BRIQUETTER TESTING AND RESULTS

Testing in a Commercial Setting

Waste to Wisdom: Task 3.6

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EXECUTIVE SUMMARY

Forest residuals are an abundant, underutilized resource that are often left stranded or burned for disposal in the forest due to their low value and high transportation costs. Densifying forest residuals into biomass briquettes in a near-woods setting can increase the economic viability of extraction by increasing their market value and reducing transportation costs by hauling more biomass fuel per truck. This report documents the results from testing a biomass briquetter in an industrial setting with a variety of feedstocks in order to understand the relationship between feedstock and briquette quality. The purpose of these experiments is to generate an initial understanding of biomass briquetting in a controlled environment with decent feedstocks before expanding the testing to a near-woods test site processing forest residuals.

Schatz Energy Research Center and Pellet Fuels Institute tested two briquetters manufactured by RUF Briquetting Systems, Inc. at Bear Mountain Forest Products, Inc. in Cascade Locks, Oregon during April 2015. Two sets of experiments were conducted. The first set of tests was to use a variety of biomass feedstocks, including sawdust, chips, mulch, and tops, to measure how briquette density, durability, and throughput rate changed. The second set of tests sent one feedstock to two machines of different capacities to monitor the relationship between machine size and electricity demand and throughput rate.

Results from the tests show that feedstock particle size and comminution method influence briquette durability and density. Chipped feedstocks, unless mixed with 50% fine particles, have low durability and will break apart during transportation and handling because larger, chipped particles are not conducive to mechanical interlocking and van der Waals attraction, which make up part of the binding process for briquettes. Furthermore, larger particle sizes cannot compress as much as finer feedstocks, such as sawdust or planar shavings, and form less dense briquettes.

Moisture content was not found to substantially reduce the durability of briquettes. However, these results are limited because most of the feedstocks were between 9% and 13% moisture content, which is within the ideal range for densification. The only feedstock outside this range, at 20% moisture content, expanded in height after exiting the briquetter to create a less dense briquette, but still maintained good binding and durability.

Two briquetters of different sizes were tested to understand the scalability of this technology. The main results from these tests are shown in Table ES.1.

Table ES.1. Main results from scalability test.

Briquetter	RUF RB 440	RUF 1100
Mass Throughput	325 kg/hr	491 kg/hr
Briquette Production	427 briq/hr	357 briq/hr
Briquette Mass	0.76 kg	1.39 kg
Nominal Briquette Dimensions	6”x2.5”x4.3”	9.5”x2.75”x4.3”
Briquette Packing Density	800 kg/m^3	975 kg/m^3
Energy Density	16 MJ/L	19.5 MJ/L
Average Electrical Demand	19 kW	42 kW

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Electric demand was consistent and stable across multiple feedstocks in the same machine, which yielded a similar number of briquettes per hour for all tests. Since the density of the briquettes changed based on feedstock properties while the electric demand and briquette production rate were constant, the specific energy requirements (in Wh/kg) decreased with denser briquettes. Surprisingly, when using the same feedstock in two machines of different throughput rates, the larger machine displayed higher specific energy consumption indicating that the larger machine was less efficient at using electricity to densify biomass. This effect may have been caused by differently-aged machines or neglected maintenance and should be verified with more briquetters before extrapolating the results.

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1 INTRODUCTION

This report provides a summary of testing and data analysis of biomass densification performed by Schatz Energy Research Center (SERC) and Pellet Fuels Institute (PFI) under the Biomass Research and Development Initiative Waste to Wisdom project. The work described here was completed during the first year of Subtask 3.6, as described in the Statement of Project Objectives:

> *PFI will operate a briquetting unit at a site in Oregon during Year 1 to create sample outputs. During this period, PFI will work closely with SERC to characterize the electricity and heat/fuel drying requirement of the briquetting unit. During Year 2, PFI will set up a briquetting unit for operating at a field site and/or will implement similar alternative densification strategies aimed at improving the economics of forest biomass utilization. PFI will provide input to Task 4 team members to support the economic analysis, market analysis and life cycle assessment tasks.*

Testing during Year 1, as described in this report, occurred in April 2015 using briquetters at Bear Mountain Forest Products, Inc.'s manufacturing facility in Cascade Locks, Oregon. The research objectives were to determine the throughput rate, electrical demand, acceptable feedstock specifications, and analyze the briquette characteristics.

Year 2 field testing was completed during July and August 2015 and material samples are currently undergoing laboratory analysis. These results will be distributed with a forthcoming report by June 2016.

This report provides an overview of the tests and results for the Year 1 set of experiments. For a complete dataset, please find the attached spreadsheet, 'W2W_BRDI_Briquetter_Ph1_Data.xlsx', which includes throughput rates, power requirements, and feedstock and briquette characteristics. This report first reviews the background on biomass densification in Section 2 and the process employed by this briquette press. Next, Section 3 details the experimental procedure and laboratory analysis methods. Results and discussion are presented in Section 4 before concluding in Section 5 and explaining the future test plans in Section 6.

2 BACKGROUND

Due to the low bulk density of forest residuals and comminuted biomass, their transportation is limited by the volume of the trailer rather than the maximum allowable gross weight of the truck. A material bulk density of at least 285 kg/m^3 is required to achieve the maximum legal payload in the volume of a typical chip van (Angus-Hankin et al. (1995). Forest residuals at 30% moisture content (wet basis) have a bulk density of 130 kg/m^3 before processing (Carlsson & Rådström, 1984) and 225 kg/m^3 after chipping (Carbon Trust, 2012), neither of which can achieve full payload in a chip van. Furthermore, transporting biomass at 30% moisture content is costly; the added water weight increases transportation fuel consumption without any economic return because biomass is typically sold on a bone dry basis.

Drying and densifying comminuted forest residuals into a high-quality briquette at a density of 450 kg/m^3 and 12.5% moisture content (Tumuluru et al. 2011) can achieve full legal payload to deliver 21.4 bone dry tons (BDT) of biomass fuel compared to a maximum of 14.9 BDT of chipped biomass or 8.6 BDT of uncompacted forest residuals in the same chip van. Thus, drying and briquetting forest residuals provides a promising pathway to reduce transportation costs by delivering more fuel per load.

The remainder of this section provides a background on briquetting technology. First, the machine, process, and binding mechanisms are described before discussing the effects of feedstock moisture content, ash content, and particle size on briquette quality.

2.1 Densification Technologies

The most widely used technologies for densifying biomass in the U.S. are pellet mills and briquetting presses (Tumuluru et al., 2010). Pellets are typically cylindrical with a diameter between 4.8 - 19.1 mm (Tumuluru et al. 2011), while briquettes are larger cylinders or rectangular prisms. Pellets have a higher bulk density and are primarily used as a residential fuel, while briquettes require less energy to produce and are used both residentially and industrially (Tumuluru et al., 2010). Furthermore, briquetting machines are more tolerant to larger particle sizes and a wider range of moisture content compared to pellet mills, where the feedstock must be finely ground and dried (Tumuluru et al., 2011). Due to the lower energy requirements and wider range of acceptable particle sizes and moisture contents, briquetting appears to be a better technology to densify forest residuals.

A briquette press works by compacting biomass into a die with a mechanical or hydraulic piston. The briquetters used for this study, manufactured by RUF Briquetting Systems, are hydraulically actuated. A diagram of their machine is shown in Figure 1. To operate the briquette press, the feedstock hopper is filled with raw biomass, and the screw conveyor moves the material into the precharger chamber. The screw conveyor automatically controls the appropriate amount of biomass to load into the chamber for each stroke, thus controlling the mass of each briquette automatically. Once the chamber is filled, the vertical precharge piston performs the first stage of compression. Then, the horizontal main ram piston compacts the material to form briquettes within the molding die. As the main piston press retracts, the molding die pushes the briquette to the side. When the piston engages again, a new briquette will be made and the briquette from the previous stroke will be ejected onto one of the two tracks. In this manner, each piston stroke compacts one briquette and ejects another onto alternating tracks.

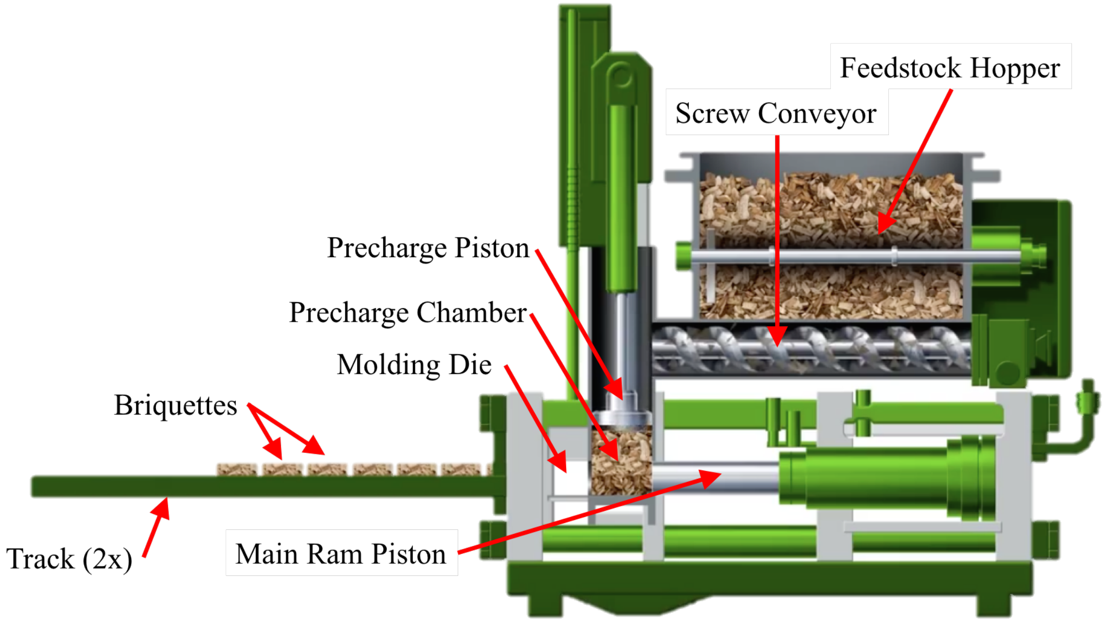

Figure 1. RUF Briquetter annotated schematic (RUF Briquetter, 2016, annotation added). The briquetter pictured is performing the first stage of compaction in the precharge chamber.

By drawing a control volume around the briquetting system during steady state operation, the process is simplified to the flow diagram depicted in Figure 2. Biomass feedstock and electricity are the only inputs to the machine, while briquettes and an insignificant amount of heat (not pictured) are the outputs.

Figure 2. Briquetting process input and output diagram.

2.2 Binding Mechanisms

As biomass is compacted, various binding forces act to form a solid briquette. First, biomass particles rearrange themselves to form a tightly-packed mass while maintaining the same chemical and mechanical properties. As compaction continues, brittle particles fold and fracture to create new interlocking mechanical bonds (Kaliyan & Morey, 2009). As pressure in the die increases, particles undergo elastic and plastic deformation, which increases the contact area between particles, and are bonded by van der Waals forces (Tumuluru et al. 2011). The binding resulting from van der Waals forces are stronger with fine biomass particles due to increased surface area contact (Grover & Mishra, 1996). Moisture content is also hypothesized to help strengthen these bonds by increasing the interfacial forces and capillary pressures between particles (Tumuluru et al. 2011). Furthermore, heat from compression and friction in the die causes lignin in biomass to soften, which acts as a natural binder (Adapa et al. 2009).

All these binding mechanisms are affected by particle size and chemical composition of the feedstock, which influence the strength and durability of the final briquette. In order to densify forest residuals, the process must be able to produce quality briquettes from a feedstock with high levels of moisture and ash content and coarse particles. The relationship between these feedstock characteristics and briquette quality are discussed below.

2.3 Effect of Moisture Content on Briquette Quality

Feedstock moisture content has been shown to affect the density and durability of briquettes. Water acts as a binding agent during densification by increasing contact area between particles and strengthening the van der Waals interactions (Kaliyan & Morey, 2009). Briquette durability tends to increase with moisture content from 0% until reaching a maximum around 8% for woody biomass then beginning to decline (Li & Lui, 2000). The ideal moisture content range is between 5% - 12% (Li & Lui, 2000). Lower moisture content briquettes have a high initial density but quickly absorb moisture from the air and become fragile. On the other hand, briquettes with moisture content above 12% produce low density briquettes and easily disintegrate with handling (Li & Lui, 2000).

2.4 Effect of Ash Content on Briquette Quality

Ash content in forest residuals is higher than that of bole wood due to the high fraction of bark, leaves, needles, and dirt that constitute it. Lehtikangas (2001) found that pellets produced from bark and forest residuals have greater durability than pellets produced from sawdust due to increased lignin content in bark, which acts as a natural binder. While Lehtikangas' results do not prove a direct relationship between ash content and durability, they show that strong, durable briquettes can be produced from forest residuals with high ash content.

Ash content in densified biomass is problematic because it can lead to sintering and slag formation during combustion, which has long been a problem in residential pellet furnaces (Öhman et al., 2004). Procuring high quality feedstocks is the simplest way to avoid fouling in a furnace, yet woody biomass fuels, which are inherently low in silicon content (see Cuiping et al., 2004), show only low to moderate slagging tendencies unless they are contaminated with sand (Gilbe et al., 2008).

2.5 Effect of Particle Size on Briquette Quality

Particle size distribution and comminution methods impact the durability of densified biomass. Li & Liu (2000) produced cylindrical briquettes from sawdust, mulch (from a tub grinder), and chips with similar moisture contents and found that briquettes produced from mulch and sawdust displayed good durability while briquettes produced from chips completely disintegrated in a tumbler. Mulch can hold together strongly in a densified log because, even while there are many large particles up to 4 cm in length, the fibrous, bulky material and rough edges allow for mechanical interlocking to bind the material together (Li & Lui, 2000). Briquettes produced from chipped biomass, in addition to low durability, also showed a lower density than mulch or sawdust at the same moisture content when compressed at the same pressure.

With this brief literature review as a background, tests were conducted to verify and investigate the effects between feedstock characteristics and briquette quality.

3 MATERIALS & METHODS

Experiments for this analysis were performed using two briquetting presses located at Bear Mountain Forest Products, Inc.'s (BMFP) processing plant in Cascade Locks, Oregon. The smaller of the two briquetters, a RUF RB 440, was tested with a variety of feedstock materials that were approved by the staff at BMFP. The larger capacity RUF 1100 briquetter was only operated with sawdust feedstock due to BMFP's expressed concerns over increased maintenance and downtime when using marginal feedstocks with this briquetter. An image of the RUF RB 440 is pictured below in Figure 3.

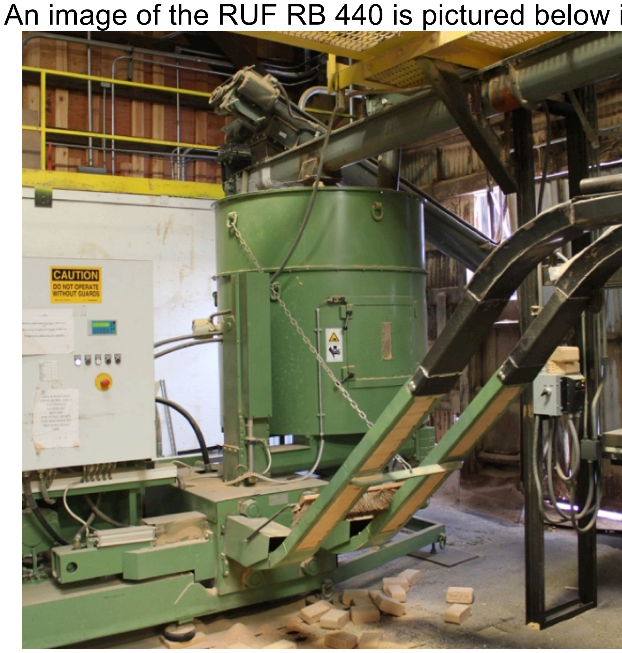

Figure 3. RUF RB 440 at Bear Mountain Forest Products, Inc.

3.1 Feedstock Supply

A variety of feedstocks were used in this study including different species and comminution methods. All feedstocks were sourced directly from BMFP at low moisture contents with the exception of the Douglas Fir tops, which were provided and chipped by Mt. Adams Resource Stewards (Glenwood, WA) then dried in a rotary dryer at BMFP. The origin of feedstocks sourced from BMFP are unknown. The feedstock species and test identification designations are listed in Table 1. Pictures of these feedstocks are provided in Figure 4.

Feedstock mixtures chips and sawdust (Ch/Sd), sawdust and mulch (Sd/M), and sawdust and tops (Sd/T) were mixed by BMFP by using a wheel loader. The mixture fractions, such as 50%/50%, are not exact but were used as a guideline when mixing the feedstock on a volumetric basis. The chips and shavings (Ck/Sh) feedstock, on the other hand, was not mixed by BMFP; this feedstock was used as received and contained planar shavings and thin chunks, which, according to BMFP, came from a poor quality planar.

All production tests using the RUF 440 and 1100 used Douglas fir and pine sawdust feedstock. This feedstock is the same feedstock that is labeled ‘Sd’ from the feedstock tests in Figure 4.

Table 1. Feedstock type and designation for briquette production. Percentage mixtures are estimated on a volumetric basis.

Test ID	*Type*	*Species*
Feedstock Quality Tests		
Sd_1 Sd_2 Sd_3	Sawdust	Douglas Fir and Pine
Sh_1	Planar Shaving	Douglas Fir and Pine
Ck/Sh_1	Chunks and Shavings	Radiata Pine
Ch/Sd_1 Ch/Sd_2	50% Chips, 50% Sawdust	Alder, Douglas Fir and Pine
Ch_1 Ch_2	Chips	Alder
Sd/M_1	67% Sawdust, 33% Mulch	Maple, Apple and Cherry
Sd/T_1 Sd/T_2	67% Sawdust, 33% Chipped Tops	Douglas Fir and Pine Douglas Fir
Production Tests		
440_1 440_2 440_3	Sawdust	Douglas Fir and Pine
1100_1 1100_2		

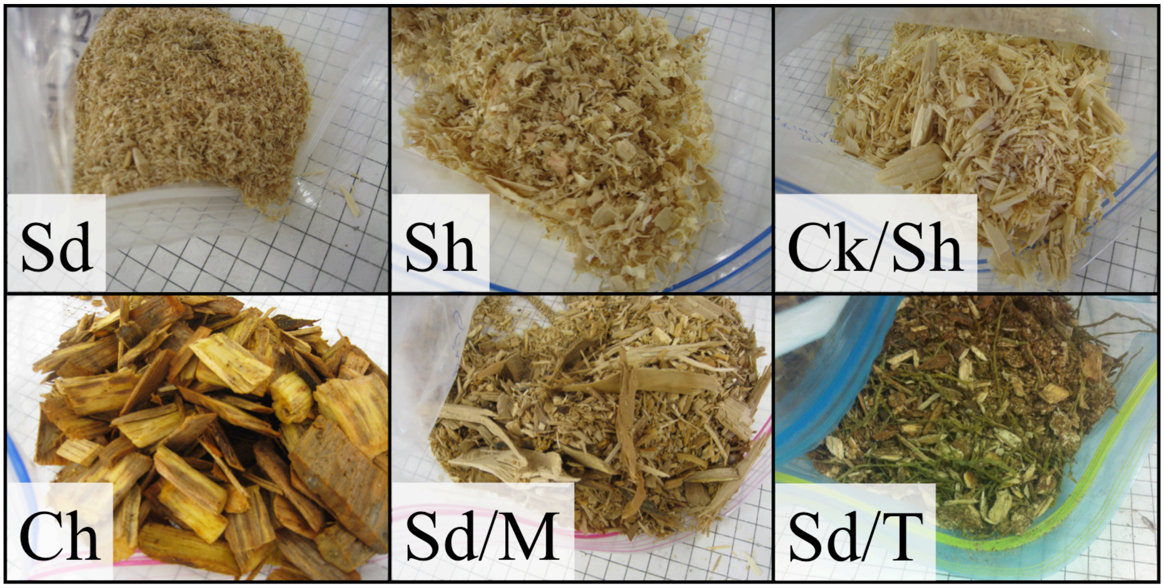

Figure 4. Feedstock images. Grid in image background is 1 cm x 1 cm grid.

3.2 Briquetting Production Process

The briquetting machines, an RB 440 and a RUF 1100, are manufactured by RUF Briquetting Systems. The RB 440 is rated to produce briquettes at a throughput of 440 kg/hr with dimensions of 6”x2.5”x4.3”, and the RUF 1100 is rated for 1,100 kg/hr producing briquettes with dimensions of 9.5”x2.75”x4.3” (RUF US, Inc.). These briquetters are typically operated continuously at Bear Mountain Forest Products using waste sawdust to produce briquettes for residential heating.

Two sets of experiments were performed on these machines. The first set of experiments was to explore the relationship between feedstock quality and briquette quality. These tests were performed with the smaller RB 440 briquetter using the feedstocks listed in the top section (i.e., labeled “feedstock quality tests”) of Table 1 (above), which includes various species, particle size distributions, comminution methods, and moisture contents. These feedstocks were processed through the RB 440 briquetter for a 30-minute steady state test to monitor and collect briquette samples. The second set of experiments (i.e., labeled “production tests” in Table 1) aimed to determine the scalability of a briquetter by simultaneously operating both machines with an identical feedstock. The second set of tests was designed to investigate the relationship between production capacity and electrical demand.

To perform a briquetting experiment, first the bulk density of the feedstock was measured and a sample was stored in an airtight plastic bag for analysis. Then, the feedstock was loaded into the cylindrical hopper on the briquetter, and the machine was turned on. The test period began after approximately five minutes of warming up, or once the briquettes were produced with consistent mass. At that moment, the machine settings, time, and value displayed on the briquette counter – which counts the number of briquettes produced – were recorded. While the test was running, briquettes were sampled from the output conveyor approximately every minute, resulting in a total of 27 briquette samples. The samples were weighed to the nearest 0.01 lb and then placed in an airtight bag to bring back to the lab for analysis. At the end of the 30 minute steady state operation time, the final value displayed on the machine's counter and the time were recorded. The machine was left running until the feedstock hopper was empty and ready for the next test. Electric power consumption was monitored with a power meter (Continental Control Systems, WCN-3D-480-MB, accuracy = ±0.5% of reading) using current transformers (Continental Control Systems, ACT-07500-200, range = 10-200 amps) and storing data in one-second intervals using LabView software.

3.3 Materials Analysis

Feedstock and briquette samples were collected during testing. Feedstock samples were removed before loading the hopper. Briquette samples were removed from the output conveyors throughout the test period. The samples were analyzed to assess their quality and characteristics. The analysis methods are described below.

- *Feedstock Bulk Density* – Measured in the field by modifying CEN/TS 15103 to use a one cubic foot metal container (12"x12"x12") and a scale with ±0.05 lb resolution (Adam Equipment CPWplus 75).
- *Briquette Mass* – The mass of 27 briquettes weighed in the field approximately two minutes after densification with a scale with ±0.01 lb resolution (Adam Equipment CPWplus 15).
- *Briquette Packing Density* – Determined by neatly stacking eight briquettes in a two by two by two cube inside a three-sided box then measuring the outermost dimensions of the stack. The packing density was calculated by the total volume of this stack divided by eight.
- *Mechanical Durability* – Tested in a tumbler with modifications to ISO/DIS 17831-2. Nine briquettes were placed in a tumbler rotating at 21 rpm for five minutes. After tumbling, the material not passing through a 2" mesh screen was weighed as the durable fraction of the briquettes.
- *Moisture Content* – Determined according to ASTM Method E871-82 using a scale with ±0.1 gram resolution. Briquettes were broken into smaller pieces with a mallet while still in an airtight plastic bag before measuring moisture content.
- *Proximate Analysis* – Measured using a thermogravimetric analyzer (TA Instruments, Q50) with the following temperature program: under a nitrogen purge gas, heat to 95°C at a ramp rate of 80°C/min then to 105°C at a ramp rate of 10°C/min and hold for 10 minutes; heat to 685°C at a ramp rate of 80°C/min then to 700°C at a ramp rate of 10°C/min and hold for 25 minutes; switch the purge gas to air and hold at 700°C for three minutes.
- *Particle-Size Distribution (Feedstock)* – Measured by mechanically shaking a stack of sieves for 10 minutes with a set of 8" diameter sieves with the following mesh sizes: 2", 1.5", 1.05", 0.75", 0.525", 0.375", 0.265", 0.185", Mesh #8, Mesh #18, and pan. After shaking, the mass retained on each sieve was measured to the nearest ±0.1 gram (BrainWeight B 3000D).
- *Grindability* – Measured by modifying the SECTOR Determination of Grinding Energy test method. Briquettes were cut into 1" x 1" x 0.5" rectangular prisms (approximately 8 g) with a band saw. Material was ground in a mill (Thomas-Wiley, Laboratory Mill Model 4) with a 2 mm grate for 120 seconds with a feed rate of one piece every 10 seconds. The mill's electricity demand was recorded in one second intervals (Continental Control System WNC-3Y-208-MB and ACT-0750-020). Grinding energy was determined as the difference between

the average power during the 120 seconds of grinding and the average idle energy consumption measured for three minutes before and after the test. The particle size distribution of ground material was measured by shaking a stack of 8” diameter sieves with mesh sizes (in mm) 2, 1, 0.5, 0.35, 0.25, 0.15, 0.075, pan for 10 minutes. After shaking, the mass retained on each sieve was measured to the nearest ±0.1 gram (BrainWeight B 3000D)

- *Water Absorption* – Measured by placing one briquette in an environmental chamber (Espec, EPL-3H) at 50°C, 95% relative humidity. Briquette mass was measured every 24 hours. The test was complete after change in mass was <0.1% in 24 hours. Water absorption is reported as the moisture content after saturation in the environmental chamber.
- *Transportation Simulation* – Measured by placing one briquette in an environmental chamber (Espec, EPL-3H) to simulate an eight-day shipping route from the Pacific Northwestern US to East Asia by changing the humidity and temperature in two-hour increments. A detailed description of this method and temperature and humidity profile is provided in Appendix A. After removal from the environmental chamber, the single briquette was put through the durability test.
- *Gross Calorific Value* – Measured in a bomb calorimeter (Parr Instruments, Model 1241).

4 RESULTS & DISCUSSION

Results from the field testing and laboratory analysis are presented in the beginning of this section followed by a discussion of the key relationships between feedstock quality and briquetter operation. Lastly, using the data available, the briquettes from each test are classified based on ISO standard 17225-3.

4.1 Feedstock Characterization

Characteristics of the feedstocks used for testing are shown in Table 2.

Table 2. Feedstock quality characteristics. Bulk density, moisture content, heating value, and particle size distribution are given on a wet-basis. Ash content, volatile matter, and fixed carbon are given on a dry-basis.

Test ID	*Bulk Density, kg/m³*	*Moisture Content, % w.b.*	*Ash Content, % d.b.*	*Volatile Matter, % d.b.*	*Fixed Carbon, % d.b.*	*HHV, MJ/kg*	*Particle Size Distribution, (>0.5” / < 0.1”)*
Sd_1	230	11.8%	0.76%	82.0%	17.3%	19.5	0% / 99%
Sd_2	200	10.2%	0.31%	83.4%	16.3%	20.1	1% / 99%
Sd_3	230	9.9%	0.30%	84.4%	15.3%	19.8	0% /100%
Sh_1	150	13.3%	0.23%	84.7%	15.1%	18.8	1% / 77%
Ck/Sh	190	9.9%	0.33%	84.9%	14.8%	19.4	6% / 50%
Ch/Sd_1	260	12.4%	0.33%	84.2%	15.4%	19.2	12% / 59%
Ch/Sd_2	260	9.5%	0.43%	84.4%	15.2%	19.2	15% / 54%
Ch_1	170	11.4%	0.49%	85.2%	14.3%	19.7	39% / 5%
Ch_2	200	10.7%	0.38%	84.7%	14.9%	19.1	39% / 4%
Sd/M	250	19.9%	0.76%	83.0%	16.3%	19.0	12% / 67%

Sd/T_1	220	12.6%				20.1	3% / 81%
Sd/T_2	240	13.0%	0.43%	83.1%	16.5%	19.6	4% / 76%
Production Tests							
440_1			0.81%	83.1%	16.1%	20.6	
440_2							
440_3							
1100_1			0.29%	84.5%	15.2%	19.5	
1100_2							

4.2 Briquette Characterization

Briquette quality parameters and characteristics are shown in Table 3. Mechanical durability is expressed as the mass percent of material that did not pass through a 2" mesh screen after tumbling. More results and measurements can be found in the spreadsheet attached to this report. Pictures of select briquettes are shown in Figure 5 and Figure 6. Pictures of briquettes at the end of the absorptivity test are presented in Appendix B.

Table 3. Briquette quality characteristics. All value are given on a wet basis.

Test ID	*Prod. Rate, briq./hr*	*Packing Density, kg/m³*	*Mass, kg*	*Moisture Content, % w.b.*	*Post-Transp. Moisture Content, % w.b.*	*Post-Absorptivity Moisture Content, % w.b.*	*Durability, % DU*	*Post-Transp. Durability, % DU*	*Grinding Energy, Wh/kg*
Sd_1	426	856	0.78	10.0%	11.2%	15.5%	98%	98%	55
Sd_2	429	856	0.71	8.7%	10.6%	16.1%	98%	97%	43
Sd_3	435	684	0.76	10.4%	12.2%	17.8%	94%	98%	41
Sh_1	448	848	0.75	9.5%	10.5%	19.4%	98%	99%	71
Ck/Sh	443	856	0.8	10.8%	12.2%	17.7%	94%	90%	65
Ch/Sd_1	434	776	0.68	10.2%	10.9%	17.7%	94%	46%	53
Ch/Sd_2	434	746	0.69	9.6%	10.9%	18.4%	84%	15%	65
Ch_1	414	674	0.65		11.8%		71%	36%	
Ch_2	443	532	0.56	10.8%	12.4%	16.5%	22%	0%	120
Sd/M	411	578	0.8	14.3%	14.1%	17.1%	93%	72%	110
Sd/T_1	447	617	0.75	10.6%	12.0%		42%	91%	
Sd/T_2	464	613	0.72	11.1%			48%		67
Production Tests									
440_1	427		0.76				98%	67%	47
440_2	422		0.76						
440_3	432		0.76						
1100_1	390		1.26						
1100_2	323	975	1.52						

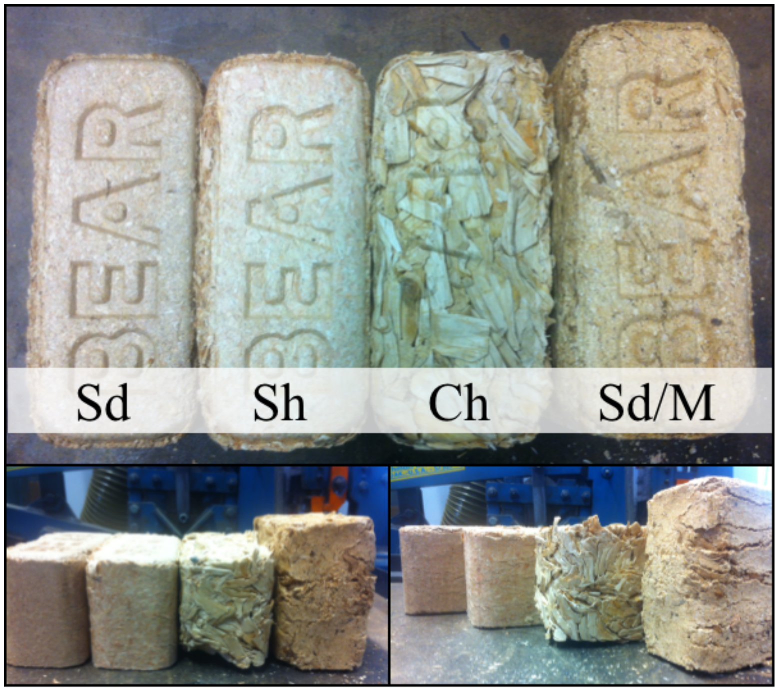

Figure 5. Picture of select briquettes produced from the RB 440.

A visual comparison of briquettes produced in the larger RUF 1100 and smaller RUF RB 440 briquetters during the production tests are shown in Figure 6.

Figure 6. Comparison of briquettes from RUF 1100 (larger) and RUF RB 440 (smaller).

4.3 Density

Briquetting increased the density of the feedstock by factors ranging from 2.3 to 5.6, as shown in Figure 7, achieving final briquette packing densities between 550 and 850 kg/m^3. Note that briquette packing density was measured as the stacked density of eight briquettes rather than the particle density of an individual briquette because the stacked density provides a better representation the volume required for transportation. Noticeably, the briquettes produced with larger particle feedstocks, such as the chips (Ch), sawdust/mulch mixture (Sd/M), and the sawdust/tops mixture (Sd/T) have a lower density than finely ground feedstocks such as sawdust (Sd) or shavings (Sh). Larger particles did not compress to remove the intraparticle pore space, and the particles appeared to remain the same dimensions (see Ch briquette in Figure 5). It appears that the larger pieces mainly increased their density by rearrangement rather than compression. The smaller particles, such as sawdust and shavings, which require more energy to comminute, likely had less space between the particles in the briquette and could compress to form a denser material.

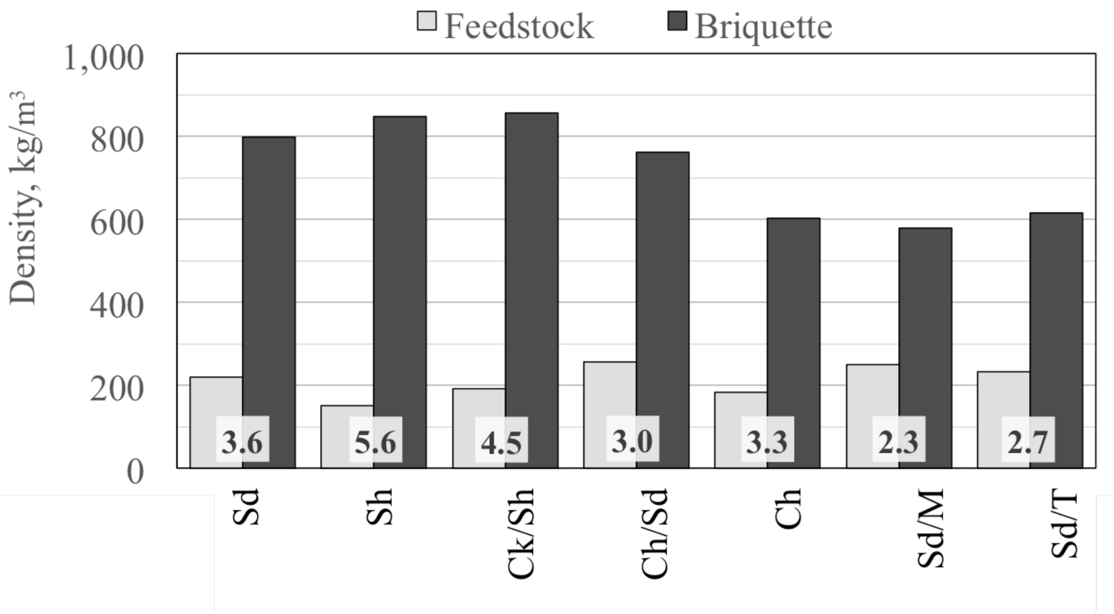

Figure 7. Average bulk density of feedstocks and packing density of briquettes on a wet basis. The number at the bottom of each bar indicates the factor by which the density increased.

4.4 Briquette Durability

Durability can be used to estimate how much mass of the briquette might be lost through transportation and handling. After rotating nine briquettes in a tumbler, durability is reported as the mass percentage that did not pass through a 2” mesh grate.

Comminution method appears to have the greatest impact on briquette durability: chipped feedstocks (including Ch and Sd/T) produced the least durable briquettes while briquettes produced from sawdust, shavings, or mulch were all over 89% durability. Briquettes produced from pure chips had an average durability of 46%, while mixing chips with 50% sawdust increased the durability to 89% compared to 97% for pure sawdust, as shown in Figure 8.

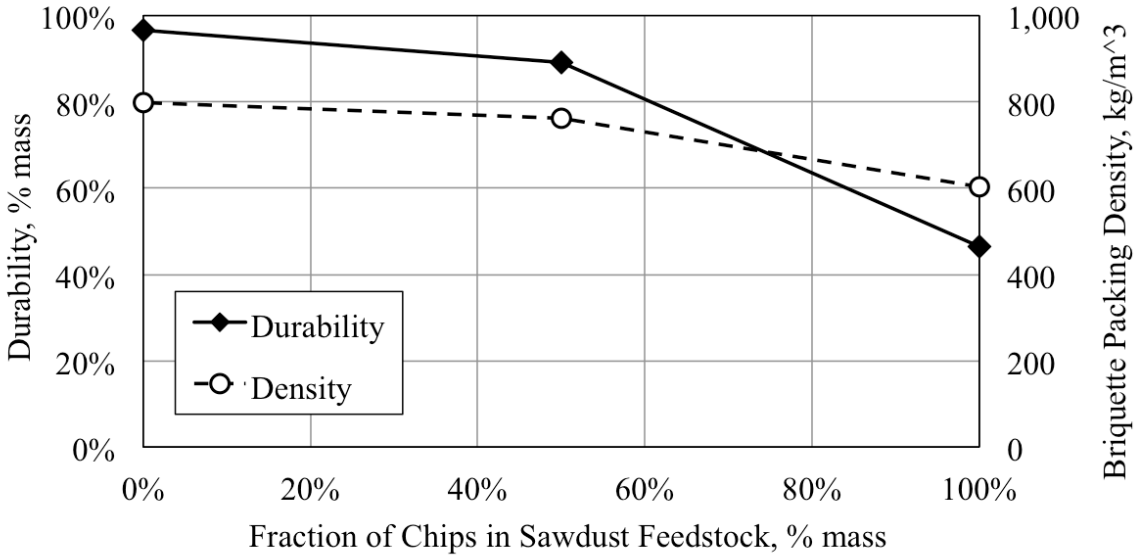

Figure 8. Briquette durability (black line, left axis) and packing density (dashed line, right axis) as a function of the mass fraction of chips in sawdust feedstock on a wet-basis.

The physical structure of biomass chips is not very compatible with the binding mechanisms of densification. First, the large particle sizes decrease the contact area between chips, which limits the binding ability through van der Waals forces. The addition of sawdust was shown to help bind them together by filling the void space between the chips. Secondly, the shape and structure of chipped particles is not conducive to mechanical bonding because the cleanly cut edges and thick particles do not easily fracture or bend to interlock with neighboring pieces. Furthermore, at the same compaction pressure, chips cannot be compressed as far as sawdust, which results in lower density briquettes, as shown on the right axis of Figure 8.

The durability was tested again after cycling a briquette through the humidity and temperature profile of a typical trans-Pacific cargo shipment (see Section 4.6 for these results and Appendix A for a description of the method).

4.5 Feedstock Moisture Content

Feedstock moisture content ranged from 9.5% to 13% for all feedstocks except the Sd/M mixture, which contained 20% moisture content on a wet basis. Sd/M briquettes displayed low density because they expanded after ejection from the briquette press. These briquettes were noticeably taller than all the other briquettes (see bottom images of Figure 5, above) but still displayed a high durability of 92%. These results do not indicate whether 20% moisture content was too high for effective production. Less energy would be required upstream to dry the feedstock, which may make this a reasonable trade-off as long as increased moisture content does not increase long-term maintenance costs of the briquetter. Overall, due to the narrow range of moisture content available for testing, the results from this preliminary study are limited. More informative results are expected from testing carried out during Phase 2 field testing.

4.6 Transportation Simulation

The briquettes were exposed to the temperatures and relative humidity experienced in an enclosed container during transit from the Pacific Northwest United States to East Asia to determine how briquette characteristics changed after transportation. The procedure for this test method is described in Appendix A.

The moisture content before and after the simulated transportation journey is shown in Figure 9. Briquettes that began with moisture content between 8% and 11% showed an increase in water content in the range of 5% to 20%, as shown on the left side of Figure 9, resulting in briquettes with a moisture content between 10% and 13% after transportation. On the other side of the spectrum, the briquette that began with 14.3% moisture content (test Sd/M) was slightly drier at 14.1% moisture content after transportation. These results indicate that the temperature and humidity fluctuations in a trans-oceanic shipping journey are not so extreme as to complete degrade the briquette. The moisture content shifts towards an equilibrium: dry briquettes become wetter, and wet briquettes become drier.

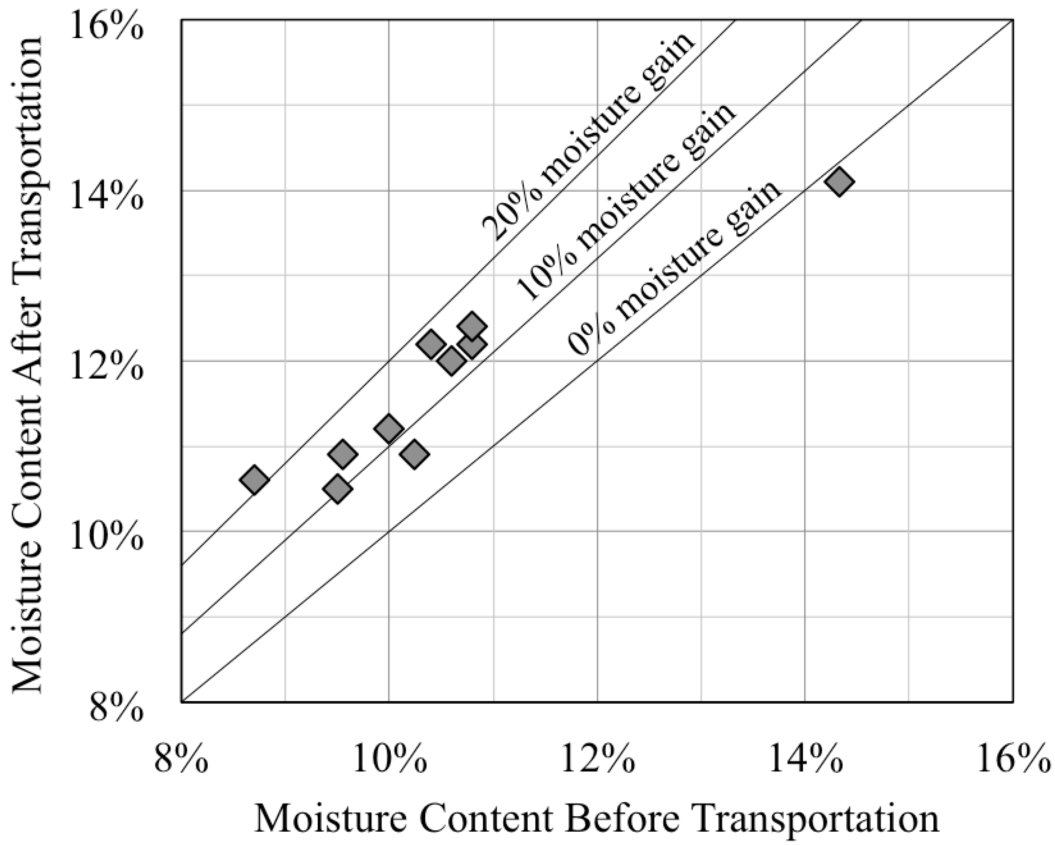

Figure 9. Briquette moisture content (wet basis) before and after transportation simulation.

The durability was tested again after the transportation simulation. The feedstocks comprising sawdust (Sd), shavings, (Sh), and shavings and chunks (Sh/Ck) displayed little to no change in durability after transportation (all within ±5% of original durability), as shown in Figure 10. The durability of feedstocks consisting of large particles (Ch/Sd, Ch, and M/Sd) decreased substantially after transportation. These feedstocks began with lower durability before transportation, and their susceptibility to decomposition was exacerbated after exposure to humidity fluctuations and handling.

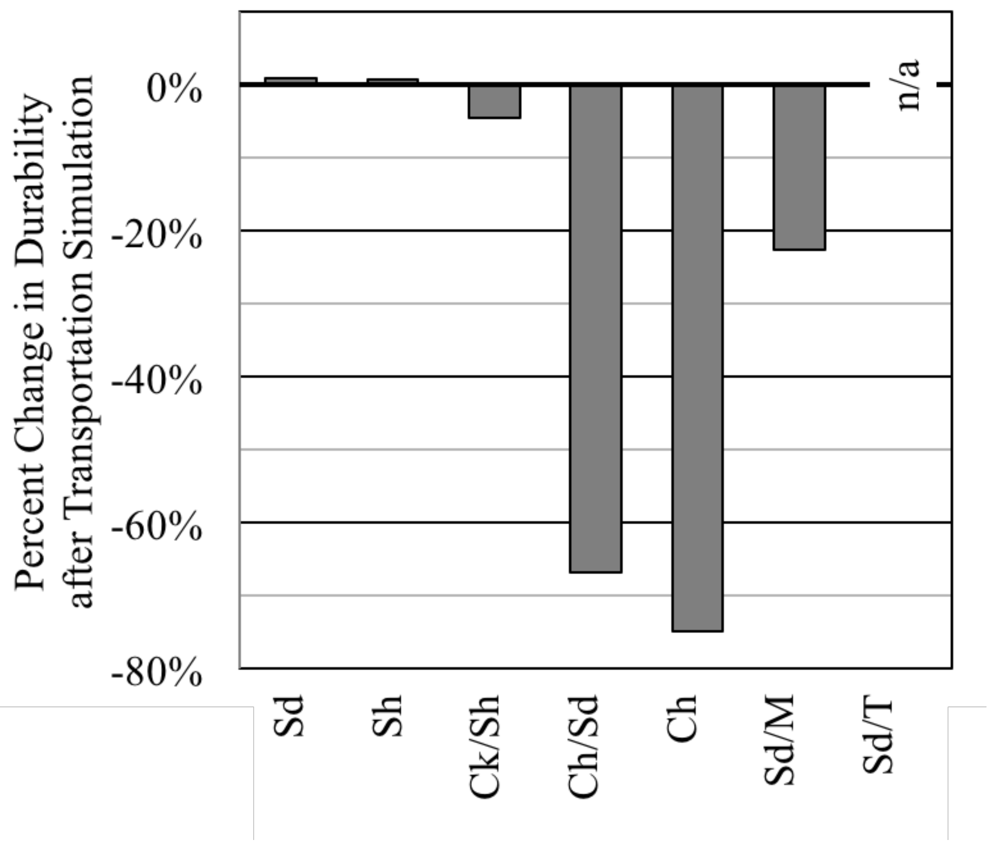

Figure 10. Average change in durability after transportation simulation for different feedstocks.

4.7 Grindability

Specific grinding energy, or the energy required to comminute the briquettes to less than 2 mm particles, for each feedstock is shown in Figure 11. Significantly more energy is required to grind the briquettes produced from Ch and Sd/M compared to grinding the same mass of briquettes produced from other feedstocks. This is because the grinder must first break the bonds that comprise the briquette and then grind the large particles to less than 2 mm. The sawdust feedstock (Sd), on the other hand, produced briquettes with the lowest specific grinding energy, but approximately 90% of the feedstock was already less than 2 mm before densification, which skews the results.

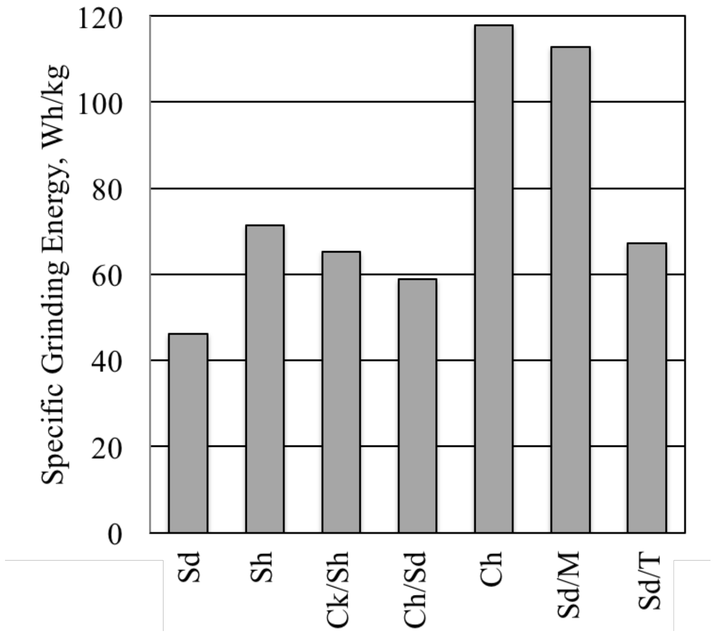

Figure 11. Average specific grinding energy for each feedstock.

There is a tradeoff between grinding energy required to produce the feedstock and grinding energy required to convert a briquette into a powdered fuel. Less energy is required upstream to produce chips or mulch feedstock, but more energy is required downstream to turn those briquettes into a fine particle fuel, while the opposite scenario is true for sawdust. Evaluating these tradeoffs depends on the source and availability of feedstock material and the end use of the briquettes. Sawdust could prove to be an economical feedstock choice if it is readily available as a waste product, and the briquettes would be co-fired at a coal power plant that pulverizes their fuel. However, for other scenarios, such as forest residual utilization, it may be more efficient to densify ground material and grind it downstream. Evaluating these tradeoffs is outside the scope of this report, but these results can lead to a future analysis of the broader supply chain.

4.8 Electricity Consumption

Electric power consumption for the RUF RB 440 was similar for all feedstocks, as shown in Figure 12, with an average of 19 kW, a minimum of 17 kW, and a maximum of 20.5 kW. A similar amount of energy was required for compacting each feedstock independent of the feedstock bulk density. The briquette operator can set the compaction pressure in the precharger and main ram chambers. These settings were largely left constant for each test but adjusted slightly at the advice of a RUF Briquetting Systems representative on site during the tests. By using consistent settings, the briquetter exerts the same amount of work on each feedstock, which results in similar electrical demand but varies the density of the briquette based on the feedstock's compressibility.

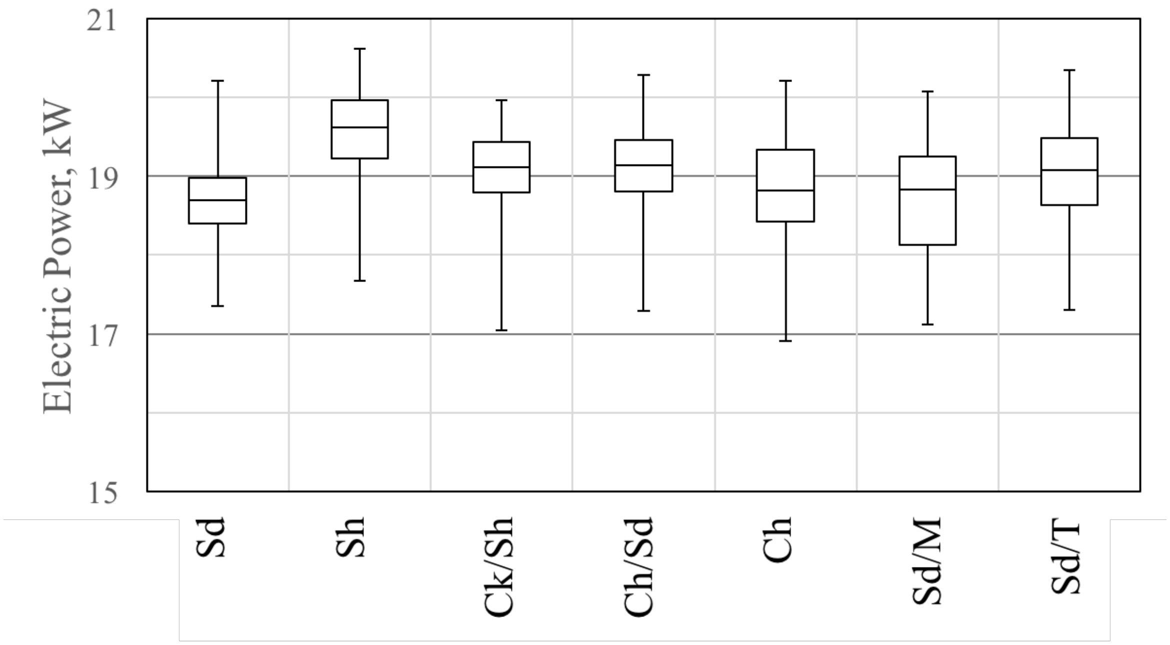

Figure 12. Electric power demand for different feedstocks in the RUF RB 440. The bars represent the first quartile, median, and third quartile and the error bars show the minimum and maximum.

4.9 System Performance and Throughput Rate

Biomass throughput rate was influenced by briquette density during the feedstock tests with the smaller RUF RB 440 briquetter. Across different feedstocks, the briquetter produced a consistent number of briquettes per hour (coefficient of variation = 3%) but showed a wider range of mass throughput rates (coefficient of variation = 9%). This shows that sourcing a feedstock that produces dense briquettes will lead to higher processing rates. Furthermore, since the density of the briquettes changed based on feedstock properties while the electric demand and briquette production rate were constant, the specific energy requirements (in Wh/kg) decreased for denser briquettes.

During the production capacity tests, the average power for the larger RUF 1100 briquetter was 42 kW compared to 19 kW for the smaller briquetter. Surprisingly, the specific energy consumption, calculated as the power divided by the throughput, increased for the larger machine, indicating that more power was required to produce the same mass throughput. The specific energy consumption versus the production rate is plotted in Figure 13, which shows two correlations. First, the grey diamond data markers show that the specific energy consumption increased with the larger briquetter compared to the smaller briquetter using the same feedstock. Second, the black ‘+’ data markers show the results from the RUF RB 440 machine with a variety of feedstocks. Interestingly, the opposite trend is displayed, where specific energy consumption decreases as the production rate increases based on feedstock characteristics.

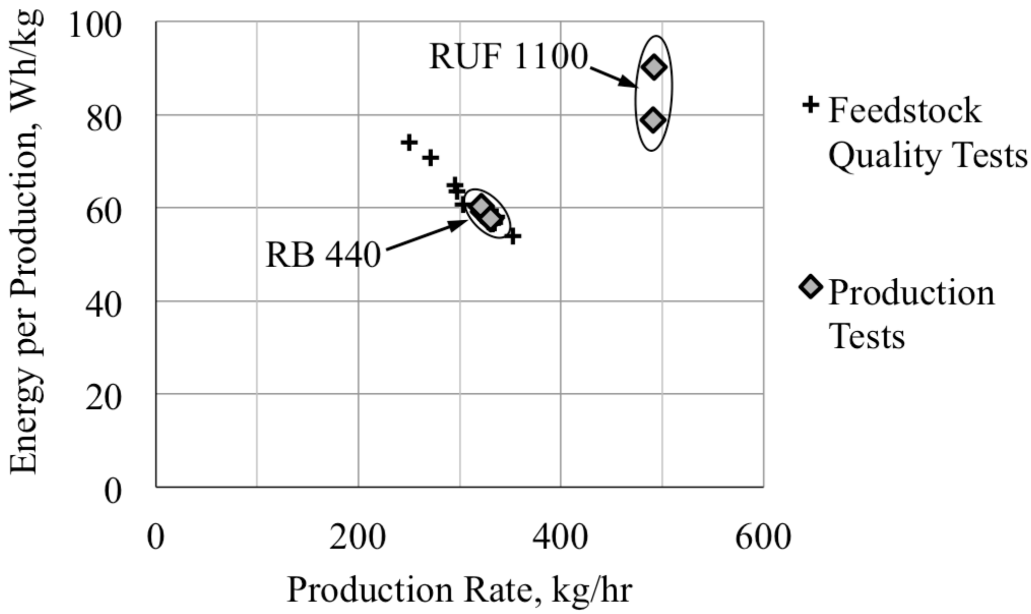

Figure 13. Specific energy as a function of production rate for both sets of experiments. Black '+' markers represent the various feedstocks tested on the smaller briquetter; grey diamonds represent production capacity runs with sawdust on both briquetters.

This indicates that the larger briquetter was less efficient at using electricity to produce briquettes, which contradicts typical economies of scale. These results should not be extrapolated without further verification. The increased specific energy requirements may be caused by the vintage of the machine, differences of internal components, a lack of maintenance and upkeep, or because energy consumption is not a major design consideration. For example, at a commercial facility receiving electricity for $0.18/kWh the RB 440 requires $0.01 of electricity and the RUF 1100 requires $0.02 to produce a single briquette, which is a very small cost. Electrical demand is a larger consideration in remote locations when the briquette producer must also supply the electrical generator.

4.10 Briquette Classifications

The International Organization for Standards (ISO) standard 17225-3 provides guidelines for grading biomass briquettes. Briquettes are classified into three categories, A1, A2, and B, based on the origin of feedstock, moisture and ash content, heating value, particle density, and amount of trace metals, where A1 is the highest grade and B the lowest grade. The classifications are described in Table 4.

Briquettes from this study were not evaluated with regard to the standards for trace metals or particle density. Setting aside these classifications, the briquettes were graded based on the other measured qualities, including origin and source, moisture, ash, and heating value.

Table 4. Description of ISO 17225-3 quality classifications for biomass briquettes.

Class	*Origin and Source*	*Moisture, as received*	*Ash, dry basis*	*Heating Value, MJ/kg, as received*
A1	- Stemwood - Untreated wood residues	≤ 12%	≤ 1.0%	≥ 15.5
A2	- Whole trees - Stemwood - Logging residues - Untreated wood residues	≤ 15%	≤ 1.5%	≥ 15.3
B	- Forest, plantation, and other virgin wood - By-products from wood processing - Untreated used wood	≤ 15%	≤ 3.0%	≥ 14.9

All the tests from this study are graded as A1 except in two cases, which were classified as A2. The maple sawdust and ground hardwood blend (Sd/M) is classified as A2 because the briquette moisture content was above 12% (actual moisture content = 14.3%). Both tests using 1/3 tops and 2/3 sawdust as the feedstock (Sd/T_1 and Sd/T_2) might be classified as A2 because of a portion of the feedstock is sourced from logging residues, even though the briquettes meet the measured quality standards.

5 CONCLUSION

These tests generated initial samples and results that show a wide variety of feedstocks can be densified into biomass briquettes. The only feedstock that may be not be a viable input is pure chips, which displayed durability below 50%. However, with the addition of fine particles, chips can be used to produce durable, dense briquettes. Feedstock moisture content between 9% and 13% did not substantially reduce briquette quality. Feedstock with 20% moisture content produced a durable briquette, even after expanding in height minutes after leaving the briquetter. After undergoing a transportation simulation, the briquettes maintained reasonable moisture contents between 10% to 15%, but the transportation significantly reduced the durability of briquettes produced with larger particles. Based on the results from this work, feedstocks for the briquetter should have a moisture content between 9% and 13% and contain a maximum of 50% chips greater than ½”.

Two briquetters of different capacities were compared with the same feedstock to understand the scalability of this technology. The smaller RUF RB 440 produced an average 427 briquettes per hour with a mass of 0.76 kg and an electrical demand of 19 kW. The larger RUF 1100 briquetter produced an average of 357 briquettes per hour with a mass of 1.39 kg and an electrical demand of 42 kW.

6 FUTURE WORK

This work has paved the way to continue investigating biomass briquetting as an option to utilize forest residuals. A second round of experiments were conducted to fulfill the second set of tests required under Subtask 3.6, as described in Section 1. During July and August 2015 a RUF 200 briquetter was operated in a near-woods setting using feedstocks more representative of forest residuals. Briquette samples from these tests are currently undergoing laboratory analysis, which should be complete in April 2016. A dataset and report summarizing the results from these tests will be distributed by June 2016.

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APPENDIX A TRANSPORTATION SIMULATION TEST METHODS

The purpose of this test is to simulate the effect of trans-oceanic shipping on biomass briquettes. These conditions are often present during trans-oceanic shipments (conditions known as “cargo sweat” or “ship sweat”). In the context of this study, the primary concern is with transport from a temperate environment to a tropical environment (Figure A.1).

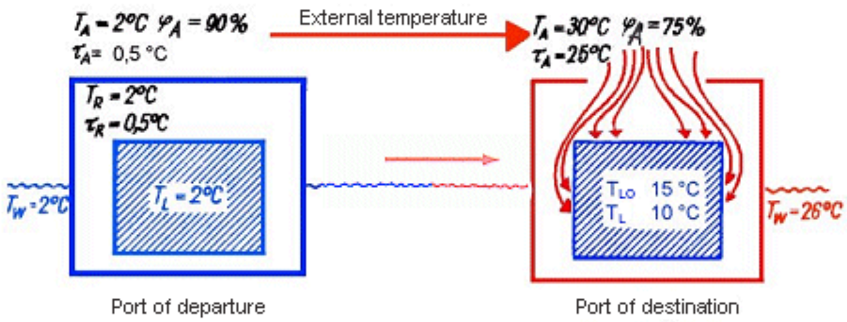

Figure A.1. Formation of cargo sweat as a result of transport from a temperate to a tropical environment (GDV, 2015)

The following test is a simulation of a trans-Pacific transport from the Pacific Northwest to East Asia including both land and sea transport. While this particular test is based off of data collected in container transport from Japan to Wilsonville, OR, it represents more generally conditions that would be present in a shipment from Pacific Northwest mill sites to East Asian docks. Figure A.2 shows a plot of the data used in this simulation.

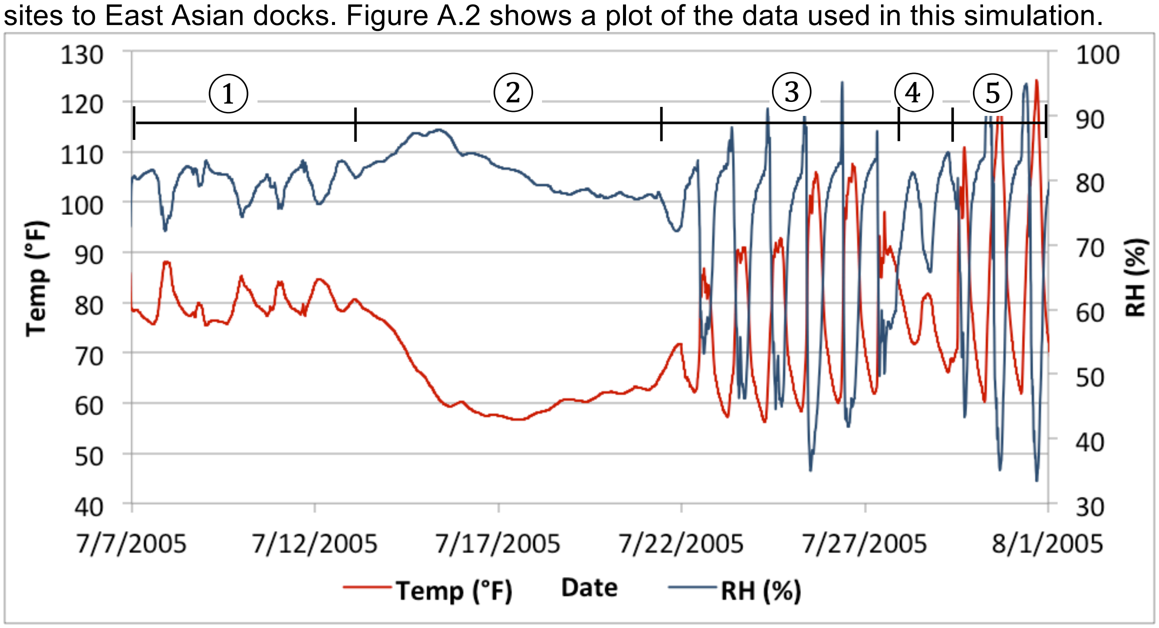

Figure A.2. Transport of a container in transit from Japan to Oregon (adapted from Leinberger, 2006). ① - Japan shipping yard ② - Ocean freight cargo hold ③ - Oregon shipping yard ④ - Freight truck to Wilsonville ⑤ - Wilsonville

The data used in this experiment has been reversed to simulate transit from the Pacific

Northwest to Japan. The data has also been standardized to a stepwise profile (two hour steps) to make programming in an environmental chamber possible (see Figure A.3).

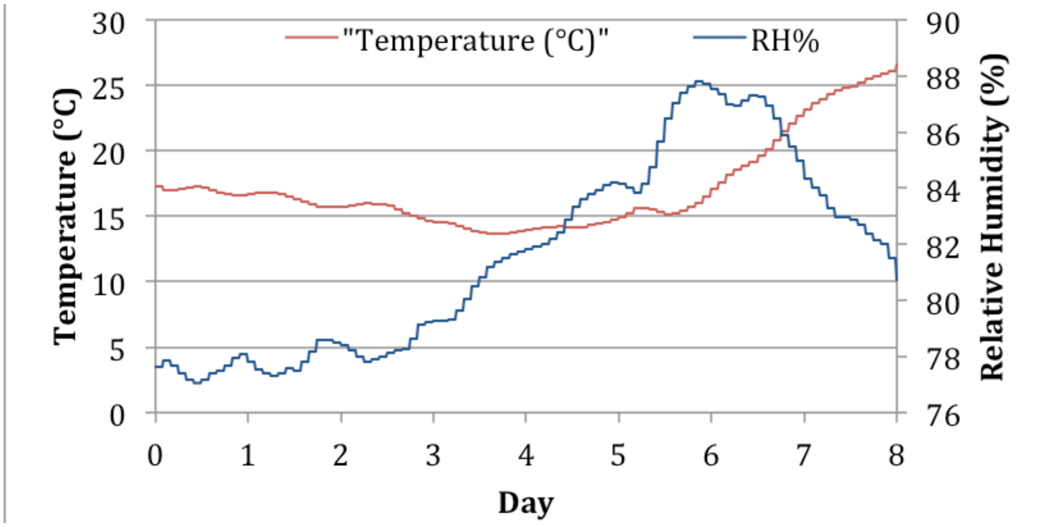

Figure A.3. Stepwise simulation of ocean freight transport from Port of Portland to Japan.

A.1 Required Items/Apparatus

The following items are required for this test:

- An environmental chamber capable of providing a range of temperatures from 15°C to 30°C and a range of humidity from 75% RH to 90% RH.
- Biomass samples, at least 10.0g each
- Non-absorbent trays (i.e., plastic) large enough to hold biomass samples and contain the sample if the sample disintegrates over time
- A digital scale, at least as precise as 0.1% of the sample size (i.e., if the sample is 100g, the scale must be precise to 0.1g)

In addition, the moisture content of the sample in question must be known. This can be done using a standard procedure for moisture content determination, such as EN14774-2.

A.2 Procedure

The following procedure should be used when performing this test:

1. Program the environmental chamber to perform the simulation based upon the stepwise temperature and relative humidity profile in Table 1 in the Appendix
2. Record the moisture content of the sample bricks
3. Weigh the sample(s) and record this initial weight
4. Place the samples on non-absorbent trays and place them in the environmental chamber

5. Begin the test
6. When the test is complete, immediately weigh the test samples

The procedure may be followed by mechanical durability testing, such as EN15210-1.

A.3 Temperature and Humidity Profile

The temperature and humidity profile for this test is shown in Table A.1.

Table A.1. Temperature and humidity profile for environmental chamber.

Hour	*Temp (°C)*	*RH %*	*Hour*	*Temp (°C)*	*RH %*
0	17.29	77.61	98	14.05	81.90
2	17.02	77.85	100	14.13	82.03
4	17.02	77.68	102	14.17	82.21
6	17.13	77.39	104	14.21	82.44
8	17.22	77.19	106	14.18	82.87
10	17.24	77.05	108	14.11	83.35
12	17.22	77.16	110	14.14	83.62
14	16.99	77.39	112	14.31	83.78
16	16.84	77.47	114	14.45	83.95
18	16.68	77.67	116	14.57	84.11
20	16.57	77.94	118	14.74	84.20
22	16.56	78.07	120	14.96	84.17
24	16.67	77.79	122	15.28	84.02
26	16.77	77.56	124	15.59	83.85
28	16.78	77.38	126	15.60	84.15
30	16.76	77.32	128	15.49	84.75
32	16.72	77.42	130	15.30	85.66
34	16.54	77.59	132	15.16	86.50
36	16.28	77.51	134	15.20	87.03
38	16.09	77.83	136	15.39	87.42
40	15.90	78.17	138	15.69	87.65
42	15.75	78.58	140	16.05	87.79
44	15.71	78.61	142	16.53	87.71
46	15.74	78.51	144	17.08	87.53
48	15.77	78.39	146	17.55	87.38
50	15.81	78.23	148	18.14	86.98
52	15.90	78.01	150	18.59	86.93
54	15.97	77.82	152	18.89	87.14
56	15.95	77.89	154	19.18	87.31
58	15.88	77.99	156	19.60	87.26
60	15.77	78.12	158	20.16	86.96
62	15.50	78.22	160	20.82	86.47
64	15.26	78.24	162	21.51	85.89
66	15.01	78.64	164	22.08	85.49
68	14.80	79.13	166	22.63	84.99
70	14.68	79.21	168	23.20	84.35
72	14.59	79.25	170	23.67	84.00
74	14.51	79.25	172	23.97	83.73
76	14.40	79.32	174	24.32	83.28
78	14.27	79.62	176	24.65	82.96
80	14.07	80.06	178	24.80	82.95
82	13.85	80.49	180	24.97	82.87
84	13.78	80.82	182	25.20	82.68
86	13.68	81.17	184	25.46	82.39

88	13.68	81.36	186	25.70	82.16
90	13.71	81.53	188	25.88	81.99
92	13.77	81.65	190	26.11	81.50
94	13.85	81.74	192	26.62	80.75
96	13.95	81.81	194	26.91	80.48

A.4 Calculations

Equation 1 can be used to determine the total (absolute) absorbed water:

$$WA = \frac{m_{wa} - m_{wi}}{m_{wi}} * 100 + WC_{or} \qquad (A.1)$$

where:

- WA = Absolute water absorption (%)
- m_{wa} = Mass of sample after absorption test (g)
- m_{wi} = Initial mass of sample (g)
- WC_{or} = Original water content (%)

A.5 Considerations

In many chambers, humidity control lags behind temperature. Therefore, it may be a good idea to bring the chamber to the initial temperature and humidity before placing the samples in the chamber.

Biomass samples should be removed immediately after the end of the test and weighed. Any additional tests should be performed as soon as possible after the test. Depending on the capabilities and precision of the environmental chamber's temperature/humidity control, steps listed in the Appendix can be combined and/or rounded.

A.6 Referenced Material

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EN15210-1, Solid biofuels – Determination of mechanical durability of pellets and briquettes, Part 1: Pellets

Leinberger, D. (2006). Temperature and humidity in ocean containers. <http://www.ista.org/forms/LEINBERGER_Dimensions06_paper.pdf>

APPENDIX B ABSORPTIVITY TEST

Briquettes were placed in the environmental chamber at 50C with 95% relative humidity. The mass of the briquettes was measured everyday. The test was complete when the briquette mass changed by less than 0.1% of the original mass between days.

The briquettes expanded as they gained moisture from the surrounding air. Pictures of the briquettes after removal from the environmental chamber are shown in Figure B.1.

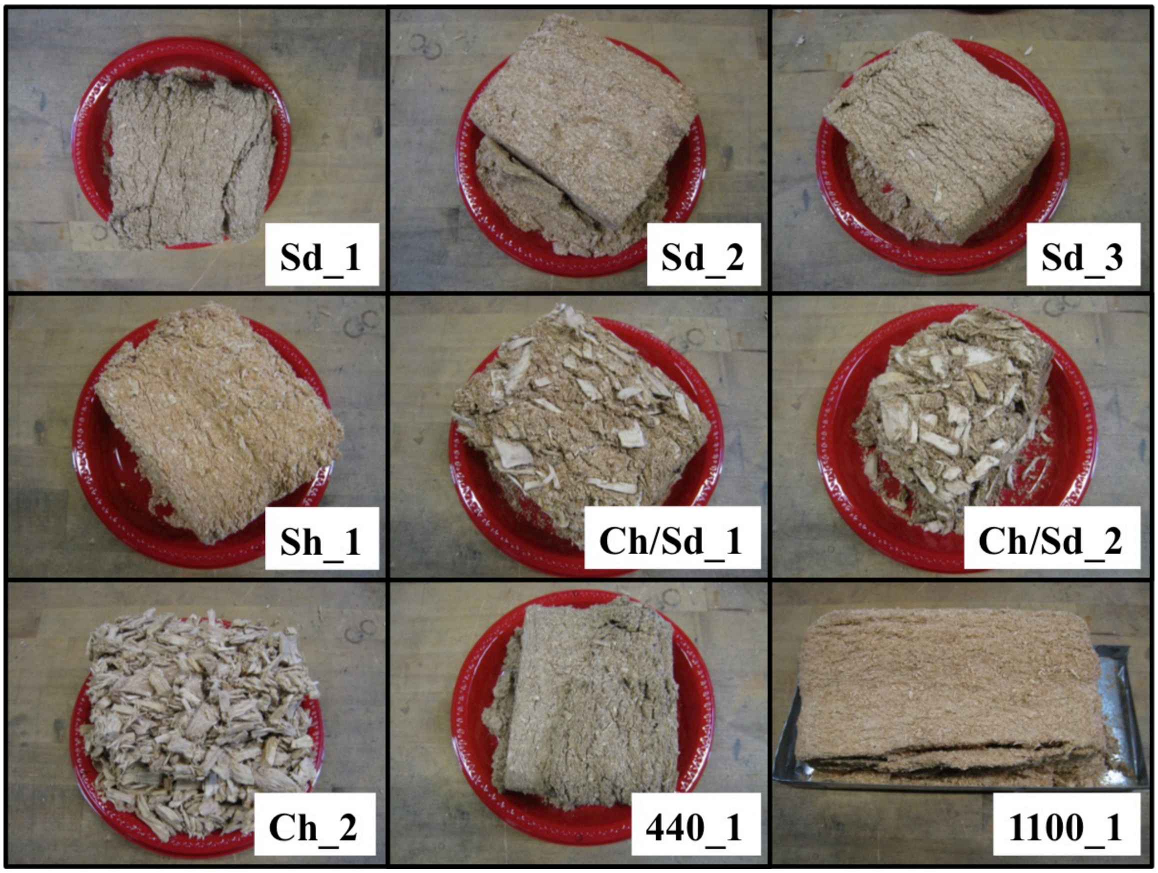

Figure B.1. Pictures of briquettes after absorptivity test.