Frictional Properties of Ground Loblolly Pine Chips

Jacob Wadkins, Anshu Shrestha, Oladiran Fasina, Sushil Adhikari, Steven Taylor

Abstract

Biomass, such as ground wood chips, is a bulk material and therefore has the typical flow problems associated with bulk materials. The frictional properties (cohesion, flow index, and angle of internal friction) of ground loblolly pine chips obtained from different harvesting operations (clean chips, dirty chips, and residues) and ground through 1.588 mm and 3.175 mm screens were measured. Grinding screen size did not significantly affect ($P<0.05$) the frictional properties of the samples. Cohesive strength and flow index of ground clean chips and dirty chips were significantly higher than those of ground residues. Based on flowability classification, the flow index value of 3.53 obtained for ground residues indicates that it has a cohesive flow behavior. Ground clean and dirty chips have easy flow behavior (flow index is 4.36). The angles of internal friction for ground clean chips, dirty chips, and residues were 45.2°, 44.9° and 46.2° respectively. The higher values of ash, cohesive strength, angle of internal friction, and flow index for the residues indicate that special handling and processing operations have to be carried out on the residues before they can be utilized in bioenergy applications.

Introduction

The South is the primary wood-producing region of the United States. Forestland covers 156 million acres or 60 percent of the land area in the southeastern part of the country (http://fia.fs.fed.us/). Over 60 percent of U.S. timber production comes from southern forests with loblolly pine being the most predominant wood species grown. With a decline in the pulp and paper manufacturing industry and in the solid wood products sectors due to reductions in housing construction, a significant amount of wood is available as biomass feedstocks for production of bioenergy, biofuels, and bioproducts (Frederick et al., 2008). Loblolly pine is the biomass feedstock that is predominantly available in the forestland of the southern part of the U.S. The three different products that are typically obtained from forest logging and chipping operations are: 'clean' chips, 'dirty' chips, and residues. Clean chips are produced from the stems of debarked wood. Dirty chips are chips produced from entire trees and typically include the stem, bark, branch wood, and leaves/needles. Residues are the unused parts above the stumps of harvested trees including live standing or downed trees that are left on site after logging. To facilitate heat and mass transfer during bioenergy conversion processes, harvested trees need to be ground before they are fed into conversion equipment at the biorefinery plants. When trees are harvested, they are typically chipped into 25 to 50 mm sizes. Wood grinds are produced at the bioenergy conversion facility by grinding the chips into sizes of 1.0 to 6.0 mm with a hammer mill. The final grind size depends on the bioenergy conversion process and the technology used. Direct grinding of trees is currently not a common practice because of the logistics of grinding on the forest land.

Since wood grinds are bulky in nature, they have flow problems that are typically exhibited by bulk materials. Core flow (as shown in Figure 1) is the default flow pattern out of storage containers, holding containers, and drying vessels for powder-like materials such as wood grinds. This flow pattern is characterized by powder discharge through a preferential flow channel that starts from the top of the stored material and results in a first-in/last-out discharge. The result is unreliable and inconsistent flow, and/or no flow caused by cohesive arching or the formation of a stable rathole (Iqbal and Fitzpatrick, 2006). Another problem with core flow is that powder around the walls and in the lower sections of the container remains there until the container is emptied. During 'mass'

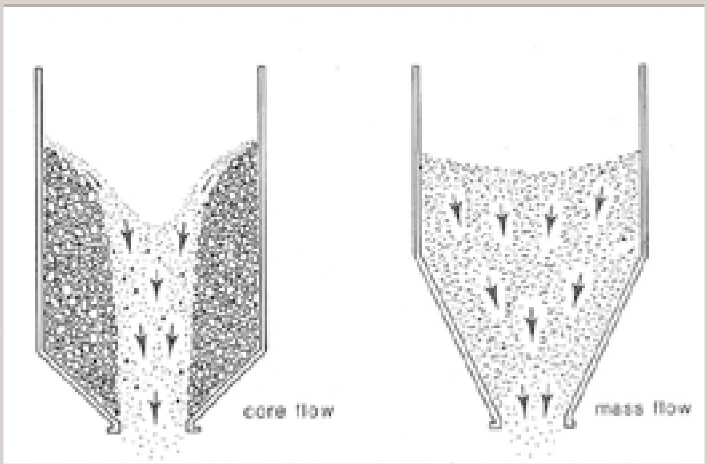

Figure 1. Patterns of discharge from hoppers (Woodcock and Mason, 1988).

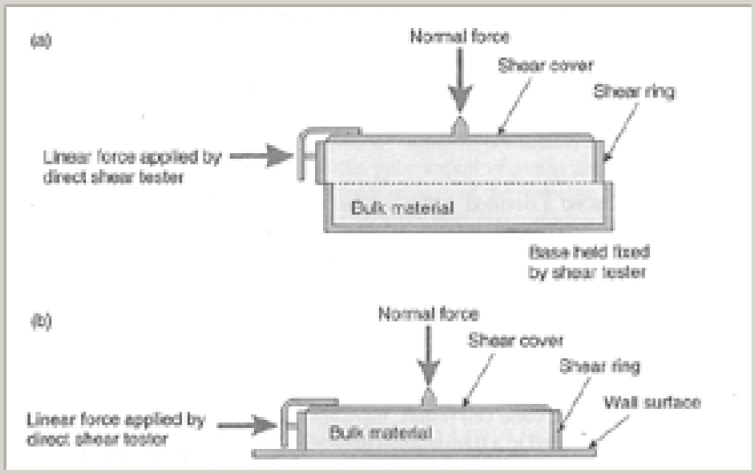

Figure 2. Jenike shear tester modes of operation for measuring (a) flow function, (b) wall friction characteristics (Fitzpatrick, 2005).

flow, all of the material in the bin is in motion (i.e., there is 'mass' movement – Figure 1) whenever the discharge outlet is opened resulting in first-in/first-out flow sequence. This flow pattern is especially desirable for cohesive solids and fine powders that are typically poor-flowing because all of the material in the bin is in motion. The result is consistent and there is reliable flow from these containers (Iqbal and Fitzpatrick, 2006). Other advantages of mass flow include an absence of surging and flooding and minimum segregation of stored products (Roberts, 2005). Process optimization in biorefineries, such as gasification plants, requires a reliable flow from these containers. Unlike the core flow pattern that naturally occurs, special design considerations must be made for the mass flow pattern to occur. Flow properties (such as the angle of internal friction, flow index, and cohesive strength) are used to design hopper angles and outlet diameters necessary for mass flow of powder-like materials such as wood grinds.

Frictional (or flow) properties of powder-like materials are usually determined with a translational or rotational shear tester that generally involves applying shear force to a material until the material fails (McGlinchey, 2005). In a translational shear tester (often referred to as the Jenike shear tester), the bulk solid specimen is subjected to a normal stress. The material is then sheared by applying a gradually increasing horizontal force on the upper side of the shear cell. This causes the upper side of the shear cell to move relative to its lower side (i.e., shearing of the sample placed in the shear cell – Figure 2). A shear tester in which the relative displacement is achieved by rotation of the top of the bulk solid specimen relative to the bottom is called a rotational shear tester (Schulze, 2008). The rotational shear cell tester was initially developed to overcome the limited shear displacement that can be achieved with the Jenike shear tester. A more detailed description of the two shear tester types can be found in Jenike (1964) and in Barbosa-Cánova et al. (2005). A yield locus curve is obtained from the shear stress test. The curve is a plot of the shear stress required to cause sample failure versus the normal stress applied. The angle of internal friction and cohesive strength of the materials are obtained from the slope and intercept of the yield locus curve respectively. Wall friction properties are measured by replacing the base of a shear cell with a plate of the material that will be used to manufacture the hopper or storage container.

The angle of internal friction measures the friction between solid particles flowing against each other. Cohesive strength is a measure of the force of attraction or bonding tendency between particles of a bulk material (Bernhart and Fasina, 2009). Flow index is used to characterize the flowability of bulk materials (Table 1). The flow index is the inverse of the flow function obtained during flow behavior tests. The flow function is the slope of the plot of unconfined yield stress versus the major consolidating stress (Fitzpatrick et al., 2004). The plot is obtained by developing Mohr stress circles on the yield locus curves obtained for a sample at various consolidating stresses. In general, materials with a cohesion of less than 2 kPa and an angle of internal friction of less than 30° are amenable to handling using gravity alone (Puri, 2002).

Factors that have been documented to affect these flow properties include particle size, moisture content, and material composition (Fasina, 2006; Zulfiqar et al., 2006). The objective of this study was to measure the physical and frictional properties of wood grinds from loblolly pine clean chips, dirty chips, and residues.

Materials and Methods

Wood chips from different harvesting operations (clean chips, dirty chips, and residues left on field after harvesting) were ground through two screen sizes (1/8" and 1/16") using a hammer mill (Glenn Mills Inc., Clifton, NJ). Ash, moisture, and volatile contents of the samples were analyzed according to ASTM Standard E1755 (ASTM, 2007), ASTM Standard E1756 (ASTM, 2008) and ISO Standard 562 (ISO, 2010) respectively. An IKA C200 bomb calorimeter (IKA Works Inc., Wilmington, NC) was used to measure the heating value of the samples. Physical properties of the ground samples that were quantified were particle density (Model 1340, Micromeritics Instrument Corp, Norcross, GA) and bulk density (Fasina, 2006). Average particle size was based on the equivalent sphere approach (i.e., diameter of the sphere that has a volume equivalent to the average volume of the particles) and was measured by a digital image particle analyzer (Camsizer, Retsch Technology, Haan, Germany).

A rotational type powder flow tester (Brookfield Engineering Laboratories, Middleboro, CA) was used to measure the friction properties (flow index, cohesion, and angle of internal friction). The tester was operated by loading a sample into the space between the inner ring and the outer ring of a sample trough. After determining the mass of the loaded sample, the trough and its contents were placed on a flow tester already fitted with a vane lid. The software supplied by the equipment manufacturer was then used to run the flow function test. The software returned the values for the friction properties of the tested sample.

All of the above analyses were carried out in duplicate. Data analysis and plotting were carried out using Microsoft Excel software. Statistical analysis was performed on all data sets using SigmaPlot (version 12.3, Systat Software Inc., San Jose, CA) and SAS statistical software package (version 9.2, SAS Institute Inc., Cary, NC, 2011). Statistical testing was carried out at the 95% confidence interval.

Results and Discussion

Values of the physical and chemical characteristics of the ground loblolly pine wood chips are shown in Table 2. Statistical analysis using ANOVA and Duncan's multiple range test showed that the physical properties (particle density, bulk density, and particle size) are significantly affected ($P<0.05$) by material type and grinding screen size. As expected, the sample type significantly affected ($P<0.05$) the chemical properties (ash, energy, and volatile contents) of the samples but screen size did not ($P>0.15$). Energy and volatile contents of the ground residues samples were about 40% lower while the ash contents of the residues were several orders of magnitude higher than the corresponding values for ground samples from clean chips or from dirty chips. In addition, the ash contents of ground dirty chips samples were significantly higher than those of clean chips. Dirty chips contain leaves, bark, and branches that may have ash contents of up to 10% (based on other analysis).

Residues are being investigated for bioenergy utilization because residues left in the forest after biomass harvest impede forest regeneration, increase the risk of forest fire, and hinder recreational use. Current technology to gather and collect residues after logging operations often results in contamination of the residues with soil, hence the significantly higher ash contents and lower volatile contents of the residues as shown in Table 2. These results show that the potential use of residues in bioenergy is questionable unless processes to gather and collect them are improved such that soil contamination is minimized.

Table 1. Classification of powder flowability by flow index (Jenike, 1964).

	Very Cohesive	Cohesive	Easy Flowing	Free Flowing
Flow Index (FI)	FI < 2	2 < FI < 4	4 < FI < 10	FI > 10

RESULTS

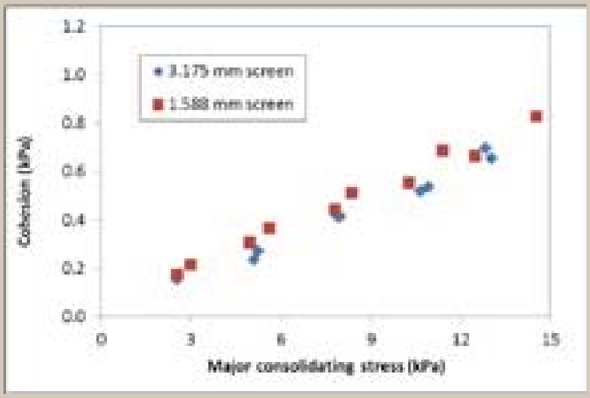

Figure 3. Effect of screen size on cohesion of clean wood chips ground through 1.588 mm and 3.175 mm screens.

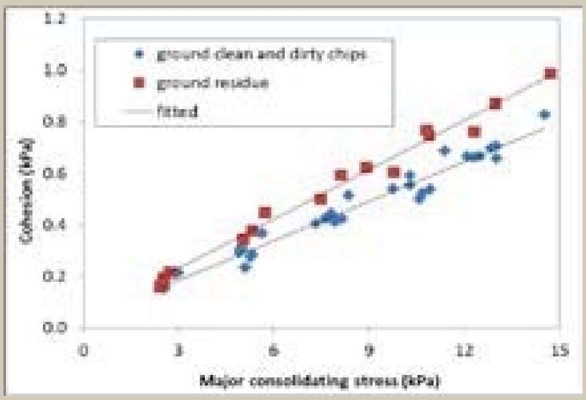

Figure 4. Fitted and experimental data of cohesion of ground clean and dirty wood chips, and residues.

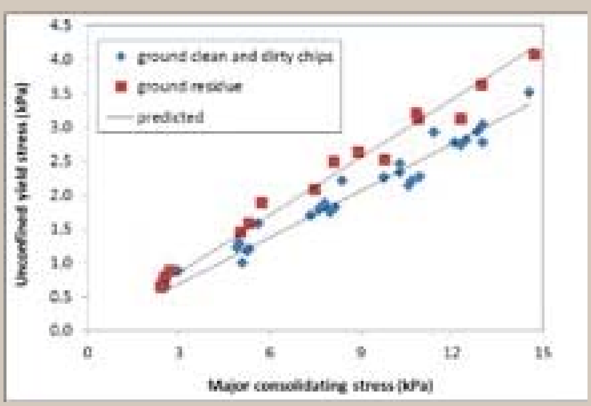

Figure 5. Unconfined yield stress versus major consolidating stress for ground clean and dirty chips, and residues.

Cohesive strength increased linearly with an increase in consolidating pressure as shown in Figure 3 for ground clean chips samples. A similar linear relationship was obtained for ground dirty chips and residues samples. Parallel line analysis in SigmaPlot showed that the linear relationships for all the samples were not significantly affected by size and that the ground clean chips and dirty chips were not significantly different from each other. Consequently, the cohesion data for ground samples from clean chips and dirty chips were pooled and a linear equation (Equation 1) was developed to relate their cohesive strength to major consolidating stress, σ_c (Figure 4). The corresponding equation for residues can be found in Equation 2.

Ground clean and dirty chips (through 1.588 mm and 3.175 mm screens)

$$C = 0.0509\,\sigma_c + 0.0334 \qquad R^2 = 0.9711 \qquad (1)$$

Ground residues (through 1.588 mm and 3.175 mm screens)

$$C = 0.0637\,\sigma_c + 0.0412 \qquad R^2 = 0.9864 \qquad (2)$$

For each feedstock type, the angle of internal friction of the ground sample was not significantly affected by size. However, the angle of internal friction for residues were significantly ($P<0.05$) higher than those of clean chips or dirty chips. The average angles of internal friction were 44.9°, 45.2°, and 46.2° for the dirty, clean, and residues respectively. The implication is that this study and other related studies (Fasina, 2006; Chevanan et al., 2009; Bhadra et al., 2009) indicate that ground biomass materials do not meet one of the two criteria listed by Puri (2002) for gravity flow; i.e., the angle of internal friction is not less than 30°. Our laboratory is currently working on systems to reduce the angle of internal friction of biomass materials.

Statistical testing showed that screen size did not significantly affect the unconfined yield strength values at the different consolidating stresses for each of the three sample types.

This is similar to the results obtained by Fasina (2006) on the effect of screen size on strength behavior of peanut hull, switchgrass, and poultry litter. Similar to the cohesive strength results, the flow function of clean chips was not significantly different from that of dirty chips; however, the flow function of the residues were significantly different from those of clean chips and dirty chips. Consequently, the flow function data of clean chips and dirty chips were lumped together and a linear fit was used to relate the unconfined yield stress to the major consolidating stress (Figure 5). A separate linear fit was developed for the flow function data of the ground residues as given below.

Ground clean and dirty chips (ground through 1.588 mm and 3.175 mm screens)

$$UYS = 0.2296\sigma_c \qquad R^2 = 0.9664 \qquad (3)$$

Ground residues (ground through 1.588 mm and 3.175 mm screens)

$$UYS = 0.2836\sigma_c \qquad R^2 = 0.9767 \qquad (4)$$

The flow indices (obtained from the inverse of the slopes of Equations 3 and 4) for ground clean/dirty chips and for ground residues are 4.36 and 3.53 respectively. The flow indices indicate that the ground clean/dirty chips are easy flowing while the ground residues are cohesive (see classification in Table 1). This result is not surprising because the residues have a higher angle of internal friction and a higher cohesive strength. The use of residues in bioenergy applications will therefore require special handling and discharge methods from silos and storage vessels before the material can be fed into biorefinery unit operation equipment.

Conclusion

It can be concluded from this study that the quality (based on ash, volatile, and energy content) of residues from forest harvest operations is significantly lower than those of clean chips or dirty chips. The presence of ground residues in forest-based feedstock destined for bioenergy applications may present flow problems in discharge hoppers and feeders. The flow index value of 3.53 for the ground residues indicates that it is cohesive in nature. The frictional properties of forest biomass feedstock were not significantly affected by grinding screen size (1.588 mm and 3.175 mm).

Table 2. Properties of ground wood chips affected by grinding screen size and sample type.

	Sample Source					
	Clean chips		Dirty chips		Residues	
Property/screen size (mm)	3.175	1.588	3.175	1.588	3.175	1.588
Energy content (J/g)	19705[a]*	19549[a]	20068[a]	19546[a]	12552[b]	10378[b]
Volatile content (%)	83.1[a]	85.4[a]	81.9[a]	83.5[a]	48.4[b]	43.1[b]
Ash content (%)	0.41[a]	0.26[b]	0.61[c]	0.65[c]	26.67[d]	34.62[e]
Particle density (kg/m^3)	1423[a]	1438[b]	1392[c]	1410[d]	1621[e]	1727[f]
Bulk density (kg/m^3)	217.1[a]	225.9[b]	260.0[c]	236.0[d]	275.4[e]	353.6[f]
Avg. particle size (mm)	1.335[a]	1.179[b]	1.230[c]	0.928[d]	0.699[e]	0.557[f]

*different letters in a row are significantly different at $P < 0.05$.

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Acknowledgments

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