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Compaction Experiences with Bulk-Format Switchgrass in Commercial Transfer Systems

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Abstract. *Supply chain efficiencies must be improved for lignocellulosic biomass to become an economically viable energy feedstock. Switchgrass round bales require labor-intensive unit handling and de-baling processes that are not readily scalable, so a bulk-chopped format was investigated to improve handling efficiencies throughout the harvest, transportation, and storage systems. However, low loose-filled bulk density of chopped switchgrass presented challenges for long distance transportation to the end user. Increasing biomass bulk density with minimal time and energy inputs was achieved using waste transfer equipment. A commercial-grade compactor was used to compress size-reduced switchgrass into a 57 m^3 reinforced, ejector-style transfer trailer. Pressure relief setting on the compactor was 20,684 kPa, corresponding with a compactor ram face pressure of 347 kPa. The compactor was cycled until the pressure relief setting was reached, and the truck was weighed to determine the compacted bulk density of the switchgrass. The trailer was then offloaded using the hydraulic-powered ejector ram. Observations were made regarding the compatibility of chopped switchgrass with existing equipment. Particle size distribution was determined according to ASABE S424.1, and moisture content was determined according to ASABE S358.2. Results indicated in-bulk compaction as a promising method to improve transportation efficiencies of loose chopped biomass as a means of increasing low bulk densities of low-moisture switchgrass feedstock by a factor of about 2x.*

Keywords. switchgrass, chopped bulk format, compaction, bulk density, transportation

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Introduction

Commercially-competitive cellulosic biofuels, biopower, and bioproducts require feedstock available in a consistent, high quality, cost-effective format. The Energy Independence and Security Act of 2007 updated the Environmental Protection Agency's Renewable Fuel Standard, calling for the production of 136 billion L/y of renewable fuel by 2022. Of this, 79 billion L/y are to originate from non-corn starch, cellulosic feedstock (Energy, 2007). A U.S. Department of Energy feasibility study found an estimated 1.2 billion Mg/y of biomass potential in the United States, 342 million Mg of which could come from perennial energy crops (Perlack et al., 2005). Delivering these quantities of biomass economically for commercial scale production of advanced biofuels will require a high-tonnage supply system capable of quickly and efficiently handling large volumes of feedstock (DOE, 2003; DOE, 2010).

Switchgrass (*Panicum virgatum L.*) was identified as a potential cellulosic energy crop for biofuel production. Like other energy crops, switchgrass presented challenges for harvesting, transportation, storage and handling. Low bulk density reduced transportation cost efficacy (Sokhansanj and Fenton, 2006), emphasizing the need for an engineered supply system. Previous lab-scale research showed that bulk density of chopped switchgrass depended on moisture content, particle size, and confining pressure (Chevenan et al., 2010; Lam et. al, 2008). Loose-filled bulk density of switchgrass varied from 44.47 to 102.87 kg/m^3 for particle geometric mean lengths of 12.99 to 3.05 mm, respectively (Chevenan et al., 2008). Compressibility (C_m) was expressed according to Equation 1 (Fayed and Skocir, 1997):

$$C_m = \left(\frac{V_i - V_f}{V_i}\right) * 100 = \left(1 - \frac{\rho_{bi}}{\rho_{bf}}\right) * 100 \qquad (1)$$

where V_i is initial volume of biomass (m^3), V_f is final volume of biomass (m^3) at a given normal pressure, ρ_{bi} is initial bulk density of the biomass (kg/m^3), and ρ_{bf} is final bulk density of the biomass (kg/m^3) at a given normal pressure. For chopped switchgrass with geometric mean particle lengths ranging from 3.05 mm to 12.99 mm, compressibility values ranged from 49.6% to 74.1%, respectively, under a 120 kPa confining pressure (Chevenan et al., 2010).

Harvesting, transportation, storage, and preprocessing contributed up to 50% of feedstock cost at the refinery gate (Hess et al., 2007). Handling efficiency improvement throughout the supply system was identified as a way to reduce this cost (DOE, 2003; Hess et al., 2007). Preprocessing early in the supply chain was identified by Idaho National Laboratory (INL) as one way to improve downstream operations (Hess et al., 2007; Wright et al., 2006). Low bulk density was noted as a drawback, especially for long-distance transport.

Feedstock for a Genera Energy pilot-scale biomass conversion facility in Tennessee was originally supplied by traditional round or large-rectangular bale formats. Bales were convenient for project launch and small scale operation, but biomass quantity required to supply a commercial scale plant with bales was projected to be cumbersome (Figure 1). Bale handling required numerous unit-handling events and low-efficiency de-baling operations.

The objective of this study was to evaluate a full-scale commercial transfer system for compacting bulk-format switchgrass and to determine compaction characteristics.

Figure 1. Switchgrass bales staged to supply a pilot-scale biomass conversion facility

Methods

Bulk Format System Overview

A bulk-format switchgrass supply system (Figure 2) was devised to investigate harvesting, transportation, storage, and handling efficiencies. Switchgrass was first cut with a rotary disc mower-conditioner. The resulting low-moisture (<20%) switchgrass windrows were size-reduced with a forage harvester, which blew chopped material into high-dump wagons. These wagons continuously serviced the forage harvester, driving to the field edge to unload into over-the-road (OTR), open-top walking-floor or dump trailers. OTR trailers hauled the chopped switchgrass in loose form to a biomass depot. Biomass was unloaded into a receiving pit and conveyed into storage by automated bulk handling equipment. The focus of this paper is switchgrass leaving the depot through a compactor loading an ejector type semi-trailer. Increased bulk density was projected to improve hauling efficiency to the biorefinery. Bulk compaction was investigated with waste transfer technology to increase bulk density and truck payloads.

It should be noted that the overall demonstration system was designed to evaluate the bulk-format system within the confines of the available budget. Very high capacity storage systems for commercial-scale quantities, as well as self-propelled forage harvesters would likely replace some of the equipment selected for demonstration, though functional steps would be similar. The compactor for commercial-scale operation would be very similar to the one evaluated in this study.

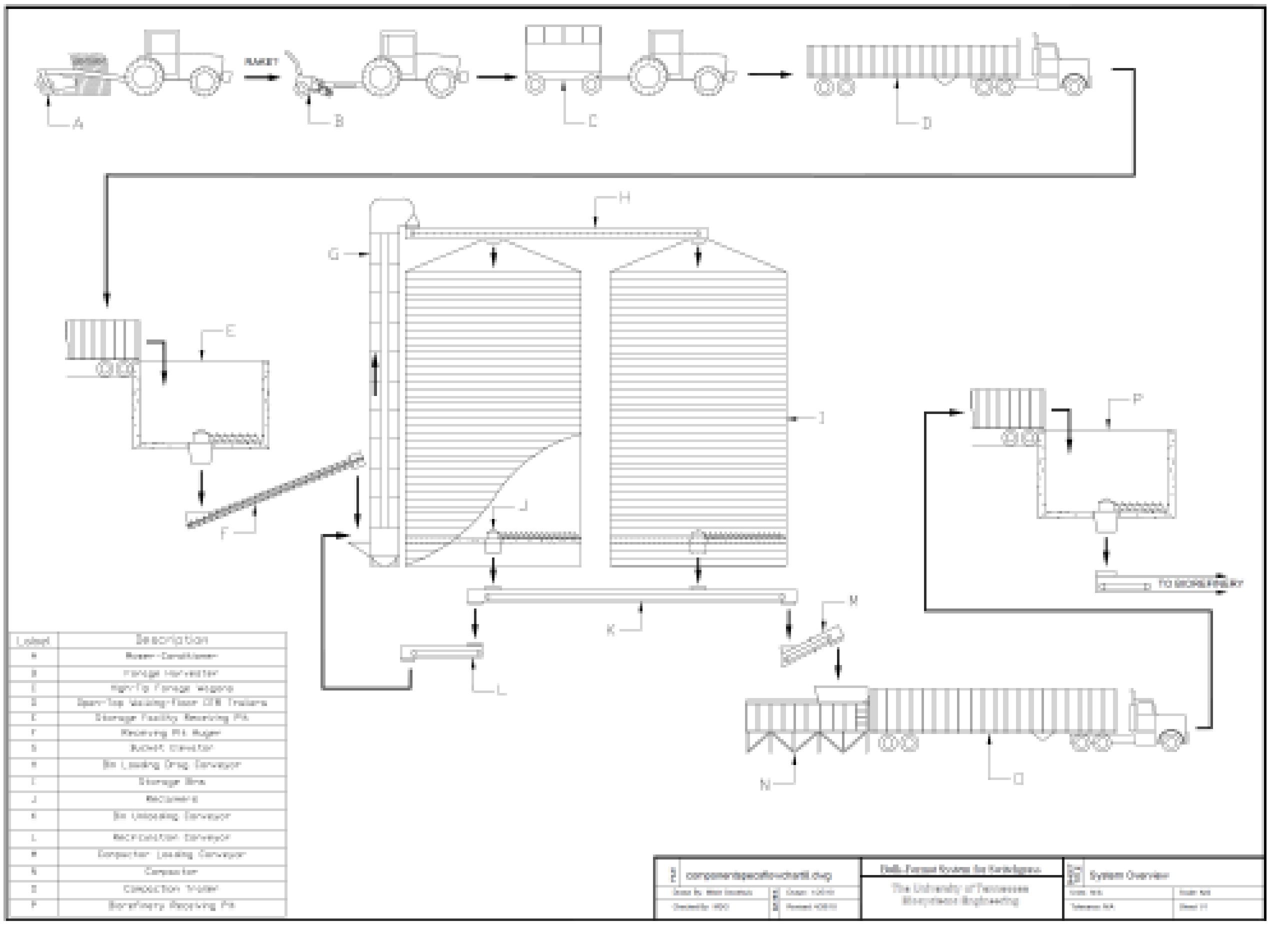

Figure 2. Bulk-Format Supply System Overview

Semi-Truck Ejector-Trailer Compaction

Equipment

The compactor tested was a Marathon M-1475XW (Figure 3), a machine typically used at transfer stations for municipal solid waste, construction, or demolition debris. Material was discharged from the compactor into an ejector type semi-trailer. The trailer and compactor were coupled via a hydraulic grab claw that engaged a 7.6 cm diameter pin (Heil pin) integrated into the rear trailer bumper. Material was loaded from the top into the compactor's charge chamber, and the charge volume, along with existing material in the trailer, was compacted by a 1.2 m x 2.0 m plunger actuated with a hydraulic cylinder. The plunger extended 0.6 m into the trailer. A 37 kW hydraulic power unit delivered up to 20,680 kPa to a hydraulic cylinder with a 22.9 cm bore diameter. The plunger was cycled until the maximum hydraulic pressure was reached, indicating a full trailer.

Figure 3. Marathon M-1475XW compactor charge chamber

The ejector-trailer used was a J&J Steel Push-Out trailer that was 13.7 m long with a 57.3 m^3 internal volume. The front of the trailer housed an ejector blade equipped with a five-stage telescopic hydraulic cylinder, having a first-stage diameter of 22.9 cm. The cylinder was powered by a hydraulic supply system (wet kit) on the attached semi truck. The rear of the trailer was equipped with a two-part (dutch) door. The large top door was opened during compactor loading, and both doors were opened for unloading.

Biomass Material

Chopped switchgrass was delivered to the compactor testing facility in two open-top, walking-floor OTR trailers. Truck and semi-trailer gross masses were measured on truck scales, switchgrass was unloaded in a pile on the concrete floor near the compactor, and the empty truck and semi-trailer tare masses were measured.

Loose-Filled Bulk Density

Internal dimensions of the open-top semi-trailers were measured manually to calculate internal volume. Net mass of the biomass load was calculated by subtracting tare mass from gross truck mass. Wet loose-filled bulk density was calculated by Equation 2.

$$\textbf{Wet Loose Filled Bulk Density} = \frac{\textit{Wet Mass of Biomass}}{\textit{Internal Trailer Volume}} \qquad (2)$$

Dry loose-filled bulk density was similarly calculated based on measured moisture content, dry mass, and internal trailer volume.

Compaction Test

The ejector-trailer was coupled to the compactor with the claw and Heil pin (Figure 4). An excavator grapple loaded the compactor charge chamber with chopped switchgrass (Figure 5) as the compactor ram cycled continuously until the compactor pressure relief setting of 20,680 kPa was reached. The grapple did not feed the compactor as uniformly as a conveyor feed, but it worked well for a facility not designed for bulk switchgrass. After being de-coupled and weighed again to determine gross mass, the trailer was unloaded using the hydraulic ejector blade at the front of the trailer (Figure 6). One goal of compaction was to load trucks near to the U.S. Department of Transportation's maximum gross combined weight (GCW) of 36,290 kg. Loaded GCW was measured for the tested truck and 57.3 m^3 trailer.

Figure 4. Compactor coupled with ejector-trailer

Figure 5. Compactor loading with excavator grapple

Figure 6. Ejector-trailer unloading

Compacted Bulk Density

Internal dimensions of the ejector-trailer were measured manually to calculate internal volume. Gross truck mass and tare mass were measured by truck scales. Net mass of the biomass load was calculated by subtracting tare mass from gross truck mass. Wet and dry compacted bulk density was calculated by Equation 3, using the appropriate wet or dry mass, respectively.

$$\textbf{Compacted Bulk Density} = \frac{Mass\ of\ Biomass}{Internal\ Trailer\ Volume} \quad (3)$$

Moisture Content

Twelve switchgrass samples (~0.5 kg each) were taken at various points throughout the pile for moisture content measurements. The samples were weighed immediately with an electronic balance (± 0.1 g accuracy) to avoid moisture loss in transit to the lab. Moisture content was determined according to ASAE Standard S358.2 (ASABE, 2003). Samples were placed in aluminum trays and dried in an oven for 24 hours at 103°C, then weighed again to determine wet basis (w.b.) moisture content (M.C.).

Particle Size

Five samples were taken for particle size analysis according to ANSI/ASAE Standard S424.1 (ASABE, 2006). The ~10 L samples were passed through a series of five stacked sieves with openings decreasing in size from top to bottom. The screens were oscillated in the horizontal plane at 144 cycles/min over a period of 120s. The mass of material left on each screen was measured with an electronic balance (± 0.01 g accuracy). The geometric mean lengths of particles on each sieve were calculated by taking the square root of the product of the diagonal opening dimension for that sieve and the same dimension for the larger sieve above it. Particle geometric mean length on each sieve was plotted against mass fraction retained on each sieve to indicate particle size distribution.

Overall geometric mean length (GML) and standard deviation by mass were calculated based on ANSI/ASAE Standard S424.1 (ASABE, 2006). This procedure was later used to determine particle size distribution of other chopped switchgrass samples used for lab-scale compaction tests.

Data Analysis

Loose-filled bulk density in the open-top semi-trailers and compacted bulk density in the ejector-trailer were calculated at the measured moisture content and also on a bone-dry basis. Projected compacted load mass was calculated for a 76.5 m^3 trailer at the measured switchgrass moisture content and bone-dry basis. This calculation assumed the same compacted bulk density as observed in the 57.3 m^3 trailer during the compaction test.

Projected GCW was calculated for the 57.3 m^3 and 76.5 m^3 ejector trailers if 20% (w.b.) moisture content switchgrass were used to simulate the effect of increased moisture content. The 76.5 m^3 ejector-trailer was assumed to have a mass of 14,288 kg and the tractor a mass of 6,804 kg.

Laboratory-Scale Compaction

Laboratory-scale tests investigated the relationship between normal pressure and bulk density for chopped switchgrass. Five switchgrass samples of varying chop lengths were tested with two replications. Each sample was loaded into a fabricated compression cell (155 mm inside diameter, 153 mm height) in approximately 10 mm layers until the cell was full. Weight of the biomass was recorded using an electronic balance (± 0.01 g accuracy). Force was applied downward on the material with a close fitting 152 mm diameter piston attached to the load cell of a universal testing machine (MTS System Corporation, Eden Prairie, MN, USA). The piston compressed the biomass at a rate of 1 mm/s, and TestWorks software (MTS System Corporation, Eden Prairie, MN, USA) recorded force and displacement 10 times per second. Pressure, volume, and density were calculated based on force and displacement data, compression cell dimensions, and sample mass.

Data Analysis

Confining pressure (kPa) was plotted against bulk density (kg/m^3) for each of the five samples. The results were then compared with semi-truck ejector-trailer compaction test findings.

Results and Discussion

Semi-Truck Ejector-Trailer Compaction

Loose-Filled Bulk Density

The two open-top OTR trailers each had an internal volume of 84.1 m^3 and were filled to the top with chopped material. Mass of the switchgrass from the two trailers combined was 15.04 Mg, resulting in an average loose-filled wet bulk density of 89.4 kg/m^3 (Table 1).

Compaction Test

The compactor loaded 10.69 Mg into the 57.3 m^3 trailer, resulting in a compacted material bulk density of 186.4 kg/m^3 at 15.4% M.C. (w.b.), or 157.7 bone-dry kg/m^3 (Table 1). The compactor successfully filled the trailer to the roof, with only a small void (~0.5 m^3) in the front uppermost corner of the trailer, as viewed through a sliding door in the roof at the front of the trailer. The compacted material supported a person's weight with little perceptible deflection. Trailer loading took 29 minutes, resulting in a compactor throughput of 18.7 dry Mg/hr, likely limited by the rate at which the excavator grapple could load the charge chamber.

Table 1. Ejector-trailer compaction test results

Switchgrass State	Trailer(s) Volume (m^3)	Chopped Switchgrass Moisture Content			
		15.4% (w.b.)		0% (w.b.)	
		Trailer Mass of Switchgrass (kg)	Bulk Density (kg/m^3)	Trailer Mass of Switchgrass (kg)	Bulk Density (kg/m^3)
Loose	168.2	15,041	89.4	12,725	75.7
Observed Compacted	57.3	10,687	186.4	9,041	157.7
Projected Compacted	76.5	14,249	186.4	12,055	157.7

GCW for the day-cab tractor and loaded ejector-trailer was 29,484 kg (Table 2). Assuming the same compacted density, projected switchgrass load in a 76.5 m^3 trailer was 14,249 kg at 15.4% (w.b.) moisture content, resulting in a GCW of 35,341 kg. At 20% M.C. (w.b.), projected GCW was 36,160 kg, just below the 36,290 kg limit.

Table 2. Observed and projected weights

	Item	Mass of Semi-Truck Combination alone, or Switchgrass at Moisture Content, or Gross Vehicle Weight (kg)	
		Switchgrass at 15.4% (w.b.)	Switchgrass at 20% (w.b.)
Observed (57.3 m^3 trailer)	Tractor	18,797	18,797
	Trailer		
	Switchgrass	10,687	11,301
	GCW	**29,484**	**30,098**
Projected (76.5 m^3 trailer)	Tractor	6,804	6,804
	Trailer	14,288	14,288
	Switchgrass	14,249	15,068
	GCW	**35,341**	**36,160**

The compactor ram face had an area of 2.45 m^2. According to manufacturer specifications, the hydraulic cylinder behind the ram was capable of exerting 845 kN at 20,680 kPa. Therefore, maximum pressure at the compactor ram face was 347 kPa. If the ram force was distributed across the full cross-section of the trailer, then the effective area was 5.57 m^2 with an effective applied pressure of 152 kPa. Force distribution wider than the ram face could occur as switchgrass particles interlocked and behaved as a body.

Ejector-trailer ram face pressure was calculated to be 101.5 kPa with 13,790 kPa of hydraulic pressure, and unloading the trailer took 12 minutes. Some difficulty was experienced during unloading, requiring the ejector ram to be cycled back and forth to clear compacted material from the trailer. This may have been due to the high elastic memory of switchgrass. It was recommended that the ejector-trailer ordered for future use should be specified with a larger hydraulic cylinder.

Moisture Content

Oven-dried moisture measurements provided a mean moisture content (w.b.) of 15.4% (Table 3). Expected moisture content of field-chopped switchgrass is 15-20% (w.b.).

Table 3. Oven-dried moisture content

Sample	Wet Mass (g)	Dry Mass (g)	% M.C. (w.b.)
1	308.3	279.8	9.2
2	410.0	356.6	13.0
3	357.3	309.2	13.5
4	464.4	398.0	14.3
5	456.5	403.7	11.6
6	496.2	420.0	15.4
7	557.6	473.3	15.1
8	398.2	338.0	15.1
9	395.0	319.3	19.2
10	505.4	386.5	23.5
11	465.5	391.6	15.9
12	432.4	351.7	18.7
Mean	-	-	15.4
Std. Dev.	-	-	3.7

Particle Size

Particle size calculations yielded geometric mean lengths (GML) of 9.81 ± 3.92 mm, 9.52 ± 3.89 mm, 8.97 ± 3.77 mm, 13.13 ± 3.84 mm, and 9.86 ± 3.52 mm for the five samples. Mean GML was 10.26 ± 3.79 mm. Particle size distribution by GML for each sieve and mean mass fraction retained on the respective sieve is shown in Figure 7, with standard error bars indicated.

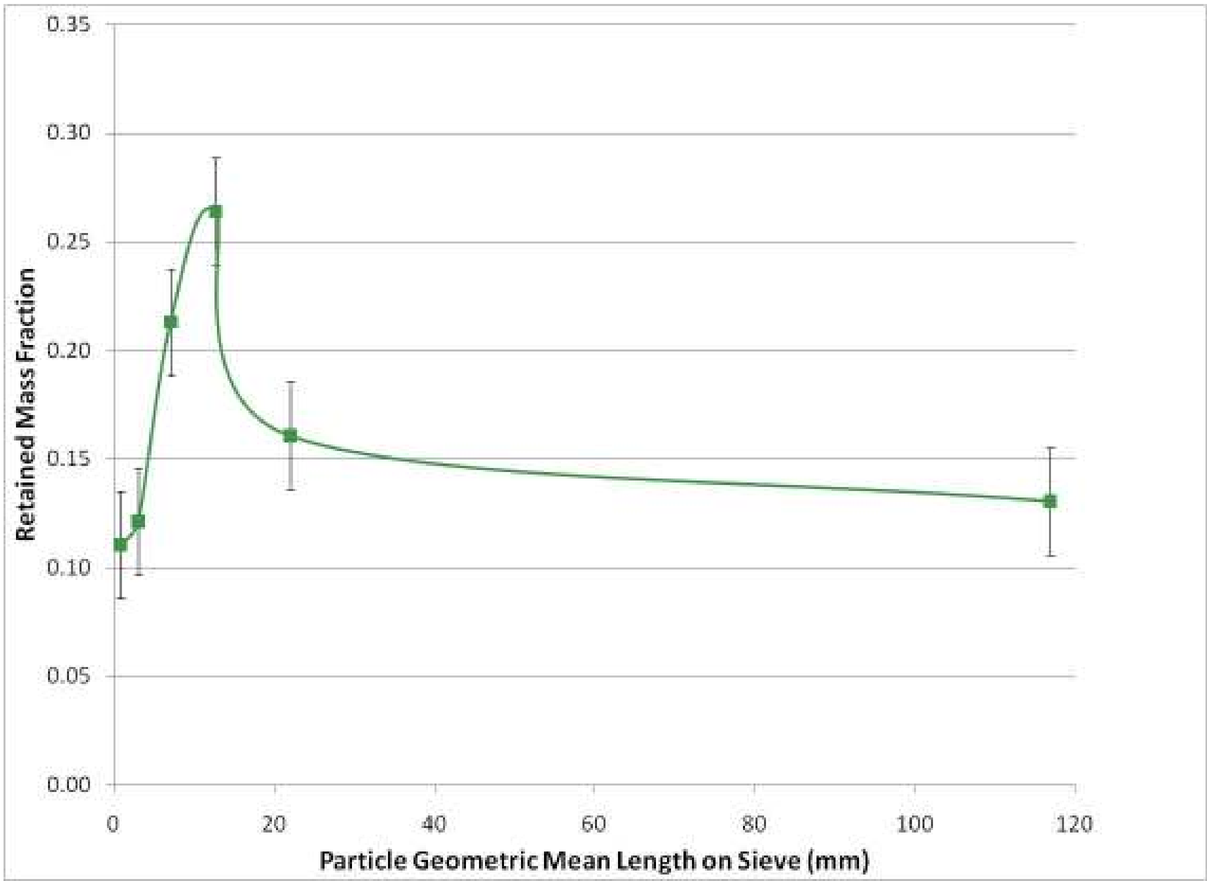

Figure 7. Particle size distribution

Lab-Scale Compaction

Lab-scale compaction results are shown in Figure 8. The single-cut late chopped sample was similar to the switchgrass used for compactor testing based on sieve results. GML was 8.51 ± 2.05 mm. Moisture content was 10% (w.b.). Comparison between lab scale and semi-truck ejector trailer results indicated improved prediction of ejector trailer results by assuming the ram force distribution across the trailer cross-section (152 kPa) rather than the actual ram face pressure (347 kPa) to achieve a bulk density of 186.4 kg/m^3 (at 15.4 %(w.b.). Other minor factors may have affect the comparisons, such as the orientation of the compaction ram and ram operation. In lab-scale tests, the compression piston was oriented vertically, while the compactor's plunger into the ejector-trailer was oriented horizontally. As a result, the effect of sliding friction may have been affected in the ejector-trailer. The compression piston in laboratory tests applied continuous force compared to the compactor plunger that cycled into the ejector-trailer with each new charge chamber volume.

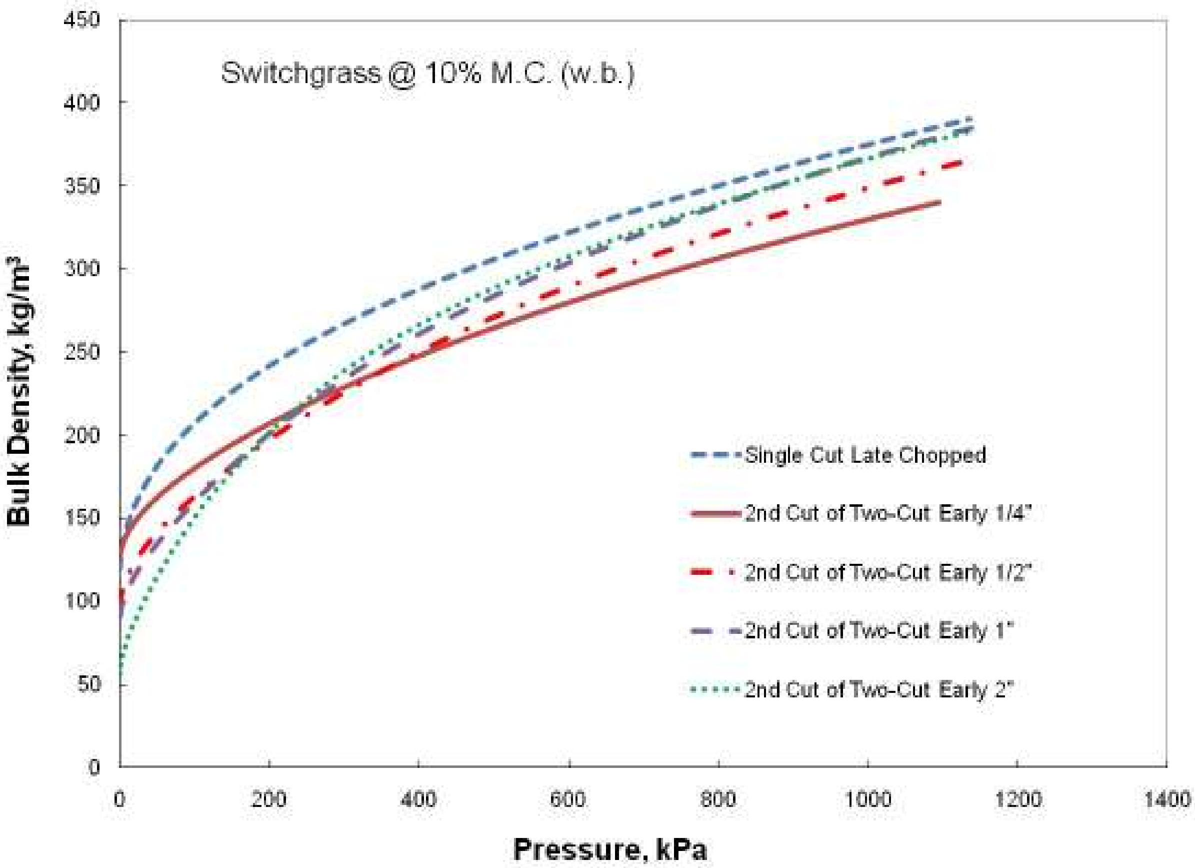

Figure 8. Bulk density of chopped switchgrass versus confining pressure

Conclusion

Waste-transfer compaction equipment was successfully used with bulk chopped biomass. Chopped switchgrass having a mean geometric mean length (GML) of 10.3 mm and a moisture content of 15.4 % (w.b.) had a loose-filled bulk density of 89.4 kg/m^3 and a compacted bulk density of 186.4 kg/m^3 in a 57.3 m^3 ejector-trailer. The compaction process roughly doubled the net load per semi-trailer compared to a non-compacted load, and has the potential to improve transportation efficiency of chopped switchgrass. This system allowed safe on-road transportation with fully-enclosed trailers, avoiding the hazards of transporting bales strapped to flatbed trailers.

Potential improvements included increased ejector-trailer volume compared to the tested size. Based on current gross combined weight (GCW) limits, dry compacted bulk density of 157.7 kg/m^3 from the test fit well with a commercially available 76.5 m^3 ejector-trailer. Another improvement is increased hydraulic cylinder size for the ejector-trailer blade to improve the unloading process.

As the semi-truck ejector-trailer became full, the compactor ram force appeared to be distributed across the full cross-section of the trailer, perhaps due to interlocking switchgrass particles – based on ejector trailer densities compared to laboratory compaction data.

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