1. Direct shear cell with biomass before shearing.

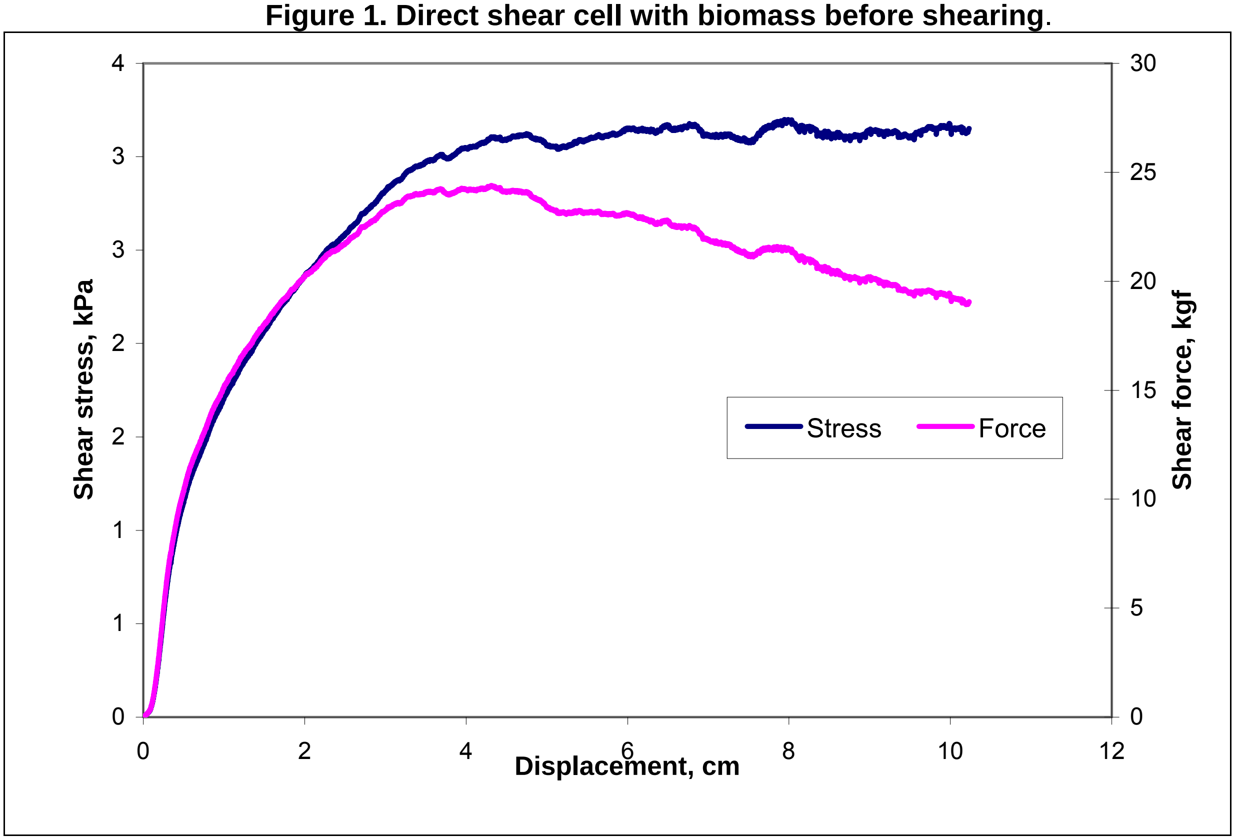

Figure 2. Typical shear stress and force curves during shear tests of chopped biomass

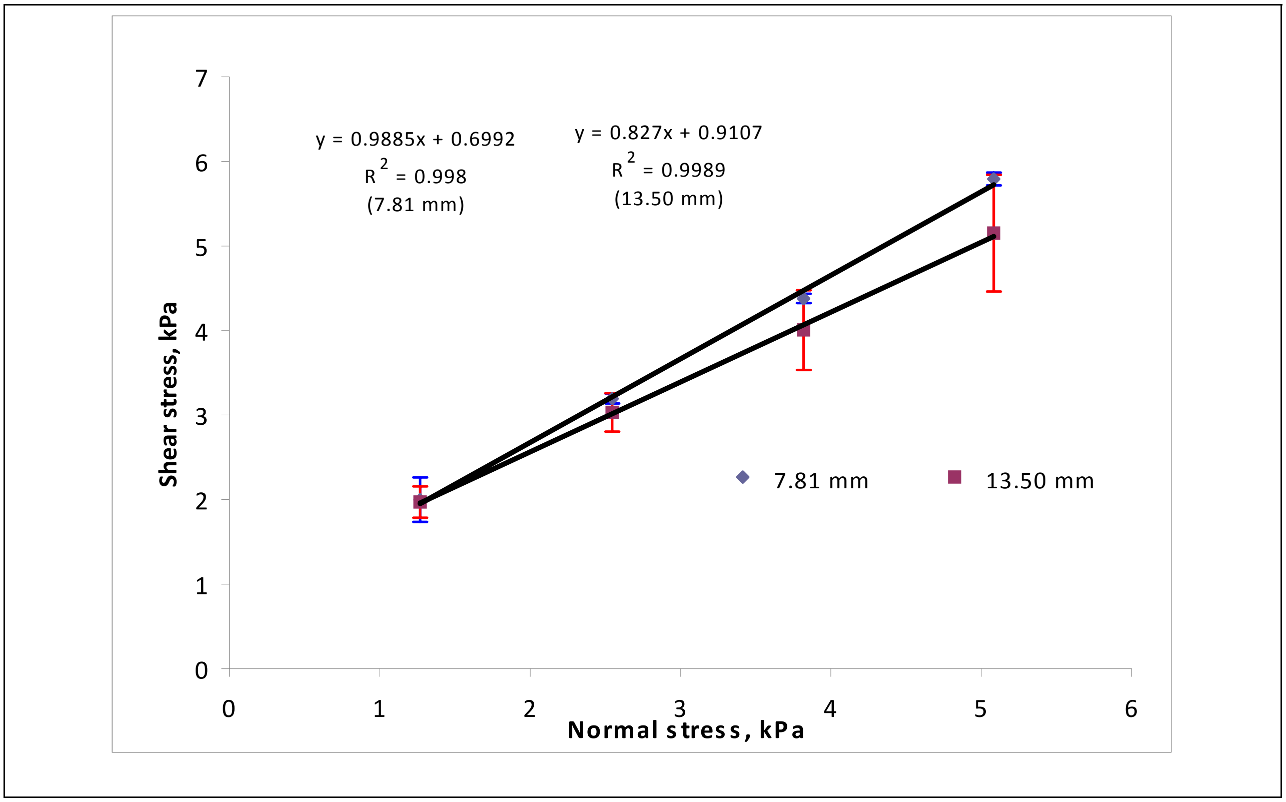

Figure 3. Yield loci for chopped switchgrass (Pre-consolidating pressure = 4.92 kPa)

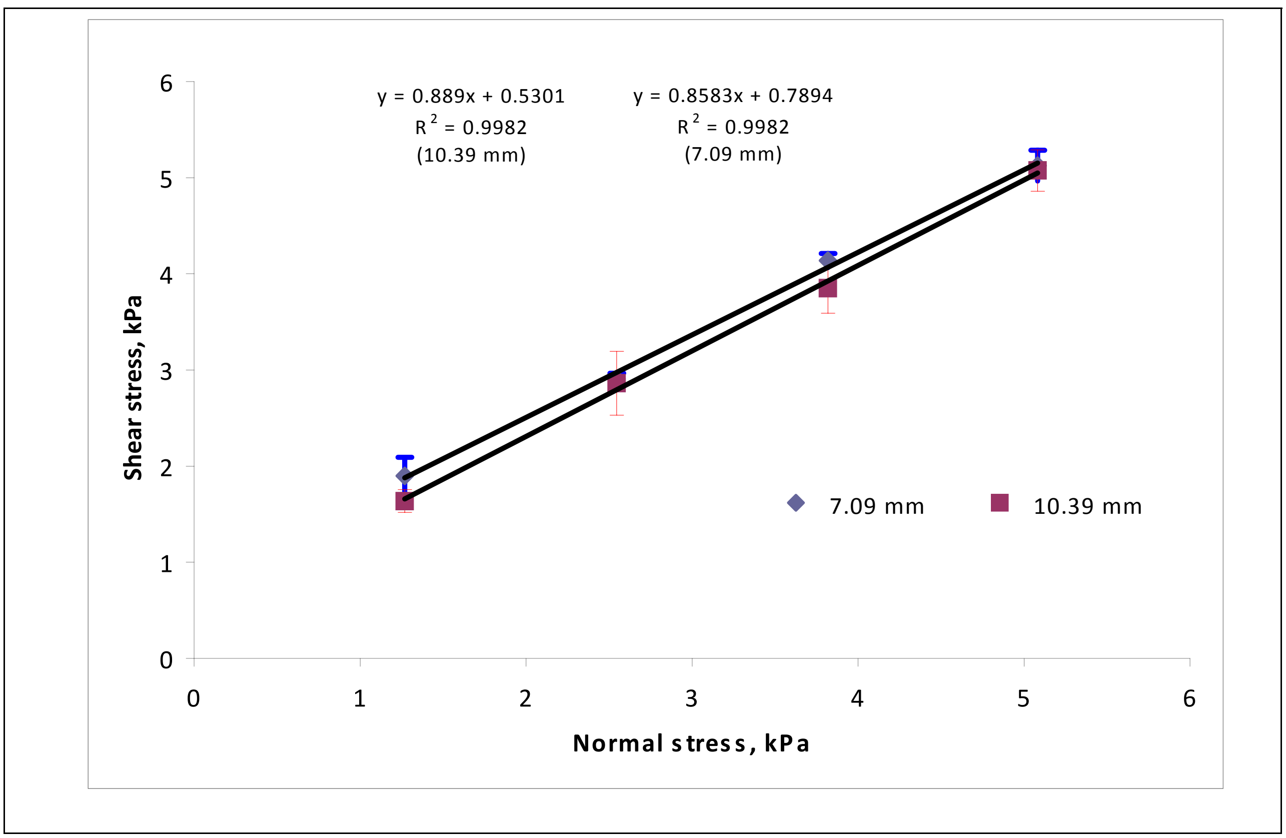

Figure 4. Yield loci for chopped wheat straw (Pre-consolidating pressure = 4.92 kPa)

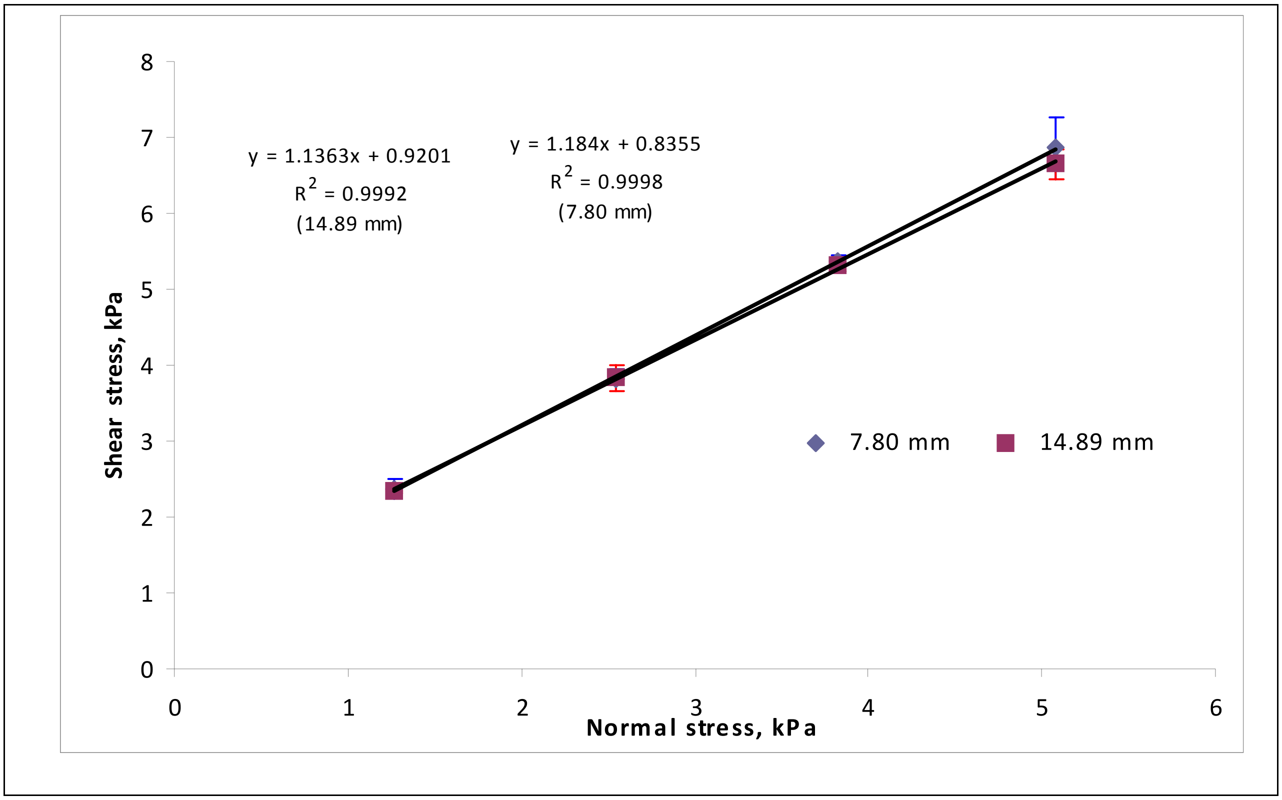

Figure 5. Yield loci for chopped corn stover (Pre-consolidating pressure = 4.92 kPa)