

Compression Characteristics and Energy Requirement of Briquettes Made from a Mixture of Corn Stover and Peanut Shells

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Corn stover and peanut shells are both abundantly available biomass feedstocks in China. To determine the compression characteristics and energy requirement of briquettes, mixtures of the corn stover and peanut shells were compressed under three different pressures (30, 60, and 90 MPa) with three moisture contents (9%, 14%, and 19%, wet basis) and five corn stover-peanut shell mixtures (0%-100%, 25%-75%, 50%-50%, 75%-25%, and 100%-0%) by mass. The results showed that applied pressure, moisture content, and the corn stover-peanut shell mixture all significantly affected briquette density and specific energy consumption. The density of the briquette ranged from 646 to 1052 kg/m³ and the specific energy consumption varied from 6.6 to 25.1 MJ/t. A moisture content of 9% was found to be better for the compression of the corn stover and peanut shells mixture. Adding peanut shells to the corn stover improved briquette density and reduced the specific energy consumption. Linear models were developed to describe the briquette density and the specific energy consumption. The briquette durability ranged from 57% to 94% and durable briquettes can be obtained when corn stover and peanut shells are compressed with the mixing ratio of 1:1 (50%-50%) at moisture content of 9%.

Keywords: Biomass; Biomass mixture; Compression; Briquettes; Specific energy consumption; Durability

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INTRODUCTION

Agricultural residues are an abundant biomass feedstock in China (Chen *et al.* 2009). There is a great interest in using biomass solid fuel, such as pellets or briquettes (Liu *et al.* 2013). Corn and peanuts are widely planted in China, and their residues are available in large quantities. Biomass is very difficult to handle, transport, store, and utilize in its original form due to its high moisture content, irregular shape, size, and low bulk density (Kaliyan and Morey 2009a). Densification of biomass can improve its handling characteristics, enhance its volumetric calorific value, reduce transportation cost, and produce a uniform, clean, and stable fuel or an input for further refining processes (Granada *et al.* 2002). The bulk density of biomass can be increased from an initial bulk density of 40 to 200 kg/m³ to a final unit density of 600 to 1200 kg/m³ through densification (Adapa *et al.* 2009).

With a goal to obtain a uniform feedstock commodity with specific characteristics, pellet and briquette presses are commonly utilized systems for bioenergy applications (Tumuluru *et al.* 2011). Pellets have higher density and can be easily handled, stored, and transported long distances compared to briquettes or cubes (Lu *et al.* 2014). Biomass

briquettes have advantages for good combustion properties, low prices, and high productivity, which earns strong market competitiveness (Xia *et al.* 2014). Compared with pellet mills, briquetting machines can handle larger-sized particles and wider moisture contents without the addition of binders (Tumuluru *et al.* 2011). So biomass briquetting and its economic aspects were considered in this study.

The energy requirement for densification of biomass depends on the applied pressure, moisture content, physical properties of the material, and the method of compaction (Mani *et al.* 2004a). Mewes (1959) reported that the energy used to compress the biomass materials (straw and hay) was about 40% of the total energy consumption, while the remaining 60% was used for overcoming friction. Bellinger and McColly (1961) showed that the ejection energy for a circular die was up to 2 MJ/t (about 10% to 15% of total applied energy) when compressing alfalfa. O'Dogherty and Wheeler (1984) reported that the specific energy for wafer formation ranged from 11 to 24 MJ/t, and the energy required to eject briquettes from the die (diameter 25, 50, and 75 mm) was equal to 1% to 2% of the forming energy when compressing oilseed rape straw, barley straw, and wheat straw with particle size 28.9 and 63.8 mm. Shaw (2008) reported that the energy used to compress the grinds (poplar wood and wheat straw with particle size 0.29 to 1.37 mm) to pellets (die diameter 6.35 mm) was 95% to 99% of the total specific energy while 1% to 5% of the total specific energy was used to extrude them. The total specific energy was in the range of 12 to 30 MJ/t and a linear equation was obtained relating specific energy to pressure and moisture content in the compression of corn stover (particle size 5.6 mm) for briquettes (die diameter 30 mm) (Mani *et al.* 2006a). Adapa *et al.* (2007) developed new statistical models to describe the specific energy consumption of sun-cured and dehydrated alfalfa using multiple regressions. Adapa *et al.* (2009) studied the compaction characteristics of ground barley, canola, oats, and wheat straw and developed the best predictor equations to calculate the total specific energy required to manufacture pellets. Kashaninejad *et al.* (2014) reported that the total specific energy required for compression and ejection of pellets (die diameter 6.35 mm) varied from 4.35 to 33.64 MJ/t and increased with compressive load and particle size (less than 1 mm).

The strength and durability of densified products can be enhanced by mixing the base feed with a feed ingredient or biomass material that has high natural binding capacity (Kaliyan and Morey 2009a). Waelti and Dobie (1973) reported that the durability of rice straw cubes was improved from an initial 30% to 80% by blending in 15% to 20% of beet pulp or ground barley. Winowiski (1988) found that the durability of turkey breeder ration pellets increased from the range 32% to 45% up to 74% by adding 15% to 60% of wheat. Coates (2000) reported that cotton stalk could replace waste paper for mixing with pecan shells to make briquettes with reduced production costs. Ståhl and Berghel (2011) reported that the increase of rapeseed cake content in wood fuel pellets resulted in the decrease of the energy consumption, mechanical durability, and bulk density of the pellets. Mixing different biomass materials can optimize properties of biomass solid fuels (Liu *et al.* 2013).

Every year, the yield of peanut shells reaches as high as 5 million tons in China. Apart from a small portion of peanut shells used as animal feed and fuel, most of them were thrown away, resulting in a tremendous waste of resource (Liu and Sun 2010). In some Chinese provinces (Shandong, Hebei, Henan, Liaoning, and Sichuan), both corn and peanuts are planted (Chen 2013). Because of the inhomogeneous nature of biomass feedstock and harsh production environment, energy consumption of briquetting machine is high and the easy wear of the ring die will shorten its service life (Xia *et al.* 2014). As a method to improve briquette density, as well as to reduce energy consumption and wear on

the ring die of the briquetting machine in the compression of corn stover, this study attempted to compress peanut shells as a component of the mixture. In addition, there is no literature on the compression of a mixture of corn stover (CS) and peanut shells (PS). The objectives of this study were: (a) to investigate the effects of applied pressure, moisture, and CS content of CS-PS mixture on the density, energy requirement, and durability of the briquettes; and (b) to determine the density and the specific energy models for the densification of the CS-PS mixture.

EXPERIMENTAL

Materials

Corn (*Zea mays* L.) stover and peanut (*Arachis hypogaea* L.) shells were acquired in August 2013 from a farm in Guan, Hebei, China (latitude 39° 28' North, longitude 116° 18' East). Figure 1 shows the raw CS and PS materials used in the experiments. CS samples were collected after being sun-dried for four months in the field and then chopped in a chopper (Jinkeyuan Machinery, China) to pass through a screen size of 12 mm before briquetting. Further reduction of CS particle size would be costly and is only required for the pelleting system. PS samples were sun-dried for about five months in the field. PS samples were not ground before briquetting, as the particle size of PS was suitable for compression. All materials were placed in plastic bags and transported to China Agricultural University (Beijing, China). The initial moisture contents of CS and PS were 6.65% and 7.30% (w.b.), respectively, measured according to ASABE standard S358.2 (ASABE 2006a) in three replicates. The samples were dried in a drying oven (Zygc Co., China) at 103 °C for 24 h. The moisture content was calculated using Eq. 1,

$$MC = \frac{m_0 - m_1}{m_0} \quad (1)$$

where MC is the moisture content (% w.b.), m_0 is the initial mass of samples (g), and m_1 is the mass of samples (g) after drying.



Fig. 1. Raw CS and PS materials used in the experiments

The CS and PS samples were wetted by spraying a predetermined amount of distilled water to adjust the moisture contents to 9%, 14%, and 19% and kept for 48 h at 5 °C. Before compression, five CS-PS mixtures (0%-100%, 25%-75%, 50%-50%, 75%-25%, and 100%-0% by mass) were prepared at three moisture content levels of 9%, 14%, and 19% w.b. For each experiment, about 7 g of the biomass sample was prepared when CS and PS were mixed by mass. The biomass samples were stirred so that they became well mixed. Then, prepared biomass samples were stored in zip-lock plastic bags at 5 °C for storage. The material was brought to room temperature before briquetting.

Methods

Bulk density and particle size

The bulk densities of chopped CS and PS were measured with a one-liter volume cube container with each edge 100 mm in length. The container was carefully filled with biomass sample, and the excess biomass grinds were removed by passing a roller over the container in a zig-zag pattern. Then the sample mass was measured on an electronic scale (Ohaus Co., China). The mass per volume gave the bulk density of the biomass samples in kg/m³. The particle sizes of PS and chopped CS before briquetting were determined by ASABE standard S424.1 DEC 01 (ASABE 2006b). A set of sieves with different opening dimensions (19.00, 12.70, 6.30, 3.96, and 1.17 mm) from top to bottom and a bottom pan were used for the test. A sample of 10 L was placed into the top screen and was sieved for 120 sec. The mass of material retained on each screen and bottom pan was weighed and recorded. The geometric mean sizes of the samples were calculated. Particle size analysis was replicated 3 times.

Chemical composition

The chemical composition analysis of CS and PS was performed by Laboratory of Biomass and Bioprocessing Engineering, China Agricultural University, Beijing, China. Protein, crude fat, acid detergent fiber (ADF), neutral detergent fiber (NDF), acid detergent lignin (ADL), and total ash were determined. The protein contents of CS and PS were determined according to the Association of Official Analytical Chemists (AOAC) standard method 2001.11 (AOAC 2001) with the nitrogen content multiplied by a factor 6.25. Crude fat was determined using the AOAC standard method 920.29 (AOAC 1990a). ADF and lignin were determined according to AOAC standard method 973.18 (AOAC 1990b), whereas NDF was determined according to AOAC standard method 992.16 (AOAC 1990c). The total ash content was determined according to AOAC standard method 942.05 (AOAC 1990d). The percentage of cellulose is calculated indirectly from percentage ADF and lignin (%ADF minus %lignin) (Mani *et al.* 2006b). The percentage of hemicellulose is calculated indirectly from percentage NDF and ADF (% NDF minus %ADF) (Mani *et al.* 2006b). The chemical composition analysis was repeated twice.

Experimental apparatus

A Suns universal testing machine (Suns Co., China, host power 1.5 kw) was used to provide the mechanical pressure (30 ± 0.08 MPa, 60 ± 0.15 MPa, 90 ± 0.28 MPa) required for compressing the biomass samples. The Suns universal testing machine was controlled by a computer loaded with Testworks software (Suns Co., China). The experimental apparatus (Fig. 2) was designed for compression and ejection of briquettes with reference to a previous study (Kaliyan and Morey 2009b).

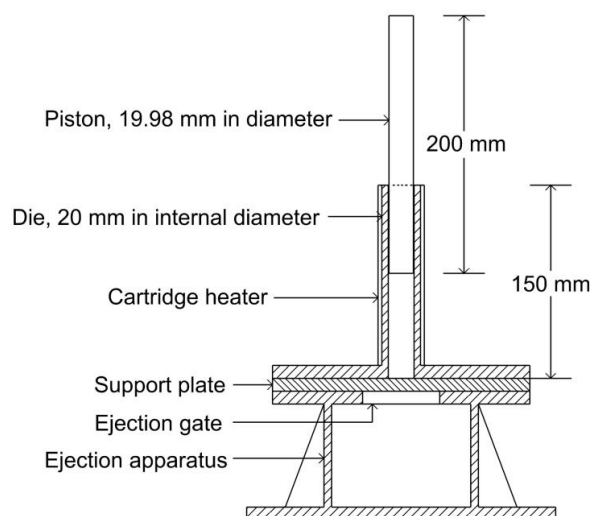


Fig. 2. Experimental apparatus used for compressing corn stover-peanut shell mixtures into briquettes

The inner diameter and length of the cylindrical die were 20 mm and 150 mm. The diameter and length of the piston were 19.98 mm and 200 mm, respectively. The support plate was placed between the cylindrical die and the ejection apparatus. An opening was designed on the upper surface of the ejection apparatus for ejecting briquettes. The ejection apparatus was placed on the base plate of the Suns machine. The support plate acted as a base plate for briquetting and allowed the piston to move straight down without lateral movement during the compression process. The cylinder die was wrapped with a cartridge heater that maintained the temperature to simulate frictional heating and soften the feedstock helping to bind of ground material. The temperature of the die was measured and controlled by a T-type thermocouple and a temperature controller. The T-type thermocouple, inserted in the cartridge heater and connected to the outer surface of the cylinder, was linked to the temperature controller which controlled the heater (Shaw 2008).

Experimental design and compression test

The present experiment trails were designed according to the following combination of conditions: (1) three preset pressures of 30, 60, and 90 MPa; (2) three moisture contents of biomass samples of 9%, 14%, and 19% w.b.; and (3) five CS-PS mixtures of 0%-100%, 25%-75%, 50%-50%, 75%-25%, and 100%-0% by mass. The briquetting process was replicated ten times for each sample.

The experimental apparatus was used to make briquettes in one stroke of the piston. In order to simulate frictional heating during industrial briquetting operation, the cylinder die was heated to $90\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$ (Adapa *et al.* 2007). About 7 g of the biomass sample was loaded into the cylindrical die each time. The speed of the piston was set at 50 mm/min. After compression, the piston was stopped and held in position for 60 sec (Kashaninejad *et al.* 2014). Then the support plate was removed and the briquette was ejected through the hole of the ejection apparatus by using the piston with a speed 50 mm/min. The force-displacement curves were logged in the computer connected with the Suns universal testing machine. The mass, diameter, and length of each briquette were measured immediately after ejection to calculate its density. Mass was weighed using an electronic balance (Ohaus

Co., China). Diameter and length of each briquette were measured using an electronic caliper (Forgestar Co., China) to calculate its volume. Density was equated to the measured mass divided by volume.

Specific energy requirement

Specific energy is defined as the energy used to produce one unit (by mass) of briquette. Specific energy, which includes compression and ejection energy for making briquettes, was determined from force-displacement data. The force-displacement data were obtained from the sensors of the universal testing machine, and the area under the force-displacement curve was integrated using the trapezoidal rule and expressed in MJ/t (Adapa *et al.* 2007). Specific energy values were calculated from ten pressure-displacement datasets for each combination of condition.

Durability

The durability rating of briquettes was measured after four weeks of storage in zip-lock plastic bags at room temperature ($21\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$). A durability tester was developed at China Agricultural University for testing briquettes according to ASABE standard S269.4 (ASABE 2007). The durability test was not replicated due to lack of samples.

Statistical analysis

Statistical analysis was conducted by using SPSS 20.0 (SPSS, USA). The Duncan multiple range test (DMRT) was performed to determine the effects of applied pressure, moisture content, and CS content at a 5% significance level (Gomez and Gomez 1984). Three DMRTs were performed.

In the first DMRT analysis, treatment means for different CS-PS mixtures at the same moisture content and applied pressure were compared and the differences were presented.

In the second DMRT analysis, treatment means for different pressures at the same CS-PS mixture and moisture content were compared and the differences were presented. The third DMRT analysis was performed for different moisture contents at the same applied pressure, and CS-PS mixture and the differences were presented.

RESULTS AND DISCUSSION

Physical Properties and Briquette Density

The geometric mean sizes and bulk densities of CS and PS are shown in Table 1. Both the geometric mean sizes and bulk densities of PS are higher than CS.

The particle size distributions of CS and PS samples are shown in Fig. 3. Skewnesses were found in the distributions of the particle size of CS and PS samples. Similar results have been reported for alfalfa, wheat straw, barley straw, corn stover, and peanut hulls grinds (Mani *et al.* 2004b; Yang *et al.* 1996; Fasina 2008). Forty-two percent (42%) and twenty-seven percent (27%) of CS samples were retained on the screens with opening dimensions of 3.96 and 1.17 mm, respectively. Sixty-four percent (64%) of PS samples was retained on the screen with opening dimensions of 6.30 mm, which could be caused by the shape of PS.

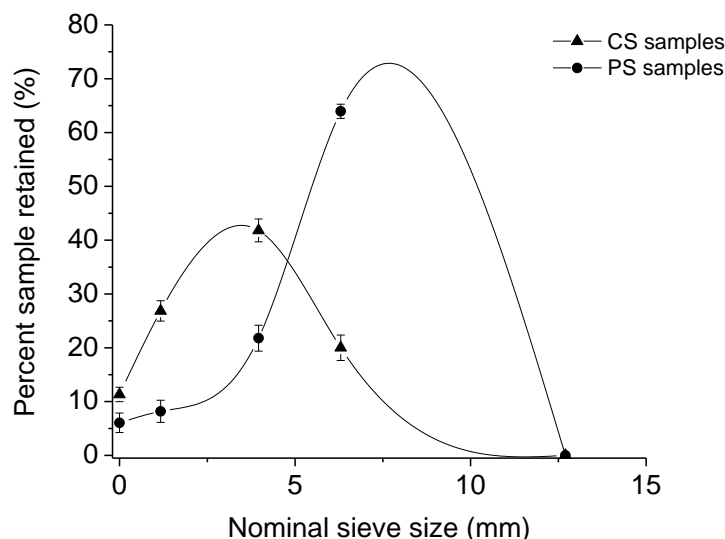


Fig. 3. Particle size distributions of CS and PS samples

Table 1. Geometric Particle Mean Size and Bulk Density of Corn Stover and Peanut Shells

Biomass	Geometric mean size (mm)	Bulk density (kg/m ³)
Corn stover	4.96 (1.88) ^a	63.3 (1.4) ^a
Peanut shells	8.38 (2.04)	85.5 (2.8)

^a Numbers in the parenthesis are standard deviations for n = 3.

Chemical Composition

The chemical composition of CS and PS samples for tests is presented in Table 2. CS samples had more cellulose and hemi-cellulose than PS samples. The content of crude fat of PS (3.90%) was significantly higher than that of CS (0.31%). Also, PS showed higher protein (7.76%), lignin (29.26%), and ash (7.17%) compared with CS.

Table 2. The Chemical Composition of Corn Stover and Peanut Shells for Tests

Biomass	Protein, % DM ^a	Crude fat, % DM	Lignin ^b , % DM	Cellulose ^c , % DM	Hemi- cellulose ^d , DM	Ash, % DM
Corn stover	5.05 (0.05) ^e	0.31 (0.02)	19.48 (0.16)	37.64 (0.49)	35.87 (0.20)	5.85 (0.12)
Peanut shells	7.76 (0.18)	3.90 (0.03)	29.26 (0.31)	29.73 (0.16)	25.77 (0.09)	7.17 (0.15)

^a DM - dry matter

^b Lignin values measured in this study were total lignin in the biomass materials.

^c The percentage of cellulose is calculated indirectly from percentage ADF and lignin (%ADF minus %lignin) (Mani *et al.* 2006b).

^d The percentage of hemicellulose is calculated indirectly from percentage NDF and ADF (%NDF minus %ADF) (Mani *et al.* 2006b).

^e two repetitions

Among the chemical components, protein and lignin may enhance binding characteristics of biomass briquettes. Protein is heated during the densification process and acts as a binder, which improves the strength of briquettes (Tumuluru *et al.* 2011). Lignin softens and helps the binding process at elevated temperatures and pressures. Lignin has a low melting point of around 140 °C (van Dam *et al.* 2004). Fat acts as a lubricant between the biomass particles, and between the biomass and the die-wall (Kaliyan and Morey 2009a). However, high fat content can hinder binding. Cavalcanti (2004) reported that fat content beyond 6.5% was deleterious to pellet durability.



Fig. 4. Briquettes made under 60 MPa in the CS content of 50% at moisture content of 9%

Briquettes were about 21 mm in diameter and 20 to 30 mm in length. Figure 4 shows the briquettes made under 60 MPa in the CS content of 50% at moisture content of 9%. The briquette density ranged from 646 to 1052 kg/m³ after preparation under different experimental conditions. Figure 5 shows the effect of CS content on briquette density at different applied pressures when biomass moisture content was 9%. The density of the briquettes significantly increased as the applied pressure was increased from 30 MPa to 60 MPa.

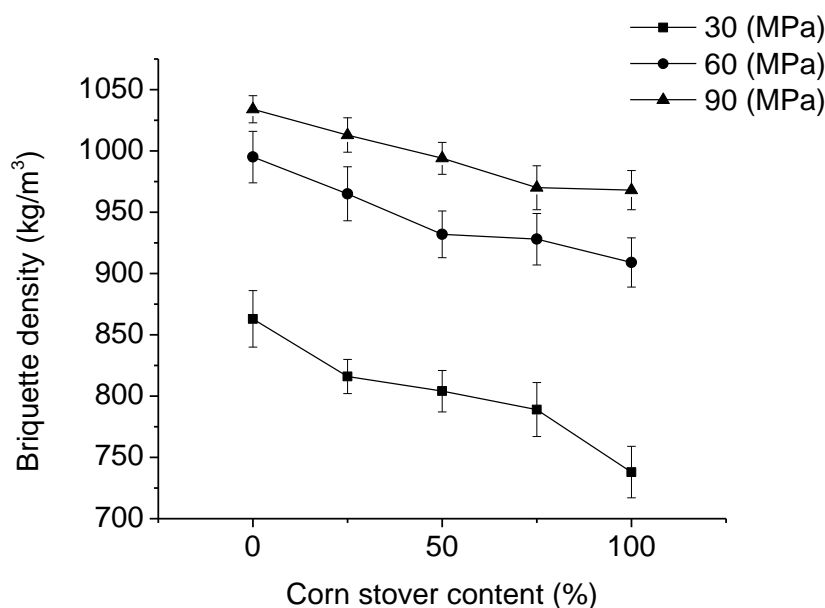


Fig. 5. Effect of corn stover content on the density of corn stover-peanut shell briquettes under three applied pressures and biomass moisture content of 9%

When the applied pressure was increased from 60 MPa to 90 MPa, the increase of briquette density was slight, which indicated that CS-PS mixture could be easily compressed at low pressures. Mani *et al.* (2006b) reported that the density of corn stover pellets reached magnitudes close to the initial density of the component particles at low pressures (31.1 to 93.3 MPa). CS content of CS-PS mixture had a negative effect on the briquette density. This indicated that PS was easier to compress than CS because PS had higher protein and lignin than CS. Protein and lignin helped to binding characteristics of biomass briquettes. Therefore, adding PS to CS could increase the CS briquette density. However, when the moisture content reaches 14% and 19%, the density of the briquettes did not show significant differences under the applied pressures of 60 MPa and 90 MPa, according to the DMRT results (data not shown in tables or figures). Mani *et al.* (2006a) compressed corn stover to make briquettes and reported that the briquette density did not show significant differences when the applied pressure increased from 5 MPa to 15 MPa at the moisture content of 15%.

Figure 6 shows the effect of CS content on the briquette density at different biomass moisture contents at an applied pressure of 60 MPa. The density of briquettes significantly decreased as moisture content was increased from 9% to 19%. The briquette density showed a declining trend as the CS content was increased in the CS-PS mixture. Some previous studies also found that the density of the densified product decreased with increasing moisture content (Gustafson and Kjelgaard 1963; Mani *et al.* 2006a; Kaliyan and Morey 2009b). Therefore, compared with 14% and 19% moisture content, a moisture content of 9% was judged to be better for the compression of the CS and PS mixture. The result showed that the effects of applied pressure, moisture content, and CS content on the briquette density of the CS-PS mixture were significant.

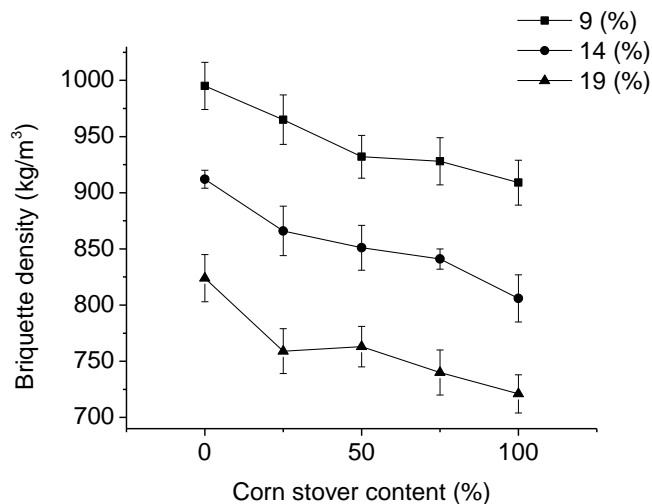


Fig. 6. Effect of corn stover content on the density of corn stover-peanut shell briquettes under three biomass moisture contents and applied pressure of 60 MPa

At moisture contents of 14% and 19%, some surface cracks were observed on the briquettes. Smith *et al.* (1977) and Mani *et al.* (2006a) found similar results when compressing wheat straw and corn stover. It could clearly be observed that the properties of briquettes compressed at high moisture contents were not stable. Water from high moisture content briquettes evaporated after the briquetting process creating surface cracks.

Specific Energy Consumption

The total specific energy consumption includes compression and ejection energy consumption. Table 3 shows the specific energy required for compressing biomass samples into briquettes at different experimental conditions. The total specific energy consumption ranged from 6.6 to 25.1 MJ/t. The specific ejection energy required to overcome friction ranged from 0.1 to 0.7 MJ/t, which accounted for 0.9 % to 4.9 % of the total specific energy consumption.

The percentage of specific ejection energy in this study was similar to the results observed by Kashaninejad (2014) in single pelleting experiments of varieties of ground wheat straw (die heated to 90 °C ± 1 °C) and Adapa (2009) in single pelleting experiments of various ground biomass samples (die heated to 95 °C ± 1 °C), while significantly lower than the results by Mani *et al.* (2006a) for briquetting corn stover (die not heated). The explanation for this could be that the friction between the die surface and biomass samples was reduced by preheating the die surface.

The DMRT results showed that moisture content and pressure had significant effects on the total specific energy consumption. The total specific energy consumption was increased significantly as the applied pressure was increased, and it decreased with the increase of moisture content. Mani *et al.* (2006a) also reported that an increase in moisture content decreased the total specific energy consumption in the compression corn stover. The DMRT results showed that changes in the CS from 25% to 75% varied slightly and the difference among CS 0%, CS (25% to 75%), and CS 100% was significant relative to the total specific energy consumption.

The results indicated that the CS content of the CS-PS mixture had a positive effect on the total specific energy consumption. Also, the ejection energy was significantly higher when the CS content was 100% compared to other CS contents. The explanation for these could be that the content of crude fat of PS (3.90%) was significantly higher than that of CS (0.31%). Fat acted as a lubricant during densification, which reduced the friction between biomass and die-wall. Therefore, higher PS content relative to the CS content to make briquettes could reduce the total specific energy consumption.

Model Analysis for Briquette Density and Specific Energy Consumption

Multiple linear regression analysis was used to analyze the relationship between the briquette density and the variables, the specific energy consumption, and the variables, respectively. The briquette density (BD) and the total specific energy consumption (E) were regarded as the dependent variables while applied pressure (P), moisture content (m), and CS content (c), their two-way interaction ($P * m$, $P * c$, $m * c$), and three-way interaction ($P * m * c$) were regarded as independent variables. A type I error rate of 5% was set for all analyses. The highest coefficients of determination (R^2) were used to choose among the possible regression models. The regression model was,

$$X = \beta_0 + \beta_1 P + \beta_2 m + \beta_3 c + \beta_4 P*m + \beta_5 P*c + \beta_6 m*c + \beta_7 P*m*c \quad (2)$$

where X is the briquette density in kg/m³ or the total specific energy consumption in MJ/t, P is the applied pressure in MPa, m is the moisture content in % wet basis, and c is the CS content in percent in the CS-PS mixture.

Table 3. Compression Specific Energy Consumption and Total Specific Energy Consumption during Briquetting of Corn Stover and Peanut Shell Mixture at Different Experimental Conditions

Moisture content (% w.b.)	Pressure (MPa)	Corn stover content (%)	Compression specific energy consumption ^{a, b} (MJ/t)		Total specific energy consumption ^{a, b} (MJ/t)	
9	30	0	9.86	±0.63aAD	10.11	±0.62aAD
		25	11.67	±0.50bAD	11.93	±0.50bAD
		50	11.92	±0.60bAD	12.16	±0.64bAD
		75	11.92	±0.61bAD	12.15	±0.61bAD
		100	14.51	±0.35cAD	15.23	±0.40cAD
	60	0	16.03	±0.64aBD	16.35	±0.66aBD
		25	17.03	±0.61bBD	17.30	±0.58bBD
		50	17.81	±0.60bBD	18.04	±0.63bBD
		75	17.28	±0.41bBD	17.52	±0.41bBD
		100	20.24	±0.63cBD	20.84	±0.79cBD
	90	0	21.92	±0.58aCD	22.25	±0.57aCD
		25	20.83	±0.54bCD	21.13	±0.56bCD
		50	22.10	±0.54aCD	22.36	±0.54aCD
		75	22.02	±0.55aCD	22.22	±0.48aCD
		100	24.19	±0.57cCD	24.52	±0.62cCD
14	30	0	8.58	±0.35aAE	8.76	±0.36aAE
		25	8.81	±0.70abAE	8.97	±0.74abAE
		50	9.12	±0.42bcAE	9.28	±0.43bcAE
		75	9.54	±0.60cdAE	9.74	±0.62cdAE
		100	9.69	±0.38dAE	10.03	±0.46dAE
	60	0	12.26	±0.50aBE	12.45	±0.51aBE
		25	13.65	±0.38bBE	13.83	±0.40bBE
		50	12.26	±0.48aBE	12.38	±0.48aBE
		75	13.90	±0.39bBE	14.13	±0.39bBE
		100	14.83	±0.24cBE	15.25	±0.23cBE
	90	0	15.57	±0.12aCE	15.73	±0.06aCE
		25	17.98	±0.66bCE	18.18	±0.71bCE
		50	17.63	±0.63bCE	17.80	±0.67bCE
		75	17.42	±0.44bCE	17.63	±0.49bCE
		100	18.66	±0.59cCE	19.18	±0.63cCE
19	30	0	7.10	±0.68aAF	7.28	±0.69aAF
		25	8.29	±0.54bAF	8.48	±0.54bAF
		50	7.61	±0.60aAF	7.73	±0.61aAF
		75	7.97	±0.49bAF	8.13	±0.50bAF
		100	8.19	±0.33bAF	8.50	±0.37bAF
	60	0	9.47	±0.84aBF	9.61	±0.82aBF
		25	12.22	±0.66bBF	12.38	±0.63bBF
		50	10.62	±0.73cBF	10.73	±0.73cBF
		75	11.84	±0.52bBF	12.01	±0.56bBF
		100	11.69	±0.48bBF	12.07	±0.45bBF
	90	0	13.34	±0.35aCF	13.56	±0.34aCF
		25	16.68	±0.75bCF	16.88	±0.71bCF
		50	14.36	±0.69cCF	14.50	±0.71cCF
		75	14.92	±0.36dCF	15.09	±0.38dCF
		100	15.37	±0.47eCF	15.85	±0.51eCF

^a 10 replicates.^b 95% confidence interval; Duncan multiple range test at 5% level of significance for corn stover content at the same moisture content and pressure (a, b, c, d, and e); for pressure at the same corn stover content and moisture content (A, B, and C); for moisture content at the same corn stover content and pressure (D, E, and F).

Stepwise regression analysis was performed to remove the independent variables that were not significant. Also, analysis of residuals was performed to test the assumptions for regression analyses. Potential outliers in the data were tested, and were removed from following analyses once identified.

The result of stepwise regression analysis for the briquette density showed that $P * c$, $m * c$, and $P * m * c$ were not significant. The final regression equation ($R^2 = 0.921$) obtained was:

$$BD = 808.186 + 4.993P - 3.910m - 0.831c - 0.214P*m \quad (3)$$

From Eq. 3, it can be seen that the applied pressure (P) had a positive effect on briquette density, while the moisture content (m), CS content (c), and the interaction term ($P * m$) had negative effects on briquette density. The magnitude of applied pressure (P) and moisture content (m) effect was significantly higher than the magnitude of CS content (c) and the interaction term ($P * m$).

For the total specific energy consumption, the results of stepwise regression analysis showed that $P * c$ and $P * m * c$ were not significant. The final regression equation ($R^2 = 0.950$) obtained was:

$$E = 7.032 + 0.216 P - 0.178m + 0.053c - 0.005 P *m - 0.002m*c \quad (4)$$

From Eq. 4, it can be seen that the applied pressure (P) and the CS content (c) had positive effects on the total specific energy consumption, while the moisture content (m), the interaction term ($P * m$), and the interaction term ($m * c$) had negative effects on total specific energy consumption. The magnitude of the interaction term ($P * m$) and the interaction term ($m * c$) was significantly lower than other main effects.

A test of residuals indicated that the distribution followed normal distributions for the complete group of residuals for both briquette density and total specific energy consumption. No outliers were identified using Lund's critical value (3.40) for briquette density and total specific energy consumption (Lund *et al.* 1975). No outliers were detected. No co-linearity was detected for the independent variables, according to the variance inflation factor and condition index.

Durability

The briquette durability ranged from 57% to 94% in the present study. Figure 7 shows the effect of applied pressure on the briquette durability under different CS contents at the moisture content of 9 %. The briquette durability significantly increased as the applied pressure increased from 30 to 60 MPa. However, when the applied pressure increased from 60 to 90 MPa, the increasing rate of briquette durability decreased with the change of CS content from 100% to 0%. The explanation for this could be that PS was more easily compressed to durable a briquette product than CS.

Figure 8 shows the effect of CS content on the briquette durability under different applied pressures at a moisture content of 9%. Durable briquettes were obtained when the CS content was between 0% and 50% under 60 and 90 MPa. For different CS contents, the chemical composition was different. Mani *et al.* (2006a) concluded that an optimal moisture content exists for each biomass feedstock to produce briquettes with high density and strength. Each CS content of samples has its own optimal moisture content for compression. So biomass samples with various CS contents showed different properties under densification process, which resulted irregular changes in durability. A mixing ratio

1:1 is a good combination of CS-PS mixture for compression at the moisture content of 9%. Liu *et al.* (2013) reported that pellet durability first increased and then decreased with the increase in rice straw content of the mixture (bamboo-rice straw), reaching the maximum durability (99.03%) in mixing ratio 2:3 of bamboo and rice straw.

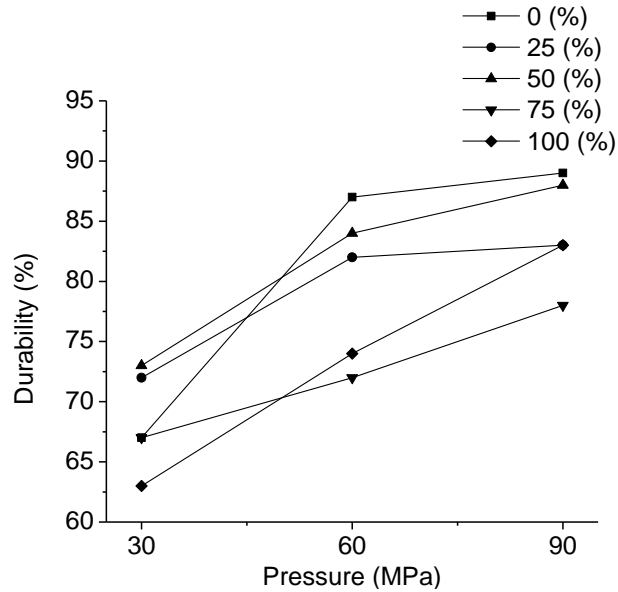


Fig. 7. Effect of applied pressure on the durability of corn stover-peanut shells briquettes at five corn stover contents and biomass moisture content of 9% (durability test was not replicated due to lack of samples)

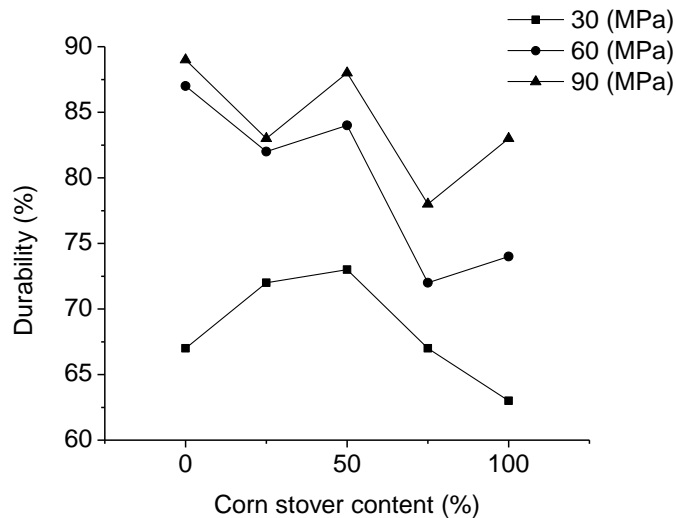


Fig. 8. Effect of corn stover content on the durability of corn stover-peanut shell briquettes at three applied pressures and biomass moisture content of 9 % (durability test was not replicated due to lack of samples)

The durability of briquettes varied from CS content 0% to 100%. Figure 9 shows the relationship between the briquette durability and the moisture content at different CS contents at applied pressure of 90 MPa. When the CS content was 0%, the briquette durability initially increased with moisture content and then decreased upon reaching the maximum moisture content of 14%. As the CS content was increased from 25% to 75%, the briquette durability initially decreased from moisture content of 9% to 14% and then

increased from a moisture content of 14% to 19%. Coates (2000) also reported that higher moisture contents (15% to 20%) produced more durable compacts for cotton plant residues. Kaliyan and Morey (2009b) reported that the higher activation of natural binders at higher moisture contents might have enhanced the binding of particles in corn stover, resulting in higher briquette durability. At the CS content of 100%, the briquette durability decreased with the increase in moisture content, having the maximum durability at a moisture content of 9%. Mani *et al.* (2006a) found that a high briquette durability was obtained at low moisture content (5%, 10%) when compressing corn stover to make briquettes. Therefore, for different CS contents, there are different optimal moisture contents for the briquette durability. The optimal moisture content for PS is higher than that for CS. This finding indicated that applied pressure and moisture content had significant effects on the durability of briquettes made from the CS-PS mixture. The durability of briquettes varied under different mixing ratios of the CS-PS mixture. A mixing ratio of 1:1 of the CS-PS mixture at a moisture content of 9%, compared to 14% and 19%, was judged to be the optimal combination necessary to make good quality briquettes.

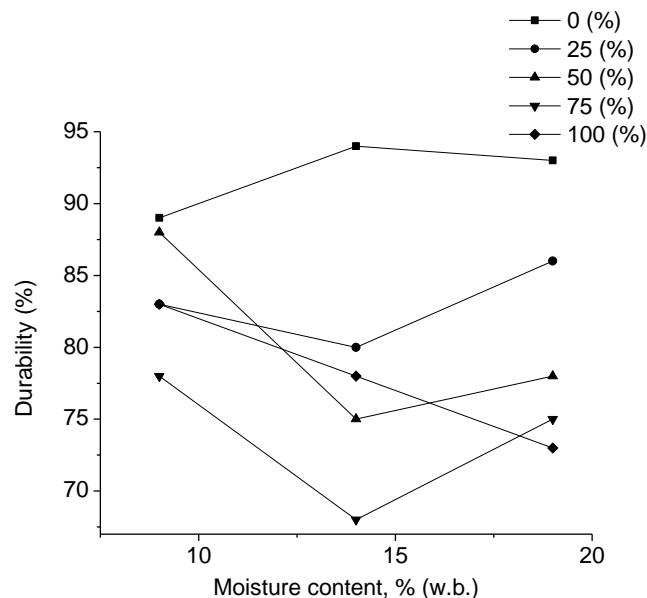


Fig. 9. Effect of moisture content on the durability of corn stover-peanut shell briquettes at four corn stover contents and applied pressure of 90 MPa (durability test was not replicated due to lack of samples)

CONCLUSIONS

1. The density of the briquettes increased as the PS content of the CS-PS mixture increased.
2. The total specific energy consumption increased as the applied pressure increased, and decreased with the increase of moisture content. The total specific energy consumption also increased as the CS content of the CS-PS mixture increased.
3. Adding PS to CS improved briquette density and reduced the specific energy consumption.
4. Linear models were developed to describe the briquette density and the specific energy

consumption of compressing the CS-PS mixture. The resulting R^2 for briquette density and specific energy consumption were 0.921 and 0.950, respectively.

5. A mixing ratio of 1:1 of the CS-PS mixture at a moisture content of 9% compared to 14% and 19% is optimal combination necessary to make good quality briquettes.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the funding provided by the Special Fund for Agro-scientific Research in the Public Interest (201203024) and China Agriculture Research System (CARS-35).

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Article submitted: March 20, 2015; Peer review completed: May 22, 2014; Revised version received and accepted: July 9, 2015; Accepted: July 13, 2015; Published: July 20, 2015.

DOI: 10.15376/biores.10.3.5515-5531