WOOD RESEARCH
63 (1): 2018
141-154

EFFECTS OF POPLAR FIBRES AS SOLID BRIDGE ON THE PHYSICAL CHARACTERISTICS OF BIOMASS BRIQUETTE MADE FROM SAWDUST AND BAMBOO POWDER

Xuehao Wang, Zhongjia Chen, Guosehng Yu, Xiangyue Yuan
Beijing Forestry University, Institute of Technology
Beijing, China

(Received November 2017)

ABSTRACT

At room temperature, on condition that the die be within temperatures of 200 - 300°C biomass briquette production made from sawdust (S) and bamboo powder (B) was conducted by a briquette extruder using post-heating method, fibre with steam explosion poplar fibres used as additive. As observed through the microscope, fibres as additive has the micro-mechanism of promoting mechanical properties of biomass briquette during densification. For verifying the feasibility and effect of fibre as additive, BBD experimental design was macroscopically adopted to compare the indicators of surface quality, relaxation density, maximum radial compression pressure, and hydrophobicity. Response surface model was used to deduce the reasonable heating temperature range for exploring the suitable condition of fibre as additive. The result showed that fibre as additive has apparent effect on briquette densification of sawdust and bamboo powder within a given temperature range. Through microscopic observation, it was found that fibres acted as solid bridges which played a positive role in densification in the heating temperature of 200~250°C. At the temperature of 240°C, the fibres started to be carbonized. And within the temperature range of 250-300°C, the carbonized fibre mainly acts as lubricant between the briquette and the channel surface of the die.

KEYWORDS: Biomass briquette, densification, poplar fibres, heating temperature, solid bridge.

INTRODUCTION

The shortage of energy supply and demand will restrict the development of human beings. Thus it is urgent to search for new and renewable energy. Compared with fossil energy, biomass has gradually become a new force in the energy industry. Because it is renewable and rich in resources (Hoogwijk et al. 2003, Lauri et al. 2014, Parikka 2004). Biomass briquette has become an important part of biomass energy and attracted people's attention since it is easy to realize industrialization and scale of products with the feature of easy production technology, convenient storage and transportation, user-friendliness, environmental protection, and high efficiency of burning. However, it also has many problems such as high energy consumption, serious wear of die and unsatisfactory densification effect (Stelte et al. 2012). Based on the above problems, the researchers found that adding suitable additives would be feasible, because additives can reduce production equipment wear, and enhance the durability and physical quality of briquette (Kuokkanen et al. 2011).

In the process of producing biomass briquettes, the frequently used additives include lignosulfonate, bentonite, starch, protein and so on, (Kaliyan and Morey 2009b, Stahl et al. 2016). Usually, lignosulfonate is considered as the most effective adhesive (El Mansouri and Salvadó 2006, Kaliyan and Morey 20009b,Tumurulu et al. 2011), which could effectively improve the physical quality of briquettes and enhance the cohesive effect between particles. Bentonite, also known as colloidal clay, is a common substance used for feed block adhesive. During the process, the binder forms gel with water, which improves the briquette characteristics (Jaya Shankar et al. 2010). Pfost and Young's (1997) study found that the ratio of 100 $kg \cdot t^{-1}$ to bentonite significantly increases the durability of poultry feed that consist of corn and sorghum

Starch is a good binder. Adding 5% of wheat starch can improve the hardness and water stability of briquette (Orire et al. 2010, Wood 1987). Protein is a natural binder. As the compression temperature goes up and the function of moisture is activated, lignin, protein, starch and fat becomes natural binder to help densification (Soleimani et al. 2017). Also, the plants containing high protein, such as alfalfa etc., can be used as adhesives too (Tumuluru et al. 2011).

Although these additives enhance the densification of the particles and improve the physical quality of briquettes to some extents, they may also cause some problems. For example, Stevens and Gardner noticed the great differences in costs and effects between different lignin, so it is necessary to have a comprehensive evaluation to select suitable lignin (Stevens and Gardner, 2010). And Chin and Siddiqui (2000) found that bentonite and lignosulfonate would reduce the calorific value of briquette and increase the burning waste. Moreover, using starch and syrup increases the cost of densification and is not good for large-scale applications. Hence, these problems impel us to find an additive that takes into account both environmental and economic.

Researchers found that steam explosion can degrade cellulose and lignin of the biomass to low molecular substances, and make the fibres loose, porous and inflammable. More importantly, blasting products contain high long-fibre, which helps material particles create a more stable structure. They may become ideal additives (Bismarck et al. 2002, Yamashiki et al. 1990). Therefore, this study used sawdust and bamboo powder as raw material, and used poplar fibre as the additive. BBD experimental design was macroscopically adopted to compare the indicators of surface quality, relaxation density, maximum radial compression pressure, and hydrophobicity, and to verify the feasibility and effect of using fibres as additive. The study also used response surface model to deduce the reasonable range of heating temperature for exploring the optimum condition of fibres as additive.

MATERIAL AND METHODS

Materials

The researchers took pine sawdust from Beijing Forestry University laboratory, took bamboo powder from Fujian furniture factory, and took steam explosion fibres made from poplar branches from Dezhou, Shangdong in China. Since the physical and chemical characteristics of wood material would be severely affected by temperature and moisture content, the wood samples within this experiment were taken in the field, and sealed up after natural air drying. The material was small fibrous pieces without using a crumbling machine. The test samples were placed in a fast moisture analyser (Model: SC69-02, Shanghai second balance instrument factory) for a period of 8h. Through calculation, the ratios of moisture content of sawdust, bamboo powder, and fibre are 5.4%, 5%, 5.2% respectively. For checking the influence of moisture content on densification, the researchers improve the ratio of moisture content in sawdust, bamboo powder to 12%, 14%, 16% respectively. One hour before the compaction test, the natural air-dried fibres was added to the experimental materials according to the mass ratio, then the mixture was evenly stirred.

Biomass briquette method

The test machine is a briquette extruder, as shown on the Fig. 1. There is a briquette die, with an inner diameter of 24.5 mm and a length of 110 mm (length to diameter ratio is 4.5 mm), connected with the coaxial plunger of the test machine outside the silo.

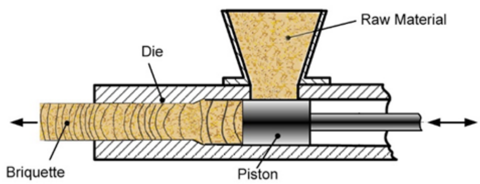

Fig.1: Mechanical structure.

The outer part of die is equipped with a heating belt for external heating. When the testing machine worked, the raw material was added to the hopper. The plunger moved back and forth so that the raw material in the front continuously pressed into die. There was densification pressure built up by the friction between the channel surface and the raw material in the die. The raw material is pressed and formed out of the die.

Experiment design

A 33 (heating temperature, moisture content, and fibre content) fractional factorial experimental design based on Box and Behnken (Ferreira et al. 2007) with three centre runs was used, giving a total of 15 experimental runs. According to a large number of previous experiments, the variables were selected as 3 levels, and the factor level combination design was shown within the Tab. 1.

Tab. 1: Factor levels and codes.

Levels	Factors		
	Temperature (°C)	Moisture content (%)	Fibre content (%)
1	200	12	0
0	250	14	5
-1	300	16	10

The independent variables (responses) analysed were relaxation density of pine sawdust and bamboo powder particles.

Relaxation density measurement

The electronic calliper was used to measure the length and diameter of briquette. For ensuring the accuracy, the researchers measure the diameter from three positions (front, middle, back) along the length of the briquette and took the average value. The mass of the briquette was measured with an electronic balance (Model: SF-400A, Yong Jie, China) of 0.01 g accuracy. The edge of the briquette was polished for getting accurate volume. Under each experimental condition, 5 samples were taken randomly. And the quality, length and diameter were measured after the samples placed 72 h indoors. The relaxation density was calculated as Eq. 1 shows below.

$$\rho = \frac{4m}{\pi d^2 L} \tag{1}$$

where: ρ - relaxation density (g·cm^{-3}),
m - mass of briquette, (g)
d - briquette diameter (cm),
L - briquette length (cm).

Radial maximum pressure measurement

The radial maximum pressure test was carried out on the universal mechanical testing instrument (Model: 4050, REGEER, China) (Fig. 2). To ensure accuracy, the briquettes were in the same length. Each test randomly took 3 samples and the maximum radial pressure of each sample was recorded and averaged.

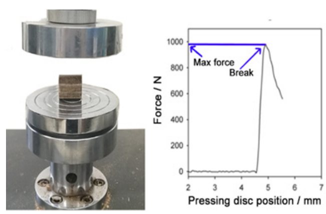

Fig. 2: Compression testing.

Hydrophobic properties measurement

The briquette was placed in a crucible at 20 under water with depth of 40 mm. After 10 s, 30 s, 60 s and 120 s, the briquette was taken out, weighed to calculate the amount of absorbed water, and the ratio of water absorption and the quality of the initial sample. The experiment was repeated 3 times.

$$S = \frac{M_1 - M_0}{M_0} \times 100\% \tag{2}$$

where: S - water absorption (%),
M_1 - mass of a briquette (g),
M_0 - mass of a briquette after water absorption (g),

Microstructure observation

A stereomicroscope (Model: XT- III, Phoenix Optical Instrument Corporation) and an electronic eyepiece (Model: SJ-U500, SAGA, China) were installed to observe the microstructure of the briquette. Due to the unsmoothed surface of the briquette, direct observing the microscopic imaging may be affected. Therefore, the lathe would be used to whittle the end face to ensure the smoothness. For accuracy's sake, the researchers selected two observation points at the centre and edge of each observed end face, to observe the briquette microstructure with the microscope of 80 times magnification. The electronic eyepiece was used to directly capture the end faces of the briquette for obtaining the image of the entire observation surface.

Thermogravimetric analysis

The experiment set up thermogravimetric Analyser (Model: DTG-60A/60AH, SHIMADZU, Japan). The heating rate was 10°C·min^{-1}. The temperature rose from AT to 300°C. The mass of each sample was about 5 mg under each trial, and the reaction atmosphere was air. The sample was at programmed temperature. And the function was made to record the temperature changes with mass changes (TG curve).

Data processing

The experimental data were analysed by Design-expert 8.0.6 data-analysis software for regression analysis, and the response surface was drawn by Matlab 2015b. The interaction between the two factors was also analysed.

RESULTS AND DISCUSSION

Microscopic characteristics

Microstructure analysis

As shown on the Fig. 3, the combination of a briquette without fibres was made through the lap of layers of particles that were in big size or at length. The interface between particles was clear. The "bonding" approach would cause the limited friction between the materials.

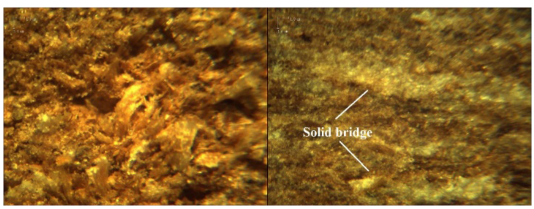

Fig . 3: Light microscopy (LM) (magnification at 80×) images of bamboo powder at 250°C -16%.

The fibres forming a briquettes appears the form of fibre tight winding, and the interface among particles was fuzzy and integrated. The reticular structure formed by the fibres became the skeleton of the briquette, and had obvious coupling and wrapping action to the biomass particles; the fibres were used as a binder to fill the pores in the forming briquette and act as a bond. The role of fibre in the briquette mechanism should be between solid particles bridging (Solid Bridge (Kaliyan and Morey 2009a, Kaliyan and Morey 2010, Kaliyan and Vance Morey 2009).

At high temperature and under high pressure lignin softening and flowing promoted intermolecular diffusion. Soluble fibres were formed solid particles bridging (Solid Bridge), separated out through crystallization, cured by adhesive, melted, and sintered with chemical reaction. It increased viscosity and had a positive effect on a particle structure (Kaliyan and Morey 2010, Pietsch 2008). The entanglement between adjacent fibres improved the stability of structure (Rumpf 1962).

Macrocharacteristics

Microstructure analysis

On the surface of the briquette, the briquette added with fibres has smoother surface and lesser cracks than that without fibres. There were many cracks on the surface of briquette with no fibres.

Fig. 4: Surface of Sawdust briquettes.

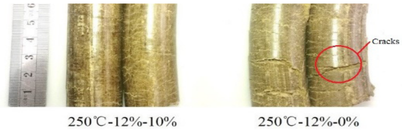

Fig. 5: Surface of bamboo briquettes.

These cracks reduced the resistance of a briquette to deformation, which led to poor mechanical durability. This may be because the mixture of fibres and sawdust or bamboo powder material densified under heating condition. The fibres melted and became "solid bridge", which promoted closer integration among particles (Kaliyan and Morey, 2009b, Kaliyan and Morey 2009c, Li et al. 2012). (Figs. 4, 5).

Relaxation density

Tab. 2 selected the test points that were below 300°C, with the same heating temperature, and same moisture content test to compare the changes of relaxation density changes.

Tab. 2: Experimental raw data.

No	Temperature (°C)	Moisture content (%)	Fibre content(%)	Relaxation density of Sawdust($g \cdot cm^{-3}$)	Relaxation density of bamboo($g \cdot cm^{-3}$)
1	150	14	5	0.916915	0.81315
2	300	14	10	0.545827	0.31185
3	250	16	0	0.62384	0.640499
4	250	14	5	0.854575	0.789197
5	300	14	0	0.646971	0.896901
6	250	12	0	0.491585	0.81365
7	200	12	5	0.742185	1.07034
8	200	16	5	0.916629	0.665039
9	300	16	5	0.898565	0.525902
10	200	14	10	1.02925	1.03551
11	300	12	5	0.83743	0.868893
12	250	16	10	0.883181	0.706128
13	250	12	10	0.875183	1.14572
14	250	14	5	0.918812	0.733164
15	200	14	0	0.76618	0.819575

The mathematical model was established and analysed. The resulting data were regressed to derive a suitable equation for each response. All variable parameters and their interactions were considered as a model for each response.

$$\rho_1 = -7.2715 - 1.19209\times10^{-3}\times x_1 + 1.14392\times x_2 + 1.03691\times x_3 + 9.95411\times10^{-4}\times x_1x_3 - 0.17146\times x_2x_3 - 0.039461\times x_2^2 + 0.028421\times x_3^2 - 1.35962\times10^{-4}\times x_1x_3^2 + 6.01268\times10^{-3}\times x_2^2x_3 \quad (3)$$

The analysis of variance showed that R12= 0.98. It showed a high coincidence of the regression equation and all the experimental values as a whole. It calculated F_1=24.14, $p<0.01$, regression equation was at a certain level of significance as a whole, and the fitting degree was good. The significance of the partial regression coefficient was shown within Tab. 3.

Tab. 3: Variance analysis of sawdust.

Source	Squares	f	Mean square	F	Sig	Significant
Model	0.33	9	0.037	25.01	0.0012	**
x_1	$1.489\ 10^{-3}$	1	$1.489\ 10^{-3}$	1.01	0.3609	
x_2	0.018	1	0.018	11.98	0.018	**
x_3	$6.555\ 10^{-3}$	1	$6.555\ 10^{-3}$	4.45	0.0887	*
x_1x_3	0.033	1	0.033	22.51	0.0051	**
x_2x_3	$3.86\ 10^{-3}$	1	$3.86\ 10^{-3}$	2.62	0.1665	
x_2^2	$5.248\ 10^{-3}$	1	$5.248\ 10^{-3}$	3.56	0.1178	
x_3^2	0.072	1	0.072	48.87	0.0009	**
$x_1x_3^2$	0.058	1	0.058	39.21	0.0015	**
$x_2^2x_3$	0.029	1	0.029	19.63	0.0068	**
Residual	$7.825\ 10^{-3}$	5	$1.565\ 10^{-3}$			
Lack of Fit	$5.153\ 10^{-3}$	3	$1.718\ 10^{-3}$	1.29	0.4656	not significant
Pure Error	$2.672\ 10^{-3}$	2	$1.336\ 10^{-3}$			
Cor Total	0.35	14				

** Said very significant($P<0.05$);* Said significant($0.05<P<0.1$) • The same as below •

$$\rho = -24.55223 + 0.073502\times x_1 + 3.68601\times x_2 + 2.19708\times x_3 - 0.010546\times x_1x_2 - 8.00985\times10^{-4}\times x_1x_3 - 0.27505\times x_2x_3 - 0.13456\times x_2^2 - 4.33266\times10^{-3}\times x_3^2 + 3.82191\times10^{-4}\times x_1x_2^2 + 9.3305\times10^{-3}\times x_2^2x_3 + 2.54744\times10^{-5}\times x_2^2x_3^2 \quad (4)$$

The analysis of variance showed that R_2^2= 0.99. It showed a high coincidence of the regression equation and all the experimental values as a whole. It calculated F_2=30.12, $p<0.01$, regression equation was at a certain level of significance as a whole, and the fitting level was good. The significance of the partial regression coefficient was shown within the Tab. 4.

Tab. 4: Variance analysis of bamboo powder.

Source	Squares	f	Mean square	F	Sig	Significant
Model	0.63	11	0.057	30.12	0.0086	**
x_1	0.1	1	0.1	55.29	0.005	**
x_2	0.23	1	0.23	122.58	0.0016	**
x_3	0.034	1	0.034	18.03	0.0239	**
x_1x_2	$9.705\ 10^{-4}$	1	$9.705\ 10^{-4}$	0.51	0.5253	
x_1x_3	0.16	1	0.16	84.91	0.0027	**
x_2x_3	0.018	1	0.018	9.4	0.0548	*
x_2^2	$2.797\ 10^{-5}$	1	$2.797\ 10^{-5}$	0.015	0.9108	
x_3^2	$2.698\ 10^{-4}$	1	$2.698\ 10^{-4}$	0.14	0.7307	
$x^1x_2^2$	0.012	1	0.012	6.19	0.0887	*
$x_2^2x_3$	0.074	1	0.074	38.91	0.0083	**
$x_2^2x_3^2$	$2.947\ 10^{-3}$	1	2.947 10-3	1.56	0.3002	
Residual	$5.667\ 10^{-3}$	3	$1.889\ 10^{-3}$			
Lack of Fit	$2.296\ 10^{-3}$	1	2.296 10-3	1.36	0.3634	not significant
Pure Error	$3.37\ 10^{-3}$	2	$1.685\ 10^{-3}$			
Cor Total	0.63	14				

Comprehensive sawdust and bamboo powder relaxation density ANOVA of analysis results showed that the influence of fibres on biomass briquette relaxation density was mainly through the interaction of heating temperature and fibres content. The effect of fibres content x_3's influence on relaxation density interaction level was significantly lower than that of the interaction between heating temperature and the fibre content. That was mainly because the temperature rose to the lignin glass transition temperature, which significantly improved the effect of briquette densification (van der Stelt et al. 2011).

Response surface analysis

As shown on the Fig. 7 (S Sawdust, B bamboo, the same below), the sawdust and bamboo powder at same temperature and with moisture content had increased significant briquette relaxation density after added fibres. Sawdust with 12% moisture content had the most obvious increase in relaxation density up to 78%.

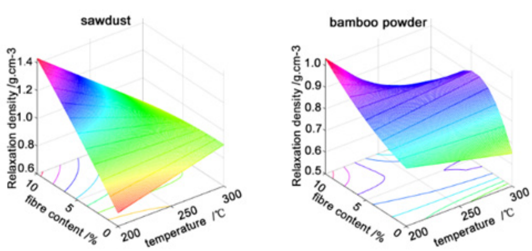

Fig. 7: Influence of heating temperature and fibre content.

According to the Tabs. 3 and 4, in the cross terms of the model, x1x3 is very significant ($P<0.01$), so the interaction between temperature and fibre content was just discussed.

By regression Eq. 3, 4 the researchers draw the response surface map using Matlab. When the moisture content is 14%, the response surface diagram of the influence of two factors, temperature and fibre content, was shown in Fig. 8.

As seen on the Fig. 8, when the temperature was between 200 ~ 250°C, the temperature was fixed at a certain level.

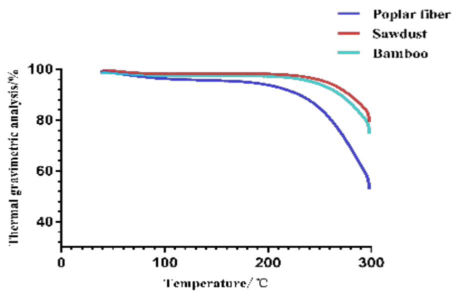

Fig. 8: TG curves of each sample under heating rate at 10°C·min^{-1}.

With the increase of fibres content, sawdust and bamboo powder briquette relaxation density increased to the maximum as the fibres content was 10%. When the temperature was between 250 to 300°C, and the temperature was fixed at a certain level, sawdust and bamboo powder briquette relaxation density would first increased and then decreased with the increase in fibre content.

Thermogravimetric analysis

The Fig. 9 showed the TG curve of sawdust, bamboo powder, and fibres with 10°C·min^{-1} of heating rate. Overall, the overall trend of the TG curves for the three samples were similar. The pyrolysis process of raw materials can be divided into three stages, physical drying stage, pre-carbonization stage and carbonization stage. Below 150°C, with the increase at temperature, the TG curves of three biomass slightly fluctuate, and the mass loss rate was from 1.68% to 4.44%. This was biomass endothermic dehydration stage, and the chemical composition of the fibre had rarely obvious change. Below 105°C, free water was mainly lost. From 105 to 150°C, the binding water and cell cavity adsorption water was continuously lost. During the pre-carbonization stage (150-240°C), the decomposition reaction mainly occurred, and hemicellulose first decomposed (hydrogen bonds and broken). The carbonization stage mainly occurred at 240-300°C. At this stage, the sample mass sharply reduced, and the mass loss rate was 28.7% ~ 51.57%. There was a maximum mass loss peak at about 300°C and fibre mass loss is the most significant one. And when the temperature is near 240°C, the loss rate of fibre mass obviously increased. The loss rate of fibre mass was far greater than that of sawdust and bamboo powder. The fibre carbonization was significantly earlier than that of sawdust and bamboo powder. At higher temperature, carbonization would be obvious. That explained Fig. 8 when the temperature went higher than 250°C, the briquette added with fibres had lower relaxation density. When the heating temperature was at 240°C, sawdust, bamboo powder and fibre started to carbonize. At the temperature range of 200~250°C, the effect of carbonization was not obvious. Macroscopically, the surface of the briquette was slightly carbonized, and the fibre as the solid bridge increased relaxation density of the briquette. When the temperature was between 250 ~ 300°C, the carbonized fibres mainily acted as lubricant between the briquette and the channel surface of the die. Thus fibres reduced the briquette density and densification quality of relaxation.

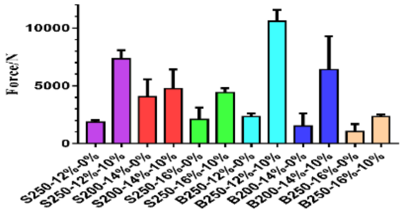

Fig. 9: Changes in max force.

Resistance to deformation

The researchers selected the same heating temperature and moisture content test point under table 300°C from Tab. 3, and carried out the radial maximum pressure test. As shown on the Fig. 9, After the sawdust and bamboo powder with the same temperature and moisture content was added fibres, the maximum radial pressure increased most significantly, which improved the performance of anti-deformation of briquette. The bamboo powder at 12% moisture content had the maximum radial pressure which most increased up to 384.4%.

Hydrophobicity

The hydrophobicity of the briquette reflected the suitable conditions for storing briquette. It can be concluded from the Fig. 10 that the hydrophobic property of the fibres briquette was better than that with no fibres at the same temperature and with same moisture content.

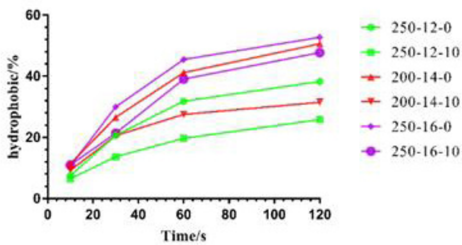

Fig. 10: Changes at water permeability.

During the test, it was found that the fibre briquette was harder to absorb and expand when soaking. This may be because the briquette of solid bridge were bonded more closely and the internal porosity was lower, which improved hydrophobicity, and to some extent, increased the physical properties of the briquette.

CONCLUSIONS

1. The steam explosion poplar fibres as an additive has significant effect on the sawdust and bamboo powder briquette relaxation density.
2. At the heating temperature of 200~250°C the fibres acts as "Solid Bridge" within the briquette process, and plays a positive role in the briquette of the particles, based on microscopic observation.

3. At the heating temperature of 200 to 250°C, as the fibre content increased, sawdust, bamboo powder briquette relaxation density, maximum radial pressure, and hydrophobicity increased significantly. For example, when the heating temperature was 200°C, the fibres content was 10%, the maximum radial pressure of the briquette was more than 6000 N, and the relaxation density is 1.03 $g \cdot cm^{-3}$, the hydrophobic property remarkably improved. When the heating temperature was 250 to 300°C, with the increase of fibres content, sawdust, bamboo powder briquette relaxation density first increased and then decreased. This was because the fibres carbonization started at a temperature of 240°C , with the increase of temperature, the carbonization rate was obviously higher than that with sawdust and bamboo powder. And at the temperature of 250-300°C , the carbonized fibres mainly acts as lubricant between the briquette and the channel surface of the die.

ACKNOWLEDGEMENTS

The authors are grateful for the support of the National Natural Science Foundation of China(Grant No.31500478), the Beijing Municipal Science & Technology Commission (Grant No.Z161100001316003) and the National College Students' innovation and entrepreneurship training program (Grant No.2016100220040).

REFERENCES

1. Bismarck, A., Aranberri-Askargorta, I., Springer, J., Lampke, T., Wielage, B., Stamboulis, A., Shenderovich, I., Limbach, H.H., 2002: Surface characterization of flax, hemp and cellulose fibres; surface properties and the water uptake behaviour, Polymer composites 23(5): 872-894.
2. Chin, O.C., Siddiqui, K.M., 2000: Characteristics of some biomass briquettes prepared under modest die pressures, Biomass and Bioenergy 18(3): 223-228.
3. El Mansouri, N.-E., Salvadó, J., 2006. Structural characterization of technical lignins for the production of adhesives: Application to lignosulfonate, kraft, soda-anthraquinone, organosolv and ethanol process lignin, Industrial Crops and Products, 24(1): 8-16.
4. Ferreira, S.L.C., Bruns, R.E., Ferreira, H.S., Matos, G.D., David, J.M., Brandao, G.C., da Silva, E.G.P., Portugal, L.A., dos Reis, P.S., Souza, A.S., dos Santos, W.N.L., 2007: Box-Behnken design: An alternative for the optimization of analytical methods, Analytica Chimica Acta 597(2): 179-186.
5. Hoogwijk, M., Faaija, A., van den Broek, R., Berndes, G., Gielen, D., Turkenburg, W., 2003: Exploration of the ranges of the global potential of biomass for energy. Biomass & Bioenergy 25(2): 119-133.
6. Jaya Shankar, T., Christopher, T.W., Kevin, L.K., Richard, J.H., 2010: A Technical Review on Biomass Processing: Densification, Preprocessing, Modeling and Optimization.
7. Kaliyan, N., Morey, R.V., 2009a: Densification characteristics of corn stover and switchgrass. Transactions of the Asabe 52(3): 907-920.
8. Kaliyan, N., Morey, R.V., 2009b: Factors affecting strength and durability of densified biomass products, Biomass & Bioenergy 33(3): 337-359.
9. Kaliyan, N., Morey, R.V., 2010. Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switchgrass, Bioresource Technology 101(3): 1082-1090.

10. Kaliyan, N., Morey, R.V., 2009c: Strategies to improve durability of switchgrass Briquettes, Transactions of the Asabe 52(6): 1943-1953.
11. Kaliyan, N., Vance Morey, R., 2009: Factors affecting strength and durability of densified biomass products, Biomass and Bioenergy 33(3): 337-359.
12. Kuokkanen, M., Vilppo, T., Kuokkanen, T., Stoor, T., Niinimaki, J. 2011. Additives in wood pellet production - A pilot-scale study of binding agent usage, Bioresources 6(4): 4331-4355.
13. Lauri, P., Havlik, P., Kindermann, G., Forsell, N., Boettcher, H., Obersteiner, M., 2014: Woody biomass energy potential in 2050, Energy Policy 66: 19-31.
14. Li, H., Liu, X., Legros, R., Bi, X.T., Lim, C.J., Sokhansanj, S. 2012: Pelletization of torrefied sawdust and properties of torrefied pellets, Applied Energy 93: 680-685.
15. Orire, A.M., Sadiku, S.O., Tiamiyu, L.O., 2010. Evaluation of yam starch (Discorea rotundata) as aquatic feed binder, Pakistan Journal of Nutrition 9(7): 668-671.
16. Parikka, M., 2004: Global biomass fuel resources, Biomass & Bioenergy 27(6): 613-620.
17. Pfost, H., Young, L., 1977: Effect of colloidal binders and other factors on pelleting, Tecnica Molitoria.
18. Pietsch, W.B., 2008: Agglomeration processes: phenomena, technologies, equipment. John Wiley & Sons.
19. Rumpf, H. 1962. The strength of granules and agglomerate. In: Agglomeration-Proceedings of the First International Symposium on Agglomeration, Philadelphia, USA.
20. Soleimani, M., Tabil, X.L., Grewal, R., Tabil, L.G., 2017: Carbohydrates as binders in biomass densification for biochemical and thermochemical processes Fuel 193: 134-141.
21. Stahl, M., Berghel, J., Granstrom, K., 2016: Improvement of wood fuel pellet quality using sustainable sugar additives, Bioresources 11(2): 3373-3383.
22. Stelte, W., Sanadi, A.R., Shang, L., Holm, J.K., Ahrenfeldt, J., Henriksen, U.B., 2012: Recent developments in biomass pelletization - A review, Bioresources 7(3): 4451-4490.
23. Stevens, J., Gardner, D.J., 2010. Enhancing the fuel value of wood pellets with the addition of lignin, Wood and Fiber Science 42(4): 439-443.
24. Tumuluru, J.S., Wright, C.T., Hess, J.R., Kenney, K.L., 2011: A review of biomass densification systems to develop uniform feedstock commodities for bioenergy application, Biofuels, Bioproducts and Biorefining 5(6): 683-707.
25. van der Stelt, M.J.C., Gerhauser, H., Kiel, J.H.A., Ptasinski, K.J., 2011: Biomass upgrading by torrefaction for the production of biofuels: A review, Biomass & Bioenergy 35(9): 3748-3762.
26. Wood, J.F., 1987: The functional properties of feed raw materials and their effect on the production and quality of feed pellets, Animal Feed Science and Technology 18(1): 1-17.
27. Yamashiki, T., Matsui, T., Saitoh, M., Okajima, K., Kamide, K., Sawada, T., 1990: Characterisation of cellulose treated by the steam explosion method. Part 2: Effect of treatment conditions on changes in morphology, degree of polymerisation, solubility in aqueous sodium hydroxide and supermolecular structure of soft wood pulp during steam explosion, Polymer International 22(2): 121-128.

Xuehao Wang, Zhongjia Chen*, Guosheng Yu, Xiangyue Yuan
Beijing Forestry University
E(Ast) Qinghua Road 35
Haidian District 100083
Beijing
China
Corresponding author: chenzhongjia@bjfu.edu.cn; sgyzh@bjfu.edu.cn