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An ASABE Meeting Presentation

Paper Number: 096658

A Tub-Grinding/Roll-Press Compaction System to Increase Biomass Bulk Density: Preliminary Study

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**Written for presentation at the
2009 ASABE Annual International Meeting
Sponsored by ASABE
Grand Sierra Resort and Casino
Reno, Nevada
June 21 – June 24, 2009**

Abstract. *Transforming biomass into a product with bulk density of 240 kg/m³ (15 lb/ft³) would enhance logistics of truck transport to users throughout the year. We evaluated a system involving tub-grinding followed by roll-press compaction to increase the bulk density of biomass such as corn stover, corn cobs and native perennial grasses. Preliminary experiments were conducted to study the effect of particle size (tub-grinder screen sizes of 19.1, 76.2, and 203.2 mm) on the bulk density of roll-press compacted biomass materials. The bulk density of tub-ground biomass ranged from 50-100 kg/m³ (3-6 lb/ft³). Tub-grinding followed by roll-press compaction increased the bulk density by two- to three-fold, and resulted in densified products with bulk density of 190-240 kg/m³ (12-15 lb/ft³). Additional increases in bulk density appear possible with improved design of the feeding system for the roll-press compaction machine.*

Keywords. Corn Stover, Corn Cobs, Native Perennial Grasses, Tub Grinding, Roll Press Compaction.

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Introduction

Users of biomass such as combined heat and power (CHP) and cellulosic ethanol industries need a consistent supply of biomass throughout the year. However, harvesting/collection of herbaceous biomass is limited to certain times of the year, usually late summer or fall. A system is needed to collect, store, accumulate, process, densify (briquette or pellet), and deliver consistent, dense, free-flowing material to the users throughout the year. Collection/harvesting occurs on an agricultural cycle (late summer or fall time frame). The user operates on an industrial cycle (year around time frame). A key component requiring new approaches is the step involving accumulation of biomass stored at numerous field or farm sites and delivery to a processing facility or end user throughout the year in a form that is easy to handle and efficient to transport.

For truck transport of biomass to the users, the bulk density of biomass should be in the range of 190 to 240 kg/m³ (12 to 15 lb/ft³) for various sizes of existing trucks to “load out” by weight limit (i.e., 25 tons per truck load). Table 1 compares the bulk density of different forms of biomass materials that can be produced using current technologies. Either loose biomass, baled biomass, or minimally processed biomass (e.g., chopped or coarsely ground biomass) may result in bulk densities lower than 190 to 240 kg/m³ (12 to 15 lb/ft³). Fine-grinding of biomass may increase the biomass bulk density close to the required range, but handling of finely ground (dusty) materials is very difficult. Intensive processing of biomass such as densification of biomass into briquettes, pellets or cubes may result in bulk densities higher than 190 to 240 kg/m³ (12 to 15 lb/ft³).

Handling and transporting biomass in baled form for longer distances is costly and inconvenient, especially for materials that have been stored outside for several months. Coarse grinding of biomass bales can be done by using a tub-grinder. A tub-grinder is a portable device in which a hammer mill applies impact and cutting forces yielding a range of particle sizes depending on the screen sizes used for the grinding process (Arthur et al., 1982; Wright et al., 2006). Tub grinding dry biomass (10 to 20% moisture content) makes it possible to handle as a bulk material, but the bulk density is low [in the range of 50 to 125 kg/m³ (3 to 8 lb/ft³)] (Arthur et al., 1982; Wright et al., 2006). The higher values in the range correspond to grinding to smaller particle sizes (< 6.4 mm), which requires significant energy and creates a dusty product to handle.

Roll press briquetting and compaction machines have been used to increase the particle size of and bulk densities of materials to improve their handling (Pietsch, 1991; Dec, 2002). In a roll press briquetter/compactor, material is densified by compression between two counter-rotating rolls (Pietsch, 1991; Dec, 2002). The roll surfaces have pockets to form briquettes of desired size and shape when the material passes between the rolls. In a roll press compaction machine, the rolls don't have pockets, but the rolls may be textured/ribbed to assist the flow and compaction. We conducted experiments on roll press briquetting of corn stover and switchgrass using a pilot-scale roll press briquetting machine (Kaliyan et al., 2009). We found that corn stover and switchgrass with particle sizes of 0.4 to 0.5 mm could be densified into highly durable briquettes [almond shape with about 30.5 mm (1.2 in.) length] with bulk densities of 400 to 560 kg/m³ (25 to 35 lb/ft³) (Kaliyan et al., 2009). The results showed that roll press briquetting would be a promising low-cost, low-energy, and high-capacity approach for densification of herbaceous biomass.

The experience gained from the roll press briquetting study motivated us to pursue roll press compaction of coarsely ground biomass. Therefore, the objective of this study was to evaluate the concept of a portable system that would take bales stored at individual farm sites, chop or

coarsely grind the biomass, then compact it to a bulk density of at least 240 kg/m³ (15 lb/ft³), and load it on trucks for delivery as a bulk product. A bulk density of 240 kg/m³ (15 lb/ft³) should be sufficient for many types of trucks to “load out” based on weight. The system would operate year around moving to various farm sites to process bales, which have been placed in storage at harvest time.

Materials and Methods

The biomass feedstocks required for the study was collected as bales during fall 2007 by the University of Minnesota West Central Research and Outreach Center (WCROC), Morris, MN. The bales were stored outdoors at WCROC until used in this study.

Tub Grinding

The coarse grinding was performed at WCROC during May 2008. The WCROC has a tub-grinder (Haybuster, H-1100, tilt-type, DuraTech Industries, Jamestown, ND). A 205-hp tractor (John Deere 8230 model) PTO was connected to the hammer mill drive shaft of the tub grinder. The speed of the tub was none to very slow depending upon the sensor that senses to feed the hammer mill when it needs feed. The speed of the hammer mill rotor was the same as the tractor PTO speed of 2000 rpm.

Three different screens having round-holes with diameters of 19.1, 76.2, and 203.2 mm (3/4, 3.0, and 8.0 in.) were used in the tub grinder to grind round bales of corn stover (6 ft diameter x 5 ft length bales weighing about 1000 lb). The 203.2 mm (8.0 in.) screen was used to tub grind a square bale (3 ft x 3 ft x 6 ft) of mixture of native perennial grasses mostly of switchgrass. The strings of the bales were not removed before feeding the bales to the tub-grinder. A bale snapper-loader (FORD 7144 model) operated by a tractor (FORD 9230 model) was used to load the tub grinder. The tub grinder discharged the ground material via a belt conveyor on to a truck. The ground biomass samples were collected in plastic bags, transported to the laboratory, and stored until use. Some samples were stored (as received) at high moistures (>15% w.b.) in a walk-in freezer at -10°C. Some samples were sun-dried for 3 to 4 hours to lower the moisture contents to about 10% (w.b.) and stored at room temperature (about 24°C). All samples were stored for 20 days before using in the roll press compaction tests.

The moisture contents of the biomass samples were measured according to ASABE Standards (2006a). The particle size of corn stover particles was measured based on ASABE Standards (2006b). The stack of sieves used for the particle size analysis was 26.67, 19.1, 12.7, 6.68, 3.35, 2.38, and 1.7 mm. The average amount of sample used for the particle size analysis was 36.0 g.

Roll Press Compaction

The roll press compaction of tub-ground corn stover and native perennial grasses, and whole corn cobs was performed at Bepex International LLC in Minneapolis, MN. A 50-hp roll press compaction machine (MS 75 Roll Compactor, Bepex International LLC, Minneapolis, MN) that had two counter rotating rolls with 520.7 mm (20.5-in.) diameter and 127.0 mm (5.0-in.) width was used. The rolls had 72 “stick” pockets per roll. The size of one pocket on one of the rolls was 114.3 mm (4.5 in.) width x 20.3 mm (0.8 in.) height x 5.1 mm (0.2 in.) depth. The pocketed rolls were used to assist the feeding. The force between the rolls was set constant at 60 tons. The gap between the rolls was set at about 1.0 mm. The speed of the rolls was set at 1.6 rpm.

The conical hopper located above the rolls had a screw feeder. In this study, the screw feeder was removed from the hopper to simulate a gravity feeding to the rolls. The coarsely ground

biomass particles were manually fed to the hopper/rolls. To assist the feeding, the particles were manually forced to the rolls using a small wooden plank. A plastic bag was used to collect the compacted sheets exiting the roll press. Due to the slow intermittent manual feeding to the rolls, the length of the compacted sheets formed was mostly shorter than 304.8 mm (1.0 ft). The compacted biomass with length of more than 304.8 mm (1.0 ft) was automatically broken down into smaller lengths while dropping from the rolls into the bags.

The bulk density of the compacted biomass was measured immediately after forming. A 304.8 mm × 304.8 mm × 304.8 mm (1.0 ft × 1.0 ft × 1.0 ft) wooden box was manually filled by discharging the compacted biomass from the bag from a height of about 304.8 mm (1.0 ft). The wooden box along with the sample was manually tapped for 5 times by dropping the box from a height of about 304.8 mm (1.0 ft) on to the concrete floor. After tapping, the top edge of the box was leveled by manually adding/removing compacted biomass in the box. Then, the compacted biomass along with the box was weighed. The bulk density was calculated as the mass of compacted biomass occupied the box divided by the volume of the box.

Immediately after the bulk density measurement (i.e., about 15 to 30 minutes after compaction), the compacted biomass was subjected to a “hand durability test”. The procedure involved manual striking/beating of plastic-bagged compacted biomass for 10 times on the concrete floor, followed by measuring the bulk density.

Results and Discussion

The geometric mean particle diameter ± geometric standard deviation of particles by mass was 2.4 ± 1.5 , 3.3 ± 3.0 , and 3.4 ± 2.9 mm for the corn stover tub-ground using the screen sizes of 19.1 mm ($\frac{3}{4}$ in.), 76.2 mm (3.0 in.), and 203.2 mm (8.0 in.), respectively. The particle size analysis also showed that 50% of corn stover particles were smaller than 2.38, 3.35, and 3.35 mm for the tub-ground material using the screen sizes of 19.1 mm ($\frac{3}{4}$ in.), 76.2 mm (3.0 in.), and 203.2 mm (8.0 in.), respectively. In addition, the percentage of particles below 1.7 mm was 42.8, 33.8, and 28.9% for the tub-ground stover using the screen sizes of 19.1 mm ($\frac{3}{4}$ in.), 76.2 mm (3.0 in.), and 203.2 mm (8.0 in.), respectively. Thus, the smaller screen produced a larger amount of fines (dust). The manually measured lengths of the larger pieces of particles were 20 to 50, 50 to 80, and 80 to 160 mm for the tub-ground stover using the screen sizes of 19.1 mm ($\frac{3}{4}$ in.), 76.2 mm (3.0 in.), and 203.2 mm (8.0 in.), respectively.

It was difficult to analyze the particle size of native perennial grasses obtained from the screen size of 8 inch using the sieve shaking apparatus. Almost all of the grass particles stayed as a “nest” on the top sieve (26.67 mm) after 15 minutes of sieve shaking. The length of the larger pieces of native perennial grass particles was 80 to 140 mm.

Tub-grinding of biomass resulted in bulk density of 50 to 100 kg/m³ (3 to 6 lb/ft³) (tables 2 and 3). The smaller the screen size, the higher the bulk density of tub-ground particles. Moisture contents in the range of 10 to 20% (w.b.) resulted in similar bulk density for the tub-ground biomass (table 2). Figures 1, 2, and 3 present pictures of roll press compacted biomass samples. The bulk density of coarsely ground material was increased by a factor of 2 to 3 by roll press compacting, yielding samples in the range of 190 to 240 kg/m³ (12 to 15 lb/ft³) (table 3). For corn stover, smaller particle size resulted in higher bulk density of compacted biomass. Roll press compaction increased the bulk density from 84 kg/m³ (5 lb/ft³) to 157 kg/m³ (10 lb/ft³) for the native perennial grasses obtained using a 203.2 mm (8.0 in.) screen in the tub-grinder. The bulk density of compacted native perennial grasses could be increased to 190 to 240 kg/m³ (12 to 15 lb/ft³) by reducing the particle size.

Significant interest has developed in the last few years in using the corn cob portion of the corn stover as a feedstock for cellulosic ethanol or for heat and power applications (Christiansen 2009). Corn cobs have advantages both because it may be possible to harvest them in conjunction with the grain and because they are more dense pieces than other parts of the stover with a bulk density of 160 to 190 kg/m³ (10 to 12 lb/ft³) (Kaliyan and Morey, 2008a). There is some interest in increasing the bulk density of corn cobs to 240 kg/m³ (15 lb/ft³) or higher. This study indicates that roll press compaction can increase the bulk density of corn cobs to 240 kg/m³ (15 lb/ft³) or higher (table 3). Size reduction of corn cobs is not necessary. The cobs are crushed as they pass through the roll press compactor which increases their bulk density.

The hand durability test slightly reduced the bulk density of the compacted biomass (table 3). This showed that vigorous handling of compacted biomass immediately after forming may break some of the weaker bonds between the particles causing the compacts to expand. In the future, the durability of compacted biomass may need to be studied using a standard durability measurement procedure.

The aim of the roll press compaction was to increase the bulk density of the tub-ground biomass particles. However, it was not intended to make highly durable regularly shaped solid products. The densification mechanisms were air removal from the individual biomass particles (i.e., intra-particle air) as well as from the inter-particles, and elastic- and plastic-deformation of particles due to the application of pressure by the rolls. The dominant binding mechanism was solid bridges created by mechanical interlocking of particles. The mechanical interlocking may occur due to the folding of particles with each other and due to the diffusion of molecules from one fiber to another at the contact points. The biomass particles may also bind to one another due to the natural binding components such as water soluble carbohydrates, protein, and lignin available in the biomass materials (Kaliyan and Morey, 2008b).

Roll feeding was found to be difficult except for corn stover particles obtained from the 19.1 mm (¾ in.) screen. No floating of rolls was observed during the tests, and thus, the force between the rolls was likely less than 60 tons. The throughput of the roll press was measured at 114.1 kg/h for corn stover particles obtained from the 19.1 mm (¾ in.) screen. The low roll press throughput may have been due to the low bulk density of the initial feed material. Sometimes the compacted biomass stuck in the bulk density measurement box after tapping. This suggests that there may be problems in field scale handling of compacted materials. In the future, the handling properties of the compacted biomass should be studied.

Future work is also required to collect data on energy and cost for tub-grinding and roll-press compaction of biomass materials. Data from the literature and preliminary estimates show that the energy required for coarse (tub) grinding of biomass to obtain a bulk density of 80 kg/m³ (5 lb/ft³) may be 100 to 200 MJ/t (Arthur et al., 1982; Wright et al., 2006). The energy required for roll press compaction of biomass materials to increase the bulk density from 80 kg/m³ (5 lb/ft³) to 240 kg/m³ (15 lb/ft³) may be 10 to 15 MJ/t (Johanson, 1965; Dec, 2002). Thus, the total energy required for coarse grinding followed by roll press compaction may be about 0.6 to 1.1% of the energy content of the biomass if the energy content of the biomass is taken as 20 MJ/kg. It should be noted that the coarse grinding step is essential in order to break up the bales and reduce the particle size (25.4 to 50.8 mm) to help feed them into hammer mills to arrive at finer particles (< 1 mm) for future processing. Moreover, the energy input for roll press compaction would likely be less than the energy consumed for handling, transporting, and storing a low bulk density biomass either in baled or ground form. Thus, the coarse grinding and roll press compaction system could possibly lower the cost, energy, and greenhouse gas (GHG) emissions of the overall biomass supply logistics system. Morey et al. (2009) present cost,

energy, and GHG emission estimates for a biomass supply logistics system including the tub-grinding/roll-press compaction process.

We believe that by optimizing ground biomass feedstock variables and machine variables, especially the roll feeding mechanism, increases in bulk density to 190 to 240 kg/m³ (12 to 15 lb/ft³) or greater can be obtained on a consistent basis at reasonable cost. We will continue this work as part of a project funded by the North Central Sun Grant Competitive Grant Program on Biomass Feedstock Logistics.

Conclusions

Tub-grinding followed by roll press compaction shows promise for increasing the bulk density of biomass such as corn stover, corn cobs, and perennial grasses to 240 kg/m³ (15 lb/ft³), which will allow for efficient transport in trucks with 25 ton loads. Future work is required to optimize the tub-grinding/roll-press compaction system.

Acknowledgements

The authors wish to thank the University of Minnesota Initiative for Renewable Energy and the Environment (IREE) for supporting this study. Also, the authors would like to acknowledge the West Central Research and Outreach Center (WCROC), University of Minnesota, Morris, MN for assistance with the tub-grinding of biomass; and Bepex International LLC, Minneapolis, MN for access to their facility and assistance with the roll press compaction tests.

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Table 1. Bulk density of various forms of biomass.

Biomass form	Shape and size	Bulk density (kg/m ³)	Reference
Loose biomass	Irregular / Fluffy	50 – 130	Sokhansanj and Turhollow (2004)
Bales	Round / Square	140 – 180	Sokhansanj et al. (2009)
Chopped	20 – 40 mm long	60 – 80	Sokhansanj et al. (2009)
Ground, switchgrass	1.5 mm, loose fill	120	Sokhansanj et al. (2009)
Ground, switchgrass	1.5 mm, tapped	200	Sokhansanj et al. (2009)
Ground, switchgrass	0.5 – 0.6 mm	185 – 220	Kaliyan et al. (2009)
Ground, corn stover	0.3 – 0.4 mm	140 – 160	Kaliyan et al. (2009)
Briquettes	25 mm width or larger	350 – 550	Kaliyan et al. (2009); Sokhansanj et al. (2009)
Cubes	13 – 38 mm width	450 – 550	Sokhansanj and Turhollow (2004); Sokhansanj et al. (2009)
Pellets	5 – 19 mm diameter	500 – 700	Kaliyan et al. (2009); Sokhansanj et al. (2009)

Table 2. Bulk density of tub-ground biomass materials.

Biomass material	Particle size (hammer mill screen size used for tub grinding)	Moisture content (% w.b.) (n = 3)	Bulk density (n = 3)	
			lb/ft ³	kg/m ³
Corn stover	19.1 mm (¾ in.)	18.7 ± 3.1 [#]	5.7 ± 0.2	91.0 ± 2.4
		10.6 ± 0.4 [*]	5.7 ± 0.5	91.0 ± 7.8
Corn stover	76.2 mm (3.0 in.)	23.0 ± 2.5 [#]	4.0 ± 0.1	63.3 ± 0.8
		11.2 ± 0.2 [*]	4.1 ± 0.5	65.6 ± 8.7
Corn stover	203.2 mm (8.0 in.)	19.4 ± 4.1 [#]	2.9 ± 0.2	47.0 ± 3.0
		8.5 ± 0.6 [*]	3.2 ± 0.2	50.6 ± 3.1
Native perennial grasses	203.2 mm (8.0 in.)	25.8 ± 0.4 [#]	4.6 ± 0.1	72.9 ± 2.2
		16.4 ± 1.0 [*]	5.1 ± 0.1	81.8 ± 1.0
		12.4 ± 0.8 [*]	4.4 ± 0.4	71.0 ± 5.9

[#] Samples collected from the tub-grinder (as received). The bulk density of the sample was measured about 7 hours after tub-grinding.

^{*} Tub-ground samples were sun-dried for 3 to 4 hours on a concrete floor to reduce the moisture content. The bulk density of the sample was measured about 48 hours after tub-grinding.

Table 3. Roll press compaction of corn stover, corn cobs, and native perennial grasses.

Biomass material	Particle size (hammer mill screen size used for tub grinding)	Moisture content (% w.b.) (n = 3)	Bulk density before roll press compaction (n = 1)		Bulk density after roll press compaction (before a hand durability test *) (n = 1 or 2)		Bulk density of compacts after a hand durability test * (n = 1)	
			lb/ft ³	kg/m ³	lb/ft ³	kg/m ³	lb/ft ³	kg/m ³
Corn stover &	19.1 mm (¾ in.)	10.6 ± 0.4	6.3	100.9	14.9	237.9	14.3	229.1
Corn stover	19.1 mm (¾ in.)	18.7 ± 3.1	5.9	93.7	14.1 ± 0.4	225.9 ± 6.8	14.3	229.1
Corn stover	76.2 mm (3.0 in.)	11.3 ± 0.3	3.7	59.3	11.2 ± 0.7	179.8 ± 11.9	9.8	156.2
Corn stover	203.2 mm (8.0 in.)	19.4 ± 4.1	3.2	51.3	5.6 ± 0.6	89.7 ± 8.9	NM ^ψ	NM
Corn cobs	No grinding	10.4 ± 0.3	9.2	147.4	15.2	243.0	NM	NM
Native perennial grasses #	203.2 mm (8.0 in.)	12.4 ± 0.8	5.3	84.1	9.8 ± 0.4	156.6 ± 6.2	9.2	146.6

* The procedure used to do the hand durability test was manual striking/beating of plastic-bagged compacts for 10 times on concrete floor. The hand durability test was done about 15 to 30 minutes after compaction.

& Thickness of the compacted sheet = 14.5 ± 4.6 mm (0.6 ± 0.2 inch). Width of the compacted sheet = 128.9 ± 1.6 mm (5.1 ± 0.1 inch).

^ψ NM = data were not measured.

Native perennial grasses did not form a continuous compacted sheet during roll press compaction. However, grass particles were compressed and thus, increased bulk density.



Figure 1. Roll press compacted corn stover. The corn stover particles were obtained using a 19.1 mm ($\frac{3}{4}$ in.) screen in the tub grinder.

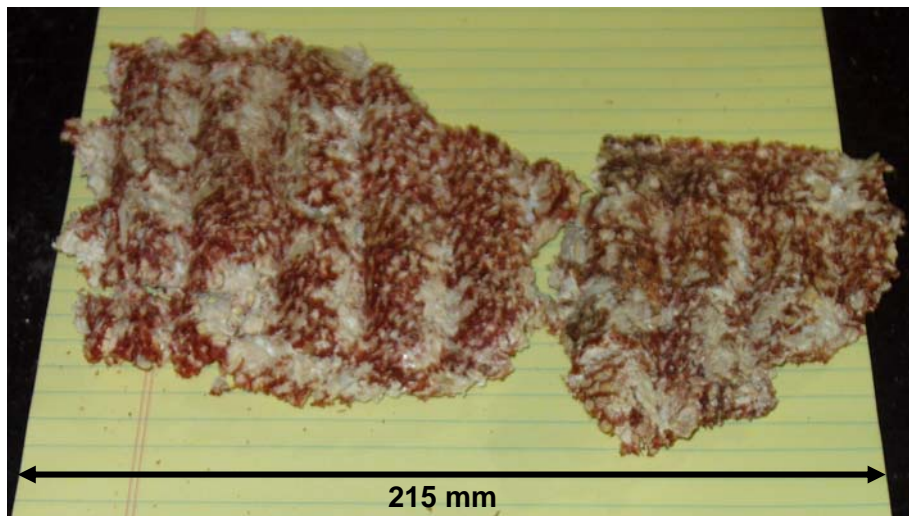


Figure 2. Roll press compacted corn cobs. Whole corn cobs were compacted in the roll press.



Figure 3. Roll press compacted native perennial grasses. The native perennial grass particles were obtained using a 203.2 mm (8.0 in.) screen in the tub grinder.