

Manufacturing Biofuel Briquettes from Industrial Sludge

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Abstract: Based on differences in the internal organization and thermal characteristics of industrial sludge, the main heat source or cementing agent is provided during the manufacture of biofuel briquettes. This study thus discusses the producibility and flammability of biofuel briquettes, and proposes the optimal formula for producing biofuel briquettes from industrial sludge. The experimental results demonstrated that food processing sludge and sewage sludge can offer excellent calorific value, combustion rate and flame temperature. Moreover, pulp sludge and sewage sludge can provide cementing properties. The four industrial sludge, including food processing sludge, pulp sludge, textile sludge and sewage sludge, can reach the surface combustion stage at 83°C, and can begin stable burning at 177–247°C. The corresponding temperature of maximum weight loss is 250–351°C. Considering the manufacturability, stability and combustion characteristics of biofuel briquettes produced from industrial sludge, the recommended appropriate additions of food processing sludge, pulp sludge, textile sludge and sewage sludge are 30–50%, 20–50%, 20–30% and 30–40% of the total mixture, respectively.

Keywords: Sludge, Optimized Formula, Biofuel Briquettes, Formability, Combustion

1. Introduction

Taiwan does not enjoy self-sufficiency in energy, and hence the development of alternative energy supplies and multiple energy sources is critical to economic development. According to statistics from the Ministry of Economic Affairs, Executive Yuan, the declared quantity of industrial waste reused as fuel increased from 103,000 MT in 2005 to 261,000 MT in 2014, suggesting that the industrial waste recycled fuel grew a significant increase in recycling of industrial waste into fuel. Waste is used as fuel to partially ease or replace demand for traditional fossil fuels, and once waste disposal is solved, it becomes possible to develop multiple energy sources and solve environmental pollution problems.

Numerous investigations have developed techniques to use biomass waste and industrial sludge to produce fuel briquettes, and such refuse derived fuel has extensive applications. Olive and paper mill wastes are extruded at normal temperature to produce fuel briquettes. The paper mill waste increases the strength of the briquettes [1]. Municipal solid waste at normal temperature is used to compact fuel without binder and under a specific pressure of 138MPa. Meanwhile, the waste paper acts as a binder, and the water content and extrusion pressure are critical production parameters [2]. Compressive strength,

particle size, and water content significantly influence the density of biomass aggregates [3, 4]. The crushed straw and rice bran are processed using a thermocompressor into densified biofuel [5]. The fuel value correlates with the proportional addition of rice bran as well as the pressing temperature. The pulp sludge can be used in hybrid tires, soft coal and RDF-5 as auxiliary fuel [6], or co-firing [7, 8]. The mixture of pulp and textile sludge can increase the calorific value and inflammability of fuel briquettes. The pulp sludge provides cementing properties since owing to its fibrous texture [9]. The organic sludge and wood chip of TFT-LCD plant are mixed with RDF-5 to produce fuel briquettes, which have a calorific value of approximately 18.2–21.0MJ/kg [10, 11]. The calorific value of the fuel derived from sewage sludge with meat and bone meal and wood chip is 13–15MJ/kg, while that of the fuel derived from sewage sludge with peat is approximately 19.0MJ/kg [12]. The olive oil waste and wood waste are used to produce solid biofuel. The olive oil waste increases the combustion temperature and exhaust emissions of solid biofuel [13]. Moreover, the organic sludge of LCD plant is mixed with waste cooking oil, and can generate a higher calorific value (about 19.9–25.8MJ/kg) after drying by frying. The rate of burning of the fry dried organic sludge increases by approximately 1.3 times [14]. The oil sludge as

main material is mixed with wood chip, coal dust and PE as auxiliary materials to yield fuel briquettes. These additions improve the firing behavior of the fuel [15]. Numerous types of waste can be used to produce fuel briquettes, allowing the simultaneous solution of problems of waste disposal and environmental pollution [16, 17].

The influence of different industrial sludge mix blends on the manufacturing characteristics and combustion behavior of biofuel briquettes is discussed by analyzing the basic properties of industrial sludge, as well as the formability, stability, calorific value and combustion flame curves of biofuel briquettes. This study thus proposes a strategy for the practical application of industrial sludge.

2. Methodology

2.1. Experimental Materials

The industrial sludge used in this study were dewatered sludge from four large-scale processing manufacturers located in Taiwan. Food processing sludge (FS) came from the dairy and beverage industries; Pulp sludge (PS) was collected from paper mill and textile sludge (TS) was collected from textile mill; Dewatered sewage sludge (SS) cakes produced by Taipei Di-hua Wastewater Treatment Plant. The four industrial sludge are processed through drying, primary screening (screening debris), crushing, grinding, and final screening, to obtain industrial sludge powder, respectively, which passed through a #100 sieve (less 150 μm).

2.2. Experimental Design

As the four industrial sludge possess different compositions, internal organizations and thermal properties, they act as main heat sources, flammable compounds or cementing agents in the production of biofuel briquettes. Therefore, this study designs nine formulas (FS60PS40, FS50PS50,

FS30PS40TS30, FS40PS30TS30, FS60PS20SS20, FS50PS20SS30, FS40PS20SS40, FS40PS30SS30, FS30PS40SS30) for the production of biofuel briquettes from industrial sludge. The manufacturability and firing behavior of biofuel briquettes are discussed by analyzing the basic property of industrial sludge, as well as the formability, stability and flame temperature of biofuel briquettes.

The procedures for four industrial sludge analysis included approximate analysis (NIEA R213, NIEA R205; “NIEA” stands for “National Inspection and Environmental Analysis Laboratory, Environmental Protection Administration, Taiwan”), elemental analysis (by Heraeus vario III–NCSH), and calorific values (by the adiabatic bomb calorimeter method, NIEA R214.01C).

Moreover, the analysis items for biofuel briquettes included formability, moisture regain, dry bulk density, penetration loading (by a penetrometer), thermo-gravimetric loss (by a thermo-gravimetric analysis / differential thermal thermo-gravimetric, TG–DTG), and flame temperature (using an infrared thermal camera in the spectral range 8–14 μm).

3. Results and Discussion

3.1. Characteristics of Industrial Sludge

The moisture contents of food processing sludge, pulp sludge, textile sludge and sewage sludge are 86.52%, 65.00%, 80.00% and 77.27%, respectively; moreover, the dry basis ash contents are 14.02%, 54.29%, 53.60% and 30.62%, respectively; and the dry basis combustible contents are 85.95%, 45.71%, 46.40% and 69.38%, respectively (Table 1). Industrial sludge is likely to cause an environmental hazard owing to its extremely high moisture content (65–85%), while the food processing sludge and sewage sludge have low ash content and high combustible content, while the pulp sludge and textile sludge exert an opposite effect.

Table 1. Characteristics of industrial sludge.

Characteristics	FS	PS	TS	SS
Moisture (%)	86.52	65.00	80.00	77.27
Ash content (% dry basis)	14.02	54.29	53.60	30.62
Combustible content (% dry basis)	85.98	45.71	46.40	69.38
Calorific value (MJ/kg dry basis)	25.70	8.73	11.99	17.25
Flame temperature ($^{\circ}\text{C}$, Max)	1,120	662	937	1,088
Heating rate ($^{\circ}\text{C}$ /sec, 1min)	0.0113	0.0032	0.0065	0.0078
Bulk density (g/cm^3 , dry basis)	0.89	1.21	1.02	0.87
Sludge-fuel value index (SFVI)	1.62	0.19	0.23	0.49

FS: Food processing sludge; PS: Pulp sludge; TS: Textile sludge; SS: Sewage sludge
 $\text{SFVI} = [\text{Calorific value (MJ/kg)} \times \text{Fuel density (g/cm}^3\text{)}] / [\text{Ash content (\%)}]$

According to the analytical results obtained for four industrial sludge (FS, PS, TS, SS), the carbon element (C) content is 47.44%, 18.48%, 32.15% and 35.08%, respectively. Food processing sludge has the highest content, followed by sewage sludge. The elemental hydrogen (H) content is 7.37%, 1.78%, 5.73% and 5.48% respectively; the food processing sludge has the highest elemental nitrogen (N) content (5.51%), followed by the sewage sludge (3.63%). The sulfur content (S) of textile sludge (1.64%) and sewage sludge (1.42%)

resembles that of bunker coal (1.7–2.0%), and that of food processing sludge (0.24%) and pulp sludge (<0.01%) is significantly lower than that of bunker coal. The chlorine element (Cl) content of food processing sludge (0.07%), pulp sludge (0.09%) and textile sludge (0.07%) resembles that of bunker coal (0.1–0.3%), while that of sewage sludge (0.01%) is lowest.

The calorific value of the four varieties of industrial sludge (FS, PS, TS, SS) is 25.70 MJ/kg, 8.73 MJ/kg, 11.99 MJ/kg and

17.25MJ/kg respectively. The calorific value of food processing sludge is observed to approximate that of bituminous coal (25.67MJ/kg). Additionally, the calorific values of sewage, textile and pulp sludge are about 2/3, 1/2 and 1/3 of those of bituminous coal, respectively (Table 1). Therefore, the biofuel potential of industrial sludge can be given a preliminary assessment based on its carbon content, combustible content and calorific value. Using the bomb calorimeter experiment, the heating rates of the four varieties of industrial sludge (FS, PS, TS, SS) during the first 60 sec are 0.0113°C /s, 0.0032°C /s, 0.0065°C /s and 0.0078°C/s respectively. Notably, the food processing sludge has the highest heating rate, while the pulp sludge has the lowest. The infrared thermal imager demonstrated that the maximum combustion flame temperatures of the four industrial sludge (FS, PS, TS, SS) are 1120°C, 662°C, 937°C and 1088°C respectively. The food processing sludge has the highest maximum temperature, while the pulp sludge has the lowest. The food processing sludge provides excellent calorific value, heating rate and flame temperature, and is followed in this regard by the sewage sludge and textile sludge. The pulp sludge is significantly worse than the other three industrial sludge.

The volatile matter initiation temperature (ITVM), fixed

carbon initiation temperature (ITFC) and the temperature of the maximum weight loss rate (T_{max}) of industrial sludge are obtained using TG-DTG curves (Figure. 1 and Table 2) [18]. The ITVM of the four varieties of industrial sludge (FS, PS, TS, SS) is 39°C, 50°C, 51°C and 83°C, respectively. The food processing sludge has the lowest ITVM, suggesting that it can achieve surface combustion at a low temperature, which implies excellent inflammability. The ITFCs of the four varieties of industrial sludge are 206°C, 235°C, 177°C and 247°C, respectively. The textile sludge has the lowest ITFC, suggesting it can reach the core combustion stage at low temperature. The T_{max} of the four varieties of industrial sludge is 309°C, 351°C, 250°C and 339°C, respectively, suggesting the food processing sludge can reach maximum weight loss at low temperature. Table 3 lists the corresponding temperatures for weight loss of 5 %, 10% and 30%, respectively. The ITVM, ITFC and T_{max} of industrial sludge thus can be obtained using TG-DTG curves to determine whether it reaches the surface combustion, stable burning, and maximum weight loss stages. The four varieties of industrial sludge can achieve surface combustion at 83°C, and followed by stable burning at 177–247°C. Meanwhile, the temperature at which maximum weight loss is reached is 250–351°C.

Table 2. TG-DTG results of industrial sludge.

Items	FS	PS	TS	SS
Volatile matter initiation temperature (ITVM, °C)	39	50	51	83
Fixed carbon initiation temperature (ITFC, °C)	206	235	177	247
Weight loss (5%, °C)	200	300	177	262
Weight loss (10%, °C)	240	350	224	285
Weight loss (30%, °C)	315	693	400	362
Weight loss (max., °C)	558	561	601	581
Temperature of maximum weight loss rate (T_{max} , °C)	309	351	561	339

FS: Food processing sludge; PS: Pulp sludge; TS: Textile sludge; SS: Sewage sludge

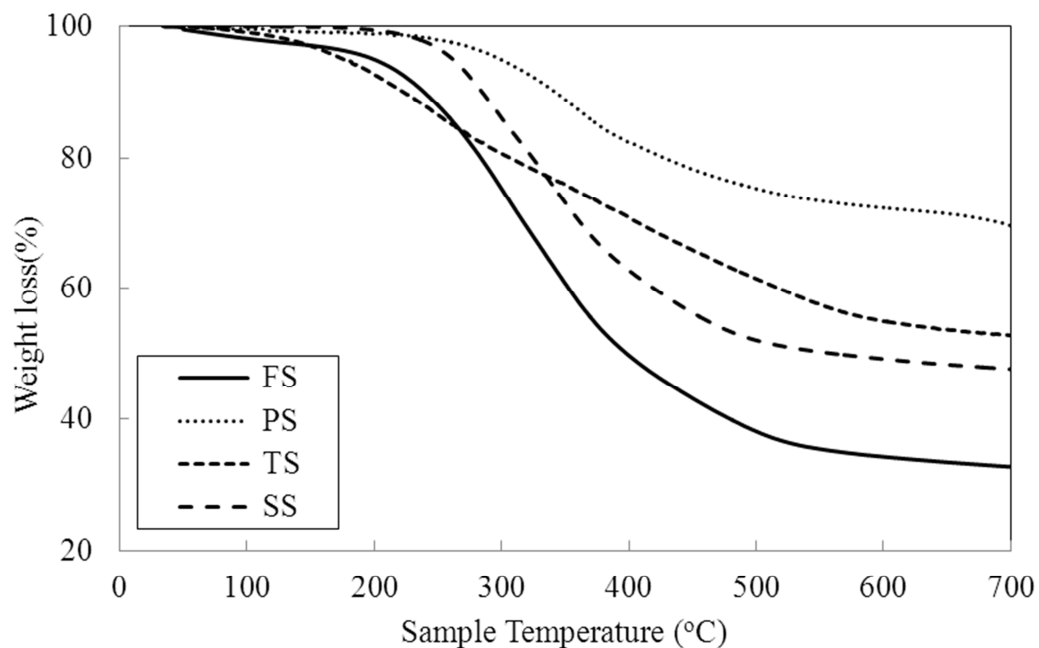


Figure 1. The thermo-gravimetric loss of industrial sludge.

3.2. Formability of Biofuel Briquettes from Industrial Sludge

The formability ($L > 10\text{mm}$) and formability ($L > 20\text{mm}$) of biofuel briquettes produced from industrial sludge are 98–99% and 61.09–95.05%, respectively, suggesting that FS50PS50 has the best formability, while FS30PS40SS30 has the worst (Table 3). Figure 2 illustrates the external appearance. The formability of biofuel briquettes can be increased through a

larger addition of pulp and sewage sludge. However, when the addition of sewage sludge exceeds 40%, the formability of biofuel briquettes reduces as the mixture becomes too viscous. This experimental result demonstrated that the pulp sludge and sewage sludge can be adopted to bind biofuel briquettes, but should be added in appropriate proportions. Excessive addition of food processing sludge to formulas will reduce the formability of biofuel briquettes.

Table 3. Formability and stability of industrial sludge biofuel briquettes.

Samples	Formability (%, $L > 10\text{mm}$)	Formability (%, $L > 20\text{mm}$)	Dry bulk density (g/cm^3)	Penetration loading (kgf)	Moisture regain (%, 72hr)
FS60PS40	94.28	67.41	0.98	2.06 ± 0.35	8.39
FS50PS50	99.55	95.05	1.10	3.51 ± 0.81	7.85
FS40PS30TS30	99.01	93.30	1.03	1.92 ± 0.86	7.95
FS30PS40TS30	99.82	92.87	1.06	3.32 ± 0.94	7.60
FS60PS20SS20	98.98	90.99	1.04	1.14 ± 0.16	8.96
FS50PS20SS30	99.37	87.48	0.94	1.86 ± 0.62	9.45
FS40PS20SS40	93.41	88.25	0.91	1.70 ± 0.27	8.28
FS40PS30SS30	98.13	75.79	1.03	1.20 ± 0.09	9.86
FS30PS40SS30	73.71	61.09	1.02	2.26 ± 1.10	8.96

FS: Food processing sludge; PS: Pulp sludge; TS: Textile sludge; SS: Sewage sludge

Table 4. Combustion of industrial sludge biofuel briquettes.

Samples	Calorific value (MJ/kg)	Flame temp ($^{\circ}\text{C}$, max)	Combustion rate ($^{\circ}\text{C}/60\text{sec}$)	Combustion rate ($^{\circ}\text{C}/120\text{sec}$)
FS60PS40	17.61	1,150	0.0087	0.0090
FS50PS50	17.00	1,079	0.0090	0.0088
FS40PS30TS30	16.42	1,082	0.0061	0.0077
FS30PS40TS30	15.02	993	0.0065	0.0072
FS60PS20SS20	20.32	1,198	0.0093	0.0108
FS50PS20SS30	18.23	1,160	0.0091	0.0097
FS40PS20SS40	18.02	1,160	0.0072	0.0091
FS40PS30SS30	17.18	1,145	0.0084	0.0090
FS30PS40SS30	15.21	1,071	0.0083	0.0079

FS: Food processing sludge; PS: Pulp sludge; TS: Textile sludge; SS: Sewage sludge



Figure 2. Appearance of industrial sludge biofuel briquettes.

3.3. Stability of Biofuel Briquettes from Industrial Sludge

The stability of biofuel briquettes produced from industrial sludge is discussed in terms of dry bulk density, penetration loading and moisture regain (Table 3). The dry bulk density of the biofuel briquettes produced from industrial sludge is 0.91–1.10g/cm³, with that of FS50PS50 being highest, and that of FS40PS20SS40 being lowest. The penetration loadings of biofuel briquettes produced from industrial sludge is 1.1–3.5kgf, suggesting high strength variability. FS50PS50 and FS30PS40TS30 have higher strength, while FS40PS30SS30 and FS60PS20SS20 have lower strength, as illustrated in

Figure 3. The moisture regain of biofuel briquettes from industrial sludge in 72 h is 7.6–9.8%, indicating a small variation range. FS30PS40TS30, FS50PS50 and FS40PS30TS30 are below 8.0%, and the moisture regain stabilizes following 96 h, as illustrated in Figure 4. The penetration loadings of biofuel briquettes can be increased by adding pulp sludge, since the pulp sludge has long fibers, and thus provides superior cementation. The addition of pulp sludge or textile sludge yields a compact structure that decreases the regain percentage of biofuel briquettes.

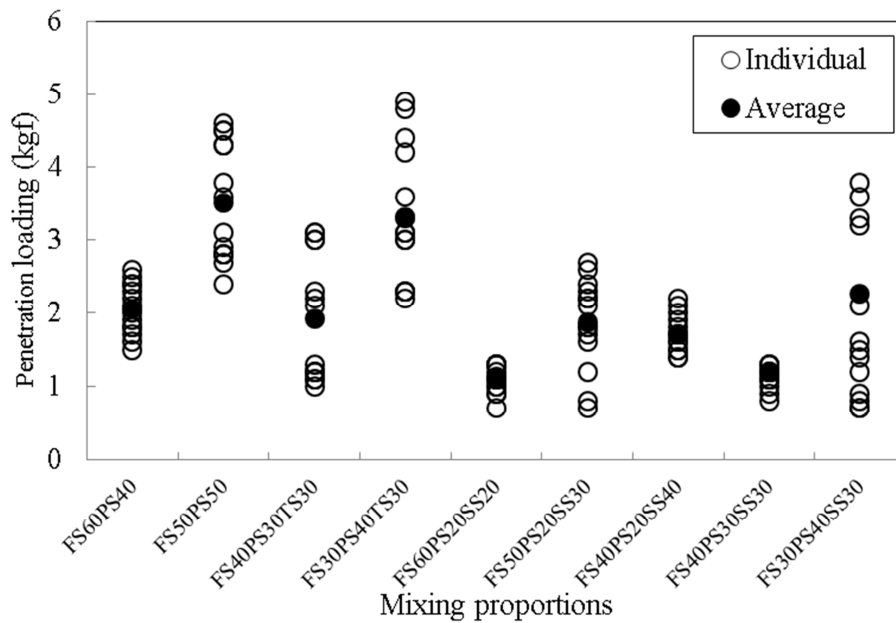


Figure 3. Penetration loading of industrial sludge biofuel briquettes.

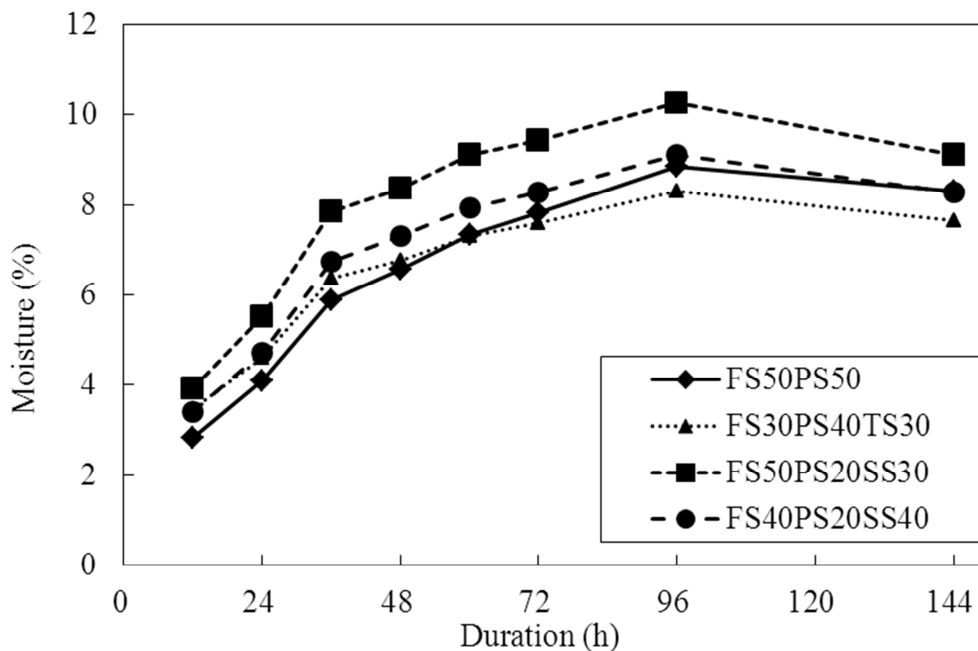


Figure 4. Moisture regain of industrial sludge biofuel briquettes.

3.4. Combustion of Biofuel Briquettes from Industrial Sludge

Table 3 lists the calorific value, flame temperature and burning rate of biofuel briquettes from industrial sludge. The calorific value of fuel briquettes produced from industrial sludge is 15.02–20.32MJ/kg. FS60PS20SS20 is better, while FS30PS40TS30 is worse, because the food processing sludge has the maximum calorific value, while the pulp sludge has the minimum. In terms of the combustion rate of biofuel briquettes from industrial sludge during the first 60 sec, FS60PS20SS20 is the highest at 0.0093°C/s, while FS30PS40TS30 is the worst (Figure. 5). The flame temperature of biofuel briquettes produced from industrial sludge is 993–1198°C, while FS60PS20SS20 has the highest

flame temperature and FS30PS40TS30 has the lowest (Figure. 6). The food processing sludge and sewage sludge can increase the combustion rate and flame temperature of biofuel briquettes, while the pulp sludge does the reverse. Because food processing and sewage sludge possess combustion-supporting and quick burning characteristics, excessive addition can reduce the formability and penetration loadings of biofuel briquettes. The recommended addition level of food processing sludge and sewage sludge is below 50% and 40%, respectively. Pulp sludge can improve the formability and stability of biofuel briquettes, but excessive addition can significantly reduce the calorific value, combustion rate and flame temperature of biofuel briquettes. The recommended addition level of pulp sludge is below 50%.

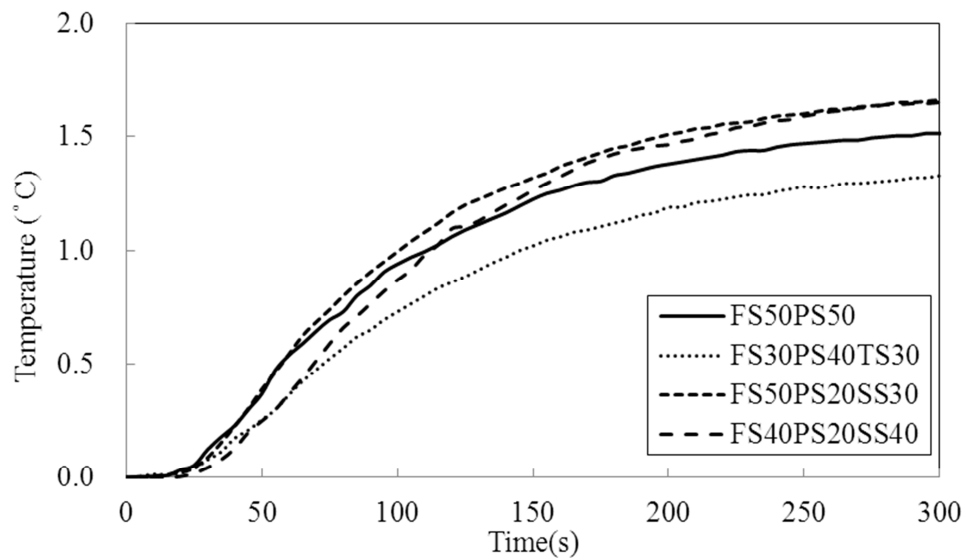


Figure 5. The heating curves of industrial sludge biofuel briquettes.

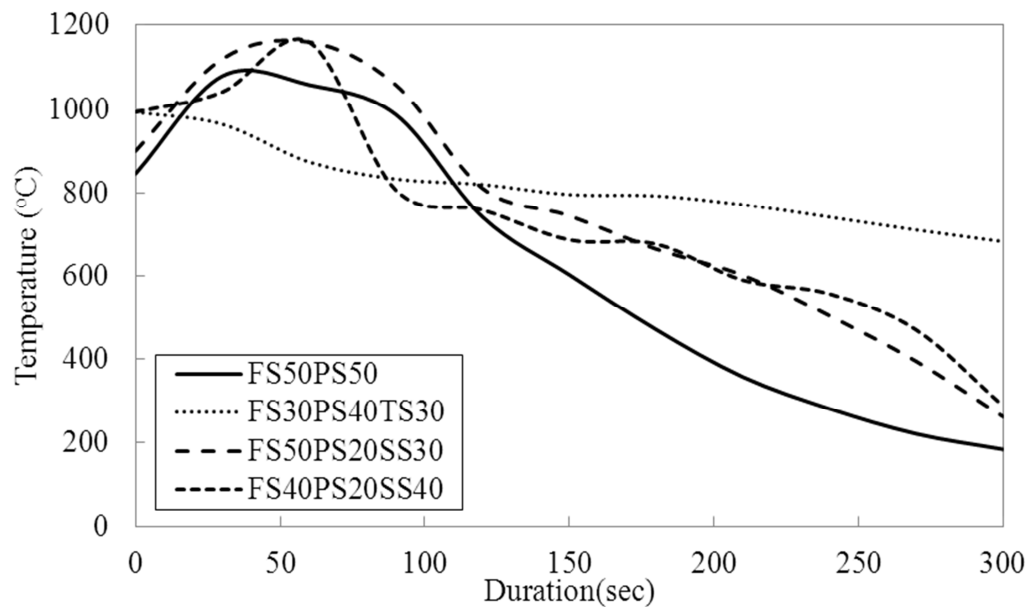


Figure 6. Flame temperature of industrial sludge biofuel briquettes.

3.5. Optimal Formula of Biofuel Briquettes from Industrial Sludge

According to the above experimental results on the stability of biofuel briquettes produced from industrial sludge, pulp sludge can increase the formability, breaking weight and regain percentage of biofuel briquettes. Pulp sludge is a suitable binder for fuel briquettes. Sewage sludge can enhance the formability of biofuel briquettes, but excessive addition (>40%) will result in excessive viscosity and reduce formability. Based on the above experimental results related to the calorific value, heating rate and combustion temperature of biofuel briquettes from industrial sludge, food processing sludge and sewage sludge can increase the calorific value, heating rate and combustion temperature of biofuel briquettes. Thus, food processing sludge and sewage sludge are suitable as the main heat source of biofuel briquettes.

Considering the manufacturability, stability and combustion characteristics of biofuel briquettes manufactured from industrial sludge, the appropriate additions of food processing sludge, pulp sludge, textile sludge and sewage sludge are recommended as 30–50%, 20–50%, 20–30% and 30–40% of the mixture, respectively. The sludge biofuel briquettes FS30PS40TS30 have high manufacturability, the sludge biofuel briquettes FS60PS20SS20 have high calorific value and inflammability, and the sludge biofuel briquettes FS50PS50, FS30PS40TS30 and FS50PS20SS30 have high manufacturability, calorific value and inflammability.

4. Conclusions

- (1) The biofuel potential of industrial sludge can be preliminarily assessed based on its carbon content, combustible content and calorific value. Food processing sludge and sewage sludge provide excellent calorific value, heating rate and flame temperature, while the characteristics of textile sludge are slightly worse, and finally pulp sludge is worst of all. Pulp sludge and sewage sludge can be used to bind biofuel briquettes, while food processing sludge reduces the formability of biofuel briquettes.
- (2) Four varieties of industrial sludge, including food processing sludge, pulp sludge, textile sludge and sewage sludge, can reach the surface combustion stage at 83°C, and the stable burning stage at 177–247°C. The temperature on reaching maximum weight loss is 250–351°C.
- (3) The optimized formulas of biofuel briquettes made from industrial sludge, the addition of food processing sludge, pulp sludge, textile sludge and sewage sludge is recommended as 30–50%, 20–50%, 20–30% and 30–40% of total mixture. The sludge biofuel briquettes FS30PS40TS30 have high manufacturability, the briquettes FS60PS20SS20 have high calorific value and inflammability, and the briquettes FS50PS50, FS30PS40TS30 and FS50PS20SS30 have high

manufacturability, calorific value and inflammability.

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