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Important properties of bamboo pellets to be used as commercial solid fuel in China

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Abstract Bamboo is a type of biomass material and has great potential as a bio-energy resource of the future in China. Some properties of bamboo pellets, length, diameter, moisture content (MC), particle density, bulk density, durability, fine content, ash, gross calorific value, combustion rate and heat release rate, were determined and the effects of MC and particle size (PS) on these properties were investigated in this research. The results showed that bamboo pellets will be the proposed new biomass solid fuel and have the potential to be developed as commercial pellets. All properties of bamboo pellets met the requirement of *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified Fuel*. The gross calorific value of bamboo pellets also met the minimum requirement for making commercial pellets according to DIN 51731 (>17,500 J/g). The effects of MC on length, diameter, MC, particle density and bulk density were significant at $p = 0.05$. There were no significant differences between PS and all properties of bamboo pellets. Due to higher MC and larger PS, bamboo pellets exhibited higher combustion rates and heat release rates. This research represents an initial stage in the study of bamboo pellets, and its objectives provide guidelines for further research.

Introduction

Biomass is a main type of energy resource in the world, especially in developing countries. It is confirmed that biomass has several disadvantages when it is directly

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fired, such as relatively low heating value per unit volume, large volume or area required for storage and economic problems associated with transportation and distribution (Werther et al. 2000). These problems are attributed to the low bulk density of raw materials. Biomass materials can be compressed into pellets depending on the conversion technology used (Cattaneo 2003). Densification into pellets reduces material waste and improves its bulk density (Adapa et al. 2006).

In recent years, biomass pellets have been widely studied around the world. Carone et al. (2011) investigated the influence of the main process parameters and biomass characteristics on some mechanical properties (density and durability) of olive tree pruning residues pellets. It was found that temperature was the most important factor for the mechanical properties of pellets, followed by the initial moisture content (MC) and the particle size (PS) of the raw material. Olsson (2006) determined specific organic compounds from five sequential combustion stages for incomplete combustion of straw and peat/wood pellets on a laboratory scale and compared them to those from softwood pellets. Rhena et al. (2007) investigated the effect of raw material composition in woody biomass pellets on combustion characteristics and found that the combustion time for a single pellet mostly depended on the raw material composition and to a minor extent on the density. Obernberger and Thek (2004) analyzed physical characterization and chemical composition of densified biomass fuels with regard to their combustion behavior. Baernthaler et al. (2006) determined major and minor ash-forming elements in solid biofuels.

Bamboo is a type of biomass material and has been widely cultivated in the west and south of China. Currently, bamboo resources are very abundant. The total area of bamboo is about 5 million ha and that of moso bamboo (*Phyllostachys heterocycla*) is about 3 million ha in China (Jiang 2002). Annual yield of moso bamboo is about 18 million tons, and it is widely used to produce furniture, flooring and interior decoration materials. Bamboo, like wood and agricultural residue, is mainly composed of cellulose, hemicelluloses and lignin, even though the contents of these compositions are different. Table 1 shows the difference of wood, bamboo and agricultural residue (Yao et al. 2008). It has great potential as a pellet resource of the future in China due to abundant resources and rapid growth. To date, little research on bamboo pellets is available. During the densification process of biomass pellet production, the MC and PS of the materials are considered as two main factors of pellet properties. It was found that most physical properties of biomass pellets are significantly affected by MC and PS of the materials (Dick et al. 2007). This study was therefore carried out to determine properties of bamboo pellets, which were manufactured using different MC and PS. The results from this research are very helpful to analyze the effect of MC and PS on the properties of bamboo pellets and provide guidelines for further research.

Materials and methods

Materials

Moso bamboo (4 years old) was used in this study, which was taken from a bamboo plantation located in Louisiana LA, USA. The initial MC of the samples was about

Table 1 Chemical composition of bamboo, wood and agriculture residue

Biomass type	Species	Cellulose (%)	Hemicelluloses (%)	Lignin (%)
Wood	Pine	40–45	25–30	26–34
	Maple	45–50	21–36	22–30
Bamboo	Moso bamboo	42–50	24–28	24–26
Agriculture residues	Rice straw	41–57	33	8–19
	Rice husk	35–45	19–25	20
	Bagasse	40–46	25–29	12.5–20
	Cotton stalk	43–44	27	27

6.1 %, and the density was about 0.65 g/cm^3. Bamboo materials were cut to a sample size of 40 mm (longitudinal) by 3–8 mm (radial) by 20–30 mm (tangential). Then, they were broken down into particles using a wood particle mill at Forestry Products Laboratory of USDA Forest Service. Finally, they were screened to obtain three different kinds of bamboo PS.

Pellet formation

Bamboo pellets were manufactured using laboratory pellet mill (L-175, Amandus Kahl Co. of Hamburg, Germany). The effects of MC and PS of bamboo were calculated using the 3^2 full-factorial design. The experimental design is shown in Table 2. The manufacturing details were as follows:

1. Bamboo particles were separated according to their PS. The three different PS used in the study were PS1 (particle diameter greater than 1.18 mm), PS2 (particle diameter of 1.18–0.84 mm) and PS3 (particle diameter less than 0.84 mm), respectively.
2. One kilogram (1 kg) of bamboo particles with PS1, PS2 and PS3 was put into the conditioning room at a temperature of 27 °C, humidity 65 % and temperature of 27 °C, humidity 90 % to adjust their MC to about 8 and 12 %, respectively. For the highest MC (16 %), bamboo particles were conditioned by adding predetermined amounts of distilled water to the samples.
3. Bamboo particles were transferred to separate Ziploc bags and sealed tightly. Then, they were kept in a conditioning room (temperature 27 °C, humidity 65 %) for 48 h to enable moisture to be distributed uniformly.
4. MC of bamboo particles was tested using a drying oven at 105 °C for 8 h. The initial and final mass was measured by a digital balance. MC of bamboo particles was calculated based on mass loss.
5. The pellet mill parameters were set to a rotary speed of 235 rpm and pellet diameter of 6.0 mm.
6. Bamboo particles were continuously fed into the pellet mill and formed into pellets.

Table 2 Experimental design

Experiment no.	MC (%)	PS
1	8	PS1
2	8	PS2
3	8	PS3
4	12	PS1
5	12	PS2
6	12	PS3
7	16	PS1
8	16	PS2
9	16	PS3

7. Bamboo pellets were collected and kept in the laboratory at a temperature of 27 °C and humidity of 50 % for more than a week, and then, their properties were tested.

Property tests

Physical properties

Pellet dimensions The pellets are cylindrical in shape. In order to determine their dimensions and individual mass, ten bamboo pellets were randomly selected in each experiment. The length (L) and diameter (d) of each sample were measured using a digital vernier caliper. The mass of bamboo pellets (m) was weighed using a precision digital balance (0.0001 Resolution).

Particle density (ρ_p) Particle density of bamboo pellets was determined by weighing the individual pellet and calculating its volume based on its length and diameter as per below equations.

$$V_{\mathrm{p}} = \pi/4d^2L \quad (1)$$

$$\rho_{\mathrm{p}} = m_{\mathrm{p}}/V_{\mathrm{p}} \quad (2)$$

where V_{p} is the volume of individual pellet (cm^3), d is the diameter of individual pellet (mm), L is the length of individual pellet (mm), ρ_{p} is the density of individual pellet (g/cm^3) and m_{p} is the mass of individual pellet (g).

Bulk density (ρ_b) Bulk density was calculated as the ratio of the mass of materials to the volume of the container. Bamboo pellets were leveled with the top surface of the container, and they were weighed using a precision digital balance. Container volume was calculated by measuring its length and diameter.

$$\rho_{\mathrm{b}} = m_{\mathrm{b}}/V_{\mathrm{b}} \tag{3}$$

where ρ_{b} is the bulk density (g/cm^3), V_{b} is the container volume (cm^3) and m_{b} is the total mass of pellets (g).

Moisture content Moisture content was determined by dry mass determination. Ten bamboo pellets in each process were heated using a drying oven under rigidly controlled temperature conditions (105 °C), time (8 h). Then, they were removed from the drying oven and put into a desiccator to cool to room temperature. Thereafter, they were weighed using a precision digital balance. Samples were returned to the drying oven at 105 °C for 2 h and cooled and weighed. When mass variability in samples was less than 0.2 %, their final mass was recorded. MC was calculated using below equation:

$$\mathrm{MC} = (m_{\mathrm{i}} - m_{\mathrm{f}})/m_{\mathrm{f}} \times 100\,\% \tag{4}$$

where MC is pellet moisture content (%), m_{i} is initial mass of samples (g) and m_{f} is final mass of samples (g).

Pellet fine content (P_f) Pellet fine content was determined according to *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified Fuel.*

Pellet durability (P_d) Pellet durability was determined by mass loss of samples. Fifty bamboo pellets in each process were randomly selected and weighed using a precision digital balance. The initial mass was recorded. Then, they were put into a vibrating sieve with screen size of 3.17 mm (1/8 in). After 10 min, they were weighed again and the final mass was recorded. Pellet durability was calculated using below equation:

$$P_{\mathrm{d}} = 100 - (m_{\mathrm{i}} - m_{\mathrm{f}})/m_{\mathrm{i}} \times 100\,\% \tag{5}$$

where P_{d} is pellet durability (%), m_{i} is initial mass of samples (g) and m_{f} is final mass of samples (g).

Combustion properties

Combustion properties such as inorganic ash, gross calorific value, combustion rate and heat release rate were investigated in this research.

Inorganic ash (I_a) Inorganic ash of pellets was determined based on inorganic material content expressed as percent. The temperature for creating ash was according to *EN 14775:2010* (Solid biofuels—determination of ash content).

Gross calorific value (G_c) The gross calorific value is the amount of energy per unit mass released upon complete combustion. The calorific value of bamboo pellets was tested using *PARR 1266 Bomb Calorimeter*. Before testing of the gross calorific value of bamboo pellets, the calorimeter was calibrated with tablets of benzoic acid whose calorific value was 26,465 J/g. In this test, about 1 g bamboo pellets was introduced into the calorimeter, which was charged slowly with pure oxygen (>99.95 vol%, quality 3.5) to a pressure of 3.0 ± 0.2 MPa without displacing the original air. No combustion aids were used, and five samples were tested in each condition. The final experimental result was the average value of five samples.

Combustion rate (C_r) and heat release rate (H_r) The fire time for complete combustion of bamboo pellet was recorded using the *PARR 1266 Bomb Calorimeter*. Based on the total amount of bamboo pellets and fire time, the combustion rate was calculated by using below equation.

$$C_{\mathrm{r}} = m/t \tag{6}$$

where C_{r} is the combustion rate (g/s), m is the mass of bamboo pellets (g) and t is fire time in every test (s).

By knowing the gross calorific value and combustion rate, the heat release rate could be calculated by using below equation (Faizal et al. 2010).

$$H_{\mathrm{r}} = G_{\mathrm{c}} \times C_{\mathrm{r}} \tag{7}$$

where H_{r} is the heat release rate (J/s), G_{c} is the gross calorific value (J/g) and C_{r} is the average combustion rate (g/s).

Thermal–mechanical properties of bamboo

Bamboo materials were cutoff as rectangles with a sample size of °C 17.5 ± 0.2 mm (longitudinal) by 2.2 ± 0.1 mm (radial) by 7.2 ± 0.1 mm (tangential). Samples were dried using a drying oven under rigidly controlled conditions of temperature (105 °C) until mass variance of samples was less than 0.2 %. The mass of samples (m_1) was recorded using a precision digital balance. Samples were placed into the conditioning room at a temperature of 27 °C and humidity 65 % to equilibrate their MC to about 8 %, and temperature of 27 °C and humidity 90 % to equilibrate their MC to about 14 %, respectively. After 14 days, the mass (m_2) was weighed and the MC was calculated based on mass change.

Thermal–mechanical properties of moso bamboo with different MC were tested by means of DMTA instrument (Q800, TA-instruments, New Castle, DE, USA) using a single cantilever grip. The viscoelastic region (strain directly proportional to stress) was determined by performing a strain sweep. Specimens were measured in their exact dimensions, immediately fixed in the grip and cooled to −50 °C using liquid nitrogen. Measurements were conducted from −50 to 150 °C with a heating rate of 5 °C/min, amplitude of 5 μm and a frequency of 1 Hz. The loss factor (tanδ) was used to determine the thermal–mechanical properties of moso bamboo.

Table 3 Properties of bamboo pellets manufactured with different MC particles

Particle MC (%)	$L \pm$ SD (mm)	$D \pm$ SD (mm)	$P_m \pm$ SD (%)	$P_b \pm$ SD (g/cm^3)	$P_d \pm$ SD (%)	$P_f \pm$ SD (%)
8	12.5 ± 2.3	6.1 ± 0.0009	4.9 ± 0.29	0.52 ± 0.0003	95.07 ± 0.48	0.41 ± 0.053
12	12.7 ± 3.5	6.0 ± 0.0009	5.0 ± 0.35	0.63 ± 0.001	97.95 ± 0.63	0.54 ± 0.052
16	11.7 ± 2.7	6.0 ± 0.0019	5.4 ± 0.35	0.65 ± 0.001	98.38 ± 0.74	0.27 ± 0.079

Results and discussion

Effects of MC on physical properties of bamboo pellets

Table 3 illustrates the effects of MC on some physical properties of bamboo pellets. For each property, the data presented the mean of measurements made on 30 pellets at each MC level from three different PS. The mean length of bamboo pellets ranged between 12.7 and 11.7 mm. The length values were 12.5, 12.7 and 11.7 mm at 8, 12 and 16 % MC levels, respectively. The mean diameter of bamboo pellets also ranged slightly, and the values were 6.1, 6.0 and 6.0 mm at 8, 12 and 16 % MC level, respectively. The diameter change of bamboo pellets could be due to water migrating from pellets to disrupting formed bonds in the pelletization process (Larsson and Rudolfsson 2012). The dimensions of pellets, both diameter and length, were important factors with respect to combustion. Experience showed that thinner pellets allowed a more uniform combustion rate than thicker ones, especially in small furnaces (Paivi 2001). The pellet MC increased slightly with increasing particle MC. The particle density and bulk density were 1.05, 1.14, 1.20 and 0.52, 0.62, 0.65 g/cm^3 at 8, 12 and 16 % particle MC, respectively. Particle density and bulk density of bamboo pellets both increased with particle MC. The higher densities of pellets are helpful to improve their processing, transportation, storage and firing. The strength of pellets is also an important factor connected with handling and transportation. In this research, the strength of pellets included two parameters, durability and fine content. Table 3 shows that pellet durability increased with increasing particle MC, and the values were 95.07, 97.95 and 98.38 %. For pellet fines, however, the minimum was observed at the 16 % MC level, and the maximum was at the 12 % MC level. Particle density was a very important parameter affecting the strength of pellets. The greater particle density, the higher durability of pellets and the less was the fine content of pellets.

Effects of MC on combustion properties of bamboo pellets

Figures 1 and 2 show the effects of MC on combustion properties of bamboo pellets. The inorganic ash of bamboo pellets slightly varied, and the values were 1.46, 1.38 and 1.34 % at 8, 12 and 16 % MC levels, respectively. The inorganic ash of biomass pellets mainly depended on the mineral constituents of source fuel and on the combustion process (Paivi 2001). However, the formation process of biomass pellets also affected inorganic ash to some extent. The proportion of organic

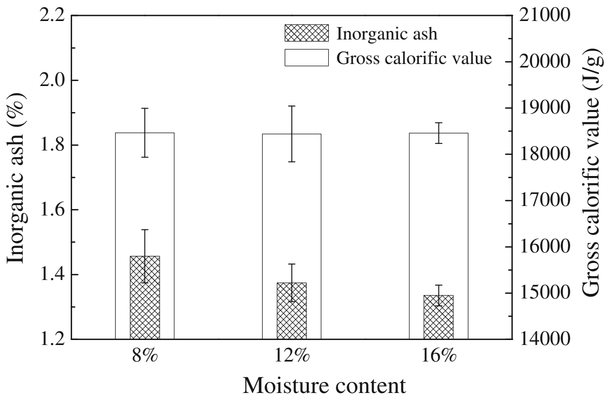

Fig. 1 Effects of MC on inorganic ash and gross calorific value of bamboo pellets

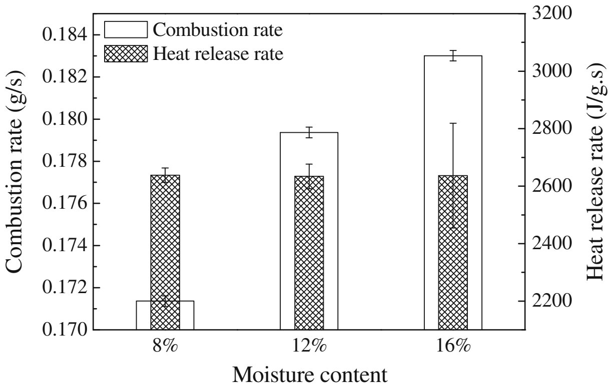

Fig. 2 Effects of MC on combustion rate and heat release rate of bamboo pellets

material decreased during the formation process of bamboo pellets due to thermal decomposition, which led to different inorganic ash content of bamboo pellets. For 16 % MC, bamboo pellets were more easily formed in the manufacturing process and the reduction of organic materials was less, which resulted in minimum inorganic ash content. Table 4 shows that the major mineral constituents were found in ash of bamboo pellets. It was found that K content of these mineral constituents was the most, which maybe resulted in sintering and agglomeration. Combustion is a series of chemical reactions by which some heavy metals can be oxidized to metallic dioxide. It is well known that K_2O exhibits much lower melting temperature during combustion of biomass. The higher the content of K, the higher is the content of K_2O, which decreases melting points of ash of bamboo pellets. Agglomeration consists mainly of SiO_2, the melting point of which is around 1,450 °C (Lin et al. 1997). The alkali oxides or salts, such as Na and K, can react

Table 4 Major ash-forming elements found in ash of bamboo pellets (mg/Kg)

Na	Mg	Al	Si	K	Ca	Ti	Fe	Zn
242.83	229.46	35.10	358.14	4,032.58	965.03	18.07	111.93	20.88

with Si compounds of the bed material accordingly to form eutectic mixtures with melting points of 874 and 764 °C, respectively (Demirbas 2004). There was no significant difference in gross calorific value of bamboo pellets manufactured using different MC. The slight variance of gross calorific value was due to the heat energy required to vaporize water because of hydrogen released during the combustion process. It was also confirmed that the gross calorific value of the pellets was most affected by the composition of bamboo rather than material MC. The bamboo pellets, equilibrated at different MC, had different combustion rates. As shown in Fig. 2, the combustion rate for bamboo pellets increased as MC increased from 8 to 16 %. This was because when MC increased, the dwell time of bamboo particles in the die set was shorter and the air gap between particles of bamboo pellets was greater. Due to better air circulation through the air gap of pellets, the combustion rate of pellets increased (Faizal et al. 2010). In this research, the combustion rate of bamboo pellets manufactured at 16 % MC was highest and the last was 8 %. It was also found that the heat release rate and combustion rate of bamboo pellets increased with MC increase, even though the gross calorific value seemed to be constant. The value of heat release rates was 3,164, 3,307 and 3,377 J/s for the 8, 12 and 16 % MC, respectively.

Based on the results of this research, it was found that particle MC affected these properties of bamboo pellets, and analysis of variance results (Table 5) showed that the effects of particle MC on length, diameter, pellet MC, particle density and bulk density were significantly different at $p = 0.05$.

Effects of PS on physical properties

Table 6 shows the effects of PS on physical properties of bamboo pellets. For each property, the data presented the mean of measurements made on 30 pellets at each PS level from three different MC. The mean length of bamboo pellets decreased with increase in PS, and the values were 12.6, 12.2 and 11.9 mm at PS1, PS2 and PS3 levels, respectively. The mean diameter of bamboo pellets ranged slightly, and the value was 6.1 mm under different PS. The particle density and bulk density values were 1.11, 1.13, 1.16 and 0.52, 0.63, 0.65 g/cm^3 at PS1, PS2 and PS3 levels, respectively. The particle density and bulk density of bamboo pellets increased with decreasing PS. Pellet durability increased with increasing PS, and the values were 97.96, 97.21 and 96.23 %. For pellet fines, however, the minimum was associated with bamboo pellets made of PS1, the maximum was observed at PS3. The smaller PS made the feedstock slippery and it slid through the die channels too easily, thereby reducing pellet strength.

Table 5 Analysis of variance

Properties	Variance	SS	*df*	MS	*F* value	*p* value	*F* crit
L	Interior-group	21.40	2	10.70	3.69	0.03	3.10
	Inter-group	251.65	87	2.89			
	Total	273.06	89				
D	Interior-group	0.04	2	0.02	16.66	7.471E−07	3.10
	Inter-group	0.11	87	0.001			
	Total	0.16	89				
MC	Interior-group	3.51	2	1.75	5.22	0.0072033	3.10
	Inter-group	29.22	87	0.33			
	Total	32.73	89				
ρ_p	Interior-group	0.33	2	0.16	11.35	4.16E−05	3.10
	Inter-group	1.25	87	0.01			
	Total	1.58	89				
ρ_b	Interior-group	0.28	2	0.14	175.08	3.167E−31	3.10
	Inter-group	0.07	87	0.001			
	Total	0.35	89				

SS sum of squares, *df* degree of freedom, *MS* mean square

Effects of PS on combustion properties of bamboo pellets

Figures 3 and 4 show the effects of PS on combustion properties of bamboo pellets. The inorganic ash of bamboo pellets decreased with the PS decrease, and the value was 1.45, 1.38 and 1.32 % for PS1, PS2 and PS3, respectively. There were no significant differences in the gross calorific value of bamboo pellets manufactured using different PS. The gross calorific value of bamboo pellets for each PS was 18,463, 18,464 and 18,434 J/g. The gross calorific of all bamboo pellets met the minimum requirement for making commercial pellets (>17,500 J/g), as stated in DIN 51731 (Mahapatra et al. 2010). Bamboo pellets made of different PS had different combustion rates. As shown in Fig. 4, combustion rates increased as PS increased. Air circulation affected the combustion rate of pellets when they were burned (Faizal et al. 2010). The bigger PS of the bamboo material, the more was the inner porosity of the pellets. The organically bound O provides a part of the O necessary for the combustion process, additional O must be supplied by air injection (Obernberger and Thek 2004). The more porous structure in the bamboo pellets was helpful for better air circulation and more oxygen supply during the combustion process. It was also found that the heat release rate of bamboo pellets increased with PS increase even though the variance was not significant. The value of heat release rates was 3,271, 3,277 and 3,301 J/s for PS1, PS2 and PS3, respectively. An experimental conclusion was drawn that the combustion process of bamboo pellets manufactured by PS3 was best, which also proved why its inorganic ash was the lowest in this research.

The PS affected these properties of bamboo pellets, but the variance of these properties was not significant at $p = 0.05$ based on analysis of variance method.

Table 6 Properties of bamboo pellets manufactured using particles with different sizes

PS	$L \pm SD$ (mm)	$D \pm SD$ (mm)	$P_m \pm SD$ (%)	$P_b \pm SD$ (g/cm^3)	$P_b \pm SD$ (g/cm^3)	$P_d \pm SD$ (%)	$P_f \pm SD$ (%)
PS1	12.6 ± 2.2	6.1 ± 0.0018	5.1 ± 0.42	1.11 ± 0.015	0.52 ± 0.0039	97.96 ± 0.85	0.27 ± 0.05
PS2	12.2 ± 2.8	6.1 ± 0.0018	5.2 ± 0.20	1.13 ± 0.019	0.63 ± 0.0042	97.21 ± 0.39	0.46 ± 0.10
PS3	11.9 ± 4.1	6.1 ± 0.0016	5.0 ± 0.46	1.16 ± 0.019	0.65 ± 0.0039	96.23 ± 0.50	0.49 ± 0.06

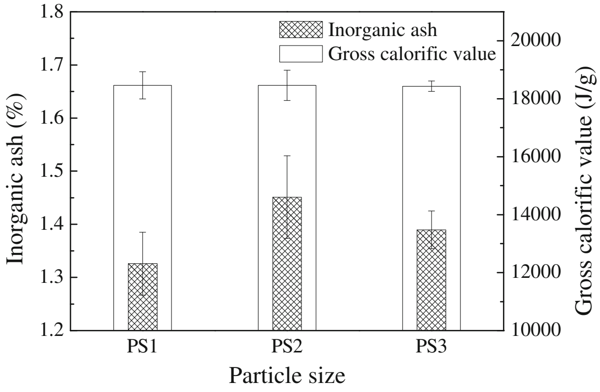

Fig. 3 Effects of PS on inorganic ash and gross calorific value of bamboo pellets

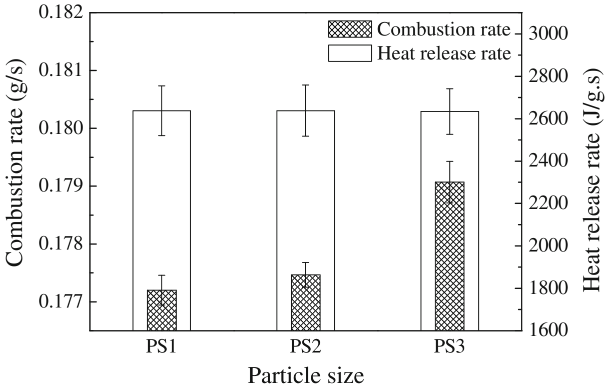

Fig. 4 Effects of PS on combustion rate and heat release rate of bamboo pellets

Colley et al. (2006) found that PS affected the pellet properties of barley straw, corn stover and switchgrass. However, different PSs of wheat straw did not produce any significant difference in pellet properties.

Effects of moisture on properties of bamboo pellets

The result from this research confirmed that MC and PS affected the properties of bamboo pellets. The effects of MC on some properties were significant at $p = 0.05$ (Table 5), but there were no significant differences between PS and all properties of bamboo pellets based on analysis of variance method. The moisture effect on properties of bamboo pellets was therefore analyzed in this research. Compression formation of different materials utilizing natural binder or binding type of particles included attractive forces between solid particles, interfacial forces, capillary pressure, adhesive and cohesive forces, mechanical interlocking behavior and formation of

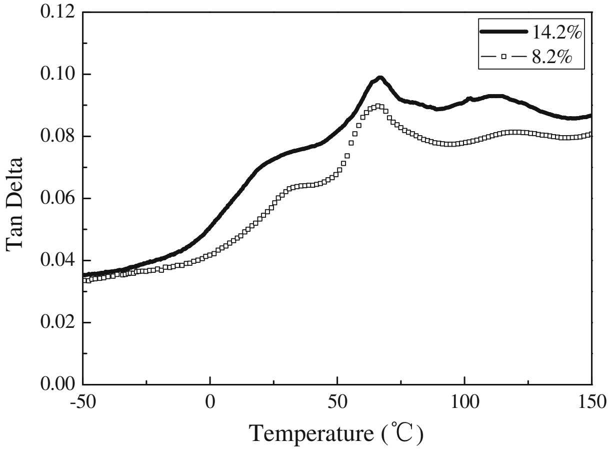

Fig. 5 Loss factor (tanδ) of moso bamboo with different MC

solid bridges (Dick et al. 2007). The bonding between particles was created mainly through solid bridges for bamboo pellets. This bonding has also been confirmed for corn stover and switchgrass pellets. The solid bridges between particles were made by natural binders in the biomass expressed during the densification process (Nalladurai and Morey 2010). Hemicelluloses, lignin and protein were essentially amorphous polymers in the bamboo components. Activating (softening) of the natural binders using moisture and temperature in the range of glass transition was important to make durable particle–particle bonding. Figure 5 shows that there was an α-transition (α_1) peaking at about 65 °C for bamboo materials with 8.2 and 14.2 % MC, respectively. The transition was mostly linked to the glass–rubber transition of lignin. Lignin has a glass transition in the temperature range of 60–200 °C, depending upon the MC and measuring technology (Salmen 1990). Olsson and Salmen (1997) showed that the α_1 transition of moist wood usually occurs between 60 and 95 °C due to the glass–rubber transition of lignin. The second major relaxation (α_2) of bamboo materials with 8.2 and 14.2 % MC occurred at 30 and 25 °C, respectively. The transition located at low temperature was probably attributed to the glass–rubber transition of hemicelluloses. Hemicelluloses had a glass transition of between −23 and 200 °C, depending upon the MC (Kelley et al. 1987). It was found that the α_2 transition temperature decreased with increasing MC of bamboo materials. The result confirmed that glass transition of lignin and hemicelluloses was affected by bamboo moisture. In the pelletization process, particle MC affected the transition temperature of natural binders of bamboo which resulted in a difference in particle bonding and properties of bamboo pellets.

Conclusion

Based on the results of this research, it was confirmed that MC and PS affected the properties of bamboo pellets. The effects of MC on these properties, such as length, diameter, pellet MC, particle density and bulk density were significant at $p = 0.05$, but there were no significant differences between PS and all properties of bamboo pellets. The bonding between particles was created mainly through solid bridges for bamboo pellets. The solid bridges between particles were made by natural binders including hemicelluloses and lignin in the bamboo during the densification process. Glass transition of lignin and hemicelluloses was affected by bamboo moisture, which resulted in a difference in particle bonding and the properties of bamboo pellets.

All properties of bamboo pellets met the requirement of *Pellet Fuels Institute Standard Specification for Residential/Commercial Densified Fuel*. The gross calorific value of bamboo pellets also met the minimum requirement for making commercial pellets according to DIN 51731 (>17,500 J/g). Due to higher MC and larger PS, bamboo pellets exhibited higher combustion rates and heat release rates. The experimental results showed that bamboo pellets could be proposed as a new biomass solid fuel and have the potential to be developed as commercial pellets. Pelletization increased the bulk density of bamboo materials and improved several disadvantages when bamboo was directly fired. This research represents an initial stage in the study of bamboo pellets and may provide guidelines for further research.

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References

Adapa PK, Singh AK, Schoenau GJ, Tabil LG (2006) Pelleting characteristics of fractionated alfalfa grinds: hardness models. Power Handl Process 18:1–6

Baernthaler G, Zischka M, Haraldsson C, Obernberger I (2006) Determination of major and minor ash-forming elements in solid biofuels. Biomass Bioenergy 30:983–997

Carone MT, Pantaleo A, Pellerano A (2011) Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of *Olea europaea* L. Biomass Bioenergy 35:402–410

Cattaneo D (2003) Briquetting: a forgotten opportunity wood energy. University of Brescia, Brescia

Colley Z, Fasina OO, Bransby D, Lee YY (2006) Moisture effect on the physical characteristics of switchgrass pellets. Trans ASABE 49:1845–1851

Faizal HM, Latiff ZA, Wahid MA, Darus, AN (2010) Physical and combustion characteristics of biomass residues from palm oil mills. Heat Transf Environ 34–38

Demirbas A (2004) Combustion characteristics of different biomass fuels. Prog Energy Combust Sci 30:219–230

Dick EP, Ryabov GA, Tugov AN, Soboleva AN (2007) Comparing properties of coal ash and alternative-fuel ash. Therm Energy 54:231–235

Jiang ZH (2002) World bamboo and rattan. Liaoning Science & Technology Press, China

Kelley SS, Rials TG, Glasser WG (1987) Relaxation behavior of the amorphous components of wood. J Mater Sci 22:617–624

Larsson SH, Rudolfsson M (2012) Temperature control in energy grass pellet production: effects on process stability and pellet quality. Appl Energy 97:24–29

Lin L, Gitte K, Kim DJ, Esther M, Bank L (1997) Agglomeration phenomena in fluidized bed combustion of straw. In: Preto FDS (ed) Proceedings of the 14th international conference on fluidized bed combustion. ASME, Vancouver, pp 831–838

Mahapatra AK, Harris DL, Durham DL, Lucas S, Terrill TH, Kouakou B, Kannan G (2010) Effects of moisture change on the physical and thermal properties of sericea lespedeza pellets. Int Agric Energy J 1:23–29

Nalladurai KR, Morey V (2010) Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass. Bioresour Technol 101:1082–1090

Obernberger I, Thek G (2004) Physical characterisation and chemical composition of densified biomass fuels with regard to their combustion behavior. Biomass Bioenergy 27:653–669

Olsson M (2006) Wheat straw and peat for fuel pellets: organic compounds from combustion. Biomass Bioenergy 30:555–564

Olsson AM, Salmen L (1997) The effect of lignin composition on viscoelastic properties of wood. Nord Pulp Pap Res 12:140–144

Paivi L (2001) Quality properties of pelletised sawdust, logging residues and bark. Biomass Bioenergy 20:351–360

Rhena C, Ohmanb M, Grefa R et al (2007) Effect of raw material composition in woody biomass pellets on combustion characteristics. Biomass Bioenergy 31:66–72

Salmen L (1990) Thermal expansion of water saturated wood. Holzforschung 44:17–19

Werther J, Saenger M, Hartge EU (2000) Combustion of agricultural residues. Prog Energy Combust Sci 26:1–27

Yao F, Wu QL, Lei Y, Guo WH, Xu YJ (2008) Thermal decomposition kinetics of natural fibers: activation energy with dynamic thermo gravimetric analysis. Polym Degrad Stab 93:90–98